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Measuring the regional availability of biomass for biofuels and the potential for microalgae

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Abstract:

Biomass is an important energy resource for producing bioenergy and growing the global economy whilst minimising greenhouse gas emissions. Many countries, like Australia have a huge amount of biomass with the potential for bioenergy, but non-edible feedstock resources are significantly under-exploited. Hence it is essential to map the availability of these feedstocks to identify the most appropriate bioenergy solution for each region and develop supply chains for biorefineries. Using Australia as a case study, we present the spatial availability and opportunities for second and third generation feedstocks. Considerations included current land use, the presence of existing biomass industries and climatic conditions. Detailed information on the regional availability of biomass was collected from government statistics, technical reports and energy assessments as well as from academic literature. Second generation biofuels have the largest opportunities in New South Wales, Queensland and Victoria (NSW, Qld and Vic) and the highest potential region for microalgae are Western Australia and Northern Territory (WA, NT). The approach can be used in other countries with a similar climate. More research is needed to overcome key technical and economic hurdles.

Keywords: Bioenergy; biomass; microalgae; Australia; biofuel

1. Introduction

Population growth and global warming have led to a focus on producing renewable and sustainable fuels for motor vehicles. First generation biofuels such as ethanol from starch and molasses, and biodiesel from some oil crops use edible feedstocks; but they have limited sustainability credentials. Their use has created the “food vs. fuel” debate, questions have arisen about sustainable land use and there has been speculation about the contribution of first generation biofuels to declining global wheat and maize stocks, with oilseed prices tripling. Although there are other factors contributing to price increases, such as drought, it appears these price rises may have been more moderate without using edible feedstocks and arable land for generating fuels [1]. First generation biofuels also raise ethics questions about converting foodstuffs to fuel when there is malnourishment in some developing countries [2]. Finally, another important aspect is the environmental damage caused by deforestation, and the destruction of ecosystems for increased biomass production [3].

The issues associated with first generation biofuels have created interest in second generation biofuels, which do not use edible feedstocks, as a renewable energy alternative. The International Energy Agency projected that second generation biofuels will account for 25% of total biofuels production by 2030 [4]. Second generation biofuels often use waste biomass from other industries such as forestry and the sugar industry, and other agriculture waste fibres which are affordable [5]. The utilisation of residues decreases the demand on arable land which could otherwise be used for food or energy crop production. In recent years, interest in feedstock supply has increased. There are publications dealing with locally available, sustainable biomass resources [6-9].

More recently there has been considerable interest in microalgae as a feedstock for biofuels[10, 11]. Microalgae are microscopic photosynthetic organisms with numerous constituents such as proteins, carbohydrates, and lipids, and are amenable for renewable biofuel production. It has the advantage of being grown in vast quantities on non-arable land, leading to the term “third generation” biofuel. Microalgae also has numerous advantages in comparison with terrestrial biomass in terms of high oil yield, short growing periods, and adaptability. However, there are also concerns about financial viability and water use with current technology, which need to be greatly refined if it can be used for fuel [12].

Unfortunately, to date, a comprehensive and mapping of the availability and potential use of bioenergy feedstock for second and third generation biorefineries in Australia was missing. The aim of this paper is to explore the sustainable energy feedstocks landscape in order to determine how land may be best used for renewable energy production. There is no single database comparing the potential amount of all lignocelluloses and microalgae resources available for biofuel utilisation and so data was collected from government and academic sources for this purpose. Many previous studies have provided analyses on the suitability of land for a single technological pathway without a detailed regional survey of existing land use. This is particularly the case in the microalgae literature. A raster graphic program based on accurate map references provides a better illustration of collated values from the available literature and statistic institutions. This paper also provides an introduction to theconversion technologies, including likely feedstock price and conversion routes.

Australia is used as a case study. It has abundant waste fibre from numerous industries for second generation biofuels, an abundance of data from these industries, and a large diversity of land and climate types. The last point would allow for observations made to have general implications in other countries. Also, if microalgae technology becomes a viable fuel option, Australia is an obvious candidate with vast areas of non-arable land in warm climates that can provide high growth rates [13].

1.1 Biofuels in Australia

In Australia energy consumption in the transport sector is increasing at the rate of 2.4% per year [9] and it is dependent on fossil fuels [14-16], and so sustainable alternatives are sought. Ethanol production uses molasses from sugar processing and starch from flour milling as feedstocks. Most of the fuel ethanol produced by the three Australian producers is blended with petrol as E10 blend petrol (10 per cent ethanol and 90 per cent petrol). Biodiesel is mainly produced from tallow and waste cooking oil. Biodiesel can be mixed with regular diesel; B5 is the common blend and B20 biodiesel blend is generally sold for commercial operations.

In terms of first generation biofuels feedstocks, in 2005-2006, Australia produced and consumed 57 million litres of biofuels, consisting of 41 million litres of ethanol fuel and 16 million litres of biodiesel, which corresponds to only 0.4% of total transport fuel consumption [17]. Renewable energy sources accounted for the remaining 6 per cent of total energy consumption in 2012–13, with its share of the energy mix increasing compared with the previous year [18]. Total production capacity of ethanol and biodiesel was about 330 million litres (ML) and 175 ML respectively in 2010 [19]. In 2013 the production of ethanol was only 280 ML and biodiesel was 110ML [20] due to the closure of several plants. While the existing ethanol and biodiesel sector is based on first generation biofuels technology, research and development of second and third generation technology biofuels is continuing. Previous workers found that second generation biofuels can overcome the major shortcomings of first generation biofuels in Australia [9]. The following subsections relate to second and third generation feedstock opportunities.

1.2 Feedstocks

In Australia, the main second generation feedstocks are tallow and used cooking oil with biodiesel production facilities in Vic, SA, WA,NSW, NT and QLD [9]. However, new forestry and sawmill residue, sugarcane waste fibre, other agricultural residues, and microalgae are being researched and developed. The feedstocks explored in this study were perceived by the authors to be the main opportunities for large scale biofuels development in Australia.

1.2.1 Forestry and sawmill residue

Forestry residues consist of the crown and branches of trees, the leaf material, bark and stump, as well as non-merchantable stem biomass, which are left in the forests or are burned. Furthermore, large areas of forests and woodlands are still cleared annually for the expansion of agricultural activity or foresting. A small fraction of the cut wood from the cleaning activity is used for energy production, but the majority is not utilised and is either burned or left to decay on site [21]. However, these sources are broadly distributed in remote locations, so collection and transportation would be expensive. Waste fibre is produced at sawmills in the form of sawdust and offcuts.

1.2.2 Sugar cane waste fibre, bagasse, and trash

Sugarcane is harvested and crushed at a sugar factory which produces juice and fibre. The juice is purified and concentrated to produce sugar crystals, and the fibre (i.e. bagasse) is typically burned to produce steam and electricity for the factory. Sugarcane bagasse has the advantage in that it is already collected at a centralised location, reducing transport costs. Sugarcane harvesters allow the leaves (known as trash) to drop to the ground so that only the stem of the plant is used. However, leaves could either be harvested together with the stem (although this generates some issues in the sugar production process), or collected separately at a higher cost. Bagasse is only produced for six months of the year, so while it has many advantages, it cannot be produced all year round and during long term storage there is a risk of biological degradation.

Australia produces over 11 million tonnes of bagasse annually and over 9 million tonnes of cane harvest waste, comprising leaves and tops, which have traditionally been burnt in the field each year [22]. However, the majority of the industry harvests green (i.e. unburned) cane. Around 95% of Australian sugar production occurs in Queensland with a small amount being produced in northern New South Wales.

1.2.3 Agricultural residues

Australia has a potentially large biomass resource in the form of agricultural crop waste. The residues from grain cropping generally comprise the stalks of the grain (i.e. stubble). The main crops in Australia are wheat (22,856kt) and barley (7472kt) with a range of smaller crops totalling 9548 kt including sorghum, cotton, canola, oats, and rice for grain in the year 2013 [23]. The proportion of the plant which is left as residue varies with plant type and is often left in the field. Currently, the stubble is not collected as a feedstock for producing bio-oil, but removed and burned in the field or used for animal feed or bedding. The most important issue for biofuels from agricultural residues is the effect on soil structure and nutrients. There are a few options: either remove only a percentage of residues for biofuel production, or use the ash residue that remains after processing as a soil conditioner.

1.2.4 Microalgae

Unlike second generation biofuel feedstocks, microalgae is not a waste biomass. It is often cultivated in extensive or intensive artificial environments - the latter being of more interest with regard to biofuels. Research in the intensive cultivation of microalgae has been conducted since the 1950s [24, 25]. Subsequent research into intensive cultivation, as found in reviews by Goldman [26], and Tapie and Bernard [27], has investigated biomass yields through different production technologies and assumptions, resulting in varying degrees of technical and financial feasibility of microalgae production. Benemann and Oswald [28] highlighted the potential of microalgae production for biodiesel through production pathways that incorporated recycled input sources of carbon dioxide and nitrogen through flue gas and wastewater respectively. This review was a pivotal catalogue of the production technology up to that point. Most economic feasibility studies since have not been able to derive economically feasible production pathways. However, hypothetical studies that make assumptions on future production efficiencies have suggested the potential for microalgae as a feasible biomass for biodiesel production.

Intensive autotrophic microalgal biomass cultivation requires substantial resources to achieve high rates of solar conversion and productivity yields. The two most common cultivation methods are through open-pond systems or some variant of photo-bioreactors (PBRs) [29]. There have been substantial research findings on the much higher capital and operating costs of PBR, and despite the higher productivity, the resulting price of biofuel (assuming similar downstream processing and hence comparing costs of biomass cultivation) was almost two times higher than open ponds [30-32]. This has been contradicted by Norsker and co-workers [33] who find little consistent difference between the unit costs of biomass and energy between the two systems. In addition, the exposed nature of open-pond systems is suggested to lead to more significant water demands in highly evaporative climates [31] and risks of exposure to contaminative elements [34], the latter increasing the risk to potential productive biomass output. Campbell and co-workers [35] suggest that based on current productivities of algal strains, producing biofuels from open-pond systems is also unfeasible, but future technological and scale investments can overcome this.

1.3 Conversion technologies

1.3.1 Waste biomass conversion technologies

There are different reviews focusing on effective technologies and the processes to convert biomass into useful liquid biofuels and bio-product [36-38]. In this paper we briefly describe the most common which are having in the most research interest. Key conversion technologies for biomass to fuel are the thermo-chemical processes such as gasification, pyrolysis, and liquefaction where high temperature is used to degrade the fibre. Gasification is the most developed and commercialised route, while liquefaction is the least developed. Gasification occurs at high temperatures (approaching 800°C) to produce syngas which can then be reformed to liquid fuels by Fischer Tropsch synthesis. Pyrolysis and liquefaction occur at lower temperatures (200-350 °C); the difference being pressure (up to 350 bar for liquefaction). More description of the thermochemical technologies and an analysis of the potential production of advanced biofuels is nicely described in Sanna's publication (2014) [39]. These processes generate a biocrude which must then be further treated to convert it to a liquid fuel. Liquefaction has a tremendous advantage in that it is feedstock agnostic and can tolerate feedstocks with very high water contents, and does not require feedstock predrying. Waste biomass can be pre-treated to liberate glucose monomers which are then fermented to produce ethanol. This process is the focus of a significant international research effort.

A well-established technology route used on a small scale is the production of fatty acid methyl esters (FAME) through various types of transesterification whereby vegetable or animal oils can be converted to fuel by reaction with methanol, producing glycerol as a waste product[40].

1.3.2 Microalgae conversion

The most common approach to produce microalgae fuels so far has been to use mechanical disruption to liberate lipids by bead milling, homogenisation, and mechanical pressing [41, 42], followed by extraction (solvent extraction or supercritical CO_2). Most commonly the lipids are converted to FAME via the same reaction as for waste vegetable oil. Liquefaction and ultrasonic-assisted extraction have also been studied. Kumar and collective provide a comprehensive review on various methods of lipid extraction from microalgae available, as well as discussion of advantages and disadvantages[43].

2 Methodology

2.1 Collation of data on existing industry biomass waste and land-use

Australia is a developed nation with a large amount of existing forestry, sugar, and other agriculture production. Australia is also vast, with both arable and non-arable land and it has a wide range of climates (desert, tropical, and temperate climates, Fig. 1), making it a suitable case study. The population is concentrated in the south east corner with New South Wales (NSW), Victoria (Vic) and Queensland (Qld) being the most populous states (>4 million inhabitants), followed by South Australia (SA) and Western Australia (WA; 1-2 million) and finally Tasmania (Tas), Northern Territory (NT), and the Australian Capital Territory (ACT; not shown in the figure due to its small geographical size).

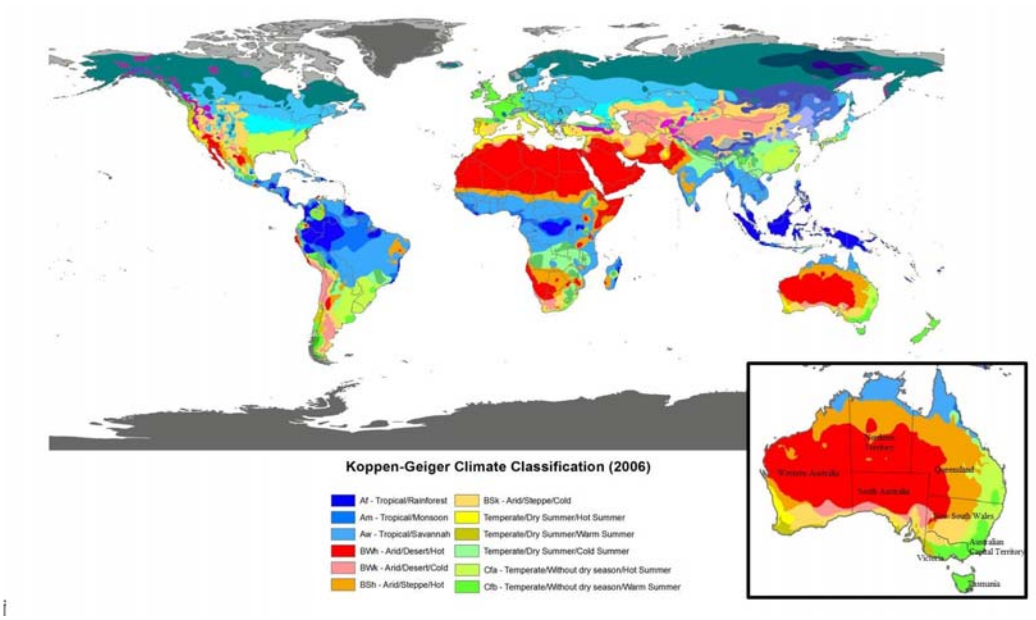

Fig. 1. Australia's key climate groups (ACT not shown due to small geographical size; adapted from[44]).

In order to study renewable fuel production and appropriate land use using existing industrial waste and microalgae, the approach has been to firstly collate information about the size and geographical location of existing industries which produce waste biomass, and hence an estimate of each region's waste. For each industry, the cultivation area and total biomass data were collected at a state level from the Australian Bureau of Statistics (ABS) for agriculture (for each of many crop types)[1], and the Department of Agriculture, Fisheries and Forestry (DAFF) for sugarcane[2] and forestry

[1] http://www.abs.gov.au/ausstats/abs@.nsf/Lookup/7121.0main+features42012-2013
[2] http://www.daff.gov.au/__data/assets/pdf_file/0005/1956011/sugar-industry-reform-report-2010.pdf

(native and plantation)[3]. These statistics were collated and then distributed proportionally on a regional basis as a proportion of the total production for each industry - agriculture [45], sugarcane [46], and forestry [45]. Assumptions were made that all of the total available residue/waste biomass could potentially be allocated for biofuels and the availability of these biomasses by state is proportionally consistent across the areas of cultivation.

For regions where there is no industry producing waste biomass, much of the land is native forest or mountainous (e.g. south eastern Australia), which was excluded from the mapping activity (these maps are shown later in this article). The areas that remain are a range of non-arable areas and unused arable land, which may be potentially useful for microalgae production. Thus, the allocation of regions for potential microalgae cultivation were based on intersecting factors of land availability, exposure to sufficient/abundant solar energy, and the presence of an abundant water supply (i.e. in coastal regions [47]). The guiding principle applied was that for microalgae production, areas could only be used that were not already dominated by existing biomass production such as agriculture and forests.

2.2 Logistical considerations

The logistics for bringing feedstock to a biorefinery will vary depending on the type of feedstock, the geographical location and the local weather/climate as well as the prevailing industry. Before biomass can be processed, considerations include:

- Harvesting and collection of biomass from sole suppliers (as in the sugar industry) or multiple suppliers (e.g. saw mills). It is more efficient when there is enough material to be collected from a single site without the need for collecting from a distributed region. Collecting biomass from the field includes the scheduling of labour, machinery and other equipment.
- Loading, handling and transport. Biomass is taken to a central location where road transport can be used. Increasing remoteness increases transportation costs.
- Unloading and loading to road vehicles in order to transport the biomass to central biorefineries, and the unloading and storage of biomass on site.
- Biomass storage. Allen and co-workers [48] modelled intermediate storage systems. This system, in which the biomass had to be transported twice, resulted in higher delivered cost than a system in which there is only one transport movement, due to the additional transport and handling cost incurred. Some feedstocks are seasonal; therefore consideration needs to be made of the length of time and the large quantities involved, which will have influence on the total cost.

[3] http://www.daff.gov.au/ABARES/forestsaustralia/Documents/sofr2013

Lakovou and co-workers [49] designed a system for the management of a waste biomass supply chain for energy production which includes a hierarchy of decision-making parameters. This system was adapted for our purposes for use in a subsequent study (Fig. 2).

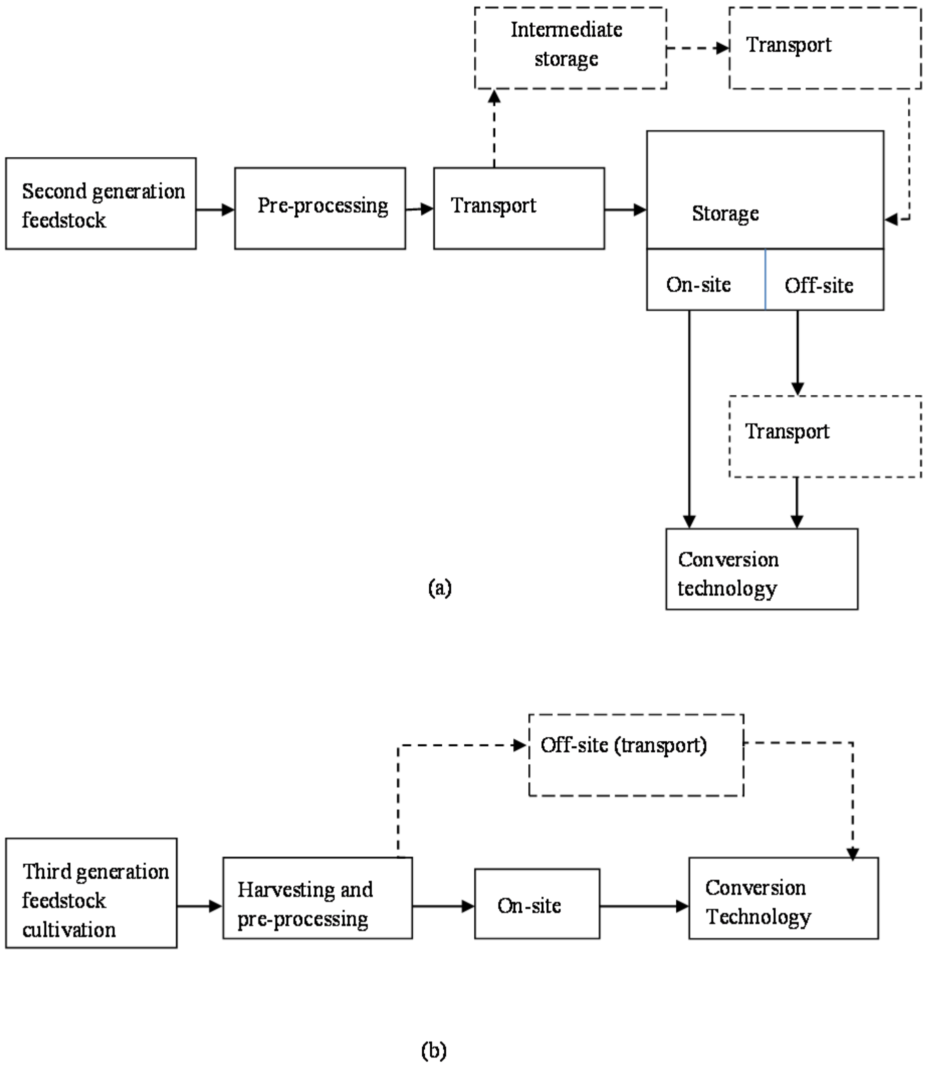

Fig. 2. Processing for (a) second and (b) third generation biofuel feedstocks. (optional steps presented by dashed lines).

Other factors for each biofuel feedstock include moisture content, energy density, and the value placed on the waste biomass by the producer. The price of the biomass can also be affected by availability of other fuels in the vicinity. The available data on Australian's biomass feedstocks are summarised in

Table 4 (in the conclusion part), which reports the amount (Mt/year) and price ($/t).

3. Results

3.1 Forest and sawmill residues

Liquid biofuels derived from wood residues are not widely used in Australia. In 2006, Australia's total forested area was 149.2 million hectares (ha) or 19% of Australia's land area [50]. However only 2.0 Mha belonged to plantation forestry comprised of hardwood (mainly eucalyptus), and softwood, consisting of various types of pine species. An overview of Australia's energy resources in 2007 estimated total forestry residues at 23 million tonnes per year [51]. Large amounts of forest residue can be produced in the regions of Australia dominated by native forest, particularly from defective trees, and the remnants of bushfires or diseased trees.

Ximenes and co-workers [52] examined the proportion of above-ground biomass (AGB) in logs and the residues of three hardwood and two softwood species, which account for approximately 65% of the total volume of sawlogs harvested in Australia. The percentage of the AGB in forest residues at harvest ranged from 30 to 55% depending on the species. The average dry weight of residues left in the forest per tree ranged from 800 to 1600 kg for hardwoods and 80 to 350 kg for softwoods.

The following graph (Fig. 3) compares the native and plantation forest area in hectares for all states and territories in Australia. The territories have minimal investment in plantation forestry, while the six states have significant plantations in the following order: Victoria and Western Australia> New South Wales>Queensland> South Australia. Queensland and Western Australia have the largest land area but less than 1% is used for plantation in both states, whereas 30% and 7% belong to native forest respectively. From the perspective of forest plantation, the largest diversity occurs in south eastern Australia which contains the majority of the paper industry.

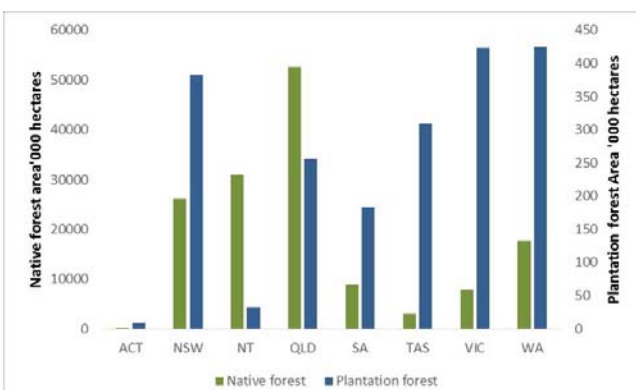

Fig. 3. Forest area by state [53], [54], [55] (NB: Different scales on each axis; ACT native area is too small to be seen (123000ha)).

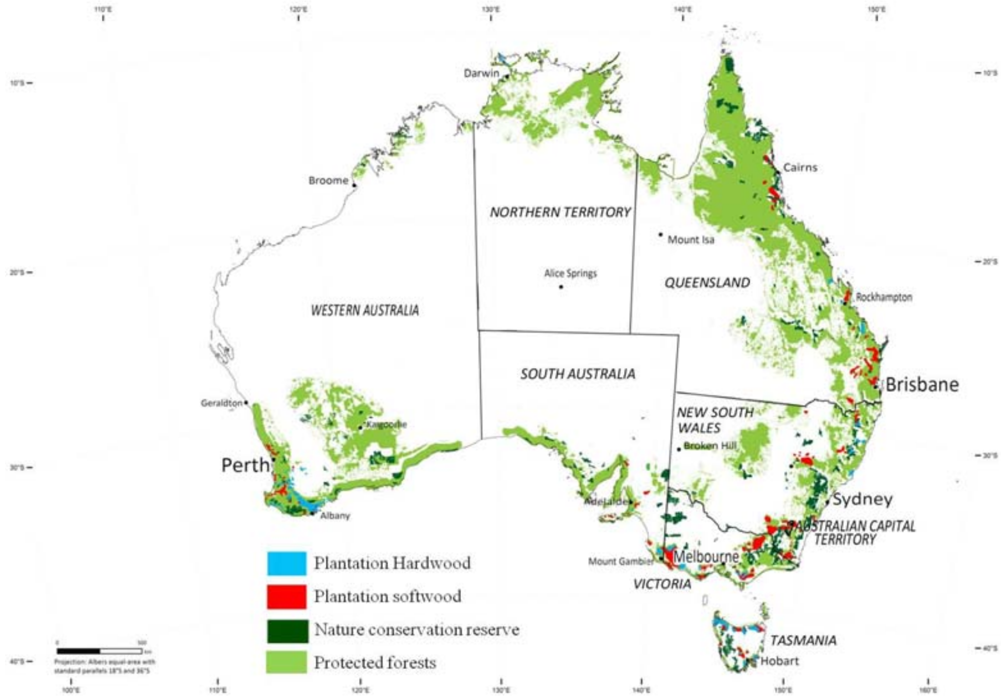

Fig. 4. Australian forest area (adapted from [54]).

Sufficient quantities of accessible forestry residues are available in most states of Australia (

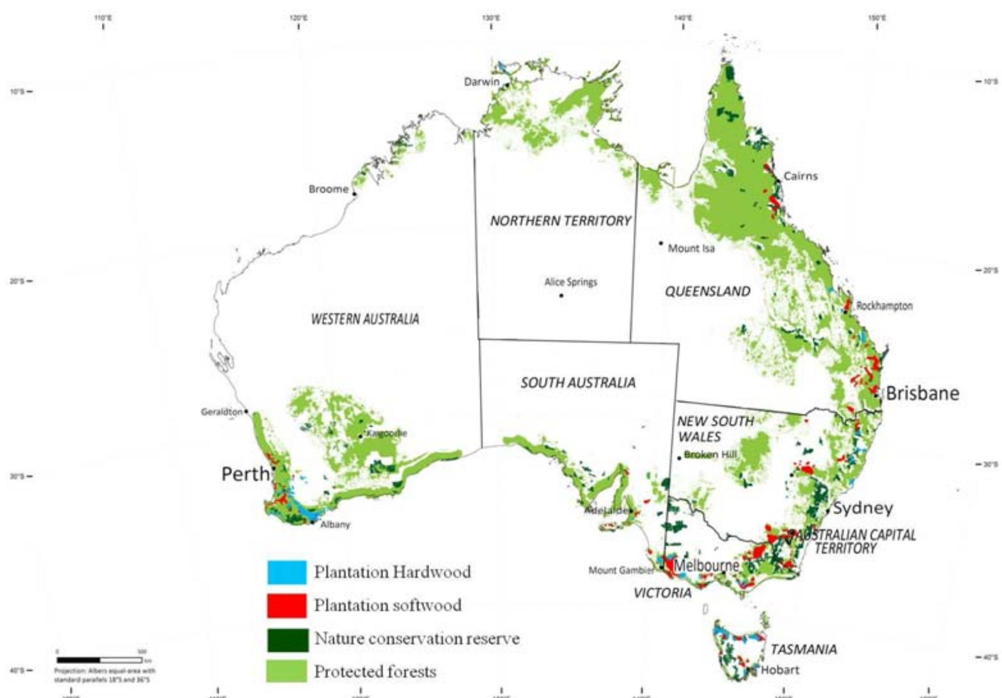

Fig. 4). The east coast of Australia (especially QLD, NSW and Victoria) is characterised by abundant natural and plantation forestry as a potential source of bioenergy. However, surveying of residues production would help to deduce sustainability for each sub-region. Forestry in the Northern Territory covers 23% of its total land area while around 53% of forest cover is in private use. The proportion of land used for forestry in Western Australia is only 12%. Hence there is ample opportunity for developing another feedstock - on unused land. South Australia's 'Green Triangle'(spans the area between Mt Gambier in South Australia and Portland in Victoria) region plantations occupy only 14% of the region's land area, compared with the 72% used for agriculture [54].

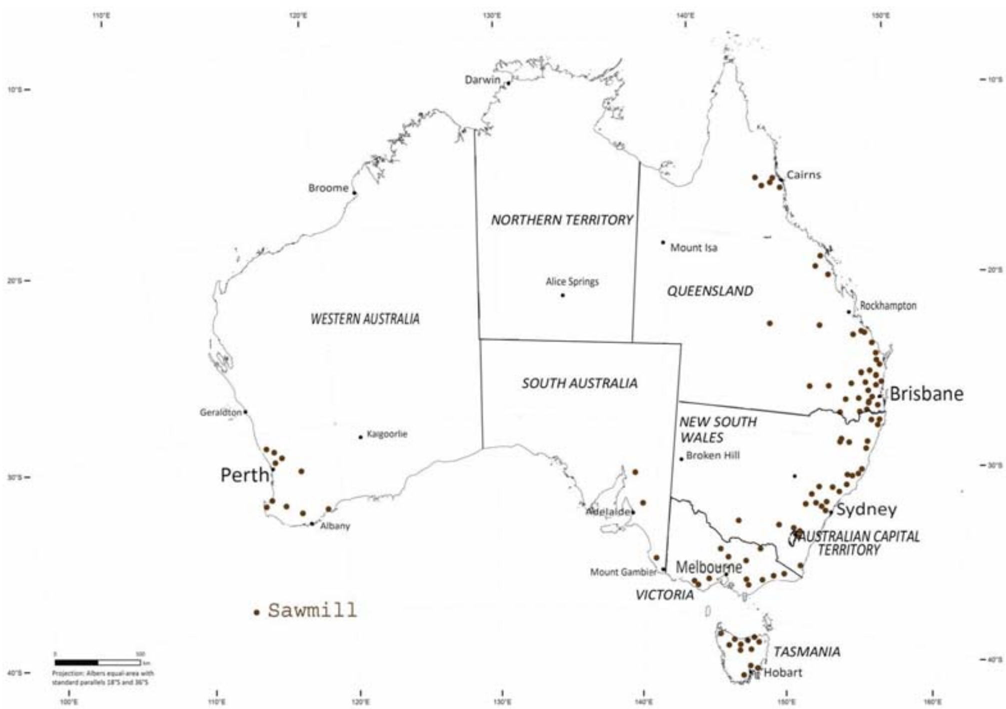

Fig. 5. The location of sawmills in Australia.

Australia has numerous sawmills (Fig. 5) mostly situated on the south east coast and Tasmania. The sawmill industry in Australia is a major producer of residues from the processing of roughly equal log volumes of softwoods and hardwoods. A breakdown of residues likely to be produced from sawmills is 70% solids (slabs, edgings and dockings), 19% sawdust and 11% bark. Additional residues are produced from the sawn timber during subsequent machining, possibly in the order of 8% - 9% of the sawn wood [21]. Of the remaining off-cuts, 30% is used to produce woodchips and the rest is sawdust and chips. Australia produces 1.25 million tonnes of sawmill waste per year and many mills pay to have this removed [51]. Sawmill residues are likely to cost between $0-$4 per dry tonne although sawmills may pay for waste disposal [56]. Therefore they prove to be an attractive candidate for biofuels production. The estimated cost of sawmill residues is shown in Table 1.

Table 1

Estimated moisture contents and average price [57].

Type	Moisture content %	Cost	
		($/t wet weight)	($/t dry weight)
Chips	53	37	79
Bark	30	11	16
Green sawdust	55	11	24
Shavings	12	21	23

Transport costs in Australia for sawmill residues are in the vicinity of $4.69-$9.17 per dry tonne for a distance of 10 kilometres [57] although this cost depends on the type of residue.

The delivery of forest residues to a central location is a key activity which includes the collection of residues, transportation and storage for up to six months. Moreover, the delivery is affected by seasonality and the conversion process. Hall and co-workers [58] compared seven different biomass delivery systems for forest residues in New Zealand. Landing residues (residues after whole felled trees are transported to a landing site) were cheaper than cutover residues (residues throughout the stand when trees are processed at the stump), because cutover residues need to be collected and then transported to the forest landing or roadside. Forestry is sensitive to moisture content and bulk density which causes costs to vary up to 9%. Storage of wood is another significant expense; Table 2 summarises some key considerations which can prolong storage time.

Table 2

Primary considerations for handling lignocellulose materials.

Issue	Solution
Contamination and hygiene	Concrete floors
Moisture	Sealed containers, roofed bunker
Overheating and biological degradation	Monitoring temperature and moisture
Particle size	Screening

The storage of wood chips for the pulp and paper industry was the subject of intensive research many years ago, but the prospect of renewable energy has brought renewed interest in recent times. Slaven and co-workers [59] pointed out factors causing the degradation and decomposition of wood biomass during storage, and suggested important prevention strategies to mitigate the issues.

In the future, expansion of forestry into drier environments for the dual purpose of wood production and environmental rehabilitation may provide significant quantities of biomass for energy and biofuels production [60].

3.2 Bagasse and cane trash

Bagasse is available for about half of each year from Australian sugar mills. In Australia, there is in excess of 10 million tonnes of bagasse potentially available for the manufacture of pulp. Rainey and co-workers [61] summarised the quantity of sugarcane crushed in each region and the potential quantity of depithed bagasse (Table 3). Some sugar mills value bagasse around $40 per dry tonne, which presents bagasse as a low cost raw material when compared to wood [46].

An important transport consideration for bagasse is its bulky nature, which makes transport potentially expensive. Bagasse has an advantage over some other feedstocks in that it is already collected at a central location (i.e. at the mill), so there are few additional collection and transport costs. Hodgson and Hocking [62] reported that the cost of transporting bagasse from one site to another was $11 per tonne. The concentration of sugar mills in northern Queensland in the Mackay, Bundaberg, Herbert and Burdekin regions is higher than in other regions. These areas offer the best prospects for a biofuels facility based on bagasse. In Table 3 it can be seen that Mackay has the highest quantity of bagasse and is also well supported by infrastructure and has low transport costs. The New South Wales region is less attractive, as it has the smallest fibre supply and relatively high transportation costs.

Table 3

Potential availability of bagasse by region [63].

Region	Cane crushed (million t/a)	Dry bagasse potential (dry tonnes per year)
Northern	7.8	856 700
Herbert	4.0	439 400
Burdekin	8.6	946 400
Mackay	10.0	1 098 500
Bundaberg	3.9	429 000
NSW	2.3	252 200

Pre-processing of the original biomass feedstock to change the energy density can decrease the price of transport and storage. Hobson [64] compared costs for the road transport and storage of raw bagasse and bagasse pre-processed torrefaction followed by pelletisation (TPB) for mills of four varying distances. Torrefaction is a thermal pre-treatment technology to upgrade ligno-cellulosic biomass to a higher quality and more attractive biofuel [65] - oxygen is removed, and torrefied biomass has a lower O/C ratio when compared to the original biomass. Hobson indicated a transport cost saving of over 30% for TPB when compared to raw bagasse for long distance haulage, although TPB was more expensive to transport than raw bagasse for distances less than 100 km.

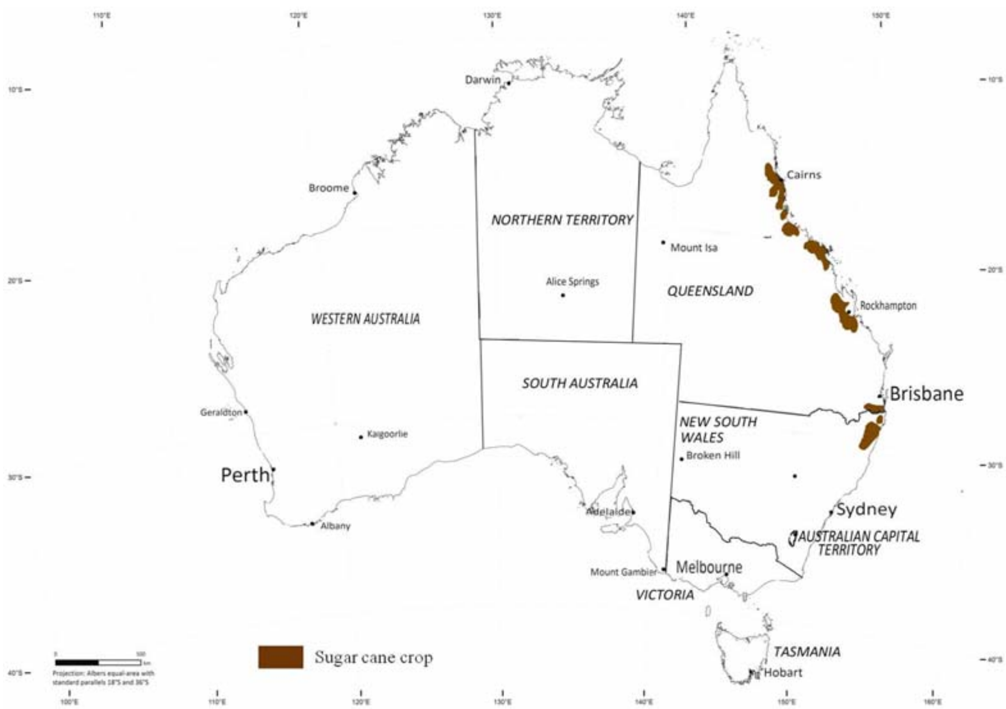

Fig. 6. Sugar cane regions in Australia (adapted from [66]) .

3.3 Agricultural residues

Quantifying the amount of feedstock from agricultural residues was problematic owing to the broad number of crop types which vary from state to state, the differences in farming and processing, and production data for each crop being reported by different organisations. The amounts of agricultural residues available per hectare vary with crop type, thus affecting the cost of collection and transportation to biorefineries. Not all crop residues are of equal value, considering the chemical composition varies, thus affecting the yield of conversion to biofuel. Not all of the non-grain biomass of a particular crop will be available for collection for biomass energy production, because most farmers will retain some straw to provide soil cover to prevent wind and water erosion, and to help maintain soil carbon and recycle nutrients [67]. Hess and co-workers [68] describe a strategy for reducing the amount of unattractive residue components shipped to centralised biorefineries by an in-field physical fractionation.

Fig. 7 (adapted from [69]) shows large cropping areas in the eastern, southern and western areas of Australia. From the map it can be seen that high productivity mainly occurs in the northwest of Victoria, and also around the Yorke Peninsula and lower north and outer Adelaide areas of South Australia, and in the west of New South Wales. In an average year, these areas have >500 kt stubble within a 70 km radius, but only 21 Mt of the total stubble production is potentially harvestable [70]. There remains an opportunity for storing agricultural fibres together with forestry residue when the two industries are in close proximity.

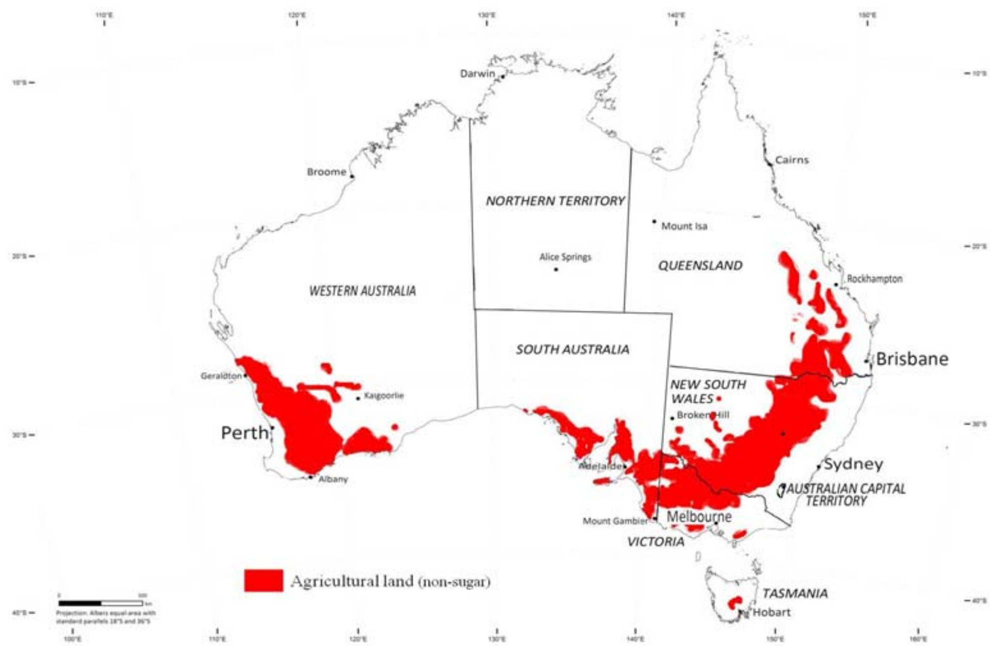

Fig. 7. Agricultural residues in Australia (1983 – 2005; adapted from [69]).

There has been little research into the potential delivery system for straw. In Europe large rectangular bales are used for transportation. Allen and co-workers [48] modelled five supply systems for straw, and showed that large Hesston rectangular bales have substantially lower delivered costs than systems involving the production of small rectangular bales or roll bales. However, large bales require specialised and relatively expensive machinery. Bale weight is approximately 500kg for Hesston bales but depends on the moisture content, packing density and size.

Straw can be stored and dried outside only in the summer (it is grown in non-tropical climates which are dry in summer). Internal storage requires good ventilation, stock must be raised off the floor on pallets, as even concrete floors can transmit moisture by capillary action, and must be kept inside a building where there is no possible moisture contamination. If the straw is wet it starts to grow mould, it can also begin to ferment and can then spontaneously combust. However, it can keep for up to a year without issues if stored correctly.

Several researchers proposed supply chains for the optimal processing of agricultural residues, taking into account the contributions of the cost of production, harvesting, collection, transportation and storage [71-73]. Kumar and co-workers [71] concluded that the production cost method essentially reflects the minimum amount a farmer has to be paid for the agricultural residues, with the estimates based on the maximum acceptable price defining the upper limit up which the energy end-user can pay for the agricultural residues. There is also a need to address cultural and social issues, as farmers' own attitudes and those of their peers will influence their management of residues [74].

3.4 Microalgae

Australia is an increasingly popular target locale for microalgae research. This is due to benefits pertaining to climate, solar insolation, and the availability of vast land areas of marginal/low agricultural value [13, 75, 76]. Griffin and co-workers [77] suggested that Asian-Pacific countries would benefit more from importing microalgal biofuels from Australia rather than cultivating their own microalgae due to these inherent benefits. There is currently no large-scale intensive microalgae production in Australia [75]. Current cultivation of microalgae for biofuels has been for mostly pilot and research activities, with many airline companies funding such programs for developing alternative aviation fuels [78], and commercial producers with as yet unreleased production data [77].

Hypothetical studies have only been able to suggest potential economic feasibility through assumptions for future developments in productivity and efficiency, with current technologies suggesting a much higher production cost than the fossil fuel diesel prices. This is also consistent with studies outside Australia. The lowest cost estimate for an Australian-based analysis was US$0.63 per litre of biodiesel, albeit with optimistic assumptions for growth rate and lipid yield [79]. US-based estimates were between US$3.54 to 8.94 per litre[4] based on the production system (i.e. open-pond or PBR with same downstream processing) [80]. As for algal oil production, Davis and co-workers [30] estimated the lowest cost being between US$0.80 to 1.30 per litre (using open-ponds), again with optimistic potential future yields; current production yields produced an algal oil price of US$2.25 to

[4]All US based studies were converted from gallons to litres using 1 gallon = 3.7854118 litres.

4.78 per litre. The corresponding diesel price was similar to Richardson and co-workers [80] at US$ 2.60 to 5.42 per litre (with PBRs yielding the higher estimate).

There has been much discussion in the literature relating to microalgae biomass cultivation (most often for biofuels), and the associated opportunities and limitations thereof. Factors related to water and energy demand have been significant in determining the feasibility of the biomass production. Although touted much for its ability to grow in saline [79] and wastewater [81], the costs involved in pre-treating and transporting the water resource have been highlighted as a potential limitation [82]. Lundquist and co-workers [83] had estimated that water provision can make up as much as 6-7% of the total cost, which is significant considering a majority of that cost is from piping and transportation. Yang at al. [84] discussed that the significant water costs (footprint) can be reduced with improved growth and lipid accumulation rates, although these two factors are counteractive. Additionally, the need for high solar irradiation to encourage biomass growth also has a correlation with water loss from evaporation in open-ponds. In the use of saline and wastewater, here recycling can reduce the water requirements by up to 90% [84], there is, however, increased risk associated with the contamination of the cultivation culture [82].

There have been a number of studies estimating the net energy return from microalgae biomass production, testing various cultivation, harvest, and drying technologies. The energy ratios have also often account for transport energy for fertilisers, water, and other related inputs. In comparing open ponds and PBRs, the former is most often found to have a more efficient energy ratio, with only Sander and Murthy [85] finding otherwise due to their relatively higher value estimates. Open ponds were also generally found to have less energy intensive cultivation, with more significant energy costs coming from the harvesting and drying stages of the biomass production, increasing the energy ratio as much as ten-fold [82, 86, 87]. In contrast, the more controlled environments associated with PBRs resulted in significant energy costs for cultivation, causing an inefficient energy ratio; the majority of energy costs were attributed to construction and culture circulation [32, 88]. Slade and Bauen [82] add that assuming the majority of the energy in the production is derived from fossil fuels, the net carbon emissions from biomass production are positive, and more significantly so for PBRs.

4 Discussion

There are challenges in the commercial transition to second generation biofuels produced from lignocellulosic feedstocks. These include the supply of the potential feedstock, associated logistics, and the cost of conversion. While the latter two factors are important to the success in commercial production of lignocellulosic biofuels, this study found that the potential supply sources of feedstock are most important in determining the location of feasible biorefineries. Large quantities of biomass are required to meet current and future transport fuel demands.

Error! Reference source not found. below illustrates the potential availability of second generation feedstock by state. This was estimated based on the state-based proportion of land use and total national feedstock availability for agricultural waste [45], sugarcane residues [46] and forest waste [45, 89]. Based on current production, the east coast of Australia (Qld, NSW, Vic) appears to have the greatest potential for second generation biofuel production. The availability of arable land and ideal climate conditions have resulted in the majority of the agricultural production, including sugarcane, being produced in this region. Queensland in particular has the highest potential for generating biofuel from sugarcane waste. In contrast, the availability of feedstock in WA is about half that of the east coast; this is even lower (5-10%) in the northern and southern regions.

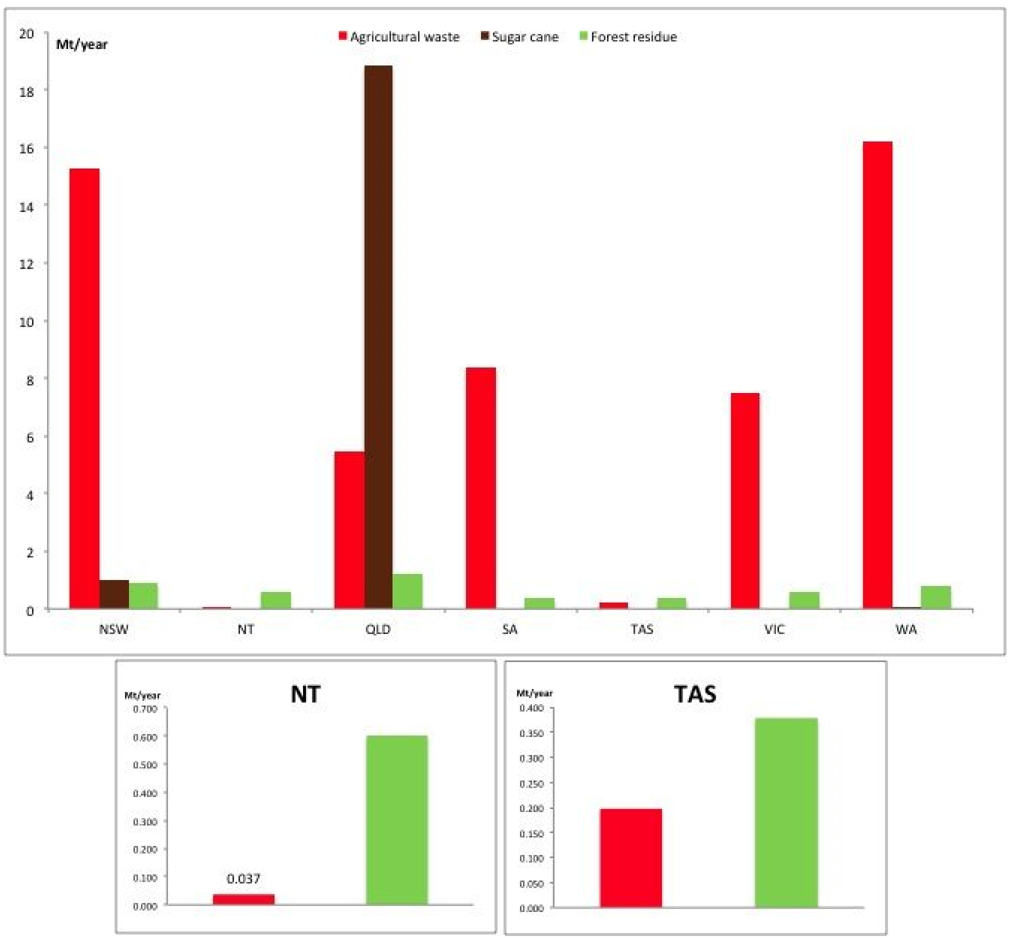

Fig. 8. Second generation biomass production in Australia by state (ACT excluded).

Despite ACT containing some agricultural land and a large area of national conservation parks (almost 88% of the total land area), the availability of feedstocks was negligible; hence ACT was excluded from the figure. At the lower end of the availability spectrum, NT and Tasmania have some proportions of forestland that at first glance, could provide a source of biofuel feedstock; Tasmania in particular is renowned for its forest-rich landscapes. However, a large proportion of these forestlands are inaccessible for the collection of waste biomass. More than 50% of Tasmania's forest are nature conservation reserves (33%) and multiple-use forests (30%) where harvesting is not permitted [90]. Similarly, NT is sparsely covered by accessible forestry with the remainder mostly held in private and leasehold tenure use for grazing.

Unlike the case with second generation biofuel feedstocks, there are no large-scale microalgae cultivation facilities in Australia and hence, a similar data analysis for potential availability could not be conducted.

The regional suitability of each feedstock is summarised in

Table 4 and potential land use is shown in **Error! Reference source not found.**, which highlights the spatial distribution of potential feedstocks. The distribution of second generation feedstock is based on location of existing cultivation, and therefore potential areas of waste biomass availability, with the assumption that all available biomass is potentially available for biofuels. The spatial distribution on feedstocks as shown in **Error! Reference source not found.** can be used to assess the feasibility of prospective biorefineries locations. Geographical locations demonstrate the potential utilisation of a diversity of supply sources that can extend the operating period of biofuel production.

Hypothetical studies pertaining to Australian-based microalgae production have suggested southwest of Broom in WA as a suitable region based on climate conditions [79, 91], with particularly high solar radiation and low average rainfall. There has also been indication of other regions in Australia as being potential cultivation regions e.g. NT and northwest Queensland [47]. Factors such as ownership, affordability, and restrictions from cultivation systems have been suggested as those which will affect the potential availability of land for microalgae cultivation, but only as secondary and tertiary to climate and land topography [91]. Thus, the allocation for potential microalgae availability in **Error! Reference source not found.** is based on the most suitable regions for microalgae cultivation stemming from these various intersecting factors.

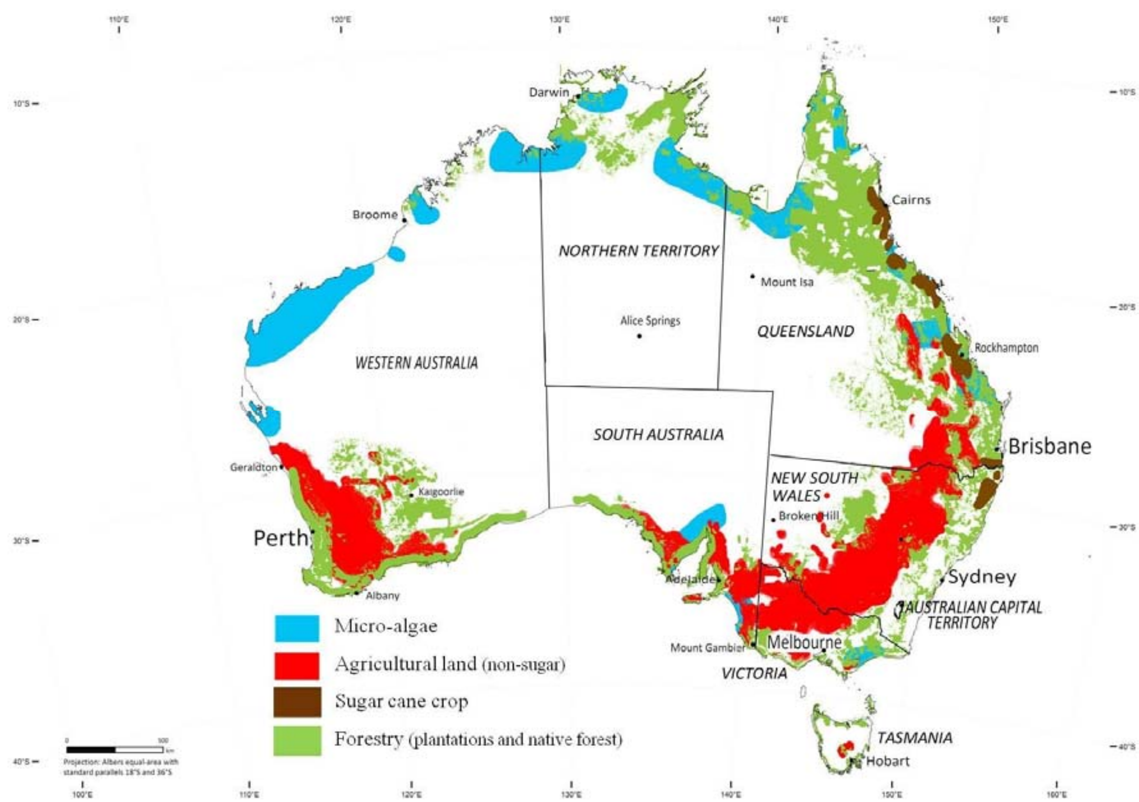

Fig. 9 Potential feedstock growth regions.

The development of microalgae-based biofuel technologies does present potential for future biofuel production. This is especially applicable to regions outside of the east coast that have substantial areas of unutilised coastal land, such as in WA. These land areas are generally plagued with inadequate land and climate conditions for terrestrial agriculture and forestry, but are suitable for artificial microalgae cultivation. This highlights one of the major benefits of intensive microalgae cultivation in artificial environments, where ideal land and climate conditions are not essential for cultivation [13, 75, 76].

However, there is a relationship between ideal climate conditions and achieving maximum biomass production, both in terrestrial and artificial environments that depend on autotrophic photosynthesis. The prevalence of agriculture and forestry in the east coast can be attributed to both the highly suitable land type and the climate. This suggests that both arable land and ideal climate are subject to scarcity and therefore, will play a key role in land use selection for biofuels. Transitioning away from existing terrestrial cultivation raises opportunity costs, especially for agriculture and food production.

For microalgae cultivation, ideal climate conditions would allow for maximum growth rates to be realised, particularly for open pond systems. Achieving high biomass growth rates of microalgae has been highlighted as a major factor that can determine the financial feasibility of microalgae production for biofuels, given high harvesting and conversion costs [79]. An assessment of microalgae cultivation locations by Borowitzka et al. [91] had detailed the climate conditions to include exposure to solar irradiation, net evaporation rates, and temperature.

The selection of regions for microalgae cultivation requires an economic analysis of the related tradeoffs, including with existing biomass industries. Although microalgae production appears possible in regions that do not compete with existing agriculture/forestry (e.g. away from coastal land), the cultivation operations will potentially be unable to realise the high growth rates and low upstream/cultivation costs compared to areas with ideal climate characteristics, which may have existing terrestrial cultivation. Developing microalgae production in ideal regions in the east coast raises opportunity costs in replacing existing agricultural and forestland particularly in terms of resource reallocation, food production, and ecosystem services; despite the potential to eclipse second generation feedstock production for bioenergy by over 7 times in the east coast, and 20 times on average across the country[5]. Therefore, this review finds that regions in WA and NT (as outlined in **Error! Reference source not found.**) are the most suitable locations for development of microalgae cultivation for biofuels due to the availability of unutilised land and preferable climate.

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[5] This estimate is based on conservative open-pond growth rates (20g/m^2/day) [62].

The approach presented in this article can be used as a foundation to better understand the regional availability of biomass feedstocks and the potential for microalgae. The authors believe that the approach and rationale used in the analysis can be applied at local, national and international scales. A large amount of data was collected for Australia as a case study and this data suggests some opportunities for the geographical location of a local biorefinery based on forestry, agriculture or sugarcane waste or microalgae.

Table 4

A regional suitability comparison of second and third generation feedstocks and their prices.

Feedstock		Region offering the best prospects	Least attractive location	Estimated Australian production amount (Mt/year)	Estimated price of transport ($/t /km)	Potential feedstock price ($/t oven dry weight)	Seasonality	Advantages	Disadvantages
Sugar cane	**Bagasse**	North of Queensland (Mackay, Bundaberg, Herbert, Burdekin)	New South Wales	10.6 [22,46,51]	$ 5-$7/t per 30km $11/t [62]	$40/t [66]	6 months production, Sustainable for storage	Cheap Proximity of the mill: no additional collection and transport cost Cane waste is not used for sugar extraction Sustainable land use Low emissions [45,46]	Bulky nature of bagasse makes transport more expensive Risk of biological contamination during storage [45,46]
	Cane trash	Based on sugar cane crops Area [66]	Based on sugar cane crops area [66]	9.25 [46,51]	N/A[d]	US5-6[b] [81]			
Forest	**Sawmill residues**	South east of Queensland, Tasmania, Victoria, South Australia, New South Wales, South Western Australia	Northern Territory, North Queensland, North Western Australia	1.3[a] [45]	$4.7-$9.2/t/10km [59] $12-$40/t per 50-200km [19]	10-60[c] [19]	Available whole year	Sawmills are currently paying for waste disposal Sustainable land use Low emissions [19,45,52,57]	Collection and transport expensive due to location of the resources Storage 6 months [19,45,52,57]
	Forest waste	Based on wood waste facility location [19]	Based on wood waste facility location [19]	2.7* from native forest 2.1* from plantation	$14-$45/t per 50-200km [19]	60-120[c] [19]			
Agricultural wastes		East, south and west coast, South Australia and Central West of New South Wales Based on the spatial distribution of stubble production for	Northern Territory, North Queensland, North Western Australia Based on the spatial distribution of stubble production for years 1983-2005 [69]	53[a] [45]	$15-$45/t per 50-200km [19]	55-70[c] [19]	Seasonal production Suitable for storage	Large amount available Sustainable land use Low emissions [42,45,56,70]	Loss of nutrients Low amount per hectare: increases collection and transportation cost Need an in-field physical fractionation to remove unattractive residue components

	years 1983-2005 [69]							Storage, biological contamination [42,45,56,70]
Algae	Pilbara, WA; Northern QLD; Borroloola, NT	Southwest WA, Southeast NSW Low solar insolation . [92] NSW High agriculture and forestry	No current commercial production		Potential estimates $80-$1300 [83]	Potential year-round production	High growth rate Can be grown in saline or hypersaline water, not competing with agriculture for limited freshwater resources Less potable water demand than land crops Can be located on marginal and non-arable land High efficiency CO_2 sequestration Nutrient fixing (N&P) of wastewater No pesticides/herbicides used	New technology, lack of risk data to warrant investment Risk of yield loss by biological contamination Harvesting algae and separating oil is energy-intensive Salt precipitation on the bioreactor walls, pumps and valves [93, 94]

5. Conclusion

Second and third generation biofuel feedstocks were studied in order to identify their regional suitability, taking into consideration land use, existing biomass industries, the relevant conversion technologies, and using Australia as a case study. The study included the collection of a large amount of detailed information on the biomass industries for the case study and a detailed mapping activity was conducted. For areas with existing agriculture and forestry, second generation biofuels appear to be more attractive than microalgae, based on opportunity costs of resource reallocation. Second generation biofuels have the best opportunities where there are areas of arable land and suitable climatic conditions. For Australia, this is particularly true in NSW, Qld and Vic. The best regions for microalgae are in regions that are coastal, warmer, and non-arable as these regions are less likely to have existing biomass industries and yet have access to water. However, this suggests that growth rates may be less than the optimal rates based on the climatic conditions of the regions which are identified as being the most suitable. For areas with existing agriculture based on operation cost, investment should be directed towards second generation biofuels. With further improvement in costs for microalgae production, microalgae cultivation may be warranted in areas that have available water and abundant unutilised, non-arable land.

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