Optimised Harvesting Cost for Mallee Supply Chain in Western Australia

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Abstract

Mallee plantations have been integrated into wheat farms in Western Australia as a large-scale and multi-purpose woody crop since the 1990s. Mallee describes the growing habit of certain eucalypt species that grow with multiple stems shooting from an underground crown root (lignotuber), usually to a height of up to 10 meters. These types of plantations could be a considerable source of biomass to produce renewable energy. In this project the supply chain of Mallee was modelled using BIOPLAN's linear programming model to investigate the impact of tree size, extraction distance and transport distance on supply chain costs. The harvesting system included a feller-buncher, front end loader, in-field chipper and truck. The mobile Bruks chipper was found to be more efficient than Peterson Pacific to chip Mallee trees. The results indicated that harvesting larger tree sizes can slightly diminish chipping cost. Extraction cost was very sensitive to the extraction distance in this case study. Long transport distances in larger management area (to meet higher energy demands) will highly increase the transport cost. From optimised supply chain cost and sensitivity analysis, the best practice for efficient Mallee biomass supply chain was suggested as following: harvesting Mallee trees when reaching larger size (about 0.3 m^3 for a tree consisting of multiple stems with an average DBH *of 5 cm to 10 cm per each stem), planning average extraction distance to be shorter than 1000–1500 m, establishing the Mallee plantations closer to energy plant with transport distance shorter than 100 km (with a radius of 50–75 km providing an effective compromise between cost and distance) or alternatively installing new bioenergy plants no farther than 100 km from existing Mallee plantations.*

Keywords: harvesting, chipping, productivity, operating cost, supply chain, optimisation

1. Introduction

Mallee plantations have formed the basis of a processing industry in Australia for more than 100 years because of their natural abundance of eucalyptus oil. They can also be integrated into wheat belts to reduce soil salinity, give shade and shelter for animals, reduce erosion by acting as windbreaks and store carbon. Once established, the biomass can be harvested every few years. As the tree resprouts, or coppices, from the underground crown root (lignotuber), there is no need to replant (http://biomassproducer.com.au). Mallee describes the growing habit of certain eucalypt species that grow with multiple stems shooting from an underground crown root (lignotuber), usually to a height of up to 10 meters. Mallee eucalypts grow in the semi-arid areas of southern Australia in: New South Wales, north-western Victoria, southern South Australia and southern Western Australia. Biomass yield of 10–20 green metric tonnes (GMt) per hectare per year can be achieved when Mallees are grown in widely spaced two-row belts in alley systems in regions with adequate rainfall and suitable soil types (http://biomassproducer.com.au). Since the early 1990s almost 13,000 ha of Mallees have been established in Western Australia (*WA*). Eight different species and subspecies have been utilised, seven of which occur naturally in Western Australia (URS Australia, 2008). These large-scale plantations integrated into wheat farms (Wu et al. 2008) have been established as multi-purpose woody crop (Nuberg 1998, Spinelli et al. 2013). These integrated plantations can be a considerable source of woody biomass to produce renewable energy. However, unlike the forestry biomass supply chain

(Ghaffariyan et al. 2013a), the Mallee plantations established in specific rows within agricultural farms require appropriate combination of harvesting equipment and working method in order to make a profitable operation, while reducing the operating cost of biomass collection and minimum damages to the environment including agricultural land and plantations area. Some of the factors that influence operating costs of the biomass supply chain include moisture content (*MC*) (Acuna et al. 2012, Gautam et al. 2013, Visser et al. 2014), harvesting equipment efficiency and transportation distance (Kühmaier et al. 2007), capacity of the plant, efficiency of the combustion (Röser et al. 2011). In this case study the research objectives included:

⇒ comparing the operating costs of different chippers to select the least expensive chipper for chipping Mallee trees;

⇒ optimising the biomass supply chain for Mallee plantations using linear programming tool (called BIOPLAN) to minimise supply chain operating cost;

⇒ verifying the impact of wood extraction distance on the supply chain operating cost;

⇒ analysing the impact of Mallee tree size on operating cost;

⇒ identifying the relationship between transport distance, total harvesting volume per area and supply chain cost;

⇒ identifying maximum allowable transport distance for establishing the farms or building new energy plant.

2. Materials and methods

2.1 Study area

Since natural drying rates of Mallee trees were not available in Western Australia, the results from a similar natural drying case study of harvesting residues of a *Eucalyptus globulus* plantation was applied in this modelling exercise (Ghaffariyan et al. 2013a). The site was located near the town of Rocky Gully in Western Australia (Ghaffariyan et al. 2013a). The site was about 30 km away from the weather station, but due to relatively consistent weather patterns in the area and to respect budget limitations, a dedicated weather station at the study site was not used. Study samples (12 samples per each sampling time, total of 120 samples per study period) were taken from a 103 m long, 4.8 m wide and 2.9 m tall pile of residues. The samples were collected from three cross sections (with the same spacing between each) at the top from the inner parts of the pile wherever possible, centre and bottom of the pile, and their moisture content (*MC*) was measured on a monthly basis from August 2011 to August 2012. Each wood sample (disk of 1–2 kg) was obtained with the help of a chainsaw and contained normal biomass components (bazrk, leaves, small branches). The wood samples were stored in plastic bags and then oven dried at 105°C for a few days for *MC* measurements, which in turn were used to develop natural drying curves over time. In addition, total rainfall per month (mm) and average min. and max. temperatures were collected (Ghaffariyan 2013) from the closest weather station located in Rocky Gully (station 009964, Australian Government, Bureau of Meteorology). Based on the long term climate data (rainfall and max. and min. temperature), and taking the *MC* curve generated from the drying study as the basis, a number of other natural drying curves with different starting date of storage were estimated based on the approach described by Acuna et al. 2012.

The case study area for modelling Mallee biomass supply chain was located near Katanning and Collie in Western Australia. It was assumed that from 14,000 ha of farm lands about 130,000 GMt of Mallee will be produced (as basic scenario) based on internal growth and yield modelling done by the department of the Western Australian Government responsible for the development of the Malley management system with wheat growers for the past 20 years. The harvesting system was assumed to be a combination of feller-buncher to fell the trees, a front-end loader to extract the bunches from the machine operating trails to the road side or chipping place (Spinelli et al. 2013) and a mobile chipper to chip the trees directly into trucks.

2.2 Method

The first step of the modelling exercise was to determine the most efficient mobile chipper with the lowest operating cost for the same tree size, operation type and chip discharge place. A Peterson Pacific chipper (Spinelli et al. 2013) was compared with a Bruks 805.2

Table 1 Machine specifications of Bruks mobile chipper

Model	Bruks 805.2 STC mobile chipper
Base	Forwarder-mounted (Ecolog forwarder, 300 HP, 223.8 kW)
Engine, to power the chipper	Scania diesel engine, 450 HP, 335.7 kW
Maximum diameter of logs to chip	50 cm
Forwarder load capacity, chipper, bin and chips	19,500 kg

STC mobile chipper (Ghaffariyan et al. 2012) mounted on a truck (Table 1) using a chipping productivity-cost model developed using Australian and Italian chipping operations (Ghaffariyan et al. 2013c).

The second step of the modelling involved a sensitivity analysis using BIOPLAN, a tool specifically designed and implemented to optimise biomass supply chains (Acuna et al. 2012). Based on a linear programming model, the BIOPLAN tool was adopted in this project to investigate the impact of extraction distance, tree size, total harvesting weight and transportation distance on supply chain costs. Using natural drying curves as an explicit parameter, the objective of the model was to minimize total supply costs including harvesting, storage, chipping and transport for the Mallee supply chain.

2.2.1 Description of the optimisation model

The BIOPLAN tool was used to determine the optimal supply of Mallee chips that satisfies the demand at the power plant. In the supply chain optimisation model, decisions on the volumes of Mallee to be harvested are made on a monthly basis and storage at the roadside of this material is allowed for a period of up to 24 months. This is a nominal time period and can be modified in BIOPLAN. Thus the optimal drying period will be determined after running the linear programming model, which will not exceed the maximum nominal drying period established in the tool (in this case 24 months). It is assumed that the chips produced from Mallee are consumed during the same month they arrive at the energy plant and, therefore, there are no costs associated with the storage of chips at the energy plant. In addition, the energy content of the chips being supplied from the Mallee plantations must meet the power plant monthly demand (tonnes) in year 2 (production year). It is assumed that a plant demand is a monthly volume of chips during the production year (year 2 for our modelling purposes), but the raw material (Mallee trees) may be harvested and stacked at the roadside for drying as from January Year 1. Thus, the optimal solution specifies when and how much to harvest (e.g. 100 m^3 in March Year 1) and for how long to stack the logs before chipping and transport to the power plant (e.g. until January Year 2).

The model provides the results in a series of matrices including among others:

- ⇒ tonnes and corresponding solid volume of Mallee to be harvested in each month (a decision variable);
- ⇒ loose volume (*lv*) of chips produced at the roadside in each period;
- ⇒ number of truck loads delivered to the energy plant;
- ⇒ energy content of chips (*GJ*) arriving at the power plant. Summary tables also provide mean energy content (*GJ*) per m^3 and tonne;
- ⇒ harvesting, extraction, chipping, storage and transportation costs.

In addition, BIOPLAN estimates the total cost for the whole supply chain and total cost by activity (harvesting, storage, chipping and transportation) as well as total energy of the fuel supplied to the plant in *GJ*.

2.2.2 Parameters of the model

The model parameters are listed in Table 2. Net calorific value was obtained from Perez et al. 2006 for *E. Globules,* as accurate figures for Mallee trees were not available. The basic wood density was assumed to be about 535 kg/solid m^3 based on given information by Western Australia Plantation Resources (*WAPRES*). Woody biomass loss due to storage and manipulation was assumed to be 2% (Acuna et al. 2012, Laitila 2006). Volume and payload of trucks were gathered in field studies carried out by the authors in Western Australia (Ghaffariyan et al. 2013a).

To calculate the cost associated with letting biomass dry, we added this amount to the cost of harvesting, extraction and piling the biomass following the same approach presented by Roise et al. 2013. The following variable definitions are used: »*CP*« is the cost to pile a GMt, »*CH*« is the cost to harvest and skid a GMt, »*r*« is the monthly interest rate (assumed to be 0.50% per month) and »*T*« is the length of drying in months. Then the drying cost at time of delivery is the future value of all the cost before drying the wood

Table 2 Parameters and conversion factors used in the analysis

Parameters/conversion factors	Value
Energy content of *E. globulus* at 0% *MC*, MJ/kg	17.38
Basic density, kg/solid m^3	535
Bulk density, kg/loose m^3	224.7
Solid content, chips from residues	0.42
Ratio loose m^3 to solid m^3	2.38
Truck payload, tonnes	40
Truck volume, loose m^3	70
Transport distance, km	50
Material loss rate, %/month	2.0
Interest rate, %/month	0.58

(Eq. 1). Future versions of the tool will include the interest on the stumpage price paid to the farmers as well as the interest on the growing costs during the drying period (time between harvest and chipping of the logs).

Cost of the dried material

$$\$/GMt = \left(CH + CP\right) \times (1+i)^{n} \tag{1}$$

2.2.3 Mathematical optimising model

The supply chain optimisation model was developed using linear programming and was implemented using the What'sBest® solver package for MS-Excel. Once the tables and solver engine were setup, a Visual Basic program was written to execute the model. The data sets, parameters and variables used in the mathematical formulation of the model are presented in Table 3.

Objective function (*FO*)

The objective function (Eq. 2) minimizes the total supply chain costs ($) associated with biomass harvesting, storage, chipping and transport.

$$FO = \sum_{t,p} SOLIDVOL_{t,p} \times \left(HARVESTC + STORAGEC_{t,p} + CHIPPINGC\right) + \sum_{t,p} LOOSEVOL_{t,p} \times TRANSPORTC \tag{2}$$

Constraints

Eq. 2 ensures that the energy content of the chips supplied satisfy the monthly demand at the plant.

$$\sum_{t \le p} LOOSEVOL_{t,p} \times ENERGY_{t,p} \ge DEMAND_{p} \; \forall p \in P \tag{3}$$

Eq. 3 ensures that an even volume of Mallee trees are harvested evenly in each year. This allows for continuous work for the harvesting and haulage contractors.

$$\sum_{p} SOLIDVOL_{t,p} = \sum_{p} SOLIDVOL_{t+1,p} \; \forall t \in \left\{1 \ldots 11, 13 \ldots 23\right\} \tag{4}$$

Table 3 Sets, parameters and variables used in the mathematical formulation of the model

Term	Definition
Set	
t,p = periods	$t \in T = \{1 \ldots 24\},\; p \in P = \{13 \ldots 24\}$
Parameters	
α	Conversion factor from m^3 solid to m^3 loose
$DEMAND_{p}$	Energy demand in period *p* at the energy plant
$ENERGYC_{t,p}$	Energy content of chips produced in period *p* from material harvested in period *t*, respectively. Depends on the moisture content of the material that is chipped
HARVESTC	Harvesting and extraction cost, $/$m^3$ solid
$STORAGEC_{t,p}$	Storage cost ($/$m^3$ solid) of whole trees stored at the roadside from period *t* to *p* ($t \le p$)
CHIPPINGC	Chipping cost ($/$m^3$ solid) for whole trees chipped at the roadside
TRANPORTC	Transportation cost ($/$m^3$) for tree chips (loose volume) transported to the energy plant
Variables	
$SOLIDVOL_{t,p}$	Solid volume of trees harvested in period *t*, and stored at the roadside until period *p* for chipping at the roadside
$LOOSEVOL_{t,p}$	$SOLIDVOL_{t,p} \times \alpha$ = Loose volume of chips from trees harvested in period *t*, and stored at the roadside until period *p* for chipping

2.2.4 Sensitivity analysis

The sensitivity analysis was carried out to determine and quantify the impact of the mentioned operational factors on the supply chain cost. To run the analysis, one parameter was changed within its operational limits while holding the other parameters constant. Then the costs for different values of each parameter were graphed using a bar chart. For the sensitivity analysis, the average extraction distance was varied from 250 m (maximum distance of 500 m) to 2500 m (maximum distance of 5000 m) to study the impacts upon the costs for short and long distances. Tree size ranged from 0.1 m^3 to 0.3 m^3 in the analysis to verify its impact upon supply chain cost. The transport distance was varied from 25 km to 150 km for three levels of harvesting weight including 130,000 GMt per year, 200,000 GMt per year and 300,000 GMt per year to see how the operating cost changed for the range of parameters. Minimum and maximum acceptable ranges of moisture content of the delivered chips were assumed to be 10% and 40%, respectively, in this study.

3. Results

3.1 Chipping

Chipping productivity and cost depend on tree size, chipper power, chip discharge place and type of operations (Ghaffariyan et al. 2013c). The chipping cost predicting model was run for both chippers considering the following factors; Bruks mobile chipper (based on truck) purchase price: $ 550,000, Peterson Pacific purchase price (truck mounted): $ 1,050,000, fuel consumption of Bruks chipper: 54.6 l/h, fuel consumption of Peterson Pacific: 100 l/h, Tree size: 0.1 m^3, chip discharge: directly into trucks and type of operation: biomass operation. Based on the results obtained, the chipping cost for the Bruks chipper and Peterson Pacific chippers were 10.73 $/GMt and 11.00 $/GMt, respectively.

3.2 Optimised supply chain for basic scenario

For a tree size of 0.2 m^3, average extraction distance of 1500 m, transport distance of 50 km, annual interest rate of 6% and harvesting volume of 130,000 GMt per year (plantation area of about 14,000 ha), the optimised supply chain cost was found at total minimised costs of $11,750,561 to meet the energy demand of 53,000 MWh per month. Operating cost of the supply chain was 45.1 $/GMt (18.5 $/MWh). Table 4 presents the minimised operating costs of the supply chain.

Table 4 Minimised operating cost ($/GMt) of the supply chain

Harvesting	Storage	Chipping	Transport	Total
19.3	0.3	14.7	10.8	45.1

3.3 Sensivity analysis

3.3.1 Impact of extraction distance on supply chain costs

The average extraction distance was varied from 250 m to 2500 m (Spinelli et al. 2013), while the other parameters were held constant as described in the basic senario (Fig. 1). Longer extraction distances increase the extraction cost on a linear fashion (Spinelli et al. 2013). Longer extraction distances also result in longer travelling time for mobile chipper to move along the larger road side piles, which may impact the chipping costs slightly (Ghaffariyan et al. 2012). Harvesting cost in Fig. 1 is the sum of felling and extraction costs.

3.3.2 Impact of tree size on supply chain costs

Decreasing chipping cost reduced total operating cost per GMt by only a small but significant amount (Fig. 2). Increasing tree size from 0.1 m^3 to 0.3 m^3 (while holding other factors constant) decreased proper chipping cost from 15.8 $/GMt (tree size of 0.1 m^3) to 13.8 $/GMt (tree size of 0.3 m^3) as larger tree size would increase the chipper productivity (Ghaffariyan et al. 2013c). Based on the availabe extraction productivity model in the study area on Mallee tree harvest-

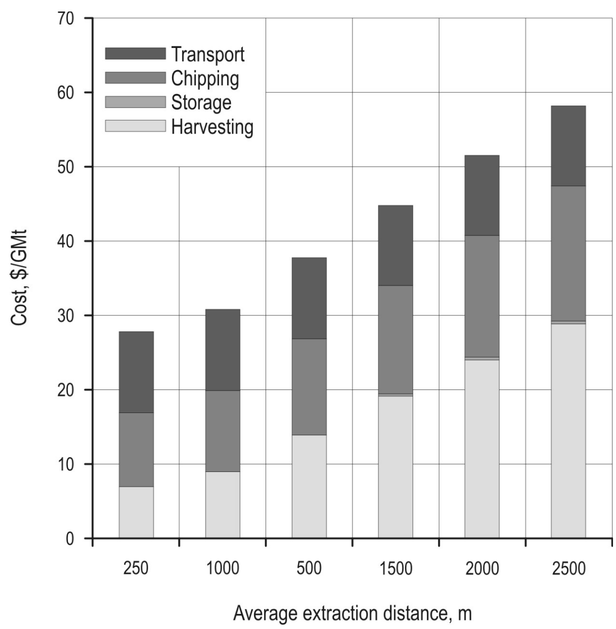

Fig. 1 Impact of different extraction distances on supply chain costs

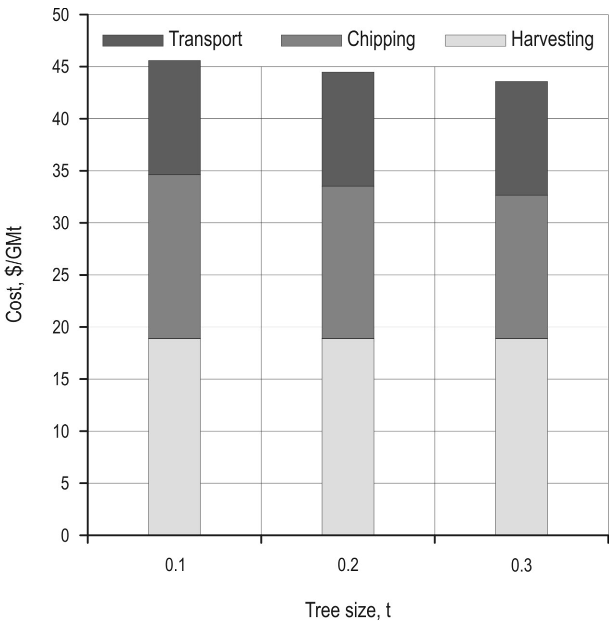

Fig. 2 Impact of different tree sizes on supply chain costs

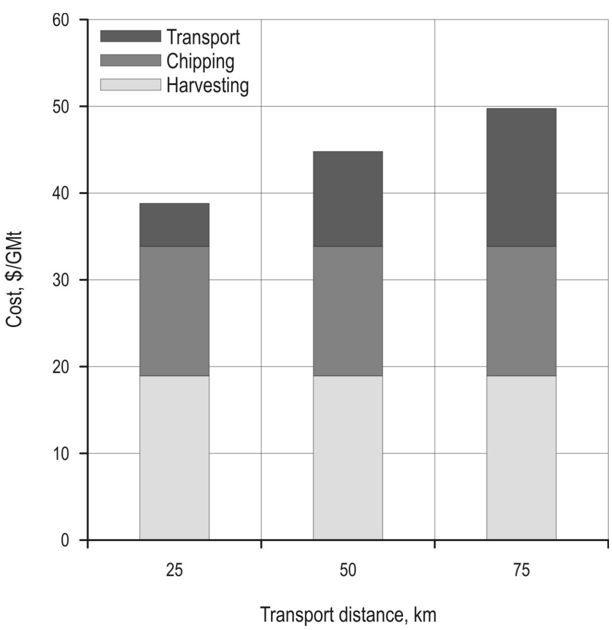

Fig. 3 Impact of transport distance on supply chain costs

ing (Spinelli et al. 2013), the extraction costs would not change highly by varying tree size from 0.1 m^3 to 0.3 m^3 as Spinelli et al. (2014) emphasized on the impact of extraction distance and load weight. Tree size was not a significant variable in their extraction productivity prediciting model. However, tree size impacts the chipping cost as shown in Fig. 2 and larger tree size results in lower cost.

3.3.3 Impact of transport distance on supply chain costs

As expected, changing transport distance from 25 km to 75 km, considering constant level of the other factors (harvesting volume of 130,000 GMt per year), resulted in a higher operating cost. A longer transport distance increases travelling time per turn and will then increase transportation costs. In this case study, transportation cost increased from 5.4 $/GMt with transport distance of 25 km to 16.2 $/km for transport distance of 75 km (10 km increase in distance results in additional cost of 2.2 $/GMt for transportaton). Total operating cost increased due to higher transportation cost for longer distances (Fig. 3).

3.3.4 Impact of harvesting volume/transport distance on supply chain costs

Total supply chain cost ($/GMt) was calculated for three levels of harvesting volume and supply points located at a close, medium and far distance from energy plant (depending on the size of managemnt area) as described in Table 5.

Table 5 Harvesting volumes and transport distances for different scenarios

Senario	Harvesting volume GMt/ha	Energy demand GWh/month	Plantation area, ha	Transport distance, km
A	130,000	53	14,000	<50
B	200,000	82	25,000	<100
C	300,000	122	32,000	<150

Transportation cost was increased for longer distances (while the other costs per GMt including harvesting, chipping and storage did not change) resulting in higher supply chain cost. Increasing harvesting volume per area and transport distance increased the total supply chain cost by a linear relationship (Fig. 4).

4. Discussion

With a significant resource of Mallee planted as row crops in Western Australia, understanding the cost drivers for the supply chain is critical for mobilising and expanding the resource for commercial purposes. Emphasis in the development of potential supply chains for energy has been on harvesting systems that are productive in the very small tree sizes. The results of this optimised modelling show that tree size has a significant impact on the costs of the supply chains. This was due to the impact of tree size on chipping

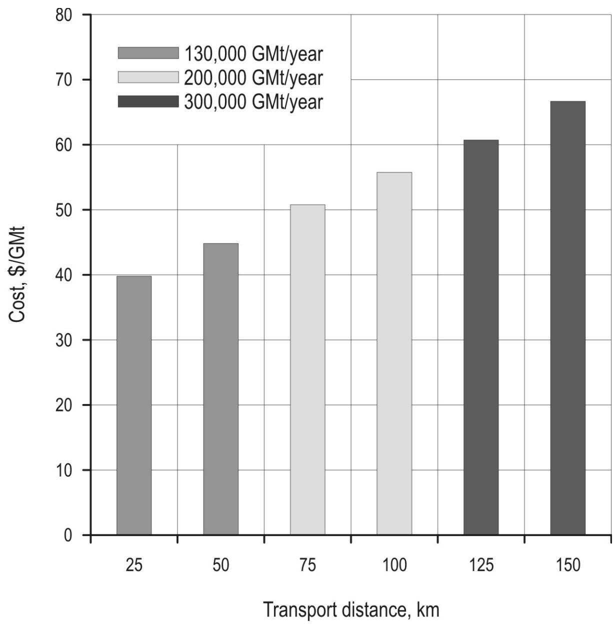

Fig. 4 Impact of harvesting volume per area per year on supply chain cost for different transport distances

productivity (Fig. 2), where larger tree size resulted in higher productivity of the chipper. This impact reduced the chipping costs. Other chipping studies by Watson et al. (1986), Spinelli and Hartsough (2006) and Ghaffariyan et al. (2013b) found similar relationship between tree size and chipping productivity.

Using the available forest harvesting system of a feller buncher, extraction and transportation of the chipped material will have a high impact on the costs. The row planting configuration used for Mallee plantings in *WA*, if not carefully planned and managed, will directly increase the delivered costs. Going from a 500 m to a 2000 m maximum extraction distance increases the delivered cost by 75%, while reducing the tree size three-fold from 0.3 m^3 per tree to 0.1 m^3 only increases the delivered costs by less than 5%. Spinelli and Hartsough (2001) compared front-end loader with a grapple skidder for extracting short rotation Eucalypt plantation in California. The loader was 40–60% more productive than the grapple skidder, depending on extraction distance. According to their study, front-end loaders might be proper extraction machines for short rotation plantations, where tree characteristics, terrain and soil conditions allow their use. In their study, increasing distances (ranging from 37 m to 366 m) decreased the extraction productivity of the loader (and skidder), which is similar to our study results although we assumed longer extraction distances to be planned due to the size and shape of Mallee plantations in Western Australia. In our case study on Mallee plantations, the front-end loader seemed to be an effective machine.

Long-term planning as to where to establish future Mallee plantations and establish industrial users for the Mallee need to take into account the impact of transport costs. As shown in the modelling, if a 200,000 GMt demand has to extend its reach from an average distance of 75 km to 100 km, the total cost of supply is increased over 12%, which can easily be the difference between a commercial facility being viable or not. Other study on utilising the harvesting residues of eucalypt plantations in Western Australia (Ghaffariyan et al. 2013a) considered a variation of 20 km to 120 km for transportation distance, where the transportation cost increased significantly for longer distances due to longer time required for travelling between plantations and mill (Kühmaier et al. 2007; Sikanen et al. 2005). In addition to transport distances, other studies in Europe (Sosa et al. 2015a, Sosa et al. 2015b) have also concluded that truck configuration can also have a substantial impact on transport costs. These studies have also shown that the volume of chips to satisfy the demand of power plants could be very sensitive to changes in *MC*, which may have a significant impact on the spatial distribution of the supply points and the corresponding delivery volumes; so future studies in *WA* should further investigate the effect of these parameters.

In addition, special consideration will have to be given to the scale of the energy plants that are planned to be built in *WA*. Optimally, matching supply and demand volumes in complex logistics scenarios will demand more sophisticated planning tools and require more efforts in operations planning. Yield of Mallee and other biomass materials per unit area, as well as the spatial location of these feedstocks will also determine the optimum size of the power plants (Cameron et al. 2007).

Finally, future studies should investigate the impact of storage time on the quality and losses of the biomass products. Despite the positive impacts on supply costs, extending the storage period in order to further reduce moisture content may cause a loss of drying matter content due to fibre deterioration. To avoid dry matter content losses, it has been suggested that biomass products should remain at the stand to dry for a few days/weeks before been transported to roadside for further drying or chipping (Routa et al. 2015). This practice could also help reduce extraction costs. In addition to drying matter content losses, reduction in moisture content could negatively affect chip quality and chipping costs. Good quality wood chip fuel is produced by machines with sharp knives, with the ability to vary the size of chips produced to meet end-user specifications (Kofman 2006). Chipping stems with reduced moisture content will increase the maintenance costs and blunt knives more often, which in turn will increase the amount of fines and the amount of overlong particles, producing chips with a less defined shape.

5. Conclusions

Modelling has demonstrated that a properly sized chipper for the resource can have an impact on the chipping cost, thus providing a 0.25 ($/GMt) lower chipping cost. Extraction distance has the largest impact on overall supply costs within the expected ranges of operating situations, with the tested range of extraction distance effectively doubling the delivered chip cost. That is due to the fact that, as extraction distance increases, the front-end loader becomes increasingly inefficient. In reality, operators are likely to change technique and deploy a proper forwarder, thus dampening the effect of the increasing extraction distance. Tree size, like most forest harvesting operations, has a significant impact on the harvest costs but its impact on the delivered chip costs is limited to less than 5%, meaning that it is likely to be a suitable system even for small trees. Transport distance plays an important role in delivered chip costs with distances over 100 km tending to exceed economically viable supply costs being sought by industry.

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