Selecting the efficient harvesting method using multiple-criteria analysis: A case study in south-west Western Australia

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ABSTRACT: Different factors can impact on the timber harvesting methods including stand characteristics, ground conditions, extraction distance, climate, silvicultural treatments and social interests. The multiple-criteria analysis is an effective methodology for helping foresters decide what system to apply depending on their operations specifications. Four harvesting methods were compared in Western Australian Eucalypt plantations including cut-to-length (CTL), in-field chipping using a delimbing and debarking flail integrated with the chipper (IFC-DDC), in-field chipping using a chipper with a separate flail machine for delimbing and debarking (IFC-F/C) and whole tree to roadside (WTR). The decision criterions consisted of total operating cost (from stand to mill gate), yield per ha, harvesting residues, fuel consumption and bark content of the chips. The Promethee method was used to evaluate the alternatives using Decision Lab software. Based on the results, the IFC-DCC was the best harvest method while WTR method was the worst harvesting alternative in the case study area. IFC-DCC method resulted in the lowest operating cost and the highest recovered yield per ha compared to the other harvesting methods.

Keywords: harvesting method; cut-to-length; in-field chipping; operating costs; yield; multiple-criteria analysis

Different factors can impact on the timber harvesting methods including stand characteristics (Stampfer et al. 2003), ground conditions (topography and soil conditions) (Stampfer, Steinmueller 2004) and extraction distance (Kellogg, Bettinger 1994), climate (Conway 1982), silvicultural treatments (Hartley 2003) and social interests (Vacik, Lexer 2001; Sheppard, Meitner 2005). Selecting the most efficient harvesting system is a difficult decision making process to include different environmental, economic and social factors. Thus multiple-criteria analysis (MCA) seems to be an effective methodology for helping foresters decide what system to apply depending on their operations specifications (Kangas 1992; Lexer et al. 2005). The Analytic Hierarchy Process (AHP) developed by Saaty (1997) has been used to solve many forestry problems (Murry, von Gadow 1991; Kangas 1992; Rauscher et al. 2000; Reynolds 2001; Vacik, Lexer 2001). The multiple-criteria analysis was previously applied to timber harvesting operations (Stampfer, Lexer 2003; Ghaffariyan 2008; Kuehmaier et al. 2010) and forest road network planning (Shiba 1995). In Australia, different individual case studies have been carried out to evaluate the productivity and costs of various harvesting systems (Acuna, Kellogg 2009; Acuna et al. 2011; Ghaffariyan et al. 2011, 2012a; Walsh et al. 2011; Brown et al. 2013; Ghaffariyan 2013). However, there has been no study to consider different economic and environmental criteria as a unit research project for helping industry managers with their decision making process under different impacting criterions. Thus this study was carried out to achieve the following objectives:

– assessing the preference of the industry users on the importance of different economic and environmental criterions,
– evaluating the operating cost, yield, remaining slash, fuel consumption and bark content of four harvesting methods including cut-to-length (CTL), in-field chipping using a delimbing and debarking flail integrated with the chipper (IFC-DDC), in-field chipping using a chipper with a separate flail

machine for delimbing and debarking (IFC-F/C) and whole tree to roadside (WTR),
– ranking the harvesting methods.

MATERIAL AND METHODS

Study area

The study area was located in a *Eucalyptus globulus* plantation in south-west Western Australia, 58 km from the delivery point for all the products – the Albany Plantation Export Company (APEC chip mill). The study site covered 5.95 ha of flat terrain. Average diameter at breast height over bark (DBHOB) and tree volume were 17.8 cm and 0.207 m^3, respectively. Stocking was about 729 stems·ha^{-1}. The layout of the study site included 8 plots where each plot consisted of 3 rows of trees (width 12 m and length 500 m). The average extraction distance was 305 m for the forwarding and 297 m for the skidding operation. The area of the plots was measured using GPS. Each harvesting system was replicated in two plots and all plots were uniform with similar slope (flat terrain over the study area), tree size, stand density and shape.

Harvesting methods

Four different harvesting methods were used to harvest the site; cut-to-length (CTL), in-field chipping using a delimbing and debarking flail integrated with the chipper (IFC-DDC), in-field chipping using a chipper with a separate flail machine for delimbing and debarking (IFC-F/C) and whole tree to roadside (WTR). Table 1 describes the machine types used in each harvesting method.

Method

A detailed time and motion study was used to evaluate machine productivity (Magagnotti, Spinelli 2012). Productivity was calculated from the delivered green metric tonnes (GMt) (derived from truck weights) and productive machine hours, excluding all delays (PMH_0). The ALPACA (Australian logging productivity and cost appraisal) model (Acuna 2012) was used to estimate the cost of operations. A chipping cost of 6.00 AUD·GMt^{-1} was assumed for chipping operations at the mill to convert logs into chips as final product as the basis of comparison in this study. Fuel consumption for each machine was recorded during the operation. The machines were fuelled while parked in a flat area before and after the operation. The working hours were recorded for each machine. The hourly fuel consumption was computed by dividing fuel consumption by working hours. For trucks, an average fuel consumption of 43.52 l·h^{-1} was used based on fuel consumption data base for logging trucks developed by FPinovations in Canada (www.fptransport.org/tfc/Default.aspx). For chipping at the mill the av-

Table 1. Harvesting methods and machines

Harvesting method	Type	Number of plots
CTL	Caterpillar harvester/processor Valmet forwarder (for extraction and loading trucks) Truck	2
IFC-F/C	Tigercat feller-buncher Tigercat skidder 630D Husky Precision flail Husky Precision chipper Truck	2
IFC-DDC	Caterpillar feller-buncher Caterpillar skidder Peterson Pacific delimber, debarker chipper (DDC) Truck	2
WTR	Timberking feller-buncher Caterpillar skidder Two Caterpillar processors Caterpillar loader Truck	2

erage fuel consumption of 0.7 from the available information was used as an assumption. The four different harvest areas were sampled to measure the weight of retained biomass (including leaves, branches, bark and stem wood) on each site after harvesting using one-square sample plot. 20 one-square meter plots per each harvesting method were laid out along transects within a systematic-random grid. All residues within these plots were weighed (Ghaffariyan et al. 2012b). To measure the yield per ha, the delivered product weight per each harvesting method was recorded. The moisture content of the products was measured using sampling at the APEC to convert the green tonnes to bone dry tonnes. 8 chip samples were collected and analysed from each harvesting method. Eight samples were taken, one from each trailer of delivered chips or logs to measure the percentage of bark content (Mitchell, Wiedemann 2012).

Multiple-criteria analysis using Promethee method

The alternatives included four harvesting methods; CTL, IFC-F/C, IFC-DCC and WTR. The criterions consisted of total operating cost (from stand to mill gate), yield per ha, harvesting residues, fuel consumption and bark content of the chips (Fig. 1). An online survey was carried out with 30 participants from the forest industry sector in Australia (who were mainly harvesting managers and officers in their companies) to evaluate the importance of each criterion. Two questions were asked; the first was to ask the participants about the preferences whether they prefer to maximise or minimise the criterion and the second question was asked to indicate the preferred weight of the criterion for the industry participants.

A usual preference method was applied to run the Promethee method to evaluate the alternative using Decision Lab software. The Promethee-GAIA methodology is known as one of the most efficient and also as one of the easiest decision aid methods in the field. Particularly user-friendly software, called Decision Lab. The Decision Lab 2000 software is an up-to-date implementation of the Promethee-GAIA methods. It includes many practical developments, such as the treatment of missing values, the definition of categories of actions or criteria, as well as powerful group decision extensions through the definition of multiple scenarios. Decision Lab was developed by the Canadian company Visual Decision (www.visualdecision.com). This software treats based on the matrix including potential alternatives and evaluation criteria. Promethee requests additional information. For each criterion a specific preference function must be defined. This function is used to compute the degree of preference associated with the best action in the case of pairwise comparisons. These shapes are usual, linear, V-shape, U-shape, level and Guassian (Brans et al. 1986). Promethee-GAIA calculates positive and negative preference flows for each alternative. The positive flow expresses how much an alternative is dominating (power) the other ones, and the negative flow how much it is dominated (weakness) by the other ones. Based on these flows the partial ranking is obtained. The ordinal ranking is based on the balance of the two preference flows (Brans, Mareschal 2000).

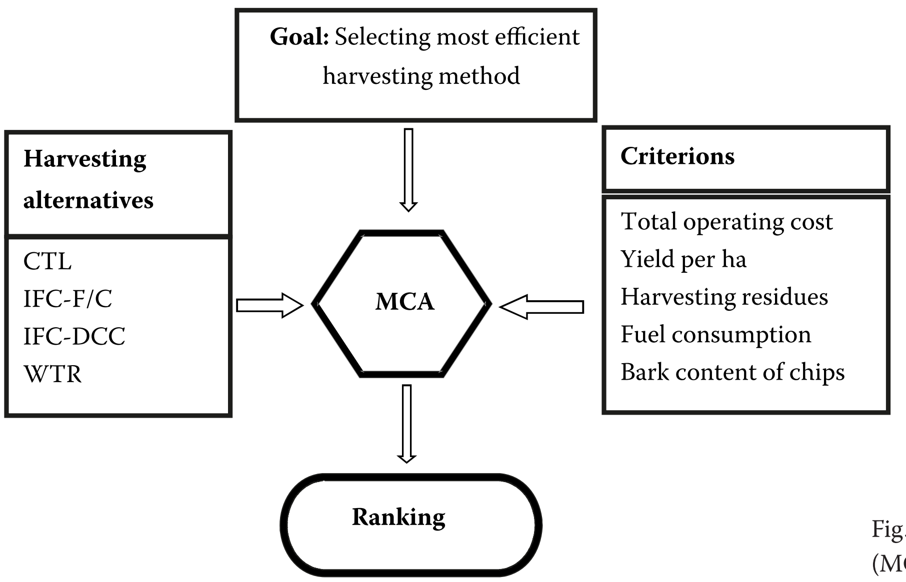

Fig. 1. The multiple-criteria analysis (MCA) framework for the case study

RESULTS

Production costs

Table 2 presents the productivity, cost and fuel consumption for each component of the harvesting methods. Harvesting and processing are the most expensive components of the CTL method. The cost of chipping the logs at the mill was assumed to be about 6.00 AUD·GMt^{-1} (Table 2) based on discussions with local supply chain managers. Skidding and chipping were costly components of the IFC-F/C method mainly due to low productivity and high machine hourly cost of skidder and chipper. The high fuel consumption rate per GMt for skidding and chipping was mostly because of the low productivity and larger size of the machine, particularly larger machine power (Holzleitner et al. 2010). Using IFC-DDC harvest method, the feller-buncher recorded lower productivity than the other harvest methods in this trial. This was attributed to the use of an inexperienced operator. Chipping was the most expensive component of this method, with an average cost of 9.50 AUD·GMt^{-1}. However, this was lower than the IFC-F/C chipping cost (12.57 AUD·GMt^{-1}). The fuel consumption rate for the IFC-DDC chipper was higher than that for the Husky Precision chipper. But the IFC-DDC had a lower harvesting cost than the IFC-F/C and two skidders (Table 2). The last method was the WTR method, producing logs with two processors. This resulted in the highest cost and fuel rate for the processing phase of the trial. The skidder in the whole tree method did not clean up the debris. However, for IFC-DDC, the skidder removed the debris, in addition to tree extraction, resulting in a longer work time and lower skidding productivity.

Grapple skidders were used in both the IFC-DDC and WTR methods. The skidder in the WTR method was used for about 1,800 h and the skidder in the IFC-DDC accumulated 3,800 h of use. The IFC-DDC skidder had higher fuel consumption, which could be attributed to the age of the machines (Tables 2).

Although in this case study the total cost per green metric tonnes of WTR harvesting method

Table 2. Productivity, cost and fuel consumption of CTL method

Harvesting method	Machine	Productivity (GMt·PMH$_0$$^{-1}$)	Cost (AUD·GMt^{-1})	Fuel consumption (l·GMt^{-1})
CTL	Harvester/processor	15.47	17.35	0.95
	Forwarder (extraction)	30.69	5.80	0.42
	Forwarder (loading)	73.15	2.43	0.18
	Truck	47.63	5.04	1.08
	Chipping at mill	–	6.00	0.7
	Total		36.62	3.33
IFC-F/C	Feller-buncher	97.26	2.55	0.33
	Grapple skidder	31.45	6.46	0.79
	Flail	57.80	5.98	0.77
	Chipper	58.18	6.59	1.24
	Truck	57.34	4.19	0.92
	Total		25.77	4.05
IFC-DDC	Feller-buncher	61.77	4.13	0.61
	Grapple skidder	38.70	5.05	0.87
	Chipper (DDC)	45.34	9.50	2.32
	Truck	47.41	5.06	0.96
	Total		23.74	4.76
WTR	Feller-buncher	86.67	3.04	0.53
	Grapple skidder	58.57	3.02	0.35
	Processor (two processors)	48.79	18.39	3.42
	Loader	67.42	2.19	0.31
	Truck	43.81	5.48	1.22
	Chipping at mill	–	6.00	0.7
	Total		38.12	6.53

is higher than in IFC-DCC, however care should be taken that it is mostly due to the inclusion of two processors instead of one processor like in the previous case study in Eucalypt plantations with average tree size of 0.205 m^3, the WTR resulted in a slightly lower cost (22.68 AUD·GMt^{-1}) than IFC-DCC (21.07 AUD·GMt^{-1}) (Ghaffariyan 2013).

Retained biomass after harvesting

The CTL harvest method retained higher biomass residues on the site after harvest (58.7 GMt·ha^{-1}). The other methods left very small amounts of biomass at the site, as they extracted the whole trees to the roadside. Removal of the tree crown in whole tree extraction resulted in low retained biomass scattered on the sites (Table 3).

Table 3. Yield, bark content of the chips and harvesting residues for different methods

Harvesting method	Yield (BDT·ha^{-1})	Bark content (%)	Retained biomass (GMt·ha^{-1})
CTL	81.4	0.02	58.7
IFC-DDC	92.0	0.67	4.2
IFC-F/C	90.3	0.18	6.5
WTR	84.0	0.11	7.7

Yield and bark content of the chips

The yield per ha was recorded based on bone dry tonnes (BDT) by using 40.75% moisture content for the chips from CTL and WTR methods, and 43.5% for the IFC-DDC and IFC-F/C systems (Table 3). For the other harvesting methods, 8 chip samples were collected (one from each trailer of delivered chips or log) to measure the bark content of the delivered chips (Table 3) (Mitchell, Wiedemann 2012). Chips produced by IFC-DDC had the highest bark content while chips delivered by CTL method consisted of only 0.02% bark content.

Ranking harvesting methods by Promethee method

Table 4 presents the output of the online survey for the preferred objective (to maximise or to minimise) and preferred weight of each criterion. Most of the participants were interested to minimise the operating cost (86.67% of the participants), harvesting residues (60%), fuel consumption (80%) and bark content (76.67%). All of the industry participants intended to maximise the yield per ha (100%) (Table 4). As the harvesting residues may also be left on the site to increase the soil quality through reduced nutrient removal (Burgers 2002; Hakkila 2002; Ghaffariyan 2012), two sensitivity analyses were performed to examine the results of ranking for maximising and minimising harvesting residues. The preferred weights for each criterion (based on the survey results) were: Operating cost (1), Yield (1), Harvest residues (0.5), Fuel usage (0.5) and Bark content (0.7).

Table 5 shows the ranking of the harvesting methods for the case of maximising harvesting residues and yield while minimising operating cost, fuel consumption and bark content (objective 1). Based on the calculated Φ (Promethee partial and complete ranking), the best alternative was IFC/DCC method due to its very low operating cost and high yield compared to the other alternatives (Table 2). CTL method was ranked as the third alternative as it resulted in the highest harvesting residues after the operations (Table 3) but as its operating cost was higher than IFC/DCC or IFC-F/C and this criterion had the highest weight (Table 4), the IFC/DCC dominated the ranking despite leaving less harvesting residues. WTR method was ranked as the worst alternative mainly due to its high operating cost and fuel consumption.

Objective 2 in Table 5 was ranking of the harvesting methods for the case of minimising harvesting residues, operating cost, fuel consumption and bark content while maximising yield per ha. For this scenario, both in-field chipping operations methods were ranked higher than the CTL method due to lower harvesting residues left on the site following harvesting operations. As IFC/DCC had lower harvesting residues and operating cost than IFC-F/C, it ranked better than IFC-F/C.

When the analysis was run with the same weight of the criterions with the objective to maximise harvest residues, the CTL method was ranked as the

Table 4. Survey output for the objective of each criterion

Criterion	Max	Min	Neither meets the target	Weight of criteria
	(%)			
Operating cost	10	86.67	3.33	1
Yield	100	0	0	1
Harvesting residues	13.33	60	26.67	0.5
Fuel consumption	6.67	80	13.33	0.5
Bark content	3.33	76.67	20	0.7

Table 5. Ranking of harvesting method according to the Φ values for different objectives

Objective	Ranking	1	2	3	4
1 – maximising harvesting residues and yield per ha while minimising operating cost, fuel consumption and bark content (weight of criterions based on Table 4)	harvesting method	IFC/DCC	IFC-F/C	CTL	WTR
	Φ	0.18	0.12	0.10	–0.38
2 – minimising harvesting residues, operating cost, fuel consumption and bark content while maximising yield per ha (weight of criterions based on Table 4)	harvesting method	IFC/DCC	IFC-F/C	CTL	WTR
	Φ	0.44	0.20	–0.18	–0.48
3 – maximising harvesting residues and yield per ha while minimising operating cost, fuel consumption and bark content (the same weight for all criterions)	harvesting method	CTL	IFC/DDC	IFC-F/C	WTR
		0.33	0.07	–0.07	–0.33
4 – minimising harvesting residues, operating cost, fuel consumption and bark content while maximising yield per ha (the same weight for all criterions)	harvesting method	IFC/DCC	IFC-F/C	CTL	WTR
	Φ	0.33	0.20	–0.07	–0.47

best system while the second ranking belonged to IFC/DDC, the third for IFC-F/C and WTR method was the worst alternative. Using the same weight for all criterions and aiming to minimise harvesting residues, the ranking from the best to the worst was as follows: 1- IFC/DDC, 2- IFC-F/C, 3- CTL and 4- WTR. The main finding is if the weight of harvesting residue criterion is equal to the others (such as operating cost and yield), then CTL method presents as the best alternative. This priority to retain residues on site seems to be occurring in Southern Tasmanian and South Australian pine plantations where the plantation managers are concerned with high residue removal and its impact on soil nutrients (Hetherington 2011) creating a strong preference for CTL harvesting method in their plantation management area.

This study included the net yield per ha, product quality and harvesting residues as part of the decision criteria (as they are relevant to the Australian forest industry managers) compared to the Austrian case study reported by Kuehmaier et al. (2010), who developed a multiple-attribute decision support system for timber harvesting planning. Unlike the Austrian case study, this current project did not include bearing pressure, stand damage, contribution to margin, work injury rate (Kuehmaier, Stampfer 2010) and human stress/strain (Stampfer, Lexer 2003) in the decision making as these criterions have not yet been investigated in Australian forest operations but they are the potential future research areas.

CONCLUSIONS

As indicated by the survey results, while the cost is a critical aspect of harvest system selection, it is important for multiple-criteria to be considered to get the best overall outcome. Depending on the site and business requirements the objectives and importance of the different criteria can change. Using multi-criteria analysis in this study, IFC-DDC was consistently shown as the preferred harvest system. Only when retaining residues on the harvest site was given a very high priority, did IFC-DDC finish the second to the CTL harvest system. In all cases the WTR harvest system proved to be the least preferred as it was hindered by both relatively high operating costs and slash removal.

The results of this study, based on observations of the authors, are consistent with what is seen in practice. By being able to formalise the evaluation different harvest systems in a multi-criteria analysis, potential gaps in the experience of decision makers can be compensated for. For both this study and other similar multi-criteria analysis approaches to harvest system selection, the range of criteria used has been limited and highly tailored to the region the study was conducted, which limits comparison between approaches. Future studies could seek to test the proposed multi-criteria approaches in different regions and seek to expand the range of criteria included to explore the scalability and transferability of the approach.

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