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General productivity model for single grip harvesters in Australian eucalypt plantations

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ABSTRACT

Australia's eucalypt plantation estate (>900 000 ha) has largely been established since 1995. The main species is *Eucalyptus globulus* producing wood chips for export on a short rotation (~10 years). Two main harvesting methods are used: cut-to-length (CTL) at the stump and infield chipping (IFC). CTL harvesting is typically carried out with single-grip harvesters and forwarders. The study objective was to develop a general productivity model for medium-sized single-grip harvesters performing CTL harvesting at the stump in short-rotation *E. globulus* plantations under typical Australian operating conditions, as few harvester productivity models have been developed for these plantations. The model was developed from 47 harvester productivity studies carried out in Australian *E. globulus* plantations. Studies were predominantly short-term counts of the trees cut over at least an hour multiplied by an estimate of mean merchantable tree volume derived from inventory plots measured where the harvester was about to work or an adjacent area. The model developed explained 80% of the variability in harvester productivity (79% was explained by mean tree volume and 1% by harvester engine power). Results from comparable published CTL eucalypt studies generally supported the model. The strength of the relationship suggests the model could be used to estimate harvester productivity for similar site conditions and harvester/harvester head combinations (which represent most Australian *E. globulus* plantations) where mean merchantable tree volume and harvester engine power were known or estimated.

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Harvesters; logging machines; productivity; logs; models; *Eucalyptus globulus*

Introduction

The Australian eucalypt plantation estate of over 900 000 ha has largely been established since 1995 (Gavran and Parsons 2011). The main species planted is *Eucalyptus globulus* (blue gum) managed on a short rotation (typically 10 years) to produce wood chips for export (Gavran and Parsons 2011). The two main harvesting methods used in Australian eucalypt plantations being managed to produce woodchips are cut-to-length (CTL) at the stump and infield chipping (IFC). The CTL harvesting method is typically carried out with single-grip harvesters and forwarders, while the IFC harvesting method uses feller-bunchers, skidders and delimb-debark-chippers.

The recent establishment of the Australian eucalypt plantation estate means that few harvesting machine productivity models have been developed. As such, development of these models has been identified as a priority by the Australian forest industry. The overwhelming majority of published single-grip harvester productivity models are based on the results of a single study or a small number of studies. These productivity models can be strongly influenced by factors specific to the study, particularly differences in operator performance (Spinelli *et al*. 2010). General harvester productivity models overcome this limitation by using a sufficiently large pool of data to even out the influence of factors other than tree size on the model (Spinelli *et al*. 2010) or by developing a series of models that explicitly include one or more important factors. The few publicly-available general harvester productivity models (e.g. Nurminen *et al*. 2006; Spinelli *et al*. 2010) were developed in Europe and cannot be applied to Australian operations due to differences in species, terrain, operator training and machine characteristics.

After tree size, the most significant factor affecting harvester productivity is the performance of the operator. Large differences in performance have been observed between operators with similar levels of experience (Ovaskainen *et al*. 2004; Purfürst and Erler 2012). Other factors that may influence harvester productivity include tree form (Puttock *et al*. 2005), stand density (Andersson 2011), terrain (slope, soils, obstructions) (Davis and Reisinger 1990) and machine properties (Sirén and Aaltio 2003; Spinelli *et al*. 2010). As eucalypts are typically debarked at the stump in CTL operations, debarking effort is another factor that may affect harvester productivity in eucalypt plantations (Hartsough and Cooper 1999). The effort required to debark eucalypts has been shown to be related to the strength of the bark–wood bond, which reduces considerably following rainfall after a dry period (van den Berg and Little 2004).

The predominant form defect in Australian *E. globulus* plantations is the presence of double leaders, which are largely the result of damage to the upper section of the stem of young trees caused by parrots (Shedley and Adams 1998). Double leaders increase processing time and decrease harvester productivity because the harvester operator generally must process each leader separately. The exception is small double leaders near the tip of the

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tree that are below the merchantable small-end diameter (SED) (typically 50 mm) and are discarded during processing. Acuna *et al*. (2009) reported there was a mean reduction in harvester productivity of 28% when processing *E. globulus* trees with double leaders.

Ideally, a harvester productivity model should be produced with the least effort and the highest precision possible (Stampfer and Steinmüller 2001). Detailed time and motion studies can produce high-precision productivity models but can take days to establish, perform and analyse and are relatively costly (Olsen and Kellogg 1983) and, as mentioned previously, can be strongly influenced by study-specific factors. In contrast, time and piece (T&P) counts, where the number of trees felled and processed is counted over a period of time, can collect relatively low-precision data covering a large range of stand and site conditions, operators and machines in a relatively short time and at a low cost. However, T&P counts provide little information about delays and can also be strongly influenced by study-specific factors, though this may be mitigated through collection of large numbers of T&P counts from a range of sites. Automated data collection can also be used to develop harvester productivity models (e.g. Heinimann 2001; Strandgard *et al*. 2013) with the advantage over manual methods of avoiding influencing the operator's performance (the 'Hawthorne effect'). However, many harvesters currently used in Australian eucalypt plantations do not record the required data.

The objective of the study was to develop a general productivity model for medium-sized single-grip harvesters performing cut-to-length (CTL) harvesting at the stump in short-rotation *E. globulus* plantations under typical Australian operating conditions.

Method

Study description

The general harvester productivity model was developed from the results of 47 harvester productivity studies carried out in CTL clearfell harvesting operations in short-rotation *E. globulus* plantations. Forty-one studies were conducted in south-western Western Australia and six studies in central Victoria, Australia (Table 1). One of the sites was a second-rotation coppiced stand that had been thinned to a single stem per stool. The remaining sites were first-rotation planted stands. Study site conditions were typical of those for most of the Australian *E. globulus* plantation estate: gentle slopes (<5°) with little undergrowth and few obstructions. Soil type and condition varied between sites but did not restrict the operation of the harvesters. Tree form was generally good across the study sites. Sites with a mean tree volume greater than 0.5 m^3 were excluded from the study as they form a minority of the Australian *E. globulus* estate. The lowest mean merchantable tree volume (MTV) in the study was 0.13 m^3 because *E. globulus* plantation stands in Australia with lower mean MTVs are typically harvested by feller-bunchers as part of an IFC harvesting system.

Twenty-four harvester operators and 17 harvester/harvesting head combinations were studied. Operator experience in working with single-grip harvesters in eucalypt plantations ranged from 1 to 20 years (mean 8.3 years). All operations studied were single shifts, so operator performance was unlikely to have been affected by fatigue (Nicholls *et al*. 2004). The harvesters used in the studies were predominantly medium-size, excavator-based machines, with small Waratah-brand harvester heads (Table 1). Harvesting consisted of felling, debarking and cutting each tree into logs (target log length ~5 m, minimum SED 50 mm) at the stump. Logs were piled into rows for later extraction by a forwarder.

Data collection

For 43 of the studies, data were collected using a T&P count method. This involved measuring several small inventory plots of 30 to 40 trees in total within or adjacent to the area to be felled by the harvester during the study. On each plot, measurements of diameter were made at 1.3 m (breast height) over bark (DBHOB) of every tree to the nearest 1 mm using a diameter tape and of the height to the nearest 0.1 m of about 10 trees using a Haglof Vertex IV. Height measurements covered the range of DBHOB values in the plots and were used to create a height/DBHOB model to estimate the heights of the remaining trees. MTV was estimated from the inventory data either using a volume model supplied by the plantation manager, where available, or using a generic *E. globulus* tree volume model that has been found to produce accurate estimates in previous unpublished studies (Model 5, Gilabert and Paci 2010). Harvester productivity (m^3 productive machine hour excluding delays $(PMH_0)^{-1}$) was estimated by counting the number of trees felled and processed over a period of at least 1 hour to obtain a count of trees cut per hour which was then multiplied by the estimated mean MTV. All delays were excluded. Where possible tree counts were obtained for longer periods to increase the accuracy of the productivity estimate and reduce the possibility of the 'Hawthorne effect' influencing the results (though this effect was not studied).

Compared with traditional detailed time and motion studies, the T&P count approach has the advantage of being quick to conduct. The main limitations of the method are:

- a relatively small number of trees is used for each estimate of harvester productivity
- it assumes the mean merchantable volume estimated from the inventory plots represents that of the harvested trees
- each T&P count produces a single estimate of harvester productivity—in contrast, a detailed time and motion study provides an estimate for each tree
- it does not collect accurate information about delays because of the short duration of data collection. This means that estimates from the model of harvester productivity must be corrected to account for delays when predicting the long-term productivity of a harvester.

The other four studies were traditional time and motion studies, where the harvester's productivity for each tree was estimated from an estimate of tree volume and the harvester's cycle time for that tree. The current study used the

Table 1. Stand and harvester/harvester head characteristics and operator years of experience for each study site.

Stand							Harvester		
Site	Age (y)	DBHOB (mm)	Height (m)	Density (sph)	Tree volume (m^3)	Operator experience (y)	Base	Engine power (kW)	Head
1	9.5	177	20.3	984	0.25	7	Cat 322CL	123	Waratah 620
2	9.5	196	20.7	686	0.26	7	Cat 322CL	123	Waratah 620
3	9.5	229	22.8	506	0.38	7	Cat 322CL	123	Waratah 620
4	9.5	245	23.1	403	0.43	7	Cat 322CL	123	Waratah 620
5	10	185	19.4	792	0.22	10	Cat 322CL	123	Waratah 620
6	9	170	15.4	909	0.14	9	Cat 322CL	123	Waratah 616C
7	8.5	159	14.9	761	0.13	12	Cat 320D	104	Southstar 450
8	8.5	162	15.9	859	0.13	13	Cat 320D	104	Southstar 450
9	10.5	179	17.6	664	0.19	15	Cat 324D FM	140	Waratah 616C
10	10.5	179	17.6	792	0.19	16	Cat 324D FM	140	Waratah 616C
11	11	197	22.0	869	0.33	10	Volvo 210	110	Waratah 616
12	12	216	24.8	854	0.39	20	Volvo 210B	110	Waratah 616
13	12	216	24.8	854	0.39	8	Volvo 210B	110	Waratah 616
14	12	216	24.8	854	0.39	8	Volvo 210B	110	Waratah 616
15	12	210	25.7	767	0.43	2	Cat 324D FM	140	Waratah 616D
16	12	210	25.7	767	0.43	2	Cat 324D FM	140	Waratah 616D
17	12	173	16.2	867	0.17	10	Volvo EC210BLC	107	Waratah 616B
18	12	173	16.2	867	0.17	11	Volvo EC210BLC	107	Maskiner 591
19	10	206	26.7	857	0.42	11	Caterpillar 511	170	Waratah 616C
20	10	212	27.3	881	0.43	11	Caterpillar 511	170	Waratah 616C
21	12	153	16.3	783	0.14	2	Cat 324D FM	140	Waratah 616D
22	13	203	21.0	708	0.30	10	Cat 320D	104	Southstar 450
23	13	175	19.4	1070	0.22	1	Cat 322C	123	Waratah 616
24	13	203	21.0	800	0.30	1	Cat 322C	123	Waratah 616
25	12	152	16.5	967	0.16	2	Cat 324D FM	140	Waratah 616c
26	12	171	17.4	833	0.20	6	Cat 324D FM	140	Waratah 616c
27	11	218	22.4	704	0.38	10	Volvo EC240C	125	Waratah 616C
28	13.5	191	20.8	941	0.27	16	Volvo 210B	107	Waratah 616C
29	12	162	19.2	1042	0.18	8	Cat 324D	140	Waratah 618c
30	12	174	20.2	1042	0.21	8	Cat 324D	140	Waratah 618c
31	12	158	18.6	1228	0.17	8	Cat 324D	140	Waratah 618c
32	13.5	200	21.9	962	0.32	16	Volvo 210B	107	Waratah 616C
33	14	192	21.2	940	0.27	10	Cat 320D	104	South Star 450
34	13.5	168	18.5	1000	0.19	16	Volvo 210B	107	Waratah 616C
35	14	164	16.4	1000	0.15	5	Valmet 425EX	224	Valmet 378
36	14	180	17.8	833	0.20	1	Cat 320D	104	South Star 450
37	12	159	15.9	1133	0.13	10	Caterpillar 511	170	Waratah 616c
38	10	198	22.3	751	0.31	2	Cat 324D FM	140	Waratah 616D
39	10	191	20.4	911	0.26	2	Cat 324D FM	140	Waratah 616D
40	12	200	18.3	556	0.24	10	Caterpillar 511	170	Waratah 616c
41	12	158	17.6	1000	0.15	20	Cat 322c	123	Waratah 616b
42	9	214	24.3	867	0.37	1	Volvo EC250DL	151	Waratah 616c
43	9	197	24.9	833	0.32	3	Cat 324DL	140	Waratah 616c
44	12	156	16.4	867	0.13	10	Cat 521	212	Waratah 620
45	12	187	20.4	833	0.22	10	Caterpillar 511	170	Waratah 616c
46	14	230	25.6	625	0.46	6	Cat 324D FM	140	Waratah 616C
47	13	171	17.4	833	0.21	2	Cat 324D FM	140	Waratah 616D
Mean	11.5	188	20.3	848	0.26	8.3	–	133	–

harvester's productivity for the mean MTV for each of the four studies.

Daily rainfall totals for the 30 days preceding each study were obtained from the meteorological station nearest to each study site.

Data analysis

Stepwise regression analysis (α = 0.05) was used to model the relationship between the dependent variable harvester productivity (m^3 PMH_0^{-1}) and the independent variables mean merchantable tree volume (m^3), stand density (stems per hectare, sph), harvester engine power (kW) and operator years of experience. Mean height and mean DBHOB were excluded because they were strongly correlated to mean merchantable tree volume and to each other.

Rainfall quantity was included in the analysis because of the link between soil moisture and eucalypt debarking difficulty found by van den Berg and Little (2004). As no standard procedure was found to divide rainfall quantity into categories, three classes were defined for the analysis: low, high and medium. The low category included sites where the preceding rainfall had been low so bark was likely to be difficult to remove and the high category included sites where the preceding rainfall had been high so bark was likely to be easy to remove. The medium category included sites with conditions in between the low and high categories. Carlyle-Moses and Gash (2011) and Benyon and Doody (2015) reported that when the daily rainfall total was less than 5 mm, 50% of the rainfall was lost through canopy interception and evaporation from the soil surface. In addition, David *et al.* (1997) found that mature *E. globulus* plantations were able to transpire up to 3.64 mm day^{-1} when soil water was available. Based on these findings, the categories were defined on the basis of the short-term (2 weeks) and long-term (30 days) rainfall preceding each trial. The 2-week rainfall figure was the sum of all rainfall in that period whereas the 30-day figure was the sum of daily rainfall totals greater than 4.9 mm. Low-rainfall sites were those with a 2-week total of <10 mm and a 30 day total of <20 mm (19 sites). High-rainfall sites were those with a 2-week total of >20 mm and a 30 day total of >40 mm (16 sites). Medium-rainfall sites were those that did not fall into the low or high rainfall categories (12 sites).

The model forms tested were compared on the basis of their goodness of fit (R^2, mean bias and RMSE) and adherence to the assumptions underlying linear regression. The selected model was tested against the results from comparable published eucalypt CTL harvesting studies (Hartsough and Cooper 1999; Spinelli *et al*. 2002; Magagnotti *et al*. 2011; Seixas and Batista 2012; Ramantswana *et al*. 2013; da Silva Leite *et al*. 2014).

Results

Two models fitted the harvester productivity data well and met the requirements of linear regression. The best fit was a multiple regression of harvester productivity against mean merchantable tree volume and harvester engine power (Figure 1 and Table 2):

$$Prod = \beta_0 + \beta_1 \times Vol + \beta_2 \times Power \quad (1)$$

where *Prod* is harvester productivity (m^3 PMH_0^{-1}), *Vol* is mean merchantable tree volume (m^3) and *Power* is harvester engine power (kW). PMH_0 is productive machine hours excluding delays (see above).

Removing harvester engine power from equation (1) explained 1% less of the variability in harvester productivity (Table 2):

$$Prod = \beta_0 + \beta_1 \times Vol \quad (2)$$

where *Prod* is harvester productivity (m^3 PMH_0^{-1}) and *Vol* is mean merchantable tree volume (m^3).

Stand density (sph) (P = 0.922) and operator years of experience (P = 0.389) were not significant variables in the model.

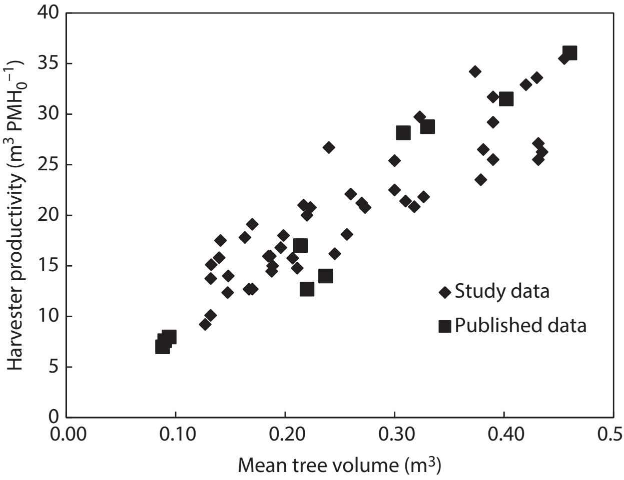

Figure 1. Harvester productivity plotted against mean tree volume for the current study and for comparable published eucalypt CTL harvesting studies.

Table 2. Harvester productivity model coefficients and goodness of fit measures.

Model	β_0	β_1	β_2	Mean bias	RMSE	R^2
Volume and engine power (Eq. 1)	0.655	58.72	0.036	0.21	8.2	0.80
Volume (Eq. 2)	5.62	57.84	–	−0.02	8.9	0.79

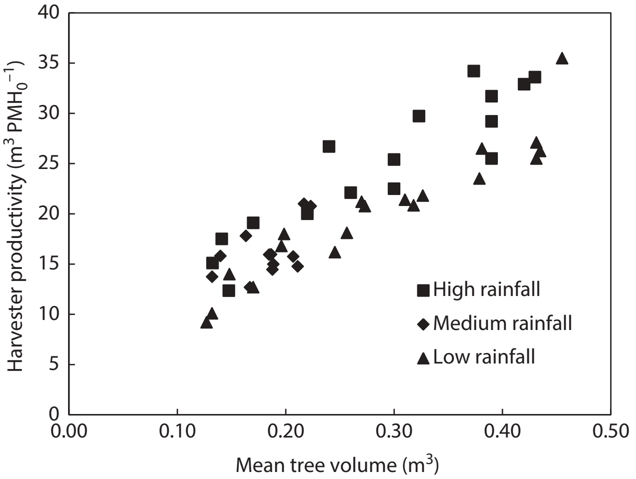

Figure 2. Harvester productivity plotted against mean tree volume for the three categories based on the quantity of rainfall preceding each study.

Data on harvester productivity (m^3 PMH_0^{-1}) from the current study and from the comparable studies were plotted against mean tree volume (m^3) (Figure 2).

Rainfall preceding each study appeared to have affected harvester productivity, with sites in the high-rainfall category generally having higher productivity than those in the lower-rainfall categories (Figure 2). The categorical variables used to model rainfall were statistically significant.

Discussion

The general harvester productivity model (Eq. 1) fitted the data well, explaining 80% of the variability in harvester productivity. Seventy-nine percent of the variability was explained by mean MTV (Eq. 2) and one percent by the harvester engine power. The high R^2 value for mean MTV is likely to reflect the fact that the analysis was based on mean harvester productivity values rather than values for individual trees (Heinimann 2001). The relative uniformity of site conditions, stand characteristics and harvester bases and heads across the study sites is also likely to have reduced the variability in the dataset. In contrast, the study by Spinelli *et al*. (2010) covered a range of species, stand types and ages, harvester bases and heads and so on, with a concomitant increase in data variability. Spinelli *et al*. (2010) also used a dataset collected over 10 years, whereas the data used in the current study were largely collected over 3 years.

The significance of tree volume in determining harvester productivity has been demonstrated in numerous published studies (e.g. Eliasson 1998; Sirén and Aaltio 2003; Nurminen *et al*. 2006; Acuna and Kellogg 2009; Strandgard *et al*. 2013). There are, however, few published results of eucalypt CTL harvesting trials comparable to the current study, and a number of these trials were conducted in stands with mean tree volumes well below that for which a CTL harvesting system would generally be used in Australian *E. globulus* plantation harvesting (~0.12 m^3 $tree^{-1}$). However, published findings of harvester productivity in stands with mean tree volumes comparable to those in the current study generally support the current study's model (Figure 1); further data would reinforce this conclusion.

Heinimann (2001) and Spinelli *et al*. (2010) also found harvester engine power to have a significant influence on harvester productivity. In the current study, the amount of variability in harvester productivity explained by engine power was small although statistically significant. This probably resulted from the combination of the relatively small range in engine power amongst harvesters in the study (104–224 kW with most being 104–140 kW) and the size of the trees relative to the engine power. Previous harvester productivity models have generally shown that harvester productivity increased, but at a decreasing rate, as tree size increased as harvesters were unable to handle larger trees as quickly as smaller trees (Visser and Spinelli 2012). In contrast, in the current study harvester productivity increased linearly with increasing tree volume, suggesting that the harvesters were working well within their capabilities. This raised the possibility that smaller harvesters could be used to perform the same task with potential cost savings (Sirén and Aaltio 2003). However, the higher work capacity of the harvesters in the current study was required when felling and processing larger, often heavily-branched trees along the edges of each stand and stands with a mean tree volume greater than 0.5 m^3, though these form the minority of the current Australian *E. globulus* estate. Turner and Han (2003) reported that the cycle time of a small harvester (76 kW) was increased by about 25% when processing heavily branched stems (branches >5 cm diameter) compared with trees with fine branches (<1.2 cm). Current practice in radiata pine plantations in South Australia is for edge trees to be removed by specialised harvesting contractors. Adopting this strategy for *E. globulus* plantations would allow the harvesting contractors felling the remainder of the stand to use harvesting equipment better suited to this task. Increasing mean tree volumes beyond the study upper limit of 0.5 m^3 is likely to result in the rate of increase in harvester productivity decreasing, as has been observed in other studies. However, it is likely that the productivity of the less powerful harvesters in the study would be affected at lower mean tree volumes than for more powerful harvesters.

Operator performance was another potential source of variability in the study. Operator performance has been found to vary significantly between experienced operators using the same harvester and cutting in the same stand (Ovaskainen *et al*. 2004) and for the same operator from day to day (Cordero *et al*. 2006). Without similar studies, it was not possible to isolate the influence of operator performance in the current study. Although operator experience may also be an indication of performance, Purfürst (2010) suggested the duration of the initial learning curve for harvester operators was only about 8 months. Most of the operators in the current study had 5 years or more of experience and only one had 1 year of experience, which may explain why operator years of experience was not a significant variable in the harvester productivity model.

The statistically significant relationship between rainfall preceding each study and harvester productivity is likely to reflect the reduction in bark adhesion that occurs when soil moisture is plentiful (van den Berg and Little 2004). However, not enough information was collected in the current study to establish a causal link between rainfall, bark adhesion and harvester debarking effort and/or harvester productivity. More research into these relationships is required to determine if there is a significant effect.

Conclusion

The general harvester productivity model developed in this study fitted the study data well, explaining 80% of the variability in harvester productivity. The model was largely developed from individual time and piece counts over an hour or more, mostly collected over a 3-year period. Results from comparable published CTL eucalypt studies also generally supported the model. Mean tree volume was the most significant independent variable, explaining 79% of the variability. The remaining 1% was explained by harvester engine power. Operator performance has been identified in other studies as a significant factor determining harvester productivity, but it could not be tested in this study. The variables operator years of experience and the stand density (stems per hectare) of each study site were not significant. These findings suggest the model could be used to estimate harvester productivity for similar site conditions, tree form and harvester/harvester head combinations (which represent most of the Australian *E. globulus* plantation estate) where mean merchantable tree volume and harvester engine power were known or could be estimated. Estimation of harvester productivity for sites outside the range of those used in the study would require further research.

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