Developing a biomass supply chain for new Australian crops

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1. SUMMARY

The development of woody short rotation crops in the southern Australian low rainfall agricultural region (the wheatbelt) is driven by the need to address an increasing problem of land degradation caused by clearing of the native vegetation. This fundamental reason determines many of the characteristics of the new crops and the parameters within which they can be grown. The crop plants include a number of native species that are suited to the environment and agroforestry systems. Two types of crop are under development. (i) Mallee eucalypts, represented by several species with a wide range of small tree forms. Mallees are a long-lived coppicing crop that may be harvested repeatedly on a three year cycle. (ii)Phase crop systems, based upon woody plants of several genera, which can be established cheaply and grown for a single harvest. Crop characteristics and the dispersed nature of the resource that they will provide determine many of the characteristics of the supply chain that is being developed. Production and market economics are also very influential upon supply chain characteristics. Neither the biomass production systems, nor the processing industries, will be supported by public subsidy, other than a mandatory requirement for electricity retailers to increase their provision of renewable energy. Even with this mandate, the market value of woody biomass used for the production of electricity will be less than the cost of producing that biomass from woody short rotation crops, so bioenergy electricity generators must coexist with other industries to utilise low value biomass residues. Consequently, for short rotation crops, woody biomass market development must be focused upon wood chip and industrial extractives such as eucalyptus oil. The potential industries based upon these new crop resources in the wheatbelt will pay modest prices, about A$30 per green tonne of mixed biomass delivered to the factory gate. Stumpages must be about A$15 per green tonne to make the new crops financially affordable for the farmers. Therefore, a supply chain must harvest, comminute, haul and transport biomass up to about 100 km for no more than A$15 per green tonne. There is no prospect of meeting this cost target with existing technology and new supply chain must be developed. The principal features of such a supply chain are described. Two projects developing a continuous harvester and a novel chipper are proceeding as finance becomes available. Other biomass production issues requiring engineering development include reducing the cost of crop establishment, integration with existing farm enterprises, and modelling and logistics development for the whole biomass production system.

Costs are given in Australian dollars; A$1.00 equals approximately €0.62, NZ$1.17, SEK5.78, UK£0.43 and US$0.72 at the time of writing.

2. INTRODUCTION

There are new short rotation crops being developed in Australia to control an increasing problem of land degradation. Bartle (2001) and Bartle and Shea (2002) provide a comprehensive description of the issues. In summary, the clearing of perennial native vegetation, for the development of agricultural systems based upon annual crops and pastures, has disturbed the balance between incoming rainfall and evapotranspiration. There is consequently increased water accumulation in the soil profiles under the agricultural areas of southern Australia, which is mobilising salt previously stored deep in the soil profiles. Large areas of the landscape are already degraded by rising saline watertables, with about 1.8 million out of a total of 18 million hectares affected in the Western Australian agricultural region alone, where the problem is most advanced. It is anticipated that degradation in WA may exceed 30% of the agricultural region by the time a new hydrological equilibrium is reached in the next 50 to 100 years. The consequences apart from loss of farmland will include loss of water resources, reduced biodiversity and damage to towns, roads and other infrastructure (Frost *et al*., 2001)

Part of the solution to this problem will involve partial revegetation of the agricultural areas with deep rooted woody vegetation to increase evapotranspiration. The problem is large, with approximately 70 million hectares of farmland lying within the lower rainfall agricultural regions (known as the "wheatbelt") of southern Australia, where the problem is expected to be most acute. It is an economic necessity that this revegetation process must fund itself and become a form of profitable enterprise for the landowners (Bartle, 2001; Bartle and Shea, 2002).

This paper considers the most promising short rotation woody crops that are under development, and in particular how it is intended to develop a supply chain to link the farm production of woody biomass to new conversion industries, including bioenergy processes.

3. OPERATING PARAMETERS FOR THE NEW CROPS AND INDUSTRIES

3.1 Crop types

Tree crops producing sawn wood or veneers have a relatively long rotation in the wheatbelt environment and the high cost of establishment makes them uncompetitive with conventional agriculture (Bartle *et al*., 2002; Olsen *et al*., in press). Tree crops must be short rotation (< 5 years) to enable farmers to recover the establishment cost quickly. Two production systems are presently under development:

- Mallees are grown as permanent coppice crops with high establishment costs, harvested repeatedly on about three year rotations. Mallees are eucalypts (several species are in use) that form a large lignotuber just below or at ground level. They coppice vigorously from the lignotuber after harvesting. In addition to harvesting the aerial parts of the plant, there is the potential to commercially sequester carbon in the retained root system. Wild mallees have been harvested for over a century (Bartle and Shea, 2002). As coppice crops, mallees are relatively permanent stands of trees, usually planted in narrow belts separated by broad alleys that are occupied by annual agricultural crops and pastures. They occupy a small proportion of the landscape all the time.

- Phase farming with woody crops that must be established efficiently over whole paddocks by direct seeding. These crops will be removed after one short rotation and then followed by annual crops and pastures for a period of several years. Phases of woody crops and annual plants will thus be alternated so that the deep rooted woody vegetation removes the excess water that accumulates under the annual crops and pastures (Bartle *et al*., 2002). These single harvest crops would occupy most of the landscape for a small proportion of the time.

The mallee coppice crops are typically grown in belt configurations, most commonly in four rows per belt, with the inter-belt alleys varying from 40 to 100 metres or more across. Row spacing within the belt is normally 2 metres and stem spacing within the row is nominally 1.5 metres. Early indications from spacing trials are that the intra-row spacing could be increased without reducing crop production per metre of row, which would significantly reduce establishment costs and increase the size of each mallee at harvest age. Establishment is by seedlings and costs about A$1300 per hectare. This cost is the most significant obstacle to widespread adoption of mallee crops and has significant impact upon the economics of tree cropping compared to annual agricultural crops (Bartle *et al*., 2002). Harvesting is considered to be a single row operation (see Section 3.3) so inter-row spacing must be at least two metres but may be more. Farmer preference is generally for a minimum inter-row spacing as it reduces the amount of land lost from conventional agricultural enterprises.

Phase crops are in the very early stages of development. They would be direct-seeded extensively in an analogous manner to annual crop establishment, but at row spacings of metres instead of centimetres. A proportion of each farm would be in a woody crop phase at any one time. As the principle of water use by the phase crop is to provide complete coverage with deep rooted woody vegetation, the “loss” of land from conventional agriculture is not an issue in inter-row spacing. A recommended stem spacing will be identified following the assessment of existing trial plots, but may be perhaps five metre inter-row by 1–2 metres intra-row. Optimum spacing will be a balance of establishment cost, access for management such as weed control, harvesting access, tree size at harvest age and the method and cost of stump removal.

There are a number of factors that are pushing these types of woody crops towards growing larger individual plants – maximising stand productivity while reducing the number of stems per hectare. This trend not only reduces establishment costs per hectare but the increased individual stem sizes will increase the wood chip proportion of the biomass. It will also increase the proportion of wood chip that will meet the specifications of the higher value markets, as the best chip comes from the biggest wood in small trees.

There are a number of trees and shrubs that will grow productively in the Australian wheatbelt. Crop species identification, drawing from the diverse native flora, is actively taking place (Olsen *et al*., in press) and a number of promising species are emerging. The largest established woody crop at this time is based upon several species of mallee eucalypts. There are species to suit most soil types across the entire wheatbelt region of WA. Mallees come in all forms, from broad spreading shrubs to comparatively tall and erect small trees. Unharvested saplings at a harvestable age of about five years, grown on suitable sites, vary from shrubs with crowns 3-4 metres high and 2-3 metres wide, to single stemmed tree forms over 6 metres tall. Form in all species is generally poor with heavy forks low in the stems being common. Coppice regeneration is typically between two and 10 stems after three years, with the plants adopting similar overall dimensions to a five year old sapling. At harvest, individual mallee weights are typically in the range of 20 kg to 50 kg of whole biomass.

The chipped biomass in its unsorted state is a mixture of wood chip, leaf, and residues of assorted fines, bark and small twigs. The proportions of wood, leaf and residues is about one third each, but these values vary widely according to tree species and age at harvest. Younger, smaller trees have high proportions of leaf and less wood, and the proportion of wood increases with age. The mixed material in chipped form is liable to decompose significantly over a period of a week. It is preferable to sort the leaf and residues from the wood chip if wood chip is to be stored for any period. Eucalyptus wood chip is commonly stored in open stacks for periods of several weeks without significant loss of quality.

Species selection for a specific site depends upon soil type and regional climatic conditions. A typical farm planting will have more than one species, primarily as a result of variations in soil types. Stands are established in monocultures, but there is often more than one species within a single paddock. Typical paddock sizes vary from 100 ha to 1,000 ha, depending upon climatic conditions and annual crop productivity, which determine conventional agricultural practices. A harvester will have to accommodate any of the tree forms that occur on a farm. Changes from one species and tree form to another will occur several times a day.

3.2 Biomass values and stumpage

Woody biomass for stand-alone bioenergy plants in Australia, according to industry sources, is worth up to $10-$12 per comminuted green tonne at 45% moisture content wet basis (m.c.w.b.), delivered to the power station. Slightly more may be offered by large coal co-firers, but only a small proportion of the landscape lies within realistic transport distance of coal-fired power stations. There is a mandatory requirement for electricity retailers in Australia to increase their annual renewable energy production by 9,500 GWhrs nationwide and this may be in the form of either directly generated "green" electricity or purchased renewable energy credits. The mandate has created a small but relatively high value market for renewable energy, which supports the $10 - $12 biomass value. Without the renewable energy mandate, demand for biomass for bioenergy would be very much reduced or even negligible. Bioenergy competes for the renewable energy market with wind, solar hot water, hydro and geothermal power. Under these conditions it is most unlikely that it will ever become economically feasible to grow, process and deliver biomass for energy alone. One possible exception is electricity in the more remote parts of the agricultural regions, where very long transmission systems incur high capital costs and energy losses.

Biomass wastes which have a disposal cost or zero value delivered to the power station are competitive sources of energy in Australia and examples include municipal green waste, chicken litter, some concentrated food and agricultural wastes, sugar cane bagasse, timber mill residues and black liquor. If competition for biomass wastes develops as mandated renewable energy production requirements increase, wastes that currently have a disposal cost are likely to acquire a market value, but then other wastes streams will also become competitive.

It is therefore imperative that biomass feedstocks from short rotation woody crops have multiple uses so that higher value fractions will increase the value of biomass produced in the paddock. The importance of multiple uses for mallee biomass, particularly in relation to eucalyptus oil, has been discussed in more detail by Cooper *et al*. (2001).

The Western Australian mallee industry is anticipating making its first deliveries to an Integrated Tree Processing (ITP) factory that is nearing completion. The multiple products from the biomass will be activated carbon from the wood chip, eucalyptus oil from the leaves and bioenergy from the residues (Chegwidden et al, 2000). Preliminary estimates indicate a delivered price in a mature mallee/ITP industry will about $30 per green tonne (45% m.c.w.b) (Enecon, 2001). It is assumed for this discussion that other industries will have the potential to pay similar prices for biomass if the chip is used for other processes such as wood panel production. Significantly higher prices are unlikely as biomass from the short rotation tree crops in the wheatbelt will contain only about 20 – 40% wood chip, depending upon the species of tree and the quality of wood chip required.

On the other side of the economic equation, stumpage must be sufficient to attract farmers to the new crops. During the first decade of mallee coppice crop establishment (from 1992 to 2002), there was partial government subsidisation of the cost of seedling production, management and distribution. Those subsidies have been progressively withdrawn and now the farmers meet all crop establishment costs. There is no subsidised “set-aside” agricultural land in Australia that would favour the adoption of these new agricultural enterprises. To compete with existing agricultural enterprises for access to productive land, stumpages of between about A$12 and A$22 per green tonne (45% m.c.w.b.) must be paid. Even under these conditions, short term cash flow, which dominates the decision making in a small business enterprise, is always more favourable for conventional agriculture due to the short term production cycles of annual crops and livestock enterprises (Olsen et al, in press). Land conservation will continue to be the main incentive for farmers to forego income and increase operating costs in the short (4 to 10 year) term while establishing short rotation tree crops.

3.3 Crop scale of production and transport distances

The scale of the new tree crops must be large to address the land conservation issues (Bartle and Shea, 2002), but how much biomass can be produced? Starting from the premise that there is a finite amount of water available per unit of land area to support the profitable growth of woody vegetation, an economic analysis has estimated the amount of woody biomass that can be produced across the agricultural landscape in Western Australia (Olsen *et al*., in press).

One of the fundamental conclusions of the economic analysis in the Olsen et al report is that the low rainfall (300-600 mm) wheatbelt environment will only support low levels of woody biomass production per square kilometre over the landscape as a whole.

- For a coppice crop grown in narrow belts with alleys of annuals-based agriculture in between, production per coppice crop hectare may be between about seven dry tonnes of whole biomass per year in 350 mm areas to about 20 dry tonnes per year in 600mm areas, but only about 8% (at 350 mm) to 25% (at 600 mm) of the land would be planted.

- A four year woody phase crop would occupy almost all of a farm paddock, but it would only be grown for between about 15% (at 350mm rainfall) and 35% (at 600mm rainfall) of the time. Productivity of phase crops would be similar to coppice crops if compared over the long term and across the whole landscape.

The principal constraint upon productivity is the availability of accessible soil moisture of utilisable quality, combined with the evaporative demand as determined by climatic conditions (Olsen *et al.,* in press). The annual crops and pastures consume most of the rainfall, and in some years and locations they use all of the rainfall. The woody crops are only intended to use the excess soil water and complement conventional annuals-based agriculture, not displace it. The low productivity of the tree crops, at the whole-of-landscape scale, means the resource will be highly dispersed, which will be a significant issue for a wheatbelt supply chain.

However, despite the highly dispersed nature of the woody biomass resource, the area of land and the scale of the land degradation is large (see Figure 1). The total production of biomass is potentially large enough to support some significant industries (see Table 1). The low rainfall agricultural areas in the eastern states of Australia are much larger than those in the south west of Western Australia, but the Western Australian example is suitable for demonstrating the principles of likely resource distribution.

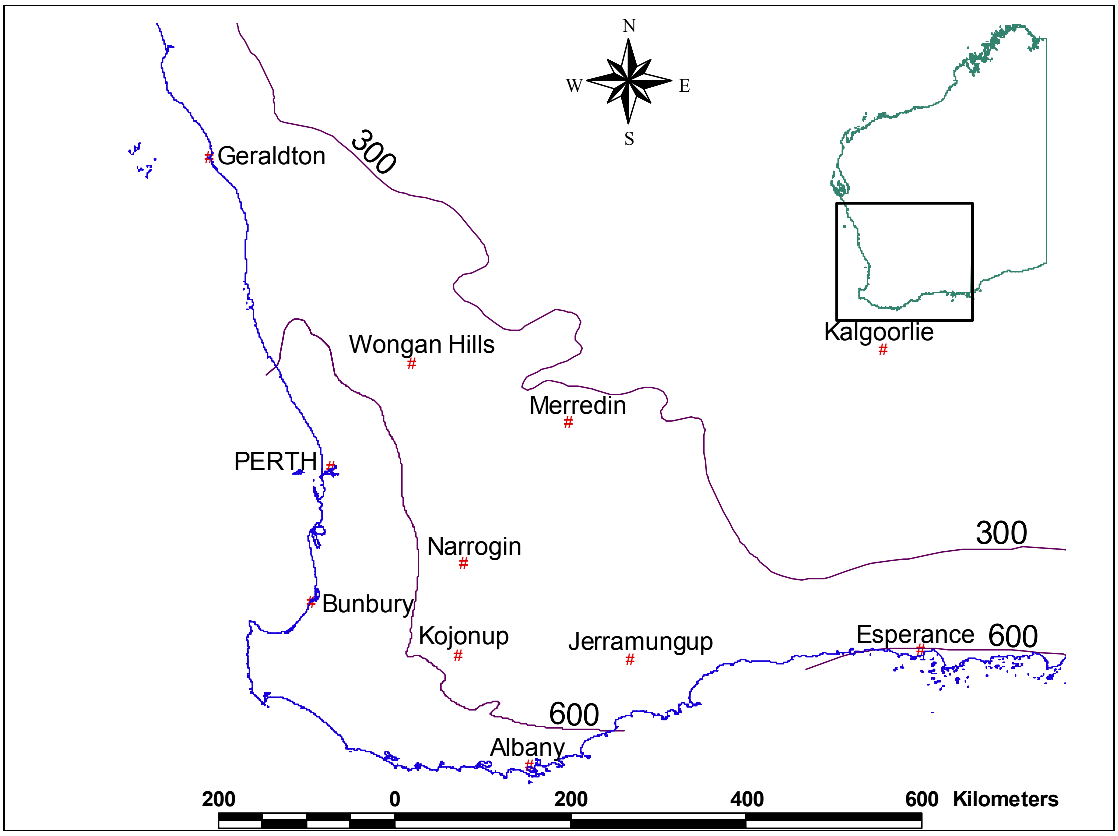

Figure 1. The 600 – 300 mm annual rainfall zone of the Western Australian wheatbelt

Table 1. Potential green biomass supply ('000 t/year, 45% m.c.w.b.) for three hypothetical regional processing centres in the Western Australia wheatbelt. (Adapted from Olsen *et al*., in press)

Climatic characteristics for 3 hypothetical processing centres **(Expressed as annual rainfall and evaporation)**	**Biomass supply ('000 t/year) for a range of transport horizons (km)**				
	200	**150**	**100**	**50**	**25**
Rainfall 500-600 mm; Evaporation < 1600 mm	5,684	3,953	2,230	797	233
Rainfall 400-500 mm; Evaporation 1600-2000 mm	4,689	3,289	1,940	421	74
Rainfall < 400 mm; Evaporation > 2000 mm	3,958	2,260	1,039	301	86

he potential biomass resource summarised in table 1 will be about 20% to 40% wood chip, depending upon the species grown, the age of the trees at harvest and the quality of wood chip required. Wood chip is likely to be the most valuable product from the biomass and it can support industries such as wood panel production, which has a feedstock requirement of 100,000–300,000 dry tonnes per year for a small scale factory. This size of industry is commensurate with the scale of the fundamental land degradation problem and the production that can be anticipated in the long term to address that problem. From the information collated in the Olsen et al report, it appears that in general terms, the lower value uses of biomass such as bioenergy can operate at smaller scale economic units, whereas the higher value uses with large markets will generally require larger factories to be economically viable. In summary:

- To supply a 300,000 dry tonne per year factory with wood chip would require a transport horizon of about 100 km.
- The 300,000 dry tonnes of chip will be selected from about 2 million tonnes of green mixed biomass.
- The mixed biomass could be transported to large centralised processing centres, where the total quantity of feedstock would be determined by the required tonnage of the highest value product. Other factories could be clustered nearby to utilise the lower value fractions of the biomass and all residues would supply a bioenergy power station.
- Alternatively the mixed material could be graded in smaller localised facilities and the lower value fractions utilised locally. Total throughput would be in the order of several hundred thousand tonnes of green biomass per year. More valuable fractions would be transported on the larger factories.

From the nature of the biomass and its dispersal, some key features of the transport and materials handling system can be identified:

- The mixed biomass must be moved from the farm to a centralised sorting and processing point quickly to avoid problems of degradation in the fresh material.
- Materials handling must be very efficient to fit within the economic constraints of the whole production and processing system.
- Materials handling at the farm scale involves modest amounts of material and must utilise diesel powered mobile equipment. For example a 5,000 hectare farm could have 10% woody crop cover, yielding 20 green tonnes per hectare per year. If one third of this material is harvested each year, only 10,000 tonnes are

removed in each harvest visit. For the next decade or more, farms are more likely to have less than 5% woody crop cover, as adoption of the new crops, which involves a revolution in agricultural practice, will generally be gradual.

- The biomass must be collected into processing facilities with throughputs in the order of several hundred thousand to millions of tonnes per year. Such facilities will be able to justify the capital cost of sophisticated handling facilities for receiving, sorting, grading, stockpiling and reclaiming from the stockpiles. The processing receival point could be linked to the various biomass conversion processes by conveyors, eliminating the need for costly loading and unloading of road or rail containers.

3.4 Biomass characteristics and markets

The biomass must be comminuted in some way to achieve acceptable bulk handling characteristics and increase the bulk density of the biomass. Baling in several forms has been considered as a compaction process, but just the baling alone is too expensive per tonne (Eriksson, 2000; Hudson and Hudson, 2000) to fit within the cost constraints. Berg (2003) states that the baling of logging residues in the form of compressed residue logs is causing only a modest reduction in the cost of biomass fuel in Sweden, when compared to chipping residues in the forest. Bales also represent small batches that create costly handling steps in other parts of the supply chain (see 3.3 for further discussion of batch handling).

As a bulk material, the biomass must flow as well as possible. This means minimising the proportion of long pieces such as twigs, sticks, and the long slivers that can be produced from larger wood sections (Mattsson and Kofman, 2002). Traditional wood chipping is seen as the most suitable method of comminution as it produces a flowable material with an acceptable level of whole twigs and small sticks. Chipping techniques are discussed further in Section 5.2.

This paper is not intended to consider specific markets, but fundamental market characteristics must be considered where they are likely to impact upon the supply chain.

The current single market opportunity for the mallee crop is the ITP process approaching commissioning in the WA wheatbelt. The wood chip will be used to make charcoal and from that activated carbon will be produced. The chip specification for the ITP is that it must pass through a 30 mm screen. Pieces less than 5 mm thick in the smallest dimension will be less valuable because they will not make the best charcoal.

Leaf oil is also an important product of the mallee crop. A comminution process that strikes an optimum balance between flowable bulk biomass and minimum leaf damage is preferred, as the leaf oil is volatile and increased leaf damage increases oil evaporation. Chipping can be suitable to meet this objective, particularly drum chipping, but the use of hammers (in tub grinders or hoggers) or shredders would cause unacceptable leaf damage. Forage harvester drum choppers that produce a consistent 1 – 2 cm long chopped material, desirable for silage production, will also cause substantial loss of leaf oil.

This example from the near future demonstrates a principle that will apply in the longer term; the most valuable foreseeable large markets will utilise wood chip. Apart from extractives such as oil, foliage will most likely become bioenergy feedstock or livestock feed, neither of which have very specific particle requirements. Wood chip for industrial processes needs to be sound and of consistent size. The comminution step must maintain a focus upon wood chip quality.

4. A WOODY CROP SUPPLY CHAIN FOR THE WHEATBELT

A useful supply chain for the new woody crops and their processing industries must work within the financial constraints of biomass values and stumpages, suit the crop types that can be grown in wheatbelt environment and accommodate the necessary scale of production and transport distances.

4.1 Constraints on supply chain costs

In financial terms, the supply chain must operate between the stumpage paid to the farmer and the value of the biomass at the factory gate. The nominal value for biomass at the factory gate is assumed to be $30 per green tonne and stumpage will be about $15 per green tonne (45% m.c.w.b.) (Enecon, 2001; Olsen *et al.*, in press) (see Section 3.2 above). The current supply chain development project aims to harvest, chip, haulout and load road transport trailers for less than A$10 per green tonne (45% m.c.w.b.) for a mature industry. A mature industry would have a reasonably uniformly dispersed crop resource, so that harvester relocation costs are at a practical minimum for this dispersed type of crop. For most economic modelling a nominal transport cost of A$5/gt has been assumed. Decreasing the cost of harvesting will increase the transport horizon or allow expansion into regions where higher stumpages must be paid to obtain access to productive land.

4.2 Crop types

The current supply chain project is focussed upon mallee harvesting. Mallees come in all forms (see Section 3.1), and the wood densities are generally between 700 kg and 1,000 kg per cubic metre (oven dried). It is reasonable to assume that a harvester capable of harvesting all mallees will be capable of harvesting any of the other woody crop species currently under investigation.

The ability to harvest any mallee form with a single type of harvester is considered highly desirable as a farm paddock will frequently contain more than one species and form of mallee. The cost of moving the harvest operation per tonne of biomass harvested must be minimised, so it is important that once landed on a farm, the harvester is capable of processing all the woody crop material that is suitable and available. This will be particularly important in the short and medium term, when the amount of biomass produced by each farm will be modest.

In the long term, a harvester visit to a farm may involve the removal of up to about 10,000 green tonnes of material from a medium sized farm covered with 10% woody crop resource (see the example discussed in Section 3.3). This would represent about 300 hours of harvester time per harvester visit at 60% harvester utilisation and 75 green tonnes per productive machine hour. This large number of harvesting hours suggests that there will be the opportunity to bring more than one type of harvester to each farm to process the different types of woody crops. However, reports from the Brazilian sugar cane industry suggest that when farm production achieves this level, the harvesting system can be made more efficient by working several identical harvesters together, so that in the event of machinery failure in any part of the in-field supply chain, there is the capacity to keep the supply chain functioning. Even under such conditions of advanced industry development, a supply chain utilising a uniform type of harvester will be more flexible and efficient than a supply chain based upon a number of different harvesters specialised for specific crop types.

4.3 Supply chain alternatives and matching transport systems

A review of supply chains in similar industries around the world was conducted, in part through the literature and also by visiting some of the European bioenergy industry. The overall conclusion of this review was that given the cost objectives that must be met by an Australian wheatbelt supply chain, only sugar cane harvesting presents a supply chain model that is economically feasible. Sugar cane, as discharged from the harvester in billets, is a product with similar bulk density, handling characteristics and low value per tonne as is expected for short rotation woody crop biomass. The sugar cane harvester itself does not handle the spreading form of many mallee species, but the principles of the supply chain can be transferred readily to small tree harvesting and transport. It has the additional advantage of being a fully operational unsubsidised commercial model where the contractor costs are well understood and are determined under Australian conditions. Most of the current Western Australian mallee supply chain development work has therefore followed the principles of the sugar cane model. One of the most important features of the most efficient cane harvesting systems is their minimisation of batch handling.

For small trees, either in the form of shrubby mallees or erect young eucalypts, local experience and the literature suggest that harvesting stems one at a time by conventional means is not efficient enough to meet the cost objectives of the new Australian industries. Costs of all the components in a conventional supply chain are strongly influenced by tree size (Hartsough and Cooper, 1999; Spinelli *et al*., 2002). The nature of conventional single stem harvesting systems is a series of batch processes and productivity is determined by the number of batches in the supply chain, the size of each batch and the batch cycle times. Reducing the number of batches is a very high priority.

A common example of a chip wood supply chain with the least number of batches in the system is whole tree logging. This system utilises a feller/buncher to fall unprocessed trees into small heaps, a grapple skidder to haul to the roadside and then a knuckleboom loader to feed the whole trees into a mobile flail chipper, which removes the bark and small limbs before chipping the wood. Chipping is direct into road trailers. These supply chains load chip into trucks with at least three batch steps: (i) accumulating stems on the feller buncher and stacking, (ii) collecting one or more stacks with the skidder, hauling to the chipper and dropping, and (iii) feeding the flail chipper with the knuckleboom. An additional loader may also required to manage the heaps of extracted trees at the landing and to handle the residues that accumulate at the flail. These supply chains are proving to be the most competitive in contract bluegum plantation harvesting where tree form is poor. Forest residue supply chains also tend to be more efficient when they have fewer batches (Hall *et al*., 2001).

The size of each batch is determined by the size of the trees and the engineering limitations of the mobile machinery. The cycle time of each batch is determined by the speed of realistic machinery movements, such as ground speed during skidding or forwarding, or boom swing rates for a knuckleboom or other crane, and the stump-to-chipper/roadside haul distance. Compared to whole tree logging, other tree harvesting systems involve more batches to convert standing trees or logging residues into chips loaded into road transport. The addition of a forwarder alone adds three batches: (i) the use of a knuckleboom to load a few logs at a time, (ii) the movement of the full forwarder to the roadside and (iii) unloading with the knuckleboom, frequently onto a stockpile at the landing rather than directly onto a truck or into a chipper. The current levels of productivity for these all systems are probably almost at their optimum. In Australia, the cost of processing young eucalypts with a DBH of about 20 cm into woodchip loaded onto trucks is over A$20 per green tonne, regardless of the supply chain employed.

Continuous harvesting and processing supply chains offer the opportunity to reduce the number of batches and significantly increase the size of the remaining batches. The cut-and-chip harvester systems used in the Swedish willow coppice industry are the most developed example of such supply chains in woody crops. Sugar cane harvesting is an agricultural analogy, and a well-coordinated sugar harvesting operation can harvest and load bulk cane billets onto road transport for less than A$6 per green tonne.

The basic principles of a proposed new short rotation tree harvesting system are:

- Harvesting of single rows is preferred for several reasons:
  - (i) Inter-row spacings of less than two metres will increase establishment costs and competition within the stand. As discussed in Section 3.1, it is probable that intra-row spacings will be increased to optimise the balance between establishment cost and crop productivity. It is very unlikely that the trends towards larger trees in a water limiting environment will see the adoption of row spacings close enough to favour two row harvesting.
  - (ii) A two row harvester would be heavier and wider than a single row machine, which would compromise mobility and ease of truck transport.
  - (iii) The harvester will be expected to work in a variety of crops and crop layouts. Phase crops may well be more productive at wide inter-row spacings, or widely spaced pairs of rows.
- The harvester must be able to work in either direction and harvest from one side of a tree belt to the other. Many tree belts are planted alongside fences and contour drains. This rules out offset machinery and means the harvester will be self propelled, straddle the row it is cutting and be able to discharge either side or behind the machine.
- The woody crops are grown in a variety of layouts, rows are not always straight and lengths between headlands vary. The harvester and the associated machinery must be manoeuvrable.
- Soil conditions vary widely, both spatially and over time. Harvesting will be a year-round operation to maintain continuity of supply. The Mediterranean climatic zones can see unstable soils become commonplace during winter. This means that any machinery entering the paddock will need to have a low ground

pressure. With the low stumps that are left by the harvester, rubber tracks will be preferable to high flotation tyres.

- The stem cutting action must be directly coupled to the chipper process by mounting the chipper into the harvester to eliminate stem handling and maintain an even feed of material to the chipper to maximise chipper performance. The comminution converts the smallest unit, the tree, into a bulk material at the first step in the supply chain.
- The harvester must move continuously to eliminate the step-by-step nature of single stem harvesting. For a given size of tree, productivity then becomes a function of ground speed and chipper capacity, which is discussed further in section 4.2. An important objective of crop silviculture is to maximise the biomass grown per metre of row, because there is a practical limit to harvester ground speed (about 5 km per hour) if the stems are to be severed close to the ground. The mallee crop will yield about 60 green tonnes per hectare at harvest, which equates to about 15 tonnes per kilometre of a single row. Harvester productivity of 75 tonnes per productive machine hour is the design objective for the mallee supply chain project.
- The chip must be accumulated on the harvester or thrown directly from the chipper to a following bulk bin “haulout”, which performs the forwarding function. At least two haulout units are required to maintain continuous harvester operation. If the chipped biomass is accumulated in a bin towed or carried by the harvester, it should be tipped directly into a haulout bin in a single action. The use of the harvester as a haulout vehicle seriously reduces the production capacity of the most expensive machine in the supply chain.
- The haulout capacity must be as large as practical as this is the smallest batch process in the system. Sugar cane experience is that hauling out can cost significantly more per tonne than harvesting and it may also cause significant loss of harvester productivity. Sugar cane haulouts of up to 14 tonne capacity are in common use. There is the option of forming trailed bins into trains to improve haulout productivity, and increasing the capacity of the haulout bin to match that of a road trailer (about 25 tonnes) would be a challenging but significant advance. Taking road trailers to the harvester is an unlikely option in many situations due to unstable soil conditions, tall high-volume trailer bins and numerous small stumps in the harvested rows.
- The haulout must tip its entire load into the road trailers in a single action. The use of conveyors or augers would be too slow. The haulout bin must be either half the capacity or the same capacity as the road trailer. Sugar cane systems have moved towards high lift and side-tip haulouts wherever road trailer bin capacity and haulout capacity are well matched.
- There must be a surge buffer between the harvest and haulout process and the road transport system. Haulout distance can be managed within the constraint of the cost of all-weather internal farm roads, but the distance from farm to factory will inevitably be highly variable. Stockpiling chipped biomass on the farm will be unaffordable as the machinery to reclaim it from the ground would be expensive and under-utilised. Road trailers represent a container that is integral with the supply chain and does not involve increased handling steps. A possible arrangement for the interface between the harvesting and the road transport is to have several pairs of road trailers and one or two prime movers per harvester. Prime movers would drop empty trailers and pick up full ones quickly and the extra trailers would provide surge buffer capacity. Extra contractor prime movers

can be added to the supply chain if harvester productivity is high and transport distances are long.

- Road transport regulations vary between nations and also within Australia. The supply chain under development in Western Australia will be able to employ a paired trailer configuration with a capacity of about 140 cubic metres and 50 tonnes. Two trailers of equal capacity provide some flexibility because they are standardised containers that may be moved in pairs or individually. It may be possible to move single trailers closer to the harvester using agricultural tractors as prime movers.
- Moving trailers in pairs means that side tipping to empty will be important to avoid cost of breaking up the road trains with each delivery to tip out of the rear. Slip on containers that load over the rear of the trailers would also be unsuitable for paired trailer configurations.
- Receival points must be well designed to control the cost of unloading. The cost of queuing trucks at the receival point can be very high, especially if it causes delays in hauling out and harvesting.

5. SPECIFICATION, DESIGN AND DEVELOPMENT OF A MALLEE HARVESTER

A continuously travelling harvester for short rotation crops is essentially a self-propelled, self-feeding chipper.

5.1 The current harvester project

Many of the issues relevant to the design of such a harvester were discussed by Kerruish in 1977. He recognised that the most efficient way to harvest a stand consisting of small stems was to process several stems at the same time, with output being independent of individual piece size. He also noted that there was considerable scope for the development of chippers better suited to mobile applications. In addition, he proposed a conceptual harvester for harvesting short rotation eucalyptus that is very similar to the existing prototype mallee harvester. He considered this concept harvester to be capable of producing 30 tonnes of wood chips per hour in a stand consisting of trees of DBH 10cm and top height 12 to 18 metres. The output of this machine would be largely dependent on the area harvested per unit time, and independent of individual tree cross-sectional area and size. While this harvester was never built, other continuous harvesters operating in softwoods in other countries were capable only of rates up to 18 tonnes per hour (for a 30 tonne 385kW machine). None of these harvesters is still operational. (Hakkila, 1989).

The current harvester development project has been in operation for several years, but progress has often been delayed. In the absence of an operating commercial short rotation industry, the project has no secure financial support. The work on this initial prototype harvester is primarily concept development. It is essential to developing our understanding of the issues and difficulties involved, but a fully functional and reliable harvester will not be available for some time. Biomass processing rates achieved in field trials to date have been about 2 kg per second for periods of up to 5 minutes.

The harvesting process may be described as a series of steps: gathering, cutting, collection and crushing, transfer to the chipper and chipping.

- The current project has done relatively little work on gathering up the sprawling form of some mallees at this stage, as trial work has been conducted on the more erect forms. However gathering will be important as it is the first step in crushing up the trees into a manageable shape and it also ensures that there is complete control over the stem before it is severed.
- The cutting element is a 700 mm diameter disc with bolt-on replaceable teeth. It is a derivative of forestry harvester hot saws, but many teeth have been used to minimise the size of the chip removed by each tooth and so reduce the damage to the top of the stump. Cutting height is nominally 100 mm.
- Crushing the trees at or just behind the saw serves two purposes:
  - (i) It maximises control over the severed stems that at this point are being held below their centre of gravity and may also be subjected to high lateral forces from wind.
  - (ii) Crushing also reduces the lower crowns of trees of any structure to relatively consistent two-dimensional shapes. If handling and processing of the diverse forms of mallees is to be achieved at the rate of one stem every 1.5–2 seconds, each stem must be reduced to a comparatively uniform and predictable shape as quickly as possible.
- Conveying the stems back onto the machine is by means of three opposing conveyor chains. The stems are held upright to make their handling independent of the trees' heights and the geometry of the upper crowns.
- The butts of the trees are then transferred to the chipper feed rollers. Control during this transition is only directly applied to the lower stems to keep the size of the controlling elements as compact as possible. The chipper feed rollers complete the crushing process as the mallees are fed through a 500 mm by 150 mm throat to a drum chipper.

5.2 Harvesting and chipping principles

Economic modelling suggests that the continuous harvesting of mallees and the transport of chipped material to a processing plant will require a mass flow rate of 75 tonnes per hour for the operation to be viable. This mass flow rate is about twice that achieved by in-forest chipping operations on whole trees, but it is equivalent to that achieved in cane harvesters. Therefore, one might expect a mallee harvester could be of the same general size and configuration as that of a cane harvester. As a mobile machine, attention must be paid to its overall mass and the installed power because both of these factors will affect its mobility in difficult soil conditions and from site to site.

As noted above, the mass flow rate of 20 kg per second envisaged (72 tonnes per hour) is substantially higher than those achieved by continuous softwood harvesters or in-forest chipping operations. For instance the survey of Italian in-forest chipping operations reported by Spinelli and Hartsough (2001) found that (based on the installed power) the specific power required to chip 80 kg pieces was of the order of 45 kW per kg per second. At a mass flow rate of 20 kg per second, 900 kW of installed power would be required, and this is obviously beyond the capacity of a mobile machine of the specifications envisaged here. The correlation for processing rate found by these authors can be further manipulated to reveal that specific power is a function of piece size only, reducing as piece size increases. While this is difficult to understand from a fundamental point of view, it may be that this finding merely reflects the additional time per tonne required to gather and feed small pieces rather than large pieces This further confirms the necessary principle of harvester design, that efficient means of gathering, severing and feeding small pieces are required.

On the other hand, Hartsough and Spinelli (2000), in their survey of continuous softwood harvesting operations found specific powers of the order of 7 to 10 kW per green kilogram per second, which imply installed powers of the order of 200 kW at a flow rate of 20 kg per second. Their expression shows that specific power depends on chip size only, which is a physically realistic proposal. The best of the harvesters they surveyed achieved a mass flow rate of about 16 green kg per second.

For small piece sizes, the difference between the two estimates of specific power (a factor of six for the examples quoted above) is critical to whether it is possible or not to operate a biomass harvester at the mass flow rates required for the operation to be viable. It is therefore important as part of the development process to be able to measure chipper specific energies directly, and to take design steps that will minimise chipper specific energy. If specific energies are of the magnitude measured on existing softwood harvesters (Hartsough and Spinelli, 2000), then a mobile harvester is possible. If they are of the magnitude measured by Spinelli and Hartsough (2001) then a mobile harvester is not a proposition.

The two processes that will control the efficiency of a mallee harvester are the feeding and the chipping. Gathering, severing and feeding mallees are being investigated in the existing simple prototype harvester, and some progress is being made towards achieving a continuous feed of material to the conventional drum chipper installed in the harvester. However, it has become obvious that the chipper represents the ultimate limitation to mass flow rate for this harvester. Because of this some fundamental work is being undertaken to overcome the limitations of conventional chippers and develop a chipper that is suited to chipping biomass in a mobile machine.

The major justifications for undertaking this chipper development work are as follows:
- Conventional chippers are optimised to produce chips of the pulping quality, and the chipper mass and chipping efficiency are not limiting design parameters.
- A biomass chipper for use in a harvester should be optimised to minimise weight and maximise the chipping efficiency while being capable of high mass flow rates.
- Maximising the chipping efficiency requires the ability to set cutting blades at angles and in configurations that will reduce cutting forces and cutting energy.
- Minimising the weight requires a chipper configuration that allows necessary mass to be distributed so that the rotary inertia can be maximised.
- Blades distributed around the circumference of the chipper will minimise torque variations and therefore the rotary inertia required to maintain chipper speed.
- Achieving high mass flow rates requires a multibladed chipper operating at feed speeds greater than in conventional chippers.

The preferred configuration for such a chipper is a drum rather than a disk. While disk chippers are much more common than drum chippers, their aperture is limited in length to about half their radius, while with a drum chipper the aperture can be as long as the drum itself. Mallee trees have a variety of forms, and even though the feeding may be highly aggressive, the largest possible aperture is to be preferred. The drum chipper has a more compact overall configuration than the equivalent disk chipper, and so can be more easily accommodated within a mobile machine. It also processes flexible branched material more effectively than disc chippers, as discs tend to pass more whole twigs through the knife slots (Spinelli and Hartsough, 2001), who recommend that a drum chipper be used for producing fuel chips from small materials. The whole twigs increase material flow problems later in the supply chain. In its conventional configuration, the blade edges are constrained to being axial, and there are no opportunities for changing blade setting angles or distributing blades in a helical arrangement around the circumference.

To overcome these basic limitations, a drum chipper featuring a novel method of construction has been designed to meet the specifications outlined above, and is currently being manufactured in prototype form for laboratory testing, with the aim of establishing suitable blade angles and configurations, and measuring chipping forces and specific power. Experimental feed rates will be equivalent to those required for a full-scale chipper, which imply that an 80 kilogram tree eight metres high should be processed in four seconds. Chip quality will also be assessed because mallee harvesting is intended to provide feed material for a variety of end uses, which may have varying chip quality specifications. Further sorting and separation of the chipped material may be necessary to meet processing specifications as they are developed.

These additional laboratory tests are aimed at producing a chipper configuration that will be suitable for the existing mallee harvester and enable it to chip more efficiently. However, there are many more configurations and combinations of piece size and shape, blade setting angles and blade edge details that need to be explored, and this work will require additional funding.

6. ENGINEERING THE PRODUCTION OF BIOMASS

There is a wider context to the harvester development work and the preliminary chipper design and laboratory development work that have been described above. This context is that the ***production*** of biomass is the only process that will enable a large-scale integrated biomass industry to exist at all. The only substantial activity in the production area has been in establishing and defining the resource base and potential cropping systems, and in identifying suitable candidate plants, particularly those suited to short rotation cropping cycles.

One major aspect of biomass production that has been identified by financial modelling is that direct seeding (rather than seedling transplantation) of tree crops has a major favourable effect on the pay-back period and returns from these crops. While acacia species suited to phase cropping generally have large seeds that should be easy to seed directly, eucalypts (mallees) have small seeds that may be difficult to direct seed. Further silvicultural and engineering work on seeding and planting systems will be required to exploit this potentially significant advantage.

Another significant aspect of biomass production relates to the transition from phase crops to annual crops and pastures. Woody phase crops have a number of valuable characteristics (Bartle *et al*., 2002), but the removal of stumps is a problem that must be considered an integral part of the woody crop. A woody phase crop will be followed quickly by the seeding of an annual crop or pasture. It is most unlikely that farmers, many of whom remember the difficulty of clearing woody vegetation, will adopt phase crops until the problems of stump and shallow lateral root removal have been resolved. Following removal, the stumps and roots could be an economic resource if they can be collected and processed economically.

Biomass based engineering research to date has been concentrated on the conversion processes, for dealing with the biomass once it has been delivered to the factory gate. Apart from the harvester development work and the chipper project described above, there has been very little, if any, research activity in Australia into the wider engineering aspects of biomass production necessary to produce and deliver this material at minimum cost.

These wider aspects of biomass production could include:
- Field systems and integration with annual cropping operations
- The logistics involved in the establishment of large areas of short rotation woody crops
- Transplantation and direct seeding
- Phase crop stump removal and stump utilisation or disposal
- Continuous harvesting
- Chipping for biomass
- Transport and transport logistics
- Harvest scheduling
- Human aspects of field operations
- Systems modelling
- Field data acquisition and precision cropping

Harvesting and transport in particular deserve proper consideration, because they represent the major cost incurred in supplying biomass to a processing plant. As detailed above, scenarios for the production of biomass from plantation mallees assume that harvesting and transport to the factory should be possible for $15 per tonne. This is an ambitious target, given that the cane industry can achieve the same task for about $12 per tonne, using dedicated railways and specialized harvesting and infield transport equipment that has benefited from thirty or forty years of continuous development.

By way of illustration, and to add some perspective to the challenges that will exist in biomass production, it is known that the Australian sugar industry has taken up the challenge of utilizing, by way of co-generation, the biomass represented by the leaf and tops being burnt before harvest in southern cane growing areas. This biomass resource is perhaps the largest currently available in Australia, the sugar mills provide ready-made sites for power generation, and it is an obvious candidate as a basis for sustainable energy production. There are no other products from gathering these residues except energy.

That the cane industry has been able to bring co-generation projects to a pre-commercial stage is in large part due to the existence of substantial, highly skilled and dedicated engineering resources within the industry, which have been turned from sugar production to biomass production. Major problems of transportation and separation of cane from trash have had to be solved, and these have involved engineering innovation and field production issues. Harvesters have had to be modified to integrate with larger infield bins, and even the transport system is being changed to improve the efficiency of transport of whole cane to a central cleaning plant, rather than the transport of cane billets cleaned and separated in the field.

Such engineering resources do not exist in the infant Australian woody biomass industry, which has even greater capacity and potential for the production of renewable energy. In addition, such industries would produce a range of other valuable products and have major environmental benefits. There is an urgent need in Australia for biomass-focused engineering research and development, and particularly for additional research and development focused on biomass production.

Without this development the nation will not be able to realise the promise of new short cycle crops and create sustainable agricultural systems.

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