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Acacia species as large-scale crop plants in the Western Australian wheatbelt

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SUMMARY

Revegetation with perennial plants is a well-accepted tool in salinity control across the agricultural regions of southern Australia but the scale on which revegetation must be undertaken in order to have significant impact on salinity has become clear only recently. This scale is so large that it must involve extensive change in the commercial plant base of agriculture. Hence, an array of profitable perennial plants must be developed to complement existing annual crops. Apart from their role in salinity control, new perennial plant crops can bring a range of other benefits to agricultural areas, including improved erosion control, protection of biodiversity (and in some cases its enhancement), diversification of farm incomes, and regional development resulting from local processing of perennial plant products.

This paper discusses some issues relevant to the development of new industries based on woody perennial crops. They include size of markets, using the whole plant to make multiple products, crop rotation length, temporal and spatial integration of perennial crops into agriculture, the financial consequences for farmers growing woody crops, and the desirability of deriving new crops from native species. These issues provide useful guidelines for the objective selection of potential new commercial crop species. From this foundation, a selection and development project called 'Search' has evolved, to systematically assess potential new large-scale tree crops and processing industries based on native species, select those with high potential for commercial development, and take the first steps towards their development.

The genus *Acacia* provides considerable potential for the development of new perennial crops. *Acacia* species appear to be especially suited for use as phase crops in rotation with conventional annual crops, or as low cost, direct-seeded coppice crops. A large number of *Acacia* species occur naturally in the Western Australian wheatbelt and several have attributes that may make them suitable for commercial development. Potential products include solid wood, panel board, paper, gum, tannin, fodder, edible seed, and large-scale generic products such as solid fuel for electricity production, liquid transport fuel and charcoal products.

BACKGROUND

During the 1990s the potential scale and impact of dryland salinity became apparent and emerged as the leading environmental issue in Australia. Major reviews focused national attention on the problem (National Land and Water Resources Audit 2000; Murray Darling Basin Ministerial Council 2000; State Salinity Council 2000; National Farm Forestry Roundtable 2000). This work shows that salinity-related damage has many impacts beyond the obvious land and water resource losses, including biodiversity loss (450 potential species extinctions in W.A. according to State Salinity Council 2000), infrastructure attrition and flood risk (Bowman and Ruprecht 2000), possible catchment-wide litigation (Turley 2000) and international sanction (Bartle 1999a). The consequences and costs of these less tangible impacts of salinity are still poorly defined.

Dryland salinity is inherently difficult to manage. In contrast to salinity arising from irrigated agriculture, dryland salinity involves only diffuse recharge from rainfall (i.e. no managed irrigated component), large areas, and long distances and time delays between recharge and discharge. Also, unlike intensive irrigated systems, broadscale dryland agricultural systems produce low returns per hectare, from which treatments for dryland salinity must ultimately be financed.

Two categories of treatment are available. Both are complex and costly:

- recharge control: a preventative strategy, using water at or near where it infiltrates the soil and enters groundwater systems. This can be achieved most effectively by increasing the proportion of deep-rooted perennial vegetation (both non-commercial and commercial) on agricultural land.
- discharge control: ameliorative measures to collect and safely dispose of groundwater that has accumulated in low landscape positions and is close enough to the surface to affect soils. Where this water is not too salty it can be used by salt-tolerant plants, some with grazing and timber value. However, groundwater in discharge areas is often too saline to be used by plants, and its control requires engineering works such as drains, pumps and discharge basins.

These two types of treatment are complementary because they apply sequentially along the same hydrologic flow path, and neither forms a complete, efficient management system on its own. If the amount of recharge can be diminished by increased use of perennial plants, then the amount of discharge will be reduced in the longer term and become more manageable. Similarly, regardless of the effectiveness of upslope recharge control, engineering treatments will be required to cope with highly saline groundwater emerging in discharge areas.

Recent hydrological research contends that perennial plants are able to control recharge on agricultural land only if they cover a substantial proportion of it, i.e. up to 80% (Hatton and Nulsen 1999; George *et al.* 1999). This would require a 'revolution' in agriculture (Bartle 1999a; Stirzaker *et al.* 2000). Not surprisingly, the requirement for such radical change, and the perceived difficulty of achieving it, give rise to the pessimistic view that we should learn to live with the problem rather than solve it! For example, the Western Australian State Salinity Council (2002) adopted the proposition that a substantial proportion of public funds available for salinity be invested in a few high-value areas to ensure their successful treatment, implying continued degradation of the balance.

What alternatives are there to this bleak outlook? Despite significant investments of public money in promoting it, large-scale revegetation with non-commercial species is unlikely to occur, because:

- farmers are unlikely to revegetate with non-commercial plants if their costs exceed the benefits,
- in most cases, the benefits to individual farmers from non-commercial revegetation are low;

Ethical imperatives, volunteer participation, peer pressure and integrated catchment management, the laudable tenets of landcare, will not be sufficient motivation if revegetation on the necessary scale would bankrupt farm businesses (Pannell 2000).

The solution is very simple in concept – expand and diversify the range of profitable perennial crops and pastures used in agriculture. So the question becomes: what are the prospects for increasing the extent and diversity of commercially viable perennial crops and pastures? There are opportunities in some areas to increase the use of existing perennial pastures and expand the area of farm forestry, but this alone will not be sufficient. A range of new herbaceous and woody perennial plants and associated industries is required.

A start has been made on woody crop development with the domestication of mallee eucalypts in Western Australia. Bartle (2001) reviewed the development of mallee and its influence on the Search Project (NHT 973849), a project funded by the Natural Heritage Trust, that aims to generalise the experience gained with mallee by applying it systematically to screen new woody crop and product prospects. More recently, this approach has been incorporated into the new Cooperative Research Centre for plant-based management of dryland salinity (www.crcsalinity.com).

This paper presents a conceptual framework for assessing attributes of tree crops that favour both their large-scale commercial success and salinity control. It then assesses the genus *Acacia* as a source of new woody crop germplasm for the Western Australian wheatbelt.

DEVELOPMENT OF NEW TREE CROPS

Four aspects to consider and integrate when developing new tree crops are the type of crop (layout, duration, type of material produced), type of site (recharge or discharge), type of product (market size, feedstock requirements) and species suitability (biological attributes). Each is described briefly below.

Woody crop types

There is currently no large-scale tree crop in use in the wheatbelt regions of southern Australia. However, three conceptual woody perennial crop types have potential for development:

1. Short-rotation coppice crops: where harvest occurs every 2 to 5 years from successive crops regenerated from rootstocks that re-sprout or coppice after each harvest. Interest in short-rotation coppice crops has been stimulated by the experience with mallee development in W.A. (Bartle 2001). Coppice crops are costly to establish (with seedlings) but are ready for harvest at an early age and can regrow many times from the same stump. They are well suited to planting in permanent belts oriented along the contour, or in other strategic locations, to intercept downslope water movement. In this concentrated form they are readily integrated into large-scale annual cropping systems in alley farming layouts.
2. Short-rotation phase crops: where the crop occupies a phase within the annual crop rotation and is harvested once and removed at age 3 to 6 years. The high cost of seedling propagation is a significant barrier to profitable production of large-volume, low-value products by phase crops (Harper *et al.* 2000). Hence, species that can be readily established by direct seeding, such as those with large seeds, are the most likely candidates to be developed. Phase cropping can be used to dewater cropland where soil characteristics limit the rate of lateral movement of subsurface water and therefore limit the potential for water consumption by permanent belts of perennial plants. The woody plant phase has the potential to improve soil structure and to utilise leguminous species to enhance subsequent annual crop production but this is offset to some extent by clean-up costs after harvest, and an increased risk that the dewatered soil profile will reduce yield in the following annual crop. Phase cropping has yet to attract much investment in research and development, despite being conceptually attractive.

3. Long-rotation crops: where the production cycle is greater than 10 years and may be as long as 100 years. Long rotation crops require intensive, long-term capital investment and very careful site selection. They are suited to planting in belts or small blocks and, in addition to timber products, they can provide shelter and aesthetic benefits. The long rotation period enables production of large logs that can be sold into existing timber industries. They have greatest potential in the wetter wheatbelt regions where growth rates are higher, rotation length will be shorter and where they will be comparatively close to current timber industries (Moore 2001).

Economic analysis of crop types

The relative economics of the three different crop types described above, and their profitability compared to current agricultural returns, will determine their attractiveness to farmers, and hence influence their priority for development.

To assess the economic performance of each crop type, discounted cash flows over 25 years were calculated. The results for each crop type were compared with each other, and with the discounted value of conventional agriculture based on annual plants.

Data were generated for four rainfall zones ranging from 300 to 600 mm mean annual rainfall. Results for the 400 mm rainfall zone are presented here. Production cost and yield were estimated for each crop type, and then used to calculate the 'stumpage', or selling price of the crop standing in the field, that would be necessary for each crop type to achieve a return equivalent to conventional agriculture (that is, averaging $65 per hectare annually over a 25-year period). These calculated 'break even' stumpages were then compared with estimates of stumpages that are likely to be paid by timber and biomass industries. Note that no allowance is made in this analysis for any positive or negative indirect effects of woody perennial crops such as erosion control, shelter, salinity control, and interactions with other crops.

Estimated values of production parameters used in the financial analysis are presented in Table 1, and results are presented in Table 2.

TABLE 1
Estimated parameters for input to financial analysis of crop types in a 400 mm/yr rainfall area in south-western WA.

	COPPICE	PHASE	LONG ROTATION
Establishment cost $/ha[1]	1500 / 380	1350 / 300	1200 / 300
Density (stems/ha)	2667	2000	500 planted100 harvested
Grazing revenue $/ha/yr	0	0	20
Annual costs $/ha	30	30	25
Prune and thin ($/ha)[1]			575 / 675
First harvest age (yrs)	5	4	25
First harvest (t/ha)[2]	60	70	90
Coppice interval (yrs)	3		
Coppice harvest (t/ha)[2]	60		

[1] First value is for planted seedlings. Second value is for direct seeding.

[2] Coppice and phase crops harvest tonnages are for total biomass. Long-rotation harvest tonnage is for sawlogs only.

Notes: Establishment by seedlings varies with planting density.

The cost of direct seeding is based on assumptions of the likely outcome of a modest investment in research.

Coppice crop establishment by direct seeding incurs a higher cost than direct seeding of phase crops or long-rotation crops, as smaller, more specialised machinery is required to seed narrow belts.

Phase crop costs include $200 per hectare for site clean-up after each harvest, to prepare the land for a resumption of annual cropping. Coppice and long-rotation crops do not include clean-up costs, as it is assumed that the land will be used for the same purpose again.

TABLE 2
Impact of establishment technique on the economics of woody crop types in the 400 mm annual rainfall zone.

CROP TYPE	SEEDLING ESTABLISHMENT			DIRECT SEEDING			
	Break even[1]	Average debt[2]	Calculated stumpage[3]	Break even[1]	Average debt[2]	Calculated stumpage[3]	Estimated stumpage[4]
Coppice	14	931	14	8	332	8	15
Phase	16	432	32	8	126	14	15
Long rotation	25	1417	130	25	696	87	60

[1] years to break even.

[2] average debt ($ per hectare) over period to break-even.

[3] selling price necessary to make return equivalent to that of conventional agriculture (in $ per tonne of biomass for short rotation crops, and $ per cubic metre of wood for long rotation crops).

[4] estimate of stumpage likely to apply for each crop types (same price basis as [3]).

The sensitivity of cash flow to establishment method is examined under two scenarios: current technology using containerised seedlings, and future technology using large-scale direct seeding. Seedling propagation is expensive, as indicated in Table 1, and greatly increases costs compared to direct seeding.

Graphs of discounted cash flows are shown in Fig. 1 (establishment using containerised seedlings) and Fig. 2 (establishment by direct seeding). Note that phase crops are shown to follow each other without break, to enable comparison of all three crop types over a 25-year period. Each successive phase crop is assumed to be located on a different piece of land.

The results of the financial analysis, shown in Table 2, indicate that coppice crops established by planting seedlings can produce biomass for a stumpage of $14 per tonne. This is slightly less than the $15 per tonne shown in Enecon's (2001) feasibility study to be a commercially viable purchase price for mallee biomass feedstocks. In contrast, phase crops established by seedlings would produce biomass at $32 per tonne, over twice the expected price. Phase crops would have to be established by direct seeding to achieve production at $15 per tonne. If coppice crops could be established by direct seeding, biomass could be produced for $8 per tonne, a price likely to stimulate large-scale demand by wood processing and bioenergy industries. The economics of long-rotation crops are far less favourable. Even using direct seeding, the selling price would have to be above the estimated stumpage of $60 per cubic metre used in this analysis.

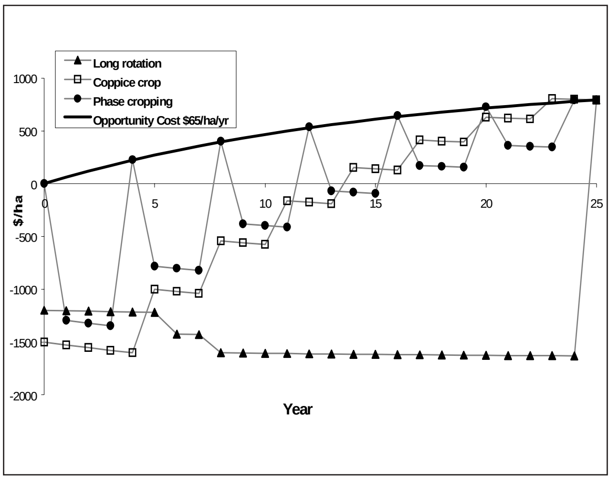

Figure 1: Discounted cash flow using conventional establishment.

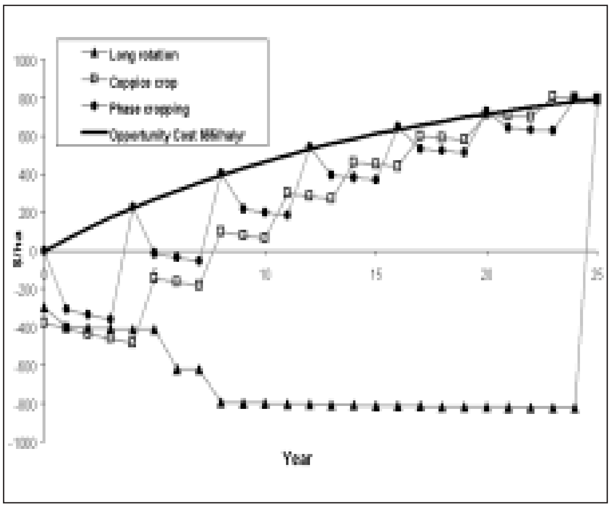

Figure 2: Discounted cash flow using direct seeding establishment.

For long-rotation crops the average debt load of $1417 per hectare over the 25-year period to harvest indicates a major financing constraint that is beyond the resources of most farm businesses. For this reason, long-rotation crops are unlikely to be planted on a large scale unless long-term arrangements involving external finance are developed. The debt level is much lower for coppice and phase crops and must be carried for a shorter period, because the time to break even for these crops is much shorter than for long-rotation crops. Coppice and phase crops are more likely to be within the financing ability of farm businesses.

This financial analysis indicates several important directions for the development of tree crops:

- Direct seeding provides a major economic advantage. Hence, large-seeded plants like *Acacia* that are relatively easy to establish by direct seeding have a significant advantage over small-seeded ones like eucalypts for which there is currently no adequate direct-seeding method.
- Direct-seeded *Acacia* phase crops could produce biomass at a cost similar to mallee coppice crops. The cost of re-establishing phase crops after each harvest is offset by the benefit of direct seeding.
- Very low cost biomass, produced from coppice crops, requires the development of direct-seeding techniques for fine seeded species like mallee eucalypts, or selection and development of *Acacia* species that establish easily by direct seeding and also coppice strongly and reliably after harvest.
- Long-rotation crops carry the burden of a large, long-term capital requirement that will limit their use. Their economics could be improved by developing species that produce high value 'appearance grade' wood rather than general construction timber.

Site types based on the hydrological setting

From the hydrological point of view sites fall into two major categories and several subcategories.

Recharge sites: where the water table is well below the soil surface and rainfall may infiltrate to some depth in the soil profile. Subcategories are:

high recharge sites: where light-textured soils permit rapid, deep infiltration; water use and productivity under annual plant agriculture are low; potential for lateral movement of water within the profile is high; and groundwater salinity is comparatively low. On these sites, woody crops in belt configuration have the potential to intercept down-slope movement of perched or deep groundwater, as observed by White *et al.* (2002).

low recharge sites: where soils are heavier-textured; leakage past annual plant root systems is less; salt storage in the profile is greater; groundwater salinity is higher; and lateral transmission of groundwater is slower. On these sites phase crops could be used intermittently but extensively to reduce soil water storage and prevent net recharge (Harper *et al.* 2000).

Discharge sites: where infiltration is impeded by a shallow water table. Groundwater is usually brackish or saline and may be discharging from the surface. The soil is poorly drained and only species that can tolerate waterlogging and salinity are present. Barrett-Lennard (2001) has proposed three subcategories based on potential productivity:

high: where groundwater is sufficiently deep that salt accumulation in the upper soil profile is not great enough to affect productivity.

medium: where the soil is salt affected but still able to support saltland pastures.

low: where salt has accumulated to the extent that only halophytes can survive.

Large-scale woody crop development is likely to focus on species and crop types suited to recharge sites and high productivity discharge sites, because plant survival and growth rates are likely to be highest in these areas.

Product types

The scale of perennial plant cover necessary to arrest salinity is very large. Therefore it is essential to choose products and markets that have the capacity to absorb very large-volume production. This argument was presented more fully by Bartle (2001). Table 3 lists products that could be produced from wheatbelt woody crops. It includes estimates of market size, and the development period for potential markets. For example, alcohols made from woody biomass are still undergoing technological development as transport fuels, but within a generation they could compete in these very large markets, at a time when the dominance of petroleum could be declining (Foran and Mardon 2000).

The priority for selection and development of tree crops will be dominated by their commercial potential. In the case of grazing, sawn timber, food and flowers, the nature of the product will limit the number of suitable species from which selections can be made. For panel and paper products, bioenergy and derived chemicals, feedstock criteria may be less demanding, allowing selection from a greater diversity of species; they may also allow a range of species grown in different locations to contribute feedstocks to a single processing centre. Bioenergy and derived chemicals are likely to be the least discriminating uses for biomass, and are most likely to be profitable when made from low-cost residues, for example, from biomass remaining after the removal of a select woodchip product for panel board manufacture.

To be profitable, it is almost certain that new woody crops will have to provide feedstock to two or more different products, to fully utilise 100 per cent of the biomass produced, and to maximise the revenue they earn. Indeed, this complementarity between products has been a factor in achieving commercial feasibility in integrated mallee processing, where activated carbon, eucalyptus oil and electricity will be produced concurrently from mallee biomass feedstocks (Enecon 2001).

Local processing of most raw materials from new woody crops will be essential because of their low value per tonne and high sensitivity to transport costs. Although this may be a disadvantage for some product types, it provides significant regional economic benefits, including

TABLE 3
Potential large scale products from woody plant crops.

PRODUCT CATEGORY	PRODUCT TYPE	MARKET SIZE[1]	DEVELOPMENT PERIOD[2]
Grazing	Meat	Large	Current
	Wool	Large	Current
	Manufactured feeds	Medium	Current
Wood	Sawn wood (appearance, construction)	Large	Current
	Panels (particle board, medium density fibreboard (MDF), oriented strand board (OSB))	Large	2010-2020
	Processed wood (pulp/paper, charcoal)	Large	2005-2020
Bioenergy	Solid fuel (electricity, heat, desalination)	Very large	2002-2025
	Liquid fuel (alcohols, biodiesel)	Very large	2015-2030
Chemicals	Extracts (oils, gums, tannins, resins)	Medium	2002-2010
	Derived (pyrolytic liquids, commodity chemicals)	Large	2020-2040
Food and flowers	Staple food (bulk grain)	Large	2005-2010
	Bush tucker	Tiny	Current
	Ingredients (oils, edible gums etc.)	Small	2005-2010
	Flowers	Tiny	Current

1 *Potential market volume in land area, very large > 5 million ha, large 1 to 5 million ha, medium 100,000 to 1 million ha, small 10,000 to 100,000 ha, tiny < 10,000 ha.*

2 *Period during which significant industry development is likely to occur.*

local investment and employment, plus greater stability to farm budgets and rural economies due to year-round harvesting and processing (CSIRO Land and Water *et al.* 2001).

Biological attributes

A large number of biological attributes may be important in selecting species for development as crop plants. Major categories are:

- survival, growth rate and yield: any species being considered for use as a commercial crop must have good yield potential over the required rotation length.
- morphology: plant morphology determines the range of products for which any species might be suited. Each product type in Table 3 could require plants of different morphology. An overriding requirement is that plants be of a form amenable to low-cost harvest.
- breeding biology: influences issues such as collection of propagules, method and ease of genetic improvement, method of establishment in the field, and assessment of weed risk.
- conservation biology: including natural distribution, diversity within species, status and security of native populations, and relationships with other species.
- adaptability: how easy new crops are to establish and manage, and how tolerant they are of the farm environment (climate, soils, pests and diseases, grazing animals, herbicides).

Native species score highly on many of the biological attributes listed above and therefore deserve further investigation of their commercial potential. Native species are well adapted to their natural environment, are less likely to become weeds in native vegetation, and may contribute directly to the maintenance of biodiversity in rural areas. A key point in their favour is that their genetic resource is available locally (Bartle 2001).

ATTRIBUTES OF *ACACIA*

The preceding sections give a broad perspective on the role of tree crops in agricultural systems. This section surveys the potential of *Acacia* species to be developed as commercially viable woody crops for salinity control.

Diversity, geographical range and ecology

Acacia is a large genus with a wide diversity of plant form and function and a large geographical range. Many species have large variation between provenances. A large part of the diversity in the genus occurs in Australia, where many species are endemic. This localisation of *Acacia* diversity provides an opportunity for Australian researchers to sift through the local flora for potentially commercial species, and then to select or breed productive crop lines from the full range of genetic diversity within those species.

Acacia species occur in all the dryland farming regions of southern Australia, on a full suite of habitats and ranging from small shrubs to trees. There are major centres of diversity in both the central wheatbelt of W.A. and in the inland slopes of the south-east of the Murray-Darling basin. Species that occur naturally in the southern Australian wheatbelt would be expected to be well adapted to many of the conditions they would encounter if grown as commercial crops in that region. For species that occur naturally in several different environments, it may be possible to select from different populations to produce different commercial lines of the same species, to suit different types of farm environment. Or, closely related species with different environmental requirements could be grown in different farm situations as part of the same industry, as long as their wood (or other saleable plant parts) had sufficiently similar attributes that could be processed together.

Many species fill a ‘pioneer’ role (rapid re-colonisers after disturbance). Such species have attributes that are potentially valuable in crops (easy establishment, rapid early growth) but these same attributes may pre-dispose them to weediness. Weed risk can be offset by developing local or regional species in preference to introduced species. Alternatively, weed risk can be controlled by various weed reduction strategies such as developing sterile hybrids, non-flowering forms or lines with reduced hard-seeded dormancy, or by developing management practices that eliminate flowering.

Many faster-growing *Acacia* species are also short-lived. This attribute is unlikely to be a disadvantage for short-rotation phase crops but may make some species unsuitable for use as coppice crops.

Commercial potential

In keeping with their diversity of form, function and distribution, *Acacia* species have found a wide range of commercial uses. Some of the larger species are used for sawn timber, firewood, charcoal, panel board pulp manufacture, and are grown in large commercial plantations (El-Lakany 1987; Brown and Ho Chin Ko 1997). Other commercial uses include tannin production from bark (Barbour 2000), and edible gum exuded from wounds on the stem, most notably from *Acacia senegal*, the source of gum arabic (Anderson and Wang Weiping 1990). *Acacia saligna* is used as a fodder crop in North Africa (El-Lakany 1987; Dumancic and Le Houerou 1981), and is being planted in farming areas in southern Australia as a combined landcare and supplementary fodder species (Lefroy *et al.* 1992). Edible seed from over 40 species from the dry zone may have been included in the diet of Australian aborigines (Devitt 1992). A small industry now exists to supply niche ‘bush food’ markets in Australia (Maslin *et al.* 1998, Simpson and Chudleigh 2001), and some Australian species have been introduced into famine-prone semi-arid regions in sub-Saharan Africa (Harwood 1994).

Many *Acacia* species are likely to provide suitable feedstocks for large-scale generic products such as solid fuels for electricity production, liquid transport fuel, charcoal and other pyrolytic products, and various commodity chemicals, as the feedstock specifications required for these products are very broad.

Most existing commercial uses of *Acacia* utilise species that are not commonly found in the wheatbelt of southern Australia and, in some cases, are not native to Australia. However, it is likely that some wheatbelt *Acacia* species also possess commercially desirable characteristics that, once identified, could lead to their development as commercial crop plants. Screening Western Australian wheatbelt species for desirable feedstock characteristics, growth rate and form is being carried out by the 'Search Project'.

Water use potential

While virtually any woody perennial species is likely to consume more water than annual crops, there is likely to be considerable variability in water use potential between species, especially within a large and diverse genus such as *Acacia*.

High water use is an important selection criterion for potential *Acacia* crop plants that are intended to play a role in salinity management in agricultural areas. Partial selection for high water use is likely to occur coincidentally during preliminary selection of *Acacia* species for commercial crops, since two key factors for commercial success, namely high survival rates in medium to low rainfall areas, and high biomass production rates, are most likely to coincide in plants that are effective at extracting water from soil. Although the relationship between water use and a plant's root size and distribution is complicated by many factors, including the availability of water and nutrients (Brouwer 1963, cited in van Noordwijk *et al.* 1996), and management of the plant's above ground parts (van Noordwijk *et al.* 1996), a useful first approximation is that 'the more extensive the root system is, the higher nutrient and water uptake efficiency may be' (van Noordwijk and de Willigen 1991).

Once several highly productive *Acacia* species have been identified for potential crop development, further testing will be needed to find particular forms with optimum root architecture and water use characteristics for the sites on which they are to be grown, and the functions they are expected to perform. Techniques suitable for low cost assessment of plant water use are available and could be used at this stage.

Various aspects of tree root architecture also need exploring, including the effect of pruning or removing the tops, as practised in short-rotation coppice crops. Some studies have found that increased severity of pruning results in an increased proportion of roots near the soil surface, due to new roots growing from the stem base (Hairiah *et al.* 1992, cited in van Noordwijk *et al.* 1996). The relevance of this finding for *Acacia* coppice crops should be tested, as it has implications for both water use and competition between *Acacia* belts and adjoining crops.

Some species have a propensity to develop deep root systems, others shallow ones, and the actual root pattern for a species on a particular site is determined by the interaction between genotype and environment (Kerfoot 1963, cited in van Noordwijk *et al.* 1996). It is likely that at least some *Acacia* species, especially those adapted to dry environments, are deep rooted, or would grow deep roots if grown as an agricultural crop, since deep rootedness is common in xerophytic species where there is access to groundwater (van Noordwijk *et al.* 1996). Knight *et al.* (2002) reported finding live tree roots at a depth of 16 metres under 4-year old belts of *Acacia saligna* and *Atriplex nummularia* (saltbush), while at a similar depth soils under adjacent annual plants had none, although it was not specified whether the deep roots were from *Acacia saligna* or saltbush. In Africa, roots of *Acacia senegal* have been reported at a depth of 32 metres (Deans 1984, cited in van Noordwijk *et al.* 1996).

Deep rootedness is likely to be a desirable attribute for *Acacia* species grown as phase crops on permeable soils, to maximise their productivity when grown at high densities, and to maximise their soil drying capacity. Deep rootedness would usually be preferred for *Acacia* species grown in alley layouts, to minimise competition for water with the adjoining crop. However, if the main aim of growing woody perennials in belts is to reduce waterlogging in the alley, or if the site on which they are grown has shallow soil, then *Acacia* species with a more spreading root architecture may be suitable.

Competition for water between annual crops and adjacent perennial woody crops will be strongly affected by the perennial crop's root architecture and water use. But other factors will also be important, including depth of soil, existing hydrological conditions, rainfall during the annual crop's growing season, and management strategies such as root ripping, or harvesting the perennial crop. In very wet areas or in very wet seasons, annual crop yields may be enhanced if adjacent perennial crops reduce waterlogging, whereas in dry years or on dry sites, they are likely to be suppressed by adjacent perennial crops unless the latter have been harvested recently or their roots are ripped.

Nitrogen fixation

Being a legume, *Acacia* can fix nitrogen and could play a significant role in nitrogen input to agricultural systems, especially when grown as a phase crop on soils poor in nitrogen.

Mele and Yunusa (2001) found significant increases in nitrogen and organic matter in soil at Rutherglen in Victoria following a six-year period under *Acacia*. This was not reflected in greater yield in a subsequent annual crop, partly because the *Acacia* phase had exhausted the soil water supply, and partly due to competition from weeds. However, modelled results from simulated wheat crops indicated that yields would be boosted for at least five years after removal of the *Acacia* crop, due to high soil nitrogen, once the soil water in the crop root zone had been replenished (by one wet year in this simulation).

Other researchers have investigated the effect of a leguminous crop on subsequent non-leguminous crops.

For example, using annual leguminous plants in rotation with maize on acid soils in the humid tropics, van Noordwijk *et al.* (1995) recorded an average increase in maize grain yield of 0.5-1 tonne per hectare following the legume rotation, compared to maize following a grass-weed fallow. The efficiency of using biomass N was found to be about 0.8 times that of applying urea in two split applications.

It appears likely that nitrogen fixed by an *Acacia* phase crop could provide a direct economic benefit by reducing the need to add N fertiliser to subsequent crops. However, to maximise this benefit, new farming systems should be developed based on optimised site selection, crop rotation sequences and integrated management.

Soil rejuvenation

In addition to producing salinity benefits by dewatering soil profiles, a range of other beneficial soil effects has been proposed for woody plants grown in rotation with annual crops. They include, 'nutrient pumping' to relocate plant nutrients from deep in the soil to the surface, 'hydraulic lift' in which dry topsoil is rehydrated with water drawn by plant roots from deep in the soil profile, thereby enabling nutrient uptake to continue in surface soils during dry seasons and droughts (van Noordwijk *et al.* 1996), and the provision of new root channels to improve soil porosity and facilitate root development in subsequent crops, a topic reviewed by Cresswell and Kirkegaard (1995). However, little information is available on these postulated influences of tree roots on soil physical properties (Ong 1996).

Acacias grown as phase crops could provide extensive soil rejuvenation that would benefit subsequent crops, through better soil aeration, reduced surface waterlogging, and easier access for roots. Working at the Rutherglen site described above, Yunusa *et al.* (2001) examined the soil under a wheat crop planted on land that had been occupied by *Acacia* for six years. In the second year after the *Acacia* harvest, the duplex soil (shallow sandy to clay loam surface over a fine sandy clay loam B horizon) contained a greater number of large pores and had a higher air-filled porosity than adjacent continuously cropped soil. Soil porosity increased between the first year after *Acacia* and the second year, as the *Acacia* roots decomposed. The wheat crop grown on the 'acacia soil' had higher root dry matter and higher root length compared to the adjacent wheat crop grown on 'annually cropped soil'. Further investigation of the effect of *Acacia* phase crops on soil physical structure and the productivity of subsequent crops is required.

Seed size and ease of harvest and establishment

Acacia carries its seed in pods, the seed size is large and, in southern Australian species, the seed is generally produced annually in a well-defined season. These attributes mean that the cost of seed collection should be relatively low and that plants can be established by direct sowing rather than by seedling production in a nursery.

The treatments required to break hard-seeded dormancy in many *Acacia* species are now well understood within the nursery trade and among companies and organisations involved in land rehabilitation and revegetation. Similar techniques are likely to be successful for new species developed as crops or, as mentioned above, it may be possible to breed forms with reduced hard-seededness, to lower long-term weed risk, while simultaneously improving ease of establishment.

Vegetative regeneration

Some *Acacia* species can regenerate vegetatively after the stem is cut and this could make them suitable for use in 'permanent' belts in alley farming systems. The ability to resprout from the cut stump (coppicing) appears to be restricted to certain species or, in some cases, provenances or variants within species. Further research is needed to understand the coppicing behaviour of potential commercial species, including variation within species, reliability of coppicing, conditions that favour successful coppicing, and the robustness of successive coppice regrowth from the same rootstock.

Root suckering, also a feature of some *Acacia* species, is likely to be a disadvantage in species that sucker indiscriminately but could be useful in those that sucker more strategically, after a trigger such as death or removal of the main stem. Again, more research is needed to determine the suckering propensity of different species and provenances within species, as well as the environmental conditions that might favour or discourage suckering, so that appropriate farming systems and management techniques can be developed.

Some preliminary information on the coppicing and suckering ability of various *Acacia* species is given in Table 4.

Assessment of individual species

Acacia species that occur naturally in the south-west of Western Australia were assessed in 2000 and 2001for their suitability to be developed as biomass crop plants. The boundaries of the study area were the regions defined in the Interim Biogeographic Regionalisation of Australia (Thackway and Cresswell 1995) as Geraldton Sandplains, Avon Wheatbelt, Mallee and Esperance Plains.

Species considered to be most suited to further investigation are listed in Table 4, along with attributes that may affect their commercial prospects. 'Plant form and growth rate' determine the amount of biomass produced and its ease of harvest, and have a strong effect on profitability, while 'other features' affect each species' potential suitability as a crop plant, the type of farming systems with which it would be compatible, its management requirements, and its potential primary uses (influenced by wood density) and secondary products (such as seed, fodder, tannin and gum).

This assessment was carried out by Bruce Maslin from the Western Australian Herbarium, in association with the Search Project.

TABLE 4
Preliminary assessment of some Western Australian *Acacia* with potential for crop development.

SPECIES AND DISTRIBUTION[1]	PLANT FORM[2] AND GROWTH RATE	OTHER FEATURES[3]
A. acuminata Widespread (wheatbelt)	Tall shrub or tree 2-7 (-10) m tall. Multi-stemmed from ground level, or with a fairly straight bole 0.3-1.5 (-2) m long and 10-30 (-45) cm dbh.Stems and main branches fairly straight. Pendulous forms occur occasionally in parts of the range. Growth rate: moderate	+ Low to moderate salt tolerance + Drought and frost tolerant - Susceptible to waterlogging, fire ± Unlikely to sucker, can coppice from rootstock + Genetically diverse- Seed yields unreliable ± Wood density: high (1 plant, 7 cm stem)
A. anthochaera Northern wheatbelt	Tall shrub 2-4 m tall, occasionally maturing to bushy tree to 8 m. Multi-stemmed from or near ground level. Each stem 6-10 cm in diameter at its base and 4-8 cm dbh. May be single-stemmed to about 1 m above ground level and reach 30 cm in diameter at the base (10-20 cm dbh). Slightly crooked trunks and main branches. Growth rate: moderate to fast	+ Moderately salt tolerant ± Not known to sucker (unlikely to coppice) + Edible seed (large reliable crops) ± Wood density: high (1 plant, 8 cm stem)
A. conniana South coast (geographically restricted)	Dense, bushy shrub or small tree 1.5–6 m tall. Sparingly divided at the base or up to 1 m above the ground Stems sub-straight and 5-8 cm dbh. Growth rate: low to moderate	± Unlikely to sucker, coppicing ability unknown ± Wood density: medium (3 plants, 5-7 cm stems)
A. cyclops ***Coastal***	Spreading shrub (1-4 m tall) or small tree (to 7 m tall). Single-stemmed to about 1 m or sparingly divided at ground level into a few sub-straight or rather crooked main stems (dbh often 10-15 cm, rarely over 20 cm). Growth rate: moderate	+ Salt tolerant + Some provenances grow in waterlogged clays ± Rarely coppices, but may sometimes sucker - Weed potential ± Wood density: medium (4 plants, 5-11 cm stems)
A. jennerae Arid zone	Shrub or small tree, often with 'mallee-like' form, 1.5-4 (-6) m tall.Sometimes single-stemmed but more commonly dividing at ground level into 2 or more, straight, rather slender stems. Often suckering to form clonal thickets. Growth rate: moderate	+ Tolerant of fire, frost, salt, drought ± Strong root suckering and coppicing + Edible seed
A. jibberdingensis Widespread (wheatbelt)	Shrub or small tree 2-4 m tall, occasionally 7 m tall. Single-stemmed to 1.5 m or sparingly dividing just above ground level. Stems up to 25 cm diameter at the base (to 15 cm dbh). Stems and main branches can be rather crooked. May be spindly when growing in dense scrub. Growth rate: moderate	+ Appears to be adaptable to a variety of habitats ± Unlikely to sucker, coppicing ability unknown, but probably poor- Variable seed set
A. lasiocalyx Widespread (wheatbelt)	Spreading shrub or tree commonly 2-5 m tall, dbh 13-15 cm. Often an erect tree around the base of granite rocks, reaching 10-15 m tall, dbh 30-50 cm, with fairly straight trunk. Usually single-stemmed or sparingly divided at the base. Growth rate: fast?	± Unlikely to sucker, coppicing ability unknown - Phyllodes contain relatively high concentrations of cyanogenic glucoside ± Wood density: medium (15 plants, 4-12 cm stems)
A. microbotrya Widespread (wheatbelt) except south-east	Bushy, tall shrub or small tree 2-4 m tall (Dandaragan variant is a tree to 7 m tall). Single trunk to about 1 m before branching (about 11 cm diameter at base), or dividing at ground level into 2-4 main trunks (6-9 cm dbh). Often forming dense clonal clumps by root suckers. Growth rate: fast	+ Slight to moderate salt tolerance? + Drought and frost tolerant± Suckers readily, and probably coppices- Taxonomically complex (under review) + Many related species that may also warrant investigation+ Edible seed, possibly gum, tannin, fodder± Wood density: medium (42 plants, 4-10 cm stems)
A. murrayana Arid zone	Large shrub or tree 2-6 (-8) m. Single- or multi-stemmed from the base. Stems straight or sometimes rather crooked, dbh to 15 cm. Commonly suckering to form clonal thickets. Growth rate: fast	- Salt sensitive + Tolerant of fire (coppices) and drought ± Suckers and coppices - Potential weed + Edible seed, possibly gum ± Wood density: low (3 plants, 8-9 cm stems)

TABLE 4 (continued)

SPECIES AND DISTRIBUTION[1]	PLANT FORM[2] AND GROWTH RATE	OTHER FEATURES[3]
A. prainii Widespread (wheatbelt)	Dense, spreading shrub 1.5-3 (-5) m tall. Branching at or just above ground level into a number of erect to ascending stems. Main stems and branches rather straight (4-6 cm dbh). Growth rate: moderately fast	+ Hardy ± Unlikely to sucker, coppicing ability unknown ± Wood density: high (1 plant, 5 cm stem)
A. aff. redolens Restricted distribution (Esperance)	Small tree 4-7 m tall, may reach 10 m on good sites. Dividing at 0.5-1.8 m above ground level into 2 or 3 main stems (9-20 cm dbh). Stems and main branches sub-straight. Growth rate: unknown	+ Moderately tolerant of salinity? + Grows in waterlogged clays ± Unlikely to sucker or coppice? + Thin bark± Wood density: medium (5 plants, 5-10 cm stems)
A. resinimarginea Northern wheatbelt	Tree 4-7 m tall. Single-stemmed or branched into 2-5 stems near base. Trunks fairly straight, generally erect, reaching 20 cm dbh. Growth rate: slow	- Low tolerance to salt? + Suited to Wodjil sands ± Unlikely to sucker, coppicing ability unknown ± Wood density: high (3 plants, 5-11 cm stems)
A. rostelliferaCoastal	Dense shrub or tree commonly 2-5 m tall. Branching near ground level, with main stems usually 5-10 cm dbh, although some specimens considerably larger. Usually clonal. Spindly when growing within dense clonal thickets, with stems about 2-3 cm dbh. Growth rate: fast	+ Suited to light soil + Root suckers, probably coppices + Many related species - Difficult to get seed ± Wood density: medium (13 plants, 4-12 cm stems)
A. saligna Widespread (wheatbelt)	Bushy shrub or tree 2-6 (-10) m tall. Either single- or multi-stemmed, mature trunks 20–40 cm dbh. Sometimes forming thickets due to root suckering. Variable growth form. The largest, tree form occurs on the Swan Coastal Plain. Growth rate: fast	- Susceptible to various insects and diseases ± Root suckers and coppices (all forms?) + Variable growth forms ± Genetically variable (currently under review) + Edible seed, gum, tannin, fodder, yellow dye-Weed potential? ± Wood density: low (34 plants, 3-15 cm stems)
A. victoriae Arid zone	Spreading, often straggly shrub or small tree 1.5-5 (-6) m tall. Main stems commonly about 6 cm dbh but reaching 12-14 (-18) cm. Readily root suckering and sometimes forming thickets. Growth rate: fast	+ Tolerant of salt, lime, fire (when young), frost and clay soils- Sensitive to severe drought + Coppices and suckers readily + Edible seed, charcoal, fodder- Quite prickly ± Wood density: medium (2 plants, 4-8 cm stems)

1. Distribution refers to the south-west of Western Australia.
2. Some heights and diameters are given for the normal range, with unusually large sizes in brackets. For example: height 2-7 (-10) m tall. 'dbh' refers to diameter at breast height (1.3 m above ground).
3. Wood density was calculated from wood cores taken from some species. Sampling was biased towards small trees. The number of plants sampled and their stem diameter at the sampling height (usually waist height or below) are included. Quoted densities are 'basic density' (oven-dry weight divided by green volume, expressed in kg per cubic metre). Density categories used in this table are: Low: less than 650, Medium: 650 to 850, High: over 850 kg per cubic metre.
4. Symbols in column 3: + advantageous attribute; - disadvantageous attribute; ± advantageous or disadvantageous attribute depending on circumstances.

Table adapted from Maslin (2001).

CONCLUSION

Large-scale revegetation for salinity management is likely to occur only if commercial perennial crops are developed. *Acacia* is a prospective genus for crop development in southern Australia due to the large number of species occurring naturally in Australia, their favourable breeding biology, and their diversity. Many have suitable growth rates and form, and the potential to produce commercially attractive products such as wood, fibre, gums, tannins and seeds.

Acacia species could be suited to each of the perennial woody crop types described in this paper. For example, species with good tree form and good wood quality may be suitable for long-rotation cropping, while species with the ability to sprout reliably from the stump after harvest could be used as short-rotation coppice crops. Obligate seeders might be particularly suitable for use as phase crops. Each crop type could fill a quite different role in agricultural systems.

The economic analysis discussed in this paper shows that *Acacia* species are most likely to be profitable if developed as short-rotation crops, producing low-cost woody biomass. These crop types are best able to utilise the biological potential of *Acacia* to improve water balance and sustainability in southern Australian wheatbelt agricultural systems. Large-seeded *Acacia* species are especially suitable for development, because low-cost establishment using direct seeding has a large, positive effect on profitability, net debt load, and time to break even.

Detailed evaluation will be required to identify taxa with the best commercial prospects. The extent to which *Acacia* crops may be developed will depend on the size of markets for low-cost biomass feedstocks, and criteria for commercial success such as:

- adequate feedstock quality for processing,
- ability to provide feedstock material for more than one product,
- low cost of production relative to competing feedstocks.

The potential of *Acacia* is being investigated in a current project in Western Australia sponsored by the Natural Heritage Trust. Known as the Search Project it is conducting systematic screening of the native flora of the Western Australian wheatbelt to identify species with the potential to be developed into large-scale crop plants.

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