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Comparison of Productivity, Cost and Chip Quality of Four Balanced Harvest Systems Operating in a *Eucalyptus globulus* Plantation in Western Australia

Martin Strandgard, Rick Mitchell, John Wiedemann

Abstract

There have been few comparative harvest system studies to provide a basis to understand the performance and chip quality of harvest systems used in eucalypt plantations.

The study compared the CTL – cut-to-length method at the stump, WTM – whole tree method where trees were processed to logs at roadside, IFC-DDC – infield chipping using a debark/delimb/chipper, IFC-F/C – infield chipping using a separate flail and chipper harvest systems on a single site in south-west Western Australia.

The WTM and IFC-F/C harvest systems were the most productive. The productivity of the CTL and IFC-DDC harvest systems was about 25% less than that of the other harvest systems. The CTL harvest system produced wood at the highest cost resulting from it having a large number of machines without a correspondingly high productivity level. However, the CTL harvest system has advantages over the other systems through retaining evenly distributed logging residues, low machinery impact on the site and flexibility to add or subtract machines as conditions change.

Two limitations of this study were that the harvest systems were only compared at a single mean tree size and operator performance differences may have influenced harvest system productivity. Previous studies have found that the balance of machines in a harvest system can change with changes in mean tree size. This is an area where further research is required.

Wood chip samples from three of the four harvest systems did not meet the company chip specifications. However, the deviations from the specifications were minor.

Keywords: forest harvest system, cut-to-length, infield chipping, Eucalyptus globulus, *wood chip, balanced system*

1. Introduction

Eucalyptus is a dominant plantation genus globally, with approximately 20 million hectares in cultivation, the majority of which are in Asia and South America (Rejmánek and Richardson 2011). Australia has approximately 960 000 ha of hardwood plantations, of which 54% is *Eucalyptus globulus* Labill. managed for chiplog production (Gavran 2015). Eucalypt plantations are increasingly being harvested using mechanised cut-to-length or infield chipping harvest systems (Spinelli et al. 2009). Two types of cut-to-length harvest systems are generally used: harvesters felling, debarking and processing trees to logs at the stump for extraction to roadside by a forwarder (CTL), or a feller-buncher, felling and bunching whole trees for extraction to roadside using grapple skidders and processing to logs at roadside using processors (WTM). In the former system, the forwarder may load trucks or a separate loader equipped with a boom and grapple may be used. In the latter system, a loader would typically be used. Infield chipping systems consist of a feller-buncher, felling and bunching trees for extraction to roadside using grapple skidders, and an infield delimb/debark/chipper (IFC-DDC) or separate flail and chipper units (IFC-F/C) discharging chips directly into trucks.

Comparative studies of harvest systems allow conclusions to be made about the relative performance of each harvest system in terms of its productivity, cost, product recovery, impacts on site productivity, etc. Conducting large harvest system comparison trials is expensive and logistically difficult resulting in few comparison trials having been carried out, and those that have mostly compared two harvest systems, often on different sites (e.g. Lanford and Stokes 1996, Adebayo et al. 2007, Acuna and Kellogg 2009, Spinelli and Magagnotti 2010). These trials typically use published utilisation rates to calculate harvest system costs, (e.g. Brinker et al. 2002), which may not reflect actual utilisation rates of each machine when working as part of the studied harvest system potentially resulting in unbalanced systems, where the shift level production of each machine or machine type was not matched within the harvest system. Theoretical balancing of each harvest system can provide a consistent basis for the comparison of harvest system productivity and costs. Other potential sources of unwanted variation in comparative studies include site and operator performance differences (Olsen et al. 1998). In the case of eucalypt harvesting trials, differences in bark adhesion can also be a significant source of variation in harvest machine performance (Strandgard et al. 2014).

The objective of this study was to compare the productivity, cost and chip quality of four mechanised harvest systems used in *E. globulus* harvesting operations to produce woodchips, all operating on the same site. For the comparison, each harvest system was balanced in a desktop exercise.

2. Material and methods

The study was carried out in a first rotation, 10.5 year old *E. globulus* plantation in south-west Western Australia (latitude –34.684, longitude 118.053). The study area was 5.95 ha in total, with slopes less than 5 degrees and a duplex sandy gravel soil. Four harvest systems were studied (Table 1) in a uniform section of the plantation (Table 2). The study was conducted over nine consecutive days in January 2011. The weather was fine and sunny until the last two days of the study when a total of ~30 mm of rain fell during the WTM harvest. Each harvest system was studied when harvesting in two non-adjacent three row swathes approximately 12 m wide and 500 m long. Stump heights were specified to be left 100–150 mm high to allow

Table 1 Description of harvest systems

Harvest system	Harvest machine type	Harvest machine make and model
Cut to length at the stump CTL	Harvester/processor	Cat 342D FM + Waratah HTH 616C harvester head
	Forwarder	Valmet 890.2
Cut to length at the roadside WTM	Feller-buncher *	Timberking TK711 + Quadco 216B shear head
	Grapple skidder	Caterpillar 545C
	Processor	Caterpillar 324DL + Waratah HTH616 harvester head
	Processor	Caterpillar 324D + Waratah HTH616 harvester head
	Loader	Caterpillar 320C LL + Ensign grapple
Infield chipping with a delimb/debark/chipper IFC–DDC	Feller-buncher *	Caterpillar 511 + Prentice 21HC shear head
	Grapple skidder	Caterpillar 545C
	Chipper (delimb/debark/chipper)	Peterson Pacific 5000G
Infield chipping with a separate flail and chipper IFC-F/C	Feller-buncher*	Tigercat 845C + Tigercat 2001 shear head
	Grapple skidder	Tigercat 630C
	Grapple skidder	Tigercat 630D
	Flail	Husky Precision 2300
	Chipper	Husky Precision 2366

* all feller-bunchers had accumulating heads

Table 2 Stand details (merchantable stems *)

Attribute	Mean	Range
Height, m	17.5	9.3–24.9
Diameter at breast height over bark (DBHOB), mm	178	71–281
Stem weight, GMt	0.21	0.02–0.66
Stocking, stems per hectare	750	664–861

* merchantable stems had a DBHOB > 75 mm

coppice regeneration of the site. The specified minimum small end diameter (SED) for the logs produced by the cut-to-length systems was 50 mm, though logs with a smaller SED were accepted. The CTL system mean log length was 4.4 m. The majority of logs cut in the WTM system had a nominal length of 10 m with shorter logs cut from the crown or shorter trees. Logs produced from the two cut-to-length systems were chipped at a static chip-mill. Chips produced from the infield chipping harvest systems were delivered to the same mill.

Logging residues from the infield chipping systems was redistributed by the skidders in small piles back onto the site during extraction, whereas the WTM harvest system logging residue was left at roadside.

The operators had a minimum of two years of experience in operating the machine type they used in the study, except for the grapple skidder operators in the IFC-F/C harvest system who each had less than one year's experience.

Machine productivity calculations were based on the total delivered green weight of wood for each system. Productivity was estimated by dividing the total weight of trees or logs in green metric tonnes (GMt) handled or processed by a machine by the total productive machine hours excluding delays (PMH_0) for that machine. Productive machine hours were measured using a stopwatch. At the start of the study each machine's fuel tank was filled. The amount of fuel required to refill the tank was measured at the end of each shift. Fuel consumption (l/PMH_0) was estimated by dividing the fuel use for the shift by the PMH_0 for that shift. Where several machines of the same type were used in a harvest system, mean productivity and fuel use figures were used in calculations. This was not adopted across harvest systems because there were only single examples of some types of machine and multiple of others so an average productivity could not be obtained for all machine types used in the study.

Table 3 Specifications used in the study for the required percentage of chips in each size class and the maximum allowable percentage of bark

>28.6 mm %	4.8–28.6 mm %	9.5–22.2 mm %	<4.8 mm %	Bark %
<5	>92	>55	<3	<0.5

Chip quality for each harvest system was assessed using eight 2 kg samples per system, one from each trailer of chips or logs. These samples were fractionated using a Kason automatic vibration machine into chip size classes and tested for bark percentage. Chip size class and bark percentages were assessed against the static mill's chip quality specifications (Table 3).

The harvest systems as tested in the study were not balanced, i.e. the shift-level productivities of each machine within a harvest system (or the combined productivities when several machines of the same type were used) were not equal. The primary strategy used to balance each harvest system at a shift-level was the adjustment of machine utilisation rates. The minimum adjustment made in utilisation rate was 1%. Where possible, utilisation rates were kept between 60–80%, which is the typical range of utilisation rates observed in other studies (Brinker et al. 2002, Spinelli and Visser 2009, Holzleitner et al. 2011). The maximum utilisation rate allowed during balancing was 80%. Where it was not possible to balance a system using this approach, additional machines were added of the same types already used in that harvest system. This assumes the major delay source was imbalance between machines (i.e. delays caused by machines waiting for other machines to complete a task). From the authors' experience this is a reasonable assumption. The additional machines were assumed to have the same productivity, fuel use and costs as existing machines of that type within that harvest system. Harvest systems were deemed to be balanced when the difference in shift-level productivity between the most and least productive machines (or machine types if the harvest system contained several machines of the same type) was 1% or less. Harvest system productivity was expressed at a shift level and was set at the level of the least productive machine (or machine type) in the harvest system. The time required per shift for the forwarder to load trucks was estimated using the forwarder loading productivity observed in the trial and the shift level production of the balanced CTL harvest system.

Costs were estimated using the approach of Miyata (1980) in Australian dollars (A$). Cost assumptions are provided in Table 4 and Table 5. Fuel consumption figures used were those measured during the study.

Table 4 Machine cost assumptions (consistent values for all studied machines)

Category	Value
Operating days per year	249
Shifts per day	1
Hours per shift	10.0
Salvage value, % of purchase price	20
Repair and maintenance, % of depreciation	75
Interest rate, % of average yearly investment	9
Insurance and tax rate, % of average yearly investment	6
Fuel cost, A$/L*	0.98
Oil & Lubricant, % of fuel cost	50
Labour costs, A$/SMH	46.59
Supervision (% of labour costs)	10

* at time of study off road vehicle use in Australia was eligible for a tax rebate of A$0.38143/litre

As the cut-to-length systems produced logs while the infield chipping systems produced chips, the estimated cost for chipping the logs at a static chip-mill (A$5/GMt) was added to the cut-to-length harvest system costs. Trucks were assumed to be available when required and not to limit the productivity of the harvest systems. Truck transport costs were assumed to be equal for chips and logs (A$5/GMt).

Analysis was performed using MS Excel 2010 and Minitab v. 16.

3. Results

For each balanced harvest system, machine productivity (hourly: GMt/PMH$_0$ and shift level: GMt/shift), utilisation rate (%), fuel consumption (l/PMH$_0$) and harvest cost (A$/GMt) are shown in Table 6. A

Table 5 Machine cost assumptions (variable between studied machines)

	Harvester/ processor	Forwarder	Feller-buncher	Grapple skidder	Processor	Loader	DDC chipper	Flail	Chipper
Purchase price, A$	750 000	660 000	650 000	670 000	750 000	280 000	1 500 000	750 000	750 000
Machine life, yrs	5	7	5	5	5	5	5	5	5

Table 6 Machine productivity at a productive machine hour level (GMt/PMH$_0$) and shift level (GMt/shift), utilisation rate (%), fuel consumption (l/PMH$_0$) and harvest system cost (A$/GMt)

Harvest system	Harvest machine type	Productivity GMt/PMH$_0$	Utilisation rate %	Productivity GMt/shift	Fuel consumption l/PMH$_0$	Harvest system cost A$/GMt
Cut to length at the stump CTL	Harvester/processor	16	69	107	14.7	34
	Harvester/processor	16	69	107	14.7	
	Harvester/processor	16	69	107	14.7	
	Forwarder	31	74	160	13	
	Forwarder	31	74	160	13	
Cut to length at the roadside WTM	Feller-buncher	87	50	435	46	31
	Grapple skidder	59	73	431	20.5	
	Processor	24	59	144	14.7	
	Processor	24	59	144	14.7	
	Processor	24	59	144	14.7	
	Loader	67	65	436	20.9	
Infield chipping with a delimb/debark/chipper (IFC–DDC)	Feller-buncher	62	48	298	38	29
	Grapple skidder	39	76	296	34	
	DDC chipper	45	66	297	105	
Infield chipping with a separate flail and chipper (IFC-F/C)	Feller-buncher	97	42	407	38	27
	Grapple skidder	29	70	203	34	
	Grapple skidder	29	70	203	34	
	Flail	58	70	406	45	
	Chipper	58	70	406	72	

Table 7 Mean load size (GMt), extraction distance (m) and travel speeds (km/h) for primary transport machines in each of the harvest systems

Machine	Load size, GMt	Extraction distance, m	Travel speed, km/h		
			Travel empty with debris	Travel empty without debris	Travel loaded
Forwarder	18.8	303	–	5.6	5.8
WTM skidder	4.4	288	–	16.0	9.7
IFC-DDC skidder	4.5	270	12.4	15.2	9.1
IFC-F/C skidder*	4.2	281	8.6	8.9	8.6

* mean values for the two grapple skidders

balanced CTL harvest system could also have been achieved using two harvester/processors and one forwarder. However, more realistic utilisation rates were obtained by adding two harvester/processors and one forwarder to the studied system (i.e. a system consisting of three harvester/processors and two forwarders). An additional processor was added to balance the WTM harvest system. To balance the three harvest systems, which included a feller-buncher (the WTM, IFC-DDC, IFC-F/C harvest systems), the feller-buncher utilisation rates were reduced to ≤50%. Balanced system productivities (GMt/shift) were: CTL 320, WTM 431, IFC-DDC 296, IFC-F/C 406. These theoretical systems and feller-buncher utilisation rates reflect actual practice as they have been observed at other locations by the authors and by McEwan (2011).

The most expensive harvest system in the study (A$/GMt) was the CTL system and the cheapest system was the IFC-F/C system (Table 6).

There were no significant differences between mean load sizes and mean extraction distances for the skidders used in the WTM, IFC-DDC and IFC-F/C harvest systems (Table 7). The IFC-F/C skidders were significantly slower than the IFC-DDC skidder when travelling empty with debris and significantly slower than the IFC-DDC and WTM skidders when travelling empty without debris. The IFC-DDC and WTM skidder speeds were not significantly different when travelling empty without debris. There were no significant differences between skidder travel loaded speeds between any of the harvest systems.

Mean wood chip percentage by size class and bark percentage for chips produced from each studied harvest system are presented in Table 8. Chip samples from the CTL, WTM and IFC-DDC harvest systems did not meet the chip specifications.

Table 8 Mean wood chip percentages by size class and bark percentage for each harvest system and the mean figures across all harvest systems (figures in italics did not meet the chip specifications)

Harvest system	>28.6 mm %	4.8–28.6 mm %	9.5–22.2 mm %	<4.8 mm %	Bark %
CTL	3.7	95.3	*53.1*	1.0	0.0
WTM	*5.2*	93.6	59.3	1.1	0.1
IFC-DDC	3.1	94.7	66.5	1.5	*0.7*
IFC-F/C	3.4	94.4	68.2	2.0	0.2
Mean	3.8	94.5	61.8	1.4	0.2

4. Discussion

The balanced WTM and IFC-F/C harvest systems were found to be the most productive systems in the current study. The balanced IFC-DDC and CTL harvest systems produced approximately 25% less wood over a shift than these systems. McEwan (2011) obtained similar results in his harvest system comparison study, though in his study the productivity of the IFC-DDC system was greater than that of the IFC-F/C. The CTL harvest system had the highest estimated costs (A$/GMt). This resulted from the CTL harvest system having a large number of machines without a correspondingly large productivity. In contrast, the high costs associated with the large number of machines in the WTM and IFC-F/C harvest systems were balanced by their correspondingly high productivities and the lower productivity of the IFC-DDC harvest system was balanced by it having the least number of machines. The relative system costs did not concur with the findings of McEwan (2011), who found the WTM harvest system to be the cheapest system. However, the processors in the WTM system he studied produced tree length logs that were then cut to length by a loader/slasher. The corresponding increase in processor productivity enabled this system to operate with one less processor than the studied WTM system. Other harvest system comparison studies have found

CTL harvest systems to be more expensive than an IFC-DDC system (Spinelli et al. 2009) or a WTM system (Adebayo et al. 2007).

A limitation of the current study was that the harvest systems were only compared at a single mean tree size. A number of studies have found that the balance of machines in a harvest system is sensitive to changes in mean tree size because the productivity of each machine type can be affected differently by tree size changes (McNeel and Rutherford 1994, Holtzscher and Lanford 1997, McEwan 2011). The restriction on stump height imposed on the study also reduced the ability of the shear head feller-bunchers to extract more of the available volume from each tree (Strandgard and Mitchell 2012), which may have reduced the productivity of the three harvest systems that incorporated a feller-buncher.

As the WTM, IFC-DDC and IFC-F/C harvest systems used the same machine types for felling and primary extraction, productivity differences between these systems were likely to reflect differences in the performance of the machines or operators. The exception to this was that the WTM harvest system left logging residues at roadside, whereas the infield chipping systems used the grapple skidders to return logging residue to the harvested area which reduced their productivity. The high productivity of the WTM harvest system was believed to reflect the ability of this system to match the productivity of the feller-buncher and skidder by adding multiple, relatively low productivity processors, which is not possible for infield chipping harvest systems with their single, high-productivity chipper. The WTM harvest system processors also cut longer logs than the CTL harvest system harvesters, which has been shown to increase the productivity of these machines (Gingras and Favreau 2005). Rainfall during the study of this harvest system may also have increased the processors' productivity through reducing bark adhesion, however bark adhesion was not measured during the current study.

Infield chipping systems can be highly productive but are very dependent on the productivity of the chipper. Major breakdowns to a feller-buncher or grapple skidder can be overcome through having spare machines onsite (Visser and Stampfer 2003, McEwan 2011), whereas the high capital cost of an infield chipper means that it is unlikely that spare chippers will be available. The productivity of the separate flail and chipper in the current study was similar to that found in previous studies (50 GMt/PMH_0 Hartsough et al. 2002, 50 m^3/PMH_0 and 55 m^3/PMH_0 McEwan 2011). However, the productivity of the DDC in the current study was lower. Major factors affecting the productivity of an infield chipper are operator performance (McEwan 2011), flail chain condition (Thompson and Sturos 1991) and knife sharpness (Hartsough et al. 2000). The productivity difference between the infield chippers in the current study was believed to be the result of one or more of these factors rather than inherent differences between the chipper types, though this was not verified. In contrast with infield chipping systems, the two log producing harvest systems have a greater degree of flexibility as they can readily adapt to site or tree size changes by adding or subtracting machines to balance productivity and/or meet weekly log quotas or adapt to equipment breakdowns. They can also potentially be used to produce sawlogs or other roundwood products.

The assumption that the shift-level productivity of the studied harvest systems was not limited by truck availability is rarely true in practice. Truck delays (Acuna et al. 2012) and insufficient truck numbers (Zamora-Cristales et al. 2013) often result in fewer trucks than required arriving at the harvest site. When insufficient trucks are available, the CTL and WTM harvest systems have a strong advantage over the infield chipping systems as they can continue to operate while log storage space is available at roadside, whereas infield chippers in most cases only operate when a truck is available or have limited on-site chip storage. A number of simulation studies have found that increasing truck availability increases chipper utilisation and productivity and reduces chipper costs (Acuna et al. 2012, Zamora-Cristales et al. 2013), though this cost saving can be reduced by corresponding increases in truck waiting times and hence in transport costs. Spinelli and Visser (2009) caution, however, that expected increases in chipper productivity from increased truck availability may be limited in practice by the consequent increase in delays related to increased chipper maintenance requirements and operational issues.

Although the CTL harvest system was less productive and more expensive than the best performing harvest systems studied, it has a number of advantages over other harvest systems. It requires the fewest machines for a functioning harvest system (one harvester and one forwarder), which minimises a contractor's capital and mobilisation costs. In areas where it is difficult to recruit and retain staff, it also minimises the crew size required, though operator training and skill levels for these machines are higher than for the other studied machines (Lapointe and Robert 2000). In addition, the retention of logging residues spread over the harvested area by CTL harvest systems can assist to maintain site productivity by minimising nutrient losses (Mendham et al. 2003) reducing surface soil evaporation (O'Connell et al. 2004) and protecting soil from machinery damage (Cambi et al. 2015). In contrast, skidders in roadside harvest systems redistribute logging residues back onto the site in heaps (Ghaffariyan et al. 2013), or in some cases, logging residues are burnt or left at roadside (Kumar et al. 2003).

Feller-bunchers have been shown in numerous previous studies to be highly productive harvesting machines (e.g. Spinelli et al. 2002, Adebayo et al. 2007, Strandgard and Mitchell 2010, Ghaffariyan et al. 2012). Use of accumulating heads on feller-bunchers, such as those in the current study, enables them to maintain high productivity when harvesting small trees (Johansson and Gullberg 2002). The productivities of the feller-bunchers in the WTM and IFC-F/C harvest systems were comparable to those reported in previous eucalypt harvesting studies with similar mean tree sizes (92 m^3/PMH_0 Strandgard and Mitchell 2010, 109 GMt/PMH_0 Ghaffariyan et al. 2012), whereas that for the IFC-DDC feller-buncher was less than expected. In the latter case, the operator was experienced in operating feller-bunchers but was not the regular operator of the studied machine. To balance the productivities of the feller-bunchers against the other machines in the studied harvest systems, their utilisation rates were reduced to ≤50%, which was also the approach taken by Adebayo et al. (2007). System balance could have been maintained by adding more machines to these systems. However, this would not replicate current practice in Australian harvest operations, in which the feller-buncher operator also operates a grapple skidder or other machine as required, or if another harvesting crew was close by the feller-buncher may support multiple harvest systems.

Grapple skidder productivity has been found in previous studies to be primarily related to extraction distance and load size (Kluender et al. 1997, Visser and Stampfer 2003, Ghaffariyan 2013). As mentioned above, the productivity of the grapple skidders used in the two infield chipping harvest systems was reduced by them being used to return logging residues to the harvested area. The productivity of the IFC-DDC system skidder was greater than that of the IFC-F/C harvest system skidders because the IFC-DDC harvest system skidder travelled significantly faster when not carrying a load. This is likely to be due to the higher maximum speed of the Caterpillar 545C (27.5 km/h) used in IFC-DDC harvest system compared with the Tigercat 640 skidders (18–19 km/h) used in the IFC-F/C harvest system.

The WTM harvest system grapple skidder was more productive at the same extraction distance than the grapple skidder studied by Spinelli and Hartsough (2001) (~40 GMt/PMH_0). In both cases logging residues were left at roadside. The difference in productivity was likely to be because the skidder mean load size in the Spinelli and Hartsough (2001) study was approximately 2/3 that of the skidder in the WTM harvest system. However, the productivity of the grapple skidder in the study by Ghaffariyan et al. (2012) (~47 GMt/PMH_0) was greater than that in the IFC-DDC harvest system although its mean load size was also approximately 2/3 that of the IFC-DDC harvest system skidder. In both cases, the grapple skidders returned logging residue to the site, however, the skidder in the Ghaffariyan et al. (2012) study spent only 2% of its time on this activity during the study, which may have accounted for its greater productivity.

Harvester and processor productivity has been shown in previous studies to be strongly related to tree size (McEwan 2011, Ghaffariyan 2013, Ramantswana et al. 2013, Strandgard et al. 2014, Strandgard et al. 2015). As was found in the current study, roadside processors have higher productivities than harvesters as they do not travel through the stand, clear undergrowth or fell trees (Spinelli et al. 2010). Similar harvester productivities to that in the current study were reported by Ramantswana et al. (2013) (16 m^3/PMH_0) and Strandgard et al. (2014) (18 m^3/PMH_0). However, the harvester productivity reported by McEwan (2011) (13 m^3/PMH_0) was less than that in the current study for the same mean tree size. The reason for this difference was not identified. Roadside processor productivities reported by Ghaffariyan (2013) and Strandgard et al. (2015) (25 GMt/PMH_0) were similar to that of the processors in the current study for similar mean tree sizes, though the trees were not debarked in the Strandgard et al. (2015) study.

Previous studies have shown forwarder productivity to be dependent on extraction distance and load size (Adebayo et al. 2007, Jiroušek et al. 2007, Nurminen et al. 2006, McEwan 2011). Forwarder productivity in the current trial was similar to that reported by Adebayo et al. (2007) (33 m^3/PMH_0) and Jiroušek et al. (2007) (27 m^3/PMH_0). Nurminen et al. (2006) reported a lower forwarder productivity (21 m^3/PMH_0), though the mean forwarder load size (14 m^3) in their study was considerably less than that in the current study.

Although the chip samples for three of the harvest systems did not meet the company specifications, each of the samples was only non-compliant in a single category and was close to meeting the company's chip specifications. Screening and re-chipping oversize chips (>28.6 mm) is routine practice at chip-mills (Brännvall 2009), which would have addressed the higher than allowable percentage of chips in that size class for the WTM harvest system chip sample. The higher than acceptable bark percentage for the IFC-DDC harvest system may indicate that the flail chains needed to be replaced or the trees fed through the flail more slowly or fewer at a time (Thompson and Sturos 1991). The finding that the mean percentage figures across all the chip samples met company specifications implied that the chips from each of the harvest systems would have been acceptable when mixed with chips from other sources.

5. Conclusions

The current study compared the cost and productivity of four harvest systems processing short-rotation eucalypt plantation trees to pulp chips. To reduce variations in the results from factors other than system differences, the trial was conducted on a single site and over a short time period and the systems were balanced in terms of their shift-level productivity in a desktop exercise to reduce potential distortions in the original study results caused by excessive machine waiting times.

The cheapest harvest system (A$/GMt) in the study was found to be the IFC-F/C system and the most productive harvest system (GMt/PMH_0) was the WTM system. However, system cost and productivity are not the only considerations used by harvest contractors to select a harvest system.

The four harvest systems tested in the study fell into two classes: systems producing logs or chips at roadside. Harvest systems producing logs are flexible as harvest contractors can adjust machine numbers to balance a harvest system to adapt to changes in mean tree size or wood quotas. Log-producing harvest systems can also produce chip logs or roundwood logs and typically are able to store logs at roadside thus reducing their dependence on truck availability. Of the two harvest systems that produced logs at roadside, the WTM system was superior to the CTL system in terms of its cost per GMt and its productivity. However, CTL harvest systems distribute logging residue more evenly over the site and the simplest and cheapest harvest system of those tested would be a single harvester and forwarder CTL system.

As shown in the current study, infield chipping harvest systems are capable of highly productive and low-cost chip production. However, these attributes are highly dependent on the mechanical availability of the chipper as few contractors will have a spare chipper and on truck availability as typically little or no chip storage is available on-site. Of the two harvest systems producing chips at roadside, the IFC-F/C harvest system was superior to the IFC-DDC harvest system in terms of its productivity and cost.

On the basis of the above considerations, the low-cost, high productivity and flexibility of the WTM harvest system suggested that it was the best harvest system of those tested under the test conditions (assuming a chip mill was available to process the logs). However, if a plantation manager specified even redistribution of logging residues to maintain site productivity, the only choice would be the CTL harvest system.

Two limitations of the current study were the impact of differences in operator performance, as can be seen by the difference in productivity between machines of the same type used in different harvest systems, and that the harvest systems were only compared at a single mean tree size. Rainfall late in the trial may also have increased the productivity of the WTM harvest system processors through reducing bark adhesion. As more studies of the harvest machines and systems studied in this trial are collected, it will be possible in future to compare the productivity and costs of »average« harvest systems of each type using a simulation study to remove the effects of differing operator performance and rainfall. The simulation study could also be used to explore the effect of changes in mean tree size as the productivity of each machine type can be affected differently by tree size changes.

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Authors' addresses:

Martin Strandgard, MSc *
e-mail: mnstra@unimelb.edu.au
AFORA
University of the Sunshine Coast
500 Yarra Boulevard
Richmond, 3121, Victoria
AUSTRALIA

Rick Mitchell, BSc
e-mail: rmitchel@usc.edu.au
AFORA
University of the Sunshine Coast
35 Shorts Place
Albany, 6330, Western Australia
AUSTRALIA

John Wiedemann, GDFSM
e-mail: john.wiedemann@wapres.com.au
Western Australian Plantation Resources (WAPRES)
PO Box 444
Manjimup, 6258, Western Australia
AUSTRALIA

* Corresponding author