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Second generation biofuel crops from poor quality water and degraded lands

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ABSTRACT

Poor quality water and lands are in ample supply in Australia. Ongoing drought in many regions has renewed and increased interest in uses of saline wastewater rather than disposal to evaporation basins. This paper reports on use of wastewater and saline land to grow a new second generation biofuel crop, Arundo donax (L.). Arundo donax, commonly known as giant reed, is a perennial, rhizomatous grass that has been grown in every state of Australia for over 150 years and in many other countries. Together with other cellulose feedstocks giant reed could form the basis of a new biofuel or pulp/paper industry for Australia and other countries. This paper reports two field studies from South Australia where high biomass yields (45-51 dry t ha^{-1}year^{-1}) of A. donax was achieved on degraded, saline soils using domestic and winery wastewater. Irrigated A. donax yields year^{-1} exceeded any alternative crop reported for warm to sub-tropical climates. The calorific value of 19 MJ kg^{-1} of dry A. donax is equivalent to about 75per cent of that obtained from a kg of coal. Within the first year of growth with saline winery wastewater, Arundo removed 528 kg N, 22 kg P, and 664 kg K respectively, in each hectare of harvested biomass while tolerating 5-10 dS/m soil water salinity for several months when the topsoil was kept near field capacity. We classed A. donax a halophyte. Successful growth and containment of A. donax spread requires careful management. Arundo donax can invade riparian systems and is declared noxious in many parts of Australia. However, due to polyploidy A. donax does not produce viable seed, this together with its clumping rhizome growth habit means that its ability to spread is limited when plantings are managed carefully, and crops are planted in non-riparian systems and not planted in riparian systems subject to flooding as described in this paper.

Keywords : *Arundo donax*, biofuel, degraded lands, giant reed grass, waste water

Good quality fresh water supply is increasingly becoming scarce in the world leaving behind increased volumes of poor quality water for agricultural use. On the other hand, soil salinity, sodicity and acidity problems have already encroached on more than 50% of the cropped land in Australia with an estimated annual impact to agricultural land of A$ 2,559 million (NLWRA, 2002). Rapid urbanisation and industrial growth are also responsible for reduced areas of traditional arable lands in many parts of the world. To make this worse, global warming is putting additional pressure on limited water and arable land resources.

First generation biofuel is made from the edible food crops. Demand for food crops (cereal grains, oilseeds, sugarcane) to produce first generation biofuel in many countries has led to increasing global food prices, very low world grain reserves and increased risks of famine (Biswas and Williams, 2009). Biofuel crops should be grown on marginal and surplus agricultural lands so that the limited arable soils are left for food crops. *Arundo Donax (L.)*, commonly known as giant reed, a second generation crop can be grown as feedstock for biofuel, pulp/paper or fodder production (Williams *et al., 2013)*.

Sustainable use of marginal lands and poor quality waters to grow second generation biofuel or pulp/paper crops is a way to provide a non-conventional source of income to farmers. Williams *et al.* (2007) suggested such practices are urgently needed in farming systems on the vast South Australian saline lands which have access to poor quality water. Being a moderately salt tolerant plant, *Arundo donax*, has been found to be more effective in treating wastewaters than the commonly recommended native reed (*Phragmites australis*) in South Australia (Williams *et al.*, 2013). *Arundo donax* has many potential uses as feedstock for biofuel, pulp/paper or fodder production (Spafford, 1941; Williams *et al.*, 2008a). According to Williams *et al.* (2013), it is a moderately salt tolerant plant tolerating up to 12 dS/m soil saturated paste extract electrical conductivity (a 50% yield loss is predicted at constant 12 dS/m). *Arundo donax* is a perennial rhizomatous grass that has persisted for over 150 years in Australia and many countries. Use

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of *A. donax* as a high biomass yield and lignocellulosic biofuel crop to utilize degraded, saline soils and wastewaters would be a highly attractive strategy, provided this was done under strict weed risk management guidelines in non-riparian zones (Williams *et al*., 2013).

Commercial plantations of *A. donax* grown in non-riparian zones are gaining acceptance as potential biofuel and/or fibre crops, in the USA (USDA 2011; Kering *et al*., 2012), in southern Europe (Angelini *et al*., 2009; Mantineo *et al*., 2009) and in South Australia (Williams *et al*., 2013) when grown under strict weed risk management guidelines. New guidelines for managing the weed risk of cultivated *A. donax* in non-riparian zones have been devised by Dr J. Virtue and a team of weed control specialists (Virtue *et al*., 2010; Williams *et al*., 2013).

The Economist (2009) reported that the commercial potential of non-food, cellulosic crop feedstocks grown on marginal lands for conversion to biofuels will increase in future if the price of fossil fuels rises significantly. Williams *et al*. (2008b) reported fuel generation of *A. donax*. A kilogram of oven dry biomass was equivalent to 19 MJ when burnt, equivalent to 75 per cent of that produced from a kg of combusted coal. One ton of dry *A. donax* biomass combustion will generate nearly 19 GJ, equivalent to 5,320 kWh, which will be enough to supply 24 hours electricity for 266 homes. Further income for farmers growing *A. donax* is likely to increase, if the perennial crops can attract carbon credits (for soil and root carbon accumulation) and/or price subsidies for bioethanol (carbon neutral).

This paper describes growing of *A. donax* as a potential new biofuel and/or pulp paper crop, for the underutilised resources of saline wastewater and saline/marginal lands in Australia.

MATERIALS AND METHODS

Two field studies were conducted in South Australia. One site was located on a former salt evaporation basin near Barmera, SA (34° 14' S, 140° 35' E). Soil at the site was a loamy sand overlying a sandy clay loam. The 1:5 soil:water extract values for layers in the top 90 cm of soil ranged from 0.62 to 1.53 dS/m (saline soils). Trial plantations *of A donax* were established by planting rhizome clusters from a nearby wild *A. donax* stand at Loveday, SA (Loveday rootstock) and from sandhills at Henley Beach (Henley Beach rootstock), both at 2-4 per linear metre in furrows 1 m apart. The paddock was irrigated with winery wastewater. Annual rainfall is 300 mm against potential evapotranspiration of 1465 mm. Salinity of soil water was measured using a bench top conductivity meter.

The second site was at the Roseworthy Agricultural college experimental site (34^{o} 52' S, 138^{o} 69' E), South Australia, which already had an established stand (over 30 years in age) of *A. donax*. The soil was a Calcareous, Regolithic, Red-Orthic Tenosol (established planting) and a Sodic, Hypercalcic, Red Dermosol (new planting), (after Isbell, 2002). The 1:5 soil:water electrical conductivity for layers in the top 90 cm of soil ranged from 0.4 to 1.0 dS/m. The climate of the region is typical of the southern Mediterranean-type environment which consists of hot, dry summers and cool, wet winters. Mean annual rainfall is 450 mm against potential evapotranspiration of 1322 mm. Pan evaporation at Rosedale, 10 kilometres east of the site was 1518 mm during this period.

Dryland planting of *A. donax* at the site was clear felled to 10 cm on 2nd June 2005, 150 kg of nitrogen (N) ha^{-1} was applied, and irrigation treatments were imposed. For the second treatment a new planting of giant reed was sown with rhizomes at 5 m^{-2} on 15 December 2005 and was irrigated. Nitrogen was applied at 150 kg ha^{-1}, 7 days before sowing. Class 3 treated sewage effluent from the Campus residential area (reclaimed water) and pond treated dairy effluent (recycled water) were used to irrigate the established and new plantings, respectively. In-line drippers (2 L hour^{-1}) at 50 cm spacing on lateral lines every 75 cm and 100 cm were used on the established and new plantings, respectively. Total reclaimed water applied to the established planting from clear fell to 5 June 2006 was 1786 mm plus rainfall of 534 mm. The new planting received in total 1139 mm of recycled water plus rainfall of 202 mm from sowing to 5th June 2006 harvest.

Four harvests of plant tops and rhizomes were conducted from quadrats 1m^{2} in area cut at 10 cm above soil level (4 or 5 per treatment) on 23rd March and 5th June 2006. Fresh weights of leaf and stem fractions were recorded, and subsamples oven dried at 70^{o}C to determine dry matter content, yields, nutrient content and uptake. Soil samples were collected to measure changes in soil nutrients over time. Plant and soil samples were analysed using procedures as described by Williams *et al*. (2004) and water by APHA (1998) methods (sampled 23rd February and 5th June 2006).

RESULTS AND DISCUSSION

Plantation and establishment of A. donax

Arundo donax does not produce viable seeds and hence vegetative propagation is the only way to grow. Successful establishment of newly planted *A. donax* is the most critical growing operation factor because it has major influence on biomass yield and overall economic viability (Lewandowski *et al*., 2003). There are three

Table 1: Biomass yield and nutrient removal by *A. donax* in South Australia

Rootstock/ land type	Biomass yield ($t\ ha^{-1}yr^{-1}$)			*Removal of C, N, P and K* ($kg\ ha^{-1}yr^{-1}$)			
	Leaf	Stem	Tops	Org C [1]	N	P	K
Barmera (saline soil) irrigated							
Loveday	9.3	35.9	45.2	20,577	528	22	664
Henley Beach	11.3	17.7	29.0	13,698	448	19	472
Roseworthy (arable land)							
Irrigated	10.3	40.7	51.0	22,200	773	40	832
Dryland	4.0	11.4	15.4	6,500	282	17	331

[1] Org C: Organic Carbon. Source: Williams et al., (2009)

Table 2: Combustion and chemical analyses of *A. donax* stem samples

	Sample #1	Sample #2	Sample #3
Combustion properties			
Volatile matter (%)	73.82	74.88	77.01
Fixed carbon (%)	21.53	20.54	19.65
Ash (%)	4.65	4.58	3.34
Sulfur (%)	0.034	0.33	0.12
Calories/gram	4507	4,478	4563
$MJ.kg^{-1}$	18.87	18.75	19.10
Chemical analysis (%)			
Carbon	46.94	46.61	47.67
Hydrogen	5.85	5.82	5.81
Nitrogen	1.17	0.63	0.13
Phosphorus	0.07	0.05	0.03
Potassium	1.27	1.01	0.31
Chlorine	0.45	0.22	0.05

[1] % dry basis, Hampton Roads Testing Labs, Inc. (Hampton, VA, USA). [2] Sample #1 and #2 are 1 year old live post-flowering stem, August 2007, Cayce, SC, USA and sample #3, is dead stem, same location as in #2. Source: Williams et al., (2013).

Table 3: Preliminary factory gate prices for oven dry tops ($A/t) to achieve 15% internal rate of return (IRR) to a company and target of mature *A. donax* plantation yields (case study)

System	Price ($\$A\ t^{-1}$)	Yield ($t\ ha^{-1}\ year^{-1}$ oven dry tops)
Rain fed only[1], fertilizer purchased	67	15
Rain fed only[1], free nutrient return from factory	52	15
Roots in water table, fertilizer purchased	49	30
Roots in water table, free nutrient return from factory	37	30
Irrigated, fertilizer purchased	80	40
Irrigated, free nutrient return from factory	70	40

[1] 450 mm annual rainfall, Mediterranean environment. Source: Black and Williams (2010); Williams et al. (2013).

main factors those directly affect crop establishment and associated costs. These factors are propagation material, plant density and available soil moisture after planting. Direct rhizome planting has been the most successful establishment method (Christou *et al*., 2001a) as compared to whole stems or stem cuttings. Planting of large rhizome pieces at 3 m^{-2}, equivalent to 30,000 plants ha^{-1}, at Barmera site in early winter and with a high irrigation volume produced a high shoot yield (45.2), 12 months after planting. Christou *et al*. (2001a), in a northern hemisphere study, reported establishment rates of nearly 100% and maximum yields ha^{-1} when large rhizome pieces with well-developed buds were planted at a lower density (1.25 rhizomes m^{-2}). He found no yield advantage of using a higher density of 25,000 plants ha^{-1}. For Southern Europe, due to the less cost of

Table 4: A case study IRR results for conversion factories using *A. donax* feedstock sited in the south east of South Australia (central price estimates shown first in each series)

Product	Product price ($A)	Capital cost (million $A)	IRR (%)
Electricity and biochar	100/KWhr, 120/t	200	8
Electricity and biochar	120/KWhr, 120/t	200	14
Electricity and biochar	80/KWhr, 120/t	200	0
Bioethanol and lignin	0.6/L, 50/t	275	22
Bioethanol and lignin	0.8/L, 50/t	275	33
Bioethanol and lignin	0.4/L, 50/t	275	9
Bioethanol, ligninElectricity, biochar	0.6/L, 50/t100/KWhr, 120/t	275160	21
Pulp/paper	1100/t	550	18
Pulp/paper	1400/t	550	28
Pulp/paper	800/t	550	5

Source: Black and Williams (2010) and Williams et al. (2013).

establishment (Christou *et al*., 2001b) suggested lower rate of 12,500 to 20,000 plants ha^{-1}.

For rapid establishment of new biofuel plantations, Williams *et al*. (2013) suggested that rhizomes and stems could be harvested from wild populations. Careful rhizome removal should not disturb the ecosystem and release fragments of *A. donax* nor release other significant weeds. Care should be exercised for all *A. donax* classes whereby only wild material that has been tested and found free of pests and diseases should be used for new plantation (Williams *et al*., 2013).

There are few studies in the literature on the planting density and yield of micropropagated plantlets of *A. donax*. In South Carolina, USA, Italy, Hungary and Australia (Williams *et al*., 2013), micropropagated plantlets from an embryonic cell line as well as rhizomes plantings were found to perform well in multiple locations and times. Williams and Biswas, (2010) reported a 61 years old *A. donax* plantation, sown by Italian prisoners of World War 2 in saline soils at Loveday, South Australia. This second world war time stand of *A. donax* is still highly productive after 74 years. Similarly, Focherini (2000) reported *A. donax* plantation established in 1938 for rayon production in Torviscosa, Italy. This plantation was later abandoned in 1965.

Fertilizers and irrigation

Because it is often classified as a weed in riparian zones, there is little information available on concentrations of nutrients in soils or plant tissues for high growth and maximum biomass yields of *A. donax* published (Williams and Biswas, 2010). The 'Giant reed Network' project in Europe found no significant biomass yield difference between nitrogen application at 40 and 120 kg ha^{-1} (Christou *et al.,* 2001b) however, in Central Italy, Angelini *et al*. (2009) found application of 200:80:200 kg ha^{-1} N:P:K fertilizer increased *A. donax* biomass yield from 23 to 27 dry t ha^{-1}. Similarly, Kering *et al.* (2012) in a field study in Oklahoma, USA reported linear increase of biomass yields of *A. donax* from 19.4 dry t ha^{-1} without nitrogen application to 33.2 dry t ha^{-1} with 168 kg N ha^{-1}. This information suggests that moderate rates of N fertilizers may be required for optimum growth and high biomass yields of *A. donax*.

Optimum soil moisture has a direct relation to high yields of *A. donax*. Christou *et al.* (2001b) reported the highest yield of *A. donax* each year with irrigation between 8.6 and 14 ML ha^{-1} year, notably in year 2, biomass yield was increased from 32 dry t ha^{-1} without irrigation to 45 dry t ha^{-1} with 859 mm of irrigation.

Pests and disease control

In its first year of establishment, cultivation between the rows and weed control by herbicide may be required after which the high growth rates and large leaf area of *A. donax* usually out competes most weeds (Williams and Biswas, 2010). When fully grown, stems and leaves of *A. donax* contain a wide range of chemicals such as silica, triterpenes, sterols, glycosides, curare-like indoles, hydroxamic acid and many other alkaloids which help protect it from most insects and diseases (Williams *et al.* (2013). Several long-term field trials in different parts of the world (Angelini *et al.,* 2009; Kering *et al.,* 2012; Williams *et al.*, 2013) concluded there is no need for pesticide applications to *A. donax* when it is fully mature.

There are introduced biological control agents such as Arundo wasp and armoured scale, which may damage any *A. donax* commercial plantation. However, it is possible to control these introduced pests by foliar or soil application of pesticides (Elbert *et al.*, 2008; Xu *et al.,* 2009) however, it will add extra costs to the *A. donax* biofuel production system. Several diseases of *A. donax* have been reported from USA (Bell, 1997; Zheng *et al.*, 2005), including root rot, lesions, crown rust, and stem

Fig. 1: Potential bioethanol production (L ha^{-1} $year^{-1}$) from food and non-food crops. Modified from Bourne (2007) and Biswas *et al*. (2009)

speckle, but none have been found to significantly reduce the biomass yield.

Arundo donax biomass yield, nutrients uptake and ethanol production

Arundo donax received 21 mega liters (ML) ha^{-1} of winery wastewater at Barmera site where the Loveday rootstock produced the highest biomass yields of 45.2 t ha^{-1} of dry tops including 35.9 t ha^{-1} of dry, bare stems in the first year (Table 1). Similarly, Roseworthy irrigated *A. donax* produced 51 t ha^{-1} of dry tops including 40.7 t ha^{-1} of dry, bare stems in the first year. These high biomass yields were similar to those reported at the highest yield sites in Spain (Lewandowski *et al*., 2003). The biomass yields of *A. donax* equated to 4 times the dry matter yield ha^{-1} yr^{-1} of irrigated blue gum (*Eucalyptus globolus*) stands (Williams *et al*., 2008b).

These exceptional yields of *A. donax* far exceed those expected from traditional biomass crops grown on arable land with ad liberal irrigation. For example, Biswas et al. (2002) reported 15 t ha^{-1} of total tops dry matter per season for forage sorghum grown on arable land and irrigated ad lib with secondary treated sewage near Griffith, New South Wales, Australia.

Photosynthesis by *A. donax* was the main mechanism for the large amount of organic carbon (20.6 and 22.2 t ha^{-1}) sequestered in the dry tops in the first year at the Barmera site for Loveday rootstock and Roseworthy irrigated site respectively (Table 1). *A. donax* crops could qualify for carbon (C) credit programs if introduced in Australia and elsewhere (annual sequestration of carbon). Uptake of nitrogen (N), phosphorus (P) and potassium (K) by the plant tops of *A. donax* from the Loveday rootstock was 528, 22 and 664 kg ha^{-1} yr^{-1}, respectively, during the first year of growth whereas for the irrigated Roseworthy site these values were 773, 40 and 832 kg ha^{-1} yr^{-1}.

In a laboratory scale trial, *A. donax* produced 299 L of ethanol t^{-1} of shoot dry matter in a process time of less than 24 hours. This trial was carried out in a Norwegian biofuel company facility who processed samples of Australian grown *A. donax* into BTL (biomass-to-liquids) ethanol. This equated to 11,000 L of bioethanol per hectare of *A. donax* growing 36.8 t ha^{-1} of dry tops $year^{-1}$ (Fig. 1). In comparison, corn kernels (*Zea mays*) produced 4,400 L ha^{-1}; switch grass (*Panicum virgatum*) 4,600 L $ha^{-1}$and sugarcane (*Saccharum officinarum*) 8,800 L ha^{-1}, respectively (Bourne, 2007).

There is a global strategy to reduce greenhouse gases and associated temperatures (Lowe *et al.,* 2009). An important driver for second generation biofuel crops is the potential to reduce carbon dioxide emissions by replacing fossil fuels. According to Eisentraut (2010), second generation crops could reduce oil well-to-vehicle wheels carbon dioxide production by 60 to 100% compared to fossil fuel. Such biofuel may be one of the most cost-effective methods of renewable, low-carbon energy for vehicle transport (Wright and Brown, 2007; Eisentraut, 2010).

Chemical composition, fire risk and harvesting

Table 2 lists combustion and chemical analyses of *A. donax* showing analyses composition of fresh, green, young shoots up to 1.8 m in length. These results are closely comparable to that of green oats, barley and wheat plants at flowering time (Spafford, 1941). According to Spafford (1941) green stems (1.8 m long) contained 10.6% carbohydrates, 1.9% crude protein, fiber 10.8%, 1.5% ash and 75% moisture.

Generally, mature stands of *A. donax* are found to be not very palatable to cattle, but during dry seasons they eat it (Williams and Biswas, 2010) as opposed to Goats who will eat it anytime.

After new growth, stems of the *A. donax* plant usually live between 2 - 4 years after which they die and often the stand remains upright and dry for many years, with large number of dead stems in wild populations and in neglected farm plantations, which are not harvested annually (Bell 1997; Williams and Biswas, 2010). From fire hazard risk point of view, wild and most non harvested populations may be extremely flammable as reported by Bell, (1997). However, Williams *et al*. (2013) concluded that for well managed and irrigated commercial plantations of *A. donax,* the risk of catching fire is minimum if they are harvested at least once each year, a practice which allows at least 95 per cent of stems to remain green and alive with 40-55 per cent moisture content. It is however important to note that a prolonged dry season may generate significant amounts of dead dry stems of *A. donax* which may pose a high fire risk.

Because of its profuse growth under good irrigation and management practices, *A. donax* can be harvested each year or every second year (Lewandowski *et al.*, 2003). For drought stricken non-irrigated crops two harvests per year will greatly reduce fire risks. According to Sharma *et al.,* 1998, repeated cutting per year is not recommended for sustained high growth rates and maximum yields of biomass. For southern Australian condition, an annual clear fell harvest of *A. donax* in late winter is recommended as the optimum harvest time for maximum yield and for rapid spring re-growth (Williams and Biswas, 2010).

Costs and benefits of A. donax plantations

Because of global perception of *A. donax* as a serious riparian weed, it has not yet been grown in large commercial scale plantations for feedstock for biofuels.

Black and Williams (2010) and Williams *et al.* (2013) assessed the cost of growing *A. donax* commercially for Meningie saline lands in South Australia. To make it a viable industry, it was assumed that the production company required a 15 per cent internal rate of return (IRR) on funds invested. Three types of systems were assessed; (i) non-irrigated (rain fed), (ii) conventionally irrigated and (iii) naturally irrigated (Table 3). In each of these production systems, the *A. donax* roots were assumed to be reach a moderately saline shallow water table and grown with standard fertilizer input. The average factory gate price for each tonne of *A. donax* from the three systems was assumed to be $A65. In addition, another system included a scenario where a large portion of the fertilizer requirements for growing *A. donax* were supplied by biofuel fermentation waste mulch from the processing factory at no cost to the company, which will reduce the average factory gate price to be $A53/oven dry ton (Table 3).

The cost benefit analysis given in table 4 clearly showed that *A. donax* has a great potential for a new industry to produce bioethanol and/or pulp/paper when $A60/dry t is paid at the factory gate and 500,000 oven dry tons supplied per year to a conversion factory. However, such an upscaling must proceed with 3 years of agronomy research and development. The preliminary estimates indicate an IRR of 22% per annum for the ethanol and lignin production and 18% per annum for the pulp/paper enterprise. When procured at a cost of $A60/oven dry t at the factory gate, electricity generation plus biochar production and a slow pyrolysis process did not appear to represent a sound private investment option.

There are no shortages of poor quality water and lands in Australia. Ongoing drought in many regions, has renewed the interest in alternate uses of saline wastewater rather than disposal to evaporation basins. With increasing demand for arable lands and good quality water for food production, the underutilized resources of moderately saline wastewater and saline lands can be used to grow *A. donax* in a contained and well managed bio-system.

Our studies with *A. donax* in South Australia have clearly demonstrated its high potential for a biofuel crop due to its high biomass yield with high nutrients removal capacity, carbon sequestration and salt tolerance properties. *Arundo donax*, a second-generation biofuel crop, produced high biomass yields (45.2 -51 t $ha^{-1} yr^{-1}$) on saline land using low quality, saline wastewater without pesticides. Being a moderately salt tolerant plant (tolerating up to 12 dS/m) *A. donax* has been found to be more effective in treating wastewaters than the commonly recommended native reed (*Phragmites australis*). Because of very high biomass yields, *A. donax* removed large quantities of N (528 -773 kg $ha^{-1} yr^{-1}$) P (22 - 40 kg $ha^{-1} yr^{-1}$) and K (664- 832 kg $ha^{-1} yr^{-1}$) from soils thus making it an ideal crop for stripping nutrients from nutrients rich wastewater. *A. donax* is often seen as a serious weed threat to riparian zones, however, it can be grown as a low weed risk, biofuel crop in non–riparian zones, if it is done under strict weed management guidelines.

From carbon sequestration point of view, *A. donax* has been qualified as a valuable, potential carbon credit crop (within a year, it accumulates between 20.6 - 22 t of organic carbon $ha^{-1} yr^{-1}$ as dry tops). If each tonne of carbon sequestered is valued at A$25, this would generate A$ 515-550 $ha^{-1} yr^{-1}$ in carbon credits.

When it comes to biofuel production, *A. donax* can potentially produce nearly 300 L of ethanol t^{-1} of dry biomass in a process time of less than 24 hours; equating to production of 11,000 L ha^{-1} $year^{-1}$, 2.5 times higher than corn (*Zea mays*) seed biofuel production from an equal area of land. Together with other lignocellulosic feedstocks, *A. donax* has a high potential to form the feedstock base for a new biofuel industry in many countries. Preliminary estimates from a South Australian case study indicated a 22 per cent internal rate of return per annum, when bioethanol was priced at \$A0.6 L^{-1} at the factory gate.

As fossil fuels become scarcer and higher in price, it is inevitable that the commercial potential of non-food, lignocellulosic crop feedstocks such as *A. donax* grown on marginal or surplus lands with poor quality irrigation water for conversion to biofuels will increase in future.

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