REVIEW

Eucalypts as a biofuel feedstock

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Eucalypts are both a proven but largely unexplored source of woody biomass for biofuel production. Few of the some 900 species have been evaluated for cropping, yet among them are the most productive and versatile biomass species in the world, grown in over 90 countries, with species found to suit most tropical and temperate climates. The biology, science and technology underlying the breeding and growing of eucalypts and their potential for biofuel production are reviewed. How eucalypts meet sustainability and economic criteria for biofuel feedstocks, and the advantages of woody feedstocks broadly, are considered. Relevant aspects of eucalypt taxonomy, evolution, natural distribution, human dispersal, composition, domestication and biotechnology of the groups' potential as a biofuel feedstock resource are reviewed. Two case studies are outlined, illustrating species identification, domestication and harvesting processes where eucalypts are prospective biofuel feedstocks. Eucalypts are strong contenders as a universal woody biomass feedstock for biofuel.

Depletion of fossil fuel energy sources and the need to move to low carbon economies to mitigate climate change is driving research and innovation in renewable sources for energy. Biofuels (primarily ethanol, methanol, diesel and hydrogen) are viewed as a critical part of the solution, already playing a significant part of liquid fuel supply in a number of major economies. Examples include; ethanol from cornstarch in the USA, ethanol from sugar in Brazil and diesel from rapeseed in Europe [1]. Increasingly, however, ethical and environmental concerns over biofuels and other bioenergy crops have been questioned, and interest has shifted to development of a second-generation biofuel industry (i.e., one based on nonedible fibrous or woody plant biomass – cellulosic and lignocellulosic feedstock) [2–6]. Nonfood feedstocks have advantages in energy balance, environment and economic performance criteria compared with food-based feedstocks such as corn- and other starch-based biofuels. Any large-scale development of biomass production will require the selection and development of bioenergy crops and cropping systems that do not compromise food production [2,7]. New sustainability standards are being developed and adopted by governments to promote a shift away from unsustainable biofuels based on grain [1,8].

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Countries such as Australia and the USA are well suited to production of second generation feedstocks, as they can be grown on marginal land, land unsuitable for agriculture or in integrated systems, so that they are complementary to conventional agriculture [9,10]. Second generation feedstocks have potential to be produced in large volumes and to create new large-scale industries that can stimulate rural economies and enhance national energy security [11]. However, the long-term sustainability of even these sources, without technological advances (i.e., efficiencies of the internal combustion engine), has also been questioned [12]. Proposals to develop such industries has been accompanied by scrutiny of their energy and carbon balances, and changes in policy and mandates for so called 'advanced biofuels' (a definition that includes sustainability criteria) are also driving change and innovation in processing technology and choices of feedstocks in some countries.

Among tree species, eucalypts are well positioned for bioenergy production. Other major species groups considered include willows, poplars, pines and casuarinas. Eucalypts are notable, however, for several reasons. They are well adapted and capable of rapid growth in a wide range of climates, ranging from temperate to tropical. Many are also capable of growing well on soils that are shallow, structurally poor and of low nutrient status, including soils that have been degraded by other activities. For these reasons they are the most widely planted hardwood in the world, with an estimated estate of some 20.5 milllion ha globally, in over 90 countries [Pers. Comm., GIT Forestry Consulting, 2009]. They are grown on an industrial scale in many tropical countries, are a major source of timber, pulp and firewood, and are increasingly considered for bioenergy (electricity, charcoal and fuel), including enzymatic conversion to ethanol, burning for production of electricity, pyrolysis for production of charcoal and bio-oils, or conversion by Fisher–Tropsch processes to biodiesel [6,10,13]. There is a huge knowledge base in the breeding, growing, production and processing of eucalypt biomass, and in the structure and chemistry of its wood. As an important commercial plant group, it has received much attention for advanced breeding and biotechnological approaches to improvement.

Biomass is available from many sources. Existing biomass residues from primary sources (forestry and agricultural field residues), secondary sources (processing residues) and tertiary wastes are still underutilized. Biomass from dedicated crops (herbaceous and woody crops) has the advantage that it can be grown for purpose. A wide range of biomass crops could emerge and compete with residue sources and with each other for production of ethanol or other biofuels [14]. In many cases the alternative annual crops will produce superior biomass yield per unit time. However, such crops will typically require higher quality land that might otherwise be used for food production. The advantage of many species of eucalypts is their ability to be productive on marginal lands.

Feedstock choice for biofuels is a highly complex process, with many uncertainties in the economics (influenced by production systems, whether it is a primary product of the crop, a co-product or from a residue stream), social and policy environments, and conversion and utilization efficiencies. New breakthroughs can rapidly change assumptions about which feedstock species would perform best [10]. Regardless of contention as to whether eucalypts should be grown on an industrial scale primarily for biofuel (as indeed applies to many feedstock choices), the opportunity for biofuel as a co-product from residues from the massive existing planted resource base of eucalypts needs to be confronted.

Our purpose here is to review the attributes of eucalypts that will serve them as feedstocks for biofuels. In the section titled 'Sustainability and economics' we briefly consider desirable attributes of feedstocks broadly, and why woody sources may have advantages. In the section titled 'Eucalypts', we review eucalypts in particular, considering features of their taxonomy, evolutionary history, natural distribution, human dispersal, composition, domestication and biotechnology that impact on their potential as a biofuel feedstock. Finally, in the section titled 'Eucalypts for biofuel production in the southern sheep/wheat & northern subtropical zones of Australia', we consider two case studies of where eucalypts are being considered as a biofuel feedstock in Australia, northern Australia and Western Australia (WA). This section focuses on the status of domestication and species selection for these regions but also links to literature on landbase evaluation and the economic feasibility of industries in these regions. We point the reader to reviews of the potential for eucalypts for bioenergy in other countries and regions of the world [10,14]. The review by Grattapaglia [13] considers eucalypts more widely for energy, fibre and wood and a recent review [15] provides a more detailed analysis of the application of biotechnology to eucalypt improvement.

Our review suggests eucalypts meet many of the social and sustainability criteria now demanded of biofuel feedstocks, but there remain some concerns over their use on industrial scales in some environments due to weediness and alteration to water tables. Uptake of eucalypt biomass as biofuel feedstock will be underpinned by a solid knowledge base of how they can be bred and grown in many countries, as well as an advanced understanding in the science of wood formation and strong opportunities in biotechnology. Eucalypts have been found to be versatile and resilient, suitable for planting in marginal environments (or degraded land) and grown with low inputs. Many species **coppice** and provide highly competitive growth performance in plantations. The large existing planted estate represents a significant resource opportunity to produce biofuel as a co-product in addition to wood and fiber production.

Sustainability & economics

In this section we review some of the generic advantages that wood feedstocks may have for biofuel production; as appropriate, focus is narrowed to eucalypts. Woody biomass has an advantage in being energy dense, a key advantage in minimizing the energy costs of biomass transport. Biofuels from woody feedstocks may have other advantages compared with agricultural sources. The perennial nature of the crop means that the product can be stored in the field until it is required (thus avoiding double handling and allowing for a continuous supply chain). It also means that woody biomass can complement nonstorable and variable-supply feedstocks such as agricultural crop field residues and biomass grass crops. In the Australian context, the use of native woody species well adapted to the Australian environments means that they can be grown with minimal inputs, and they may also offer environmental services, such as providing habitat for native fauna or bioremediation [6]. Many woody species, especially the eucalypts, also have the advantage that they can resprout (coppice) from rootstocks after harvest, thus help build a permanent store of carbon in below-ground biomass [6]. Eucalypts have many of the desirable silvicultural features of energy plantations; they can be grown at high densities for fast site occupancy, or low density in agroforestry or in an inter-cropping configuration. They can achieve high growth rates under intensive silviculture, and many species may be grown in short harvest cycles.

▪ Sustainability

As a cellulose feedstock, eucalypt biomass would appear to also have many favorable sustainability criteria. Assessing sustainability is a highly complex and contentious science, but a recent analysis of biofuel sustainability concluded that cellulosic ethanol has the potential to be among the most sustainable of all the current and foreseeable commercial biofuels (not necessarily referring to wood sources, however) whereas ethanol from cornstarch was not sustainable, and ethanol from sugar was questionable [1]. The reasons for this include "a larger resource and landbase for feedstock (than current 1st generation sources), higher energy return on investment, potentially greater economical efficiency and equitable resource distribution" [1]. Feedstocks from trees also offer advantages in improving social equity as production can be much more wide spread in developing countries, grown with little or no conflict with food resources, lower GHG emissions and provide other environmental benefits. Energy efficiency, measured as energy return on investment from cellulosic ethanol, was estimated as 4:4 to 6.6:1, higher than estimates for ethanol from cornstarch (1.3:1) or soybean biodiesel (3.7:1), comparable to sugarcane (3.1:1 to 10:1), and approaching current values for fossil fuels [1].

Not all assessments of biofuel sustainability are in agreement. Some discrepancy appears to be due to use of different bases and assumptions [1]. Some analyses of the thermodynamics of bioenergy (including electricity and biofuels), regardless of feedstock (woody or otherwise) and conversion technologies, conclude bioenergy can not be truly 'sustainable' with current technologies where purpose-grown industrial-scale feedstock are used [12]. Two key observations relating to the overall energy balance in the production of ethanol from woody feedstocks were the low efficiency of the internal combustion engine (35%) at converting fuel into useful (rotation) energy and high-energy inputs in the drying, processing (pelleting) and transport of woody biomass. This highlighted the need for technological advancements to continue to improve overall energy balance of biofuel production.

The growing of eucalypts on an industrial scale does nonetheless present a number of specific environmental concerns. Where they are grown as an exotic, there is a need to assess their weed potential [16]. Even in Australia, where they are endemic, there may be gene conservation concerns due to gene flow between plantings of locally exotic species or provenances, and native species [17,18]. In some areas, growing eucalypts gives rise to concerns over impacts on water tables [19]. Nutrient removal from soils of low nutrient status, particularly in the context of short-rotation coppice cycles and/or where nutrient-rich leaves are removed, is also an important consideration.

▪ Economics

As with sustainability, assessing the economic feasibility of biofuel from eucalypts is complex and tends to be conducted at national or regional scales. It is not possible to give a detailed review here, and we are selective, giving examples mainly from the USA or Australia, where there is a well-developed policy and legislative framework that has received recent review and analysis. This is used to illustrate the impact that factors, such as the policy environment, production system and biology, may have on the economic feasibility of a biomass crop. Much of this encompasses, but is not specific to, eucalypt biomass. Earlier adoption of feedstocks from a forest source may be facilitated by comprehensive existing, robust and

Key term

Coppice: Regrowth shoots or stems arising from the base of the stem or lignotuber after damage or harvest of the main stem. The capacity to coppice allows a second or further crops without replanting, saving costs and allowing for shorter rotations. A practice used in producing fuelwood since Roman times.

Key terms

Corymbia: A genus of over 100 species of trees or shrubs mainly from northern Australia known as the bloodwoods and ghostgums. Formerly, the *Corymbia* were classified as a subgenus within the genus *Eucalyptus*. *Corymbia citriodora* (lemon scented spotted gum) and *C. maculata* (spotted gum) are cultivated widely throughout the world as a source of timber and/or for highly-prized terpenoid leaf oils.

Mallee: A low growing multi-stemmed eucalypt with tree or shrub form and a large rootstock (lignotuber) at the apex of the root system. They are able to resprout or coppice from the lignotuber after loss of aboveground parts due to fire, drought or harvest. Some eucalypt species always have a multistemmed habit; others may be induced into a mallee growth form. Species with mallee growth forms exist across a wide range of eucalypt botanical regions and taxonomic subdivisions.

mature policy frameworks for sustainable harvesting; this may give trees an initial edge over agricultural sources where comparable policy and regulatory frameworks are not in place [5].

Recently, Jensen *et al.* looked at the influence of policy on stimulating the development of lignocellulosic biofuel industry in the USA and considered three elements in the diffusion of innovation; time, risk and communication [20]. The USA has three major Acts that impact on the lignocellulosic ethanol industry enacted over the period from 2005 to 2008, which specify mandates for production of biofuel and its displacement of fossil-fuel use, subsidies and incentives for simulating research and development, and communication of innovations. A key development was the Energy Independence and Security Act 2007 and the setting of targets for the amount of advanced biofuel (i.e., renewable fuel other than ethanol) and for life cycle GHG emissions that are at least 50% less than baseline life cycle GHG emissions in consumption targets. The study noted that, while policy had considerable impact on uptake of ethanol from lignocellulosics and stimulation of innovation in the processing stage of the biofuel life cycle, there was a gap in policy in addressing risks for feedstock producers. Where there was help, it was aimed at reducing financial risk, and not addressing technological risk [20]. Another example of a successful policy environment that helped establish biofuels was the subsidy to growers of sugarcane in Brazil. The subsidy was established during the 1970s, but phased out during the 1990s as the industry became economically viable (see citations in [1]).

Eucalypts were considered among the most promising species (group) among hardwoods for future commercial feedstock production for bioenergy in southeastern USA, a region were biomass is presently the most promising renewable-energy resource [10]. Eucalypts were viewed as being highly productive, and required fewer inputs than other hardwoods considered for the region. Eucalypts were most suited to coastal lowlands, where risk from freezing was low. Growth tended to be limited by water availability, but eucalypts could be grown on degraded lands and tolerated a wide range of soil pH. Kline *et al.* concluded, however, that "the current state of the forest-products industry casts considerable doubts about the role of commercial hardwood plantations in biofuel feedstock supply in near and medium term, given existing market prices and supplies" [10]. This perception accorded with the lack of incentives for growing wood for biofuel in the USA in the policy review by Jensen *et al.,* and emphasized the need for further policy and technological developments to make biofuel from woody biomasses viable in this region [20]. The economics of energy from eucalypts may be more favorable for electricity production in the southeastern USA region, as one study found production costs for energy from eucalypts may match coal [21]. Feedstock costs may be more competitive for eucalypt species that coppice. This eliminates replanting costs for a number of harvest cycles and provides extra productivity from existing root biomass in second and later cycles. Coppice crops may still need intensive management or productive sites to achieve economic viability.

The production system used, and whether eucalypts are grown purpose-specific for energy, will have a major impact on their value as a feedstock. Mead, when reviewing the use of forests for energy, noted that energy production from industrial plantations is currently usually a secondary management objective, with a few exceptions of small areas of willows and poplar plantations in Europe and the USA, and the industrial eucalypts plantations used for charcoal in Brazil [22]. Generally, the feedstocks used for bioenergy are not costed, and are generated from industrial residues that can be essentially considered 'free' goods. In this context, the vast existing estate of planted eucalypts in many countries represents a largely untapped resource with potential for biofuels.

Eucalypts

▪ Taxonomy, evolution & natural distribution

The eucalypt group belongs to the Myrtaceae family, a large family of approximately 130–150 genera, mostly of southern hemisphere origin and occurrence [23]. As with the Myrtaceae family, eucalypts (genera *Eucalyptus*, ***Corymbia*** and *Angophora*) are noted for their species richness, with approximately 900 described species of trees or shrubs (or **mallee**), all but a few restricted in their distribution to mainland Australia and Tasmania [24]. There are ten subgenera recognized within *Eucalyptus*, with most species of economic importance belonging to the subgenus *Symphyomyrtus* (~470 species including *E. grandis*, *E. urophylla*, *E. globulus*, *E. camaldulensis*) or the subgenus *Eucalyptus* (formerly *Monocalyptus*) (e.g. *E. pilularis*, *E. obliqua*) [19,24]. The bloodwoods (genus *Corymbia*), recognized as a separate genus in 1995 [25], are a group of approximately 113 species, mainly from northern Australia, and include several taxa in the spotted gum group (section *Maculatae*; *C. maculata*; *C. citriodora*) or (section *Torellianae*; *C. torelliana*) considered important for forestry in the subtropical regions in Australia and other countries [26,27]. *Angophora* is a small genus of around nine tree species from eastern Australia, allied to the *Corymbia*. They have tended not to be considered for forestry purposes due to poor stem form [24], but this does not preclude their use as a biofuel crop.

The eucalypts are the product of a 65–70 million year evolutionary history, conditioned by adversity and isolation [28,29]. They are a major component of ecosystems across Australia and can be found in virtually every forest or woodland habitat, ranging from sea level to subalpine environments, and span tropical to temperate climes [30,31]. Prior to the early Tertiary period (~50 million years), *Myrtaceae* species were widespread in the tropical north and these progenitors of *Eucalyptus* spread across southern Australia along with other elements of the existing rainforest vegetation. By this time, the progenitors of eucalypts had most likely expanded to all corners of the continent [32]. The rainforest receded, however, in response to periods of increased aridity and decreasing soil fertility, but over time, the "Proto-eucalyptus" (*sensu* M.I.H. Brooker) that had developed during the *Myrtaceae* radiation diversified into new species or became extinct [33].

The great diversity of the Australian continent's climate and soils, and that of the islands to the north where eucalypts are endemic, provided ample environmental stimuli for the speciation events that led to the large number of eucalypt species in existence today. It is this range of adaptation available within the group and the resilience of many species that has contributed to their successful establishment as exotics (see later discussion) [34] . The relatively recent and rapid adaptive radiation and high rates of natural hybridization among species, on the one hand complicate lower order phylogenetic analysis [35,36], but on the other hand may facilitate the exchange of genetic and genomic information within eucalypts [15] (see later discussion). The attributes of adaptive diversity and reproductive promiscuity facilitate the ability of tree breeders and geneticists to bring together traits from disparate species, and transfer genetic information relatively widely within the group. This then provides a strong basis for selection within the eucalypts, and development and repackaging of species or varieties with desirable adaptive and production attributes for biofuel feedstock production.

▪ Distribution, use, culture & productivity in planted forests

Eucalypts represent a significant proportion of the planted forests worldwide. Recent estimates by the Food and Agriculture Organization of planted forest resources (of which 76% are estimated to be primarily for production purposes) will reach 300 million ha by 2020 from an area of 264 million ha in 2010 [37]. Planted forests will be increasingly important in supply of wood, fiber and fuel, with major increases in planting over the past two decades occurring in China, the USA, Canada, India, Vietnam, Brazil and Mexico.

Eucalypts accounted for an estimated 20.5 million ha of planted forests in 2009 [Pers. Comm., GIT Forestry Consulting, 2009]. A rapid growth in plantings that has led to a doubling in the eucalypt estate from around 10 million ha in 1990, dominated by plantings in tropical America and tropical Asia. They are now grown in more than 90 countries; many, such as Brazil, Uruguay, Chile, Indonesia, India, China, Spain, Portugal, South Africa, The Democratic Republic of Congo and Australia, have major plantation estates and associated well-developed breeding programs (see later discussion) for at least one variety of eucalypt [19,38]. Since they were first encountered in the 16th Century by Portuguese explorers in Timor and Indonesia, eucalypts are now the most widely planted hardwood in the world, in many cases becoming the cornerstones of vibrant forest industries [19,38].

Eucalypts have been used for a variety of functions around the world: wood production for fuel, paper, solid wood, essential oils and management of local water balance [19,38]. Biofuel production is an additional use that could be combined with other uses or become the sole purpose of production. Highly selected and developed biofuel genotypes may be single-purpose crops located in areas where crop and livestock production is low. An example of where biofuel feedstock from eucalypts might be emulated on an industrial scale is the production of wood fiber from selections and clonal plantings of *E. grandis* and its hybrids in a number of South American countries, where 40% of the global supply of eucalypts is grown [38]. The capacity to obtain root cuttings of the tropical and subtropical species has made hybrids among species such as *E. grandis*, *E. camaldulensis*, *E. urophylla*, *E. tereticornis* and *E. pellita* a common source of material for clonal forests [39]. On the other hand, multipurpose production means that biomass currently not commercially utilized can be captured for biofuel production, and breeding better biofuel traits into the trees destined for traditional uses, such as for fuelwood or terpenoid leaf oil production, may ensure better use of existing resources. Existing examples of this are found in the agroforestry applications of eucalypts in countries such as China and India, where eucalypts are grown by small landholders, or on a small-industrial scale in WA where eucalypts are integrated in agriculture systems and grown for bioenergy and terpenoid leaf oils, as well as environmental benefits [6,19].

Eucalypt plantation productivity is determined by climate, soils, stand management (silviculture) and the species planted; a wide range of productivity estimates have been reported in the literature. Some of the most detailed information on the productivity of managed eucalypt plantation comes from Brazil, where productivity has increased from 10 m^3 ha^{-1} yr^{-1} in the 1960s to 20–60 m^3 ha^{-1} yr^{-1} due to improved genetics and silviculture [19,40,41]. Even within highly productive regions, climate can have a major impact on productivity as evidenced by the current annual increment of a single stand reducing from >80 m^3 ha^{-1} $year^{-1}$ to a current annual increment of <10 m^3 ha^{-1} $year^{-1}$ over a 6 month period [40]. While on the one hand planted eucalypt forests can be extremely productive and suitable for the production of commodity products, they are also capable of developing into economically viable stands with markedly lower growth rates [41,42]. In regions where environmental conditions are less favorable, eucalypt plantation productivity may remain static while stands persist through long periods of drought and maintain low levels of mortality [43].

To date, most effort has been placed on eucalypts that have a tree habit. Many of these species are lignotuberous and coppice well **(Table 1)**. The numerous mallee species that are generally found in semi-arid and arid environments have been relatively little explored, though an important exception is a pioneering example from WA where a handful of mallee species have been developed for broad-scale intercropping with wheat [44]. An important aspect of these mallee species, and probably others such as those now being trialed in northern Australia **(Table 1)**, is that vigor does not appear to decline even after many decades of regular harvest as it does with many of the other species.

Domestication

The remarkable adaptability of eucalypts to a wide range of environmental conditions (reflective of their wide geographic distribution) coupled with relatively

Table 1. A total of 39 eucalypts of interest for biofuel production in northern Australia†.

Genus	Species	Subspecies	Common name	Range‡	Habit§	Status for biofuel¶	Use#	Note
E	*hybrid*	*grandis x camaldulensis*	Flooded gum × River red gum	S	T	1	P, B	
E	*dunnii*		Dunn's white gum	S	T	1	S, P, B	High site quality required
E	*cloeziana*		Gympie messmate	S	T	1	S, B	Good coppicing
E	*moluccana*		Grey box	S	T	1	S, B	Drier regions
E	*camaldulensis*		River red gum	W	T	1	S, B	Good coppicing
C	*citriodora*	*variegata*	Spotted gum	S	T	1	S, P, B	Good coppicing
C	*hybrid*	*torelliana x variegata*	Cadagi × spotted gum	S	T	1	S, P, B	Good coppicing
E	*longirostrata*		Grey gum	S	T	1	S, P, B	Drier regions
E	*pellita*		Large fruited mahogany	S	T	1	S, P, B	Tropics only
E	*grandis*		Flooded gum	S	T	1	S, P, B	Good coppicing
E	*agglomerata*		Blue leafed stringybark	T	T	2	S, P	Coppicing
E	*biturbinata*			S	T	2	P, B	
E	*saligna*		Sydney blue gum	S	T	2	P, B	
E	*globulus*	*maidenii*	Blue gum	T	T	2	P, B	
C	*henryi*		Large fruited spotted gum	S	T	2	S, B	
C	*citriodora*	*citriodora*	Lemon scented spotted gum	S	T	2	S, B	Good coppicing
E	*crebra*		Narrow leaved red ironbark	S	T	2	S, B	
E	*drepanophylla*			S	T	2	S, B	

†Species are from the genera *Corymbia* (C) or *Eucalyptus* (E) and arranged by growth habit, biofuel production potential and use.
‡Range: natural range noted as (S)ubtropical, (T)emperate or (W)idespread.
§Habit: growth Habit recorded as (T)ree or (M)allee. Trees with mallee habit have demonstrated, or are highly likely to have excellent coppicing ability with little or no decline in productivity over rotations.
¶Status for biofuel production rates as 1= promising or 2 = worth further evaluating. A promising species has been tested in northern Australia environments and show promise as a biomass species. A species worth testing has attributes which suggest it maybe suitable for biomass and/or has been tested in southern Australia.
#Uses: potential uses noted as (S)olid wood product, (P)ulp, (B)iomass and (O)ther.
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Table 1. A total of 39 eucalypts of interest for biofuel production in northern Australia[†].

Genus	Species	Subspecies	Common name	Range[‡]	Habit[§]	Status for biofuel[¶]	Use[#]	Note
E	*argophloia*		Western white gum	S	T	2	S, B	Drier regions
E	*pilularis*		Blackbutt	W	T	2	S, B	High site quality required
E	*siderophloia*		Ironbark	S	T	2	S, P, B	
E	*curtisii*		Plunkett mallee	S	M	2	B	Drier regions
E	*gamophylla*		Warilu and blue-leaved mallee	S	M	2	B	Drier regions
E	*chlorophylla*			S	M	2	B	Drier regions
E	*normantonensis*			S	M	2	B	Drier regions
E	*polybractea*		Blue-leaved mallee	T	M	2	B	Drier regions
E	*viridis*		Green mallee	S	M	2	B	Drier regions
E	*bakeri*		Baker's mallee	S	M	2	B	Drier regions
E	*mannensis*	*mannensis*	Mann range mallee	S	M	2	B	Drier regions
E	*mannensis*	*vespertina*		S	M	2	B	Drier regions
E	*oxymitra*		Sharp capped mallee	S	M	2	B	Drier regions
E	*pachyphylla*		Red bud mallee	S	M	2	B	Drier regions
E	*trivalvis*		Desert mallee	S	M	2	B	Drier regions
E	*exserta*		Yellow messmate	S	M	2	B	Drier regions
E	*gillenii*		Mallee red gum and Mt Gillen mallee	S	M	2	B	Drier regions
E	*herbertiana*		Kalumburu gum	S	M	2	B	Drier regions
E	*infera*		Durikai mallee	S	M	2	B	Drier regions
E	*nudicaulis*			S	M	2	B	Drier regions
E	*kochii*	*borealis and plenissima*	Oil mallee	T and S	M	2	B, O	Drier regions; foliar oils

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[#] Uses: potential uses noted as (S)olid wood product, (P)ulp, (B)iomass and (O)ther.
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high growth rates is the principal explanation as to why they have been so widely distributed and propagated as exotics on such a large scale across the world [34]. Concerted domestication, targeted introductions and international provenance testing during the last 30 years has seen eucalypt planting rates, especially in the tropics, increase dramatically. The existing technical knowledge and genetic resources available for the breeding of eucalypts is unlikely to be equaled for any other tree genus. These resources provide the necessary building blocks for the development of eucalypt varieties suited to biofuel feedstock production in areas where production forestry is currently practiced. There is an opportunity for bioenergy production from existing commercial varieties of eucalypts, which have typically been selected from relatively high-quality sites and bred for intensively managed plantation environments. In addition, there is considerable scope for less well-known species, which are suited to areas marginal for food-crop production or traditional forest plantations, to be domesticated relatively quickly or utilized for hybrid production. This would vastly increase the area available for dedicated eucalypt biofuels crops [45].

Historical introductions of eucalypts, which were very often sourced from few trees, have provided naturalized populations from which a range of wood production populations have been developed [46–49]. In more recent times, diverse base populations have been sourced and formal breeding programs have been established in order to provide existing propagation populations with more consistent increases in genetic quality across a wider range of selection traits [50]. These formal tree-improvement programs have typically been associated

Key term

Eucalypt genome: In April 2011, the genome of *Eucalyptus grandis* was the third woody plant species to be sequenced and the first with southern hemisphere origins. It was selected for sequencing because it is one of the fastest growing woody plants in the world. At 691 x 109 base pairs (691 Mb) in length, the nuclear genome is approximately sixfold larger than the 115.4 Mb genome of the first plant sequenced in 2000 (*Arabidopsis thaliana*).

with large-scale industrial production facilities dedicated to producing commodities such as pulp and paper [51,52]. As breeding programs have matured, selection for traits other that those directly associated with these commodities has become more common [19,41,53,54]. Differentiated breeding populations of eucalypts have been developed for multiple end uses or smaller niche markets, such as terpenoid leaf oils [55], carbon credits [56] and high-value solid wood products within dryland environments [57]. Given the range of environments in which eucalypts are profitably grown, the high quality of existing germplasm, the wealth of genetic diversity available within the native range, the well-developed propagation systems and the diversity of products for which improved breeds have already been developed, there are few obstacles in the path of domesticating eucalypts for dedicated biofuel crops. Indeed, given the rate of advance in the phenotyping [58] and genotyping [59] technologies that are contributing to the holistic analytical processes [60] developed to sift through complex volumes of data, the development of new varieties of eucalypts for biofuel production could be a straightforward process.

Biotechnology

Forest biotechnology promises to add to the productivity of planted forests, and indeed may be the only way sufficient productivity may be achieved to meet future world wood requirements and avoid further degradation of natural forests [61]. Forest biotechnology is usually taken to encompass a range of molecular technologies such as gene manipulation and gene transfer (genetic engineering), or DNA typing using molecular markers, which may be selected upon to improve characteristics in a population, or otherwise provide information for gene conservation and management of forests. An important goal for forest biotechnology is to provide new ways to manipulate wood composition and flowering (for reviews see elsewhere [13,61–63]). The scope for biotechnology to impact on the productivity and quality of planted eucalypts and other Myrtaceous species for a range of purposes is set to expand, owing to the recent release of the **eucalypt genome** sequence [15].

▪ The impact of a genome sequence

As the sequencing of the poplar genome was a turning point in efforts to generate new cultivars for biofuel production from woody species in temperate regions [64,65], a genome sequence for *Eucalyptus* will be a key stimulus in the realization of the genus as a leading bioenergy feedstock in the tropics. A full *Eucalyptus grandis* genome (8 × coverage) with gene annotation was released as a part of the Phytozome 7.0 update in April 2011 [201]. A genome sequence is a key resource for developing new cultivars both via engineering or selection routes. For example, tree species can possess extensive natural variation in cell-wall attributes that impact on the efficiency of the bioconversion processes for biofuel, especially biomass pretreatment and enzymatic saccharification [66]. In forward genomics approaches a genome sequence may be a source of candidate genes that may be associated with variation in cell-wall characteristics that occurs naturally in a tree species. These approaches provide both insights into the genetics underlying economic traits and ways to manipulate them in applied tree-improvement programs [67]. Alternatively, reverse genetic approaches, based on transgenics or mutated populations, will also be advanced by the availability of a genome sequence [67]. Reverse genomics can also be used to provide knowledge of the genes underlying biochemical pathways that alter basic density, lignin and cellulose content and composition, traits of interest for biofuel (see later discussion) [64,68].

▪ Advanced breeding approaches

The use of advanced methods for breeding of eucalypts has largely paralleled their use in other annual or tree crops that commenced in the early 1990s [69,70]. Advanced methods of breeding are defined here as approaches where selection incorporates information from genetic markers associated with phenotypes or breeding values, and includes genome-assisted breeding [67]. The development of advanced methods of breeding, and the effort invested in understanding the genetics that underpin them, are allowing us to not only manipulate wood composition and fiber properties in tree populations, but also grow more productive and resilient forests. Like conventional tree improvement, advanced breeding approaches uses the natural variation inherent within a species to make genetic gains.

The application of advanced breeding methods has largely been restricted to a handful of the most economically valuable species such as, *E. grandis*, *E. camaldulensis*, *E. globulus*, and *C. citriodora* (formerly *Eucalyptus citriodora*) [67,71]. As prospects for transfer of genomic information among eucalypt species are promising, however, advanced breeding approaches will allow the benefits of the developments that occur in these few species to flow to other species in the genus, that may also have potential as biofuel feedstocks [13,15,72].

Marker-aided selection can be used to increase the frequency of favorable phenotypes in a population by selecting on a marker (or sets of markers) that is a functional polymorphism or more commonly, *associated* with a functional polymorphism [73]. The markers used for selecting can be identified from quantitative trait loci (QTL) mapping studies using bi-parental mating schemes [74], or association studies using large, unstructured populations [75]. QTL mapping has been valuable in providing insight into the genetic architecture of many economic traits in eucalypts (recently reviewed in [67]), in forward genomics [76], and for validation of marker-trait associations [77–80]. To date, however, the application of marker-aided selection for QTL in applied tree improvement has been restricted [81], and the present review does not consider this further. In the future, an approach allied to marker-aided selection for QTL, genomic selection, where genome-wide marker sets are associated with genotype-estimated breeding values in populations representative of breeding populations, may be realized for eucalypts [81,82].

▪ Association studies in eucalypts

In the last half decade, association studies have linked structural and regulatory genes underlying lignin and cellulose biosynthesis with fiber and wood properties that are also likely to be important in considering biofuel and bioenergy properties of eucalypts. Association between a marker and a functional polymorphism arise because of linkage disequilibrium, the nonrandom association of alleles at different genetic loci [83]. Linkage disequilibrium is a function of a species' selection history, its mating system, population size and recombination rates [82]. In natural populations of outcrossing trees, linkage disequilibrium is generally thought to extend over short distances [75,84]; thus, association studies in eucalypts have typically used a candidate gene, rather than a whole-genome approach, to link genes with phenotypic variation [15]. An extensive effort to elucidate the biochemical steps of lignin and cellulose biosynthesis and its underlying molecular genetics (e.g., [85,86]) has been necessary to underpin association studies by providing candidate genes, that is, those genes likely to influence wood and fiber properties.

Association studies aimed at finding markers to manipulate wood chemistry and structure may be particularly valuable for future efforts to generate improved eucalypts for biofuel production via fermentation. In the first reported association study in a tree, variation in the *Cinnamoyl CoA Reductase (CCR)* gene was associated with microfibril angle (MFA) in *E. nitens* [87]. CCR converts hydroxycinnamoyl CoA esters into cinnamaldehydes in the penultimate step in the synthesis of the precursor for lignin, hydroxyl-cinnamoyl alcohols, and is a key lignin gene affecting physical properties of secondary wall in *Arabidopsis thaliana* [88]. Since then, the effort to find genes in *E. nitens* has been expanded to include approximately 100 genes in major developmental pathways likely to influence wood and cell-wall properties, including cellulose and lignin synthesis, cytoskeleton synthesis, cell expansion and transcription factors. Significant associations were identified between markers and MFA, cellulose, pulp yield and total lignin traits [81,89]. The *E. nitens* COBRA-like gene (*COBL4A*) as well as Eni-HB1 (a transcription factor), cinnamyl alcohol dehydrogenase (Eni-CAD1) involved in lignin biosynthesis and an expansin (Eni-EXP), a class of cell-wall protein regulating cell expansion during growth, were linked with fiber or cell-wall properties. Several of these associations, including the earlier detected association between CCR and MFA were validated using *E. nitens* and/or *E. globulus* mapping populations [59,87].

Association studies have also implicated other genes in control of wood composition and structure in eucalypts. A study testing for association between more than 50 physical and chemical attributes of wood with four candidate genes, *CCR*, *CAD*, *MYB1* and *MYB2* in *E. pilularis*, a plantation species for timber production in the subtropics, found that the transcription factor MYB2 was associated with structural properties of average collapse grade and radial shrinkage [90]. Further studies using a set of 37 candidate genes has also shown that a gene involved the synthesis of pectin, a key constituent of the plant cell wall, pectin methylesterase (PME6) is associated with shrinkage and collapse during the drying of *E. pilularis* timber [72]. Pectins are highly hydrophilic polysaccharides, their water holding capacity dependent upon the degree and pattern of methyl esterification. It was reasoned, therefore, that trees of varying PME6 efficacy may differ in the water binding capacity of their cell walls, and thus the degree to which shrinkage or collapse occurs upon drying.

Transgenics

Genetic engineering offers an alternative to advanced breeding approaches for plant improvement by allowing access to genes beyond the primary and secondary gene pools (reviewed elsewhere [67,71]). Transgenics may be particularly important for improving wood quality, disease and abiotic stress tolerance of largely clonal, industrial plantings of eucalypts [67] and, thus, are likely to have high relevance to improving eucalypts as feedstock for biofuels. Despite the promise of transgenics, there are still few public reports of transgenic eucalypts [15]. There are technical challenges for transformation of eucalypts that need to be overcome, but these should be surmountable in the near future, in which time strategic issues will dominate decisions to develop and deploy transgenics [67]. The recent approval for field testing of transgenic eucalypts with freeze tolerance in the southern USA is evidence that technical challenges with transgenics are being overcome [202].

Regardless of the issues with testing and deployment of transgenics, combined with the use of *in vitro* wood systems, transgenics also provide powerful experimental tools for validation of gene function [91]. Recently, transgenics were used to show that the β-*tubulin* gene has a role in determining the angle of cellulose microfibrils in the cell walls of a eucalypt [92]. The study exemplifies how transgenic approaches might improve the value of eucalypt biomass for biofuel, as the microfibril angle in the secondary fiber cell walls is an important wood quality trait that influences cell-wall strength, and flexibility, and therefore timber, pulp and fuel properties.

▪ Biomass composition & conversion

Evidence is accumulating that many eucalypts have favorable compositional attributes for effective and scalable enzymatic conversion to biofuel relative to other candidate woody biomass resources, such as *Pinus radiata*, *Picea abies*, and *Populus* spp. For the biochemical conversion approaches, these include high polysaccharide content (reported as high as up to 80% for *E. globulus* [93], high syringyl lignin content [94] and the ability to select for species without high levels of inhibitory terpenoid leaf oils [95]. High yields of fermentable sugars have been generated from several eucalypt species after pretreatment and saccharification, including *E. globulus* [96,97] and *E. grandis* [98,99].

For the thermochemical conversion technologies, such as pyrolysis and gasification, other attributes of eucalypts are compelling from a feedstocks perspective. These include several traits demonstrated to be under genetic control in several eucalypts species, such as increased energy density of the short rotation woody crop (in BTU/ha), adjusted lignin levels, and controlled polysaccharide content. Eucalypt biomass has been utilized for pyrolysis, a leading thermochemical conversion technology that is being rapidly commercialized in several nations, which produces a 'bio-oil' that can be upgraded into fuels and chemicals using conventional refinery technologies [100]. Several eucalypt species have also been evaluated as a feedstock for gasification, including *E. camaldulensis* [101] and *E. globulus* [102]. These reports highlight the potential of the eucalypts as a short-rotation woody crop that can be efficiently converted through all of the leading biochemical and thermochemical conversion technologies into renewable fuels and chemicals that can complement petroleum.

Eucalypts for biofuel production in the southern sheep/wheat & northern subtropical zones of Australia

Australia is viewed as having a strategic advantage in use of biofuels because of the availability of large areas where the crop and livestock yields are low, but are suitable for growing lignocellulosic biomass from trees [9]. Two prospective production zones are the temperate sheep and wheat belt of southern Australia, and the subtropical regions of Queensland and New South Wales (NSW) of northern Australia. For each of these situations, we review the status of relevant eucalypt domestication programs to identify species of interest and where further research is needed.

▪ Wheat & sheep region of southern Australia

Background & context

The major motivation for the recent investment in domestication of southern mallee eucalypts has been the urgent need to remedy natural resource management problems in the extensive dryland wheat and sheep regions of southern Australia [103]. These regions occupy areas in the south west (latitude 28° to 35°S; longitude 114° to 123°E) and south east (latitude 29° to 37°S; longitude 135° to 149°E) of the continent, between the 300–700 mm/year rainfall isohyets. Except for the northern half of the southeast region, the climate is winter rainfall dominant. Evaporation exceeds rainfall by factors of 3 to 8 (south to north) across these regions [203]. There is some 50 million ha of arable land within these regions but the proportion that can be effectively planted to woody crops is constrained by availability of water to less than 10% [104,105].

Western Australia has been the focus of mallee domestication. WA has perhaps the greatest extent of natural resource degradation induced by dryland agriculture in Australia. Secondary salinity is the major degradation process. It is caused by the altered water balance following the recent (<100 years ago) conversion of native woodlands to farmland based on annual crops and pasture [106]. The small reduction in plant water use is expressed as slow accumulation of groundwater in the deep subsoils, which in the generally low-relief landscape, is eventually manifest as extensive saline-water discharge on valley floors [107]. Conceptually there are only two management options; increasing water use to return back towards the native system with a lower water table by using deep-rooted perennials: or draining or pumping the saline water away from the sites. The scale of activity required means that the use of deep-rooted perennials will only be feasible if they are of an economic value comparable to the annual agricultural plants they will replace [108]. This principle underwrote the long term commitment by the State (WA) to invest in developing mallee as a profitable crop for wheatbelt agriculture [44,109].

Over the past two decades there has been consistent investment in mallee development such, that to date an estimated AU$70 million has been spent. Some 20% of WA wheatbelt farmers have made test plantings of mallees totaling approximately 12,000 ha [110], and this has generated a robust knowledge base for planting design, establishment and management. The alley farming concept of wide-spaced narrow belts of mallees separated by an 'alley' is widely used. Central technologies, such as breeding, growth modeling and harvest regimes, harvester and supply-chain systems, and processing options, have all been systematically addressed, and continue to make steady progress.

Species selection, genetic improvement & seed production

Species selection and breeding commenced in the early 1990s. It drew upon the species testing and selection done in WA in the 1980s by Barton, who saw potential large-scale industrial use for cineole, commonly the major constituent of the terpenoid leaf oil in mallee species [111]. Candidate species for domestication were biased to native WA species with high oil content (>1% oil in whole biomass and up to 90% cineole content). The species being developed are listed in **Table 2**. They are all native to the south west of WA with the exception of *E. polybractea* (blue mallee) from disjunct populations in Victoria and NSW. The technical basis for potential industrial use of cineole as foreseen by Barton is emerging [112,113].

Native stands of *E. polybractea* in NSW and Victoria have been harvested for terpenoid leaf oils for over 100 years [114]. *E. polybractea* has been subject to recent breeding and propagation research that has shown this species to be amenable to micropropagation [115–119]. The WA species were not well known so taxonomic and molecular genetics investigation has been conducted to confirm species taxonomic boundaries [120–123], and to assess potential risk of gene-flow from planted populations back into native stands [124–126]. Some species have several subspecies or variants and it was necessary to clarify the degree of difference between them to decide whether separate breeding populations should be established or if they are genetically different but of similar appearance. It is important that they can be recognized and segregated in field seed collection.

The breeding strategy adopted uses recurrent selection to accumulate desirable genes in breeding populations through progeny testing from a wide selection of native germplasm, to select and outcross over many generations [127]. The major objectives are to increase biomass and oil productivity. Progeny tested and selected populations from each generation are used for seed orchards for field planting. Clonal propagation by cuttings is being developed to create clonal seed orchards.

The domestication program assumes that, in order to be profitable, efficient harvest and utilization of all components of the mallee crop will need to be achieved. This will involve multiple products including bioenergy and engineered and processed wood products, as well as chemicals derived from eucalyptus oil. To cater for this wide range of potential products, current breeding populations are maintained with a high level of genetic diversity to provide scope to add new selection attributes into the breeding program as this becomes necessary.

Biomass productivity, growth modeling & economics

The major objective in using narrow belts in alley layouts is to maximize access to water. Water is by far the most limiting resource for mallee growth in the wheatbelt environment, where evaporation exceeds rainfall by a factor of 3 to 8. This is manifest by exceptionally high transpiration when water is freely available [128], by the broad (5–10 m each side of the belt) and deep (>10 m) volume of soil depleted of available soil water by age 5–7 years [129,130], and by strong inner row suppression even in four-row belts [131].

Table 2. Summary of information on mallee species planted in West Australia since 1994.

Species	Common name	Planted† (%)	Subgeneric category	Soil texture preference	West Australia range mm/annum	
					Rainfall	Evaporation
Eucalyptus loxophleba ssp. *lissophloia*	Smoothbark york gum	39	Series *Loxophlebae*	Medium	250–400	1800–2400
Eucalyptus loxophleba ssp. *gratiae*	Lake Grace gum	8	Series *Loxophlebae*	Medium	300–400	1600–2200
Eucalyptus kochii ssp.*plenissima*	Oil mallee	23	Series *Oleosae*	Light-to-medium	250–400	2200–3200
Eucalyptus kochii ssp. *borealis*	Oil mallee	18	Series *Oleosae*	Light-to-medium	300–400	2400–2800
Eucalyptus kochii ssp. *kochii*	Oil mallee	2	Series *Oleosae*	Light-to-medium	350–450	2200–2800
Eucalyptus polybractea	Blue mallee	8	Section *Adnataria*	Medium	400–600	1600–2000
Eucalyptus myriadena	Blue mallee	1	Series *Ovulares*	Medium-to-heavy	300–450	1800–2600
Eucalyptus angustissima ssp. *angustissima*		1	Series *Cneorifoliae*	Light/salt tolerant	350–500	1600–2000

†From 1994 to 2008 some 12,000 ha of mallee was planted in the Western Australian wheatbelt.
Adapted from the Western Australia mallee industry development plan [110].

Wide belt intervals provide better access to stored water and better opportunity to intercept any lateral flows of water from the adjacent high soil water content alleys, where regular replenishment of soil water storage occurs under annual plant agriculture. To facilitate capture of sufficient lateral flow of water to achieve economic yield it has been estimated that belt intervals greater than 100 m would be required [104]. A negative outcome of narrow belts is the wide lateral reach of the mallee root system that imposes competition on the adjacent agricultural crop or pasture [6,132,133]. It had been anticipated that competition could be strongly controlled by regular harvest, but initial data from experiments on harvest regimes show the benefit is weaker than expected [133]. It appears likely that the opportunity cost of the competition zone can be carried by greater spacing between rows within the belt. Therefore the economic optimum belt width is likely to be 8–12 m, rather than the commonly used 6 m [133].

Mallee belt system design and yield prediction is therefore likely to require coupled hydrology and growth model components. This is a major area of current research and development.

Mallee species are well adapted to low nutrient supply in the native environment. However, regular harvest of whole above-ground biomass, even in the nutrient-enhanced agricultural environment, will soon require nutrient input to maintain mallee productivity. Some initial work on nutrient export has been completed [134] and more work is underway.

Harvester & supply chain

Mallee crops need more than 2 years following harvest for root-system biomass to return to the preharvest level [135,136]. They start to impose full lateral competition 4 years after the previous harvest. These two times impose the boundaries for a sustainable mallee harvest frequency. Above-ground biomass of crops at these ages in a 400–500 mm rainfall/year area are 20 to 80 green tonnes/ha. These biomass levels are too low for conventional forestry harvest systems [137]. They are in the right range for continuous-row harvest, but existing equipment adapted from forage harvesters is too light in construction to handle the high wood density and difficult form of mallee [137]. For these reasons, mallee development in WA embarked on a course to design and develop a mobile, single-row chipper harvester [204].

The harvester is only one component of a supply chain reaching from the mallee belt in the paddock to the delivery platform at the processing plant. The design options for such a supply chain have been subject to considerable scrutiny [137–139]. These studies show that the inevitable wide distribution of the mallee resource will generate on-farm haulage costs that will probably be larger than the harvester cost. The capacities and integration of the harvester, the on-farm haulage, and road transport components requires very careful design to achieve low operating costs. The system will have a tight road transport distance constraint, meaning that regional processing to at least achieve some initial value adding will be required. Some form of vertical integration of administration of the business and services will also be required to streamline the supply chain and minimize costs. The Future Farm Industries Cooperative Research Centre report (2010) provides an estimate of how the $/tonne green biomass delivered will decline over time with the increasing scale, technical advances and operational experience [140].

Due to the need for wide separation between narrow belts, the biomass production capacity in a fully planted project region (7.5% of area planted and averaging 16 green tonnes/ha/year) would only be 120 green tonnes/km^2/year. This wide dispersal of biomass production incurs a large proportion of its financial and energy costs in harvest and transport. In spite of this, mallee biomass production achieves a ratio of energy output to nonrenewable energy input of 41.7 [141]. Energy and carbon balance on a whole life cycle basis have been examined [142].

Processing & products

Extensive investigation of product options for use of mallee biomass has been undertaken [143]. The concept of segregation of bulk chipped biomass into its components and then aiming to extract greatest product value from each component was followed. Implicit in this approach was the lower value or residue fractions of the biomass that could be converted to bioenergy. Wood products and chemicals were considered to have greatest potential value and the first feasibility assessment undertaken proposed an integrated processing operation where the wood-chip fraction would be converted to activated carbon, the eucalyptus oil extracted from the leaf fraction, and the spent leaf, with other residue fractions, would be used as fuel for electricity generation [144]. A 20%-scale engineering demonstration plant was built to test process components and quality of products but the concept did not proceed to commercial operations.

More recently, research has turned to developing bioenergy processing concepts that might be best adapted to the dispersed mallee resource and which open the option to produce biofuels. This research has focused on fast pyrolysis, the thermal decomposition of biomass in the absence of oxygen. The conditions under which this thermochemical process takes place can be modified to produce various proportions of char, bio-oil and gas. Fast pyrolysis requires fast heating, small biomass particle sizes (<3 mm) and moderate temperatures

(~500°C) to produce a high proportion of bio-oil. Fast pyrolysis for liquids can yield up to 75% of the feedstock dry matter as bio-oil and is attracting particular attention because of its versatility – bio-oil can be stored, transported, used for bioenergy or chemicals, and can potentially be converted to high quality biofuels [145].

Initial work on fast pyrolysis of mallee focused on how reaction conditions [146,147], biomass particle size [148,149] and alkali and alkali-earth metals [150] influence the yield and composition of bio-oil. Work has commenced on investigation of how the physical and chemical properties of bio-oil can be improved to make it acceptable for incorporation with crude petroleum as feedstock for oil refineries. The main problems are the reactive, oxygen-containing functional groups, such as organic acids and aldehydes, which can be converted to more stable esters and acetals [151]. This area of research is being conducted by the WA Curtin University Fuels and Energy Technology Institute.

Subtropical northern Australia

▪ Background & context

The feasibility of a biomass industry based on planted eucalypts in subtropical Australia has not been researched or developed to the extent of that for WA. Nonetheless, there is some prospect for eucalypt biomass feedstocks in the region, given the existing plantation industry, knowledge in the breeding and production of eucalypts for timber and fiber, and the availability of a suitable landbase to expand production. The region of interest is an 'expanded' subtropical region in Queensland and NSW [57,152]. This includes the subtropical region for traditional forestry, but extended west to the lower limit of rainfall for mallees and is defined by latitudes from approximately 20 to 30°S, and by the east coast as far westward as the 400 mm isohyet. A recent review of woody species suitable for biomass in northern Australia concluded that it was not yet possible to recommend eucalypt species for planting as a biofuel feedstock in this region; however, 38 eucalypt species were either considered as prospective, given their performance in trials for timber production, or are currently under evaluation as biomass species **(Table 1)** [153]. Species considered included those suitable for long-rotation tree plantations and short-rotation 'mallees'; including mallees both indigenous to northern Australia and mallees from the sheep/wheat belt of southern Australia. It was recommended that a strategy for identifying eucalypts for biofuel production should include a Search WA process of species selection [143] to verify whether there are additional species beyond the 38 identified, as some species may have been discarded for forestry because of poor form, but may have high biomass productivity and carbon density potential.

Evaluation of the capacity and availability of northern Australia as a region for biomass production has been carried out at a broad-scale, and those studies conducted so far indicate there could be substantial land available. A state-wide analysis of land suitable for tree planting activities in NSW indicated 6.3 million ha could be available for conventional timber plantings, most of which is in the western and dryland areas [154,155]. Similar state-wide analysis is not available for Queensland, but analysis of the land-base available for timber plantations in south east Queensland and modeling of the land base required for bioenergy production from woody species in the region suggests there is potential for adequate feedstock to supply a medium-scale bioenergy plant from this region alone [156,157]. Further fine-scale characterization of the land base and of the climatic conditions that will prevail in the region over the next 30 years is needed, however, to identify eucalypts matched to the land likely to be available for biofuel production in the north.

▪ Species selection & genetic improvement

Breeding programs of relevance for eucalypts for planting in the north fall broadly into either those focusing on tree-plantation cropping, following more traditional forestry practices and longer rotations (>20 years), or programs for short cycle cropping, using short rotations of around 5 years of 'mallee'.

Tree cropping programs

In northern Australia, the principal species currently being established in traditional forest plantations include spotted gums (primarily *Corymbia citriodora* ssp. *variegata*), *E. dunnii*, *E. pilularis, E. pellita*, *E. argophloia* and *E. grandis* and its hybrids with *E. camaldulensis*. These species were selected following evaluation in field trials that sampled the range of environments where plantation forests could be established. Assessments of a range of trials at approximately 6 years of age indicated that *Corymbia citriodora* ssp. *variegata* was very reliable across a range of site types and is less likely to be severely impacted by pests and disease than many other species [41]. The vast majority of the forest species field trials were designed and managed with the intent of producing conventional forest products such as timber. When solid wood products were the target end product, the silviculture was focused on producing high quality logs (straight and free of defects) over long rotations (20–30 years), where competition is managed by thinning to focus production onto the trees that would be harvested at final rotation. Alternatively, trials were managed to replicate the production system used to generate a crop of trees that could be utilized for pulpwood. While both of these typical plantation forest management regimes can be adjusted to faciliate biofuel production, few research trials of woody crops have been established with the intent of evaluating species for biofuel potential. One major exception was a series of trials evaluating tree species for fuel-wood production in northern Australia dating back to 1984, a collaborative program between CSIRO and the Queensland Government. Following an extensive review of woody species with potential for fuelwood production, these trials tested over 160 species across two sites in southern Queensland. In general, these projects indicated that species suitable for fuelwood crops in northern Australia were the tall tree species, which showed higher productivity potential under plantation conditions when grown on higher productivity sites.

The shared interest in eucalypts for the subtropics in NSW has resulted in overlap and strong collaborative ties with Queensland [158]. Since 1994, around 20 species of eucalypts have been established in commercial plantations in NSW. This includes species such as *E. pilularis, E. dunnii, E. grandis, C. citriodora* ssp. *variegata,* and to a lesser degree *E. saligna, E. cloeziana, E. agglomerata* and *E. nitens*, with a broad base of provenances in each species usually used in plantings. These most common species cultivated are those with demonstrated acceptable growth, vigor and wood quality when grown in specific regions of NSW. The primary objective for establishing hardwood plantations in southern Queensland and NSW has been to meet future needs for high-value solid wood products, as the resource base for these products shifts away from a reliance on native forests [159]. The typical rotation length for a solid wood production regime is around 25 years, with commercial thinning operations at mid-rotation age on the plantings with higher productivity. A small proportion of this plantation resource is also earmarked to supply the pulpwood industry.

Species testing in NSW has been extensive, with more than 65 species of *Eucalyptus* tested over different geographic strata throughout NSW [160]. More than 25 of these species are represented as provenance trials and have been periodically measured for traits that usually include, tree height, diameter at breast height (1.3 m from tree base), tree growth form, wood basic density, stiffness and strength [161]. More extensive evaluation of chemical and physical wood properties has also been carried out on priority species such as *E. dunnii* and *E. pilularis* [162,163].

Northern mallees

In the last 2 years, a program of testing dryland 'mallee' species potentially suitable for subtropical and tropical latitudes was initiated by CSIRO. These environments present a number of challenges and opportunities for the development of bioenergy crops. Good quality, coastal sites that receive high rainfall are potentially very productive and could be well placed for bioenergy production. However, the opportunity cost may increase in the future as these sites become critical in achieving food security. Northern Australia has vast areas that are of marginal productivity, due largely to the fact that they receive low annual rainfall (< 800 mm) and have a protracted dry season and low nutrient levels. It is these areas where there is the potential for growing extensive bioenergy crops with less impact on food production. There are, however, numerous technical challenges to achieving this, with many scientific and economic questions that would need to be answered. One of the first questions is whether there are indeed suitable species for cropping in this region.

Future perspective

Eucalypts are strong contenders for use as a universal woody biomass feedstock for biofuel production. Eucalypts combine rapid biomass growth rates and wide adaptability to diverse production environments and conversion technologies. There are a number of opportunities for the future. First, the growth and quality of biomass production of many of the approximate 900 species has not been fully explored; indeed, some species have not been tested and a few are probably yet to be discovered. Most testing has been undertaken with the aim of wood production in relatively high rainfall environments. The least-known species are those of the semi-arid and arid inland at subtropical and tropical latitudes. These species may be particularly well suited to very marginal agricultural land and sites unsuitable for food production. A further key development was the release of a reference sequence for the relatively small eucalypt genome. This was a turning point for study of eucalypt biology, and will accelerate molecular breeding of eucalypts for traits such as cell-wall traits (cellulose and lignin composition for example) and genetic modification to develop dedicated eucalypt genotypes for biomass and biofuel production.

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Executive summary

- Eucalypt diversity allows species to be found to suit most tropical and temperate climates where trees might be grown.
- Eucalypts have a proven track record, having been tested in many countries already. We have a large knowledge and experience base to work from – cultivation and breeding is well documented.
- Land where crop and livestock yields are low can be improved by growing eucalypts that are well adapted to these and likely future climate conditions.
- Eucalypts have already been demonstrated to be a viable biofuel feedstock. The composition of eucalypt biomass seems suitable and variable enough to allow selection for improved biofuel conversion efficiencies. The availability of a reference genome sequence will facilitate the application of plant biotechnology to improvement of the composition of woody plant biomass [164] and especially lignocellulosic biomass [165] from eucalypts to develop varieties that are a better substrate for biofuel production.
- The use of eucalypts will assist with the social and political acceptance of bioenergy by providing a major nonfood source. Eucalypts are adapted to the type of lower productivity land likely to be available for bioenergy and as such do not compete directly with food production.

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