Productivity Model for Cut-to-Length Harvester Operation in South African Eucalyptus Pulpwood Plantations

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Abstract

There has been a concerted shift from traditional motor-manual and semi-mechanised timber harvesting systems to mechanised cut-to length (CTL) operations in South Africa. This is particularly true in Eucalyptus pulpwood felling and processing, South Africa's largest commercial wood resources used in the pulp and paper industry. Mechanisation improvements are typically driven by increasing safety regulations, product quality and productivity concerns related to traditional harvesting systems. The objective of this study is to develop productivity models for mechanised Eucalyptus pulpwood CTL felling and processing operations by combining the results of a number of individual studies done over a period of 24 months in the summer rainfall areas of South Africa. The study takes into account species, machine type (purpose built vs. excavator based), silvicultural practices (planted vs. coppiced) and slope. The pooled data revealed general productivity ranges from 5.16 m^3 PMH^{-1} to 27.49 m^3 PMH^{-1}.

Keywords: cut-to-length, eucalyptus, pulpwood, full-mechanized system, productivity study

1. Introduction

Commercial forestry has experienced a global shift toward mechanised harvesting operations (FAO 1997, Nurminen et al. 2006, Jiroušek et al. 2007). This change has also occurred in the South African Forest Industry, with the key drivers being forest worker health and product quality. With this transition, there has been an increase in studies dealing with timber harvesting and transport productivity aimed at determining and modelling equipment productivity. These investigations can provide the means to optimise economic gains and volume yields to managers and contractors (Williams and Ackerman 2016). Although a multitude of research related to mechanised harvesting systems have been conducted internationally, little research has been published in related operations in South Africa.

In South Africa, Eucalyptus is the predominant genus used for pulpwood and it accounts for 83% of the commercial wood resources for the pulp and paper industry in South African (FES 2011, FSA 2013). Although Eucalyptus is considered the most commonly planted (18 million ha in 90 countries) and valued hardwood, there remains a global deficiency of published data on mechanised Eucalyptus harvester operations (FAO 2006). As the South African industry has rapidly transitioned to fully mechanised CTL operations, there has been a need to determine the influencing factors that affect harvester productivity within a South African setting. In a review of scientific and peer reviewed publications, domestic and international, a total of 13 articles were found to be related to fully mechanised harvester-based Eucalyptus operations, but they were inconsistent in recording data in one way or another.

Although inconsistent, these studies identified and analysed influencing factors that are vital to understanding harvesting productivity. Factors include tree volume (Spinelli et al. 2010), species composition (Nurminen et al. 2010), equipment type (Siren and Aaltio 2003, Spinelli et al. 2010), site characteristics (Puttock et al. 2005, Andersson 2011), silviculture practices (Kellogg and Bettinger 1994, Ramantswana et al. 2013), operator training (Ovaskainen et al. 2004, Purfürst and Erler 2012), delimbing and debarking (Hartsough and Cooper 1999).

According to Spinelli et al. (2010), tree volume has been identified as the most significant variable to determine harvester productivity and is a reliable predictor of productivity. Additional studies not only verified this, but suggested that production rate is positively correlated to increasing tree volume (Akay et al. 2004, Eriksson and Lindroos 2014). Other projects used diameter at breast height (DBH) as the continual predictor of productivity, which made it difficult to compare with studies that used tree volume (McEwan et al. 2016, Acuna and Kellogg 2009, Hartsough and Copper 1999). Literature also found operator performance as an influencing factor to harvester productivity, but it has been challenging to quantify because training is not standardised globally (Ovaskainen et al. 2004, Purfürst and Erler 2012). The human factor and work shift were considered by Passicot and Murphy (2013), but operations observed consisted of tree volume exceeding the common South African range to be applicable. In addition, productivity was often recorded as m^3 PMH^{-1}, but in Hartsough and Nakamura (1990) and Acuna and Kellogg (2009), productivity was recorded as bone dry tonne per scheduled hour (BDT/SH) or tonnes PMH^{-1} with no information on the machine used. Terrain, more specifically slope, was identified in some of the studies and proven to have a considerable effect on productivity (Davis and Reisinger 1990, Spinelli et al. 2002, Acuna and Kellogg 2009). In Acuna and Kellogg (2009), slope, ranging from gentle to moderate slope, was identified as a significant factor, but productivity was recorded inconsistently when compared to other literature.

Despite a few factors within each published paper applicable to a South African context, most were inconsistently recorded and could not be used as a predictor of productivity trends. As a means to address the limited literature, the individual studies performed in South Africa were combined in an attempt to develop general productivity models.

The objective of this study is to develop general productivity models for mechanised Eucalyptus pulpwood CTL harvesting (felling and processing) operations by combining the results of five individual and independent productivity studies completed over a period of 24 months in Eucalyptus clearfelling pulpwood stands in the summer rainfall area of South Africa. This study will take into account species, silvicultural practices (planted vs. coppiced), machine type (purpose built vs. excavator based) and slope inherent in the five studies.

2. Material and methods

2.1 Case studies

Five individual productivity study sites located in the north-east of South Africa were included in this study. The sites have been sequentially numbered and referred to by this numbering throughout this paper (Fig. 1). These studies covered four different species of Eucalyptus and were all clear-felling pulpwood compartments that were harvested during the dry winter months. Only two components of the harvester operation were considered: felling and processing. The four species harvested included: *Eucalyptus grandis* x *camaldulensis* (*G* x *C*), *Eucalyptus grandis* x *urophylla* (*G* x *U*), *Eucalyptus smitthii* (*ES*) and *Eucalyptus dunnii* (*ED*). Further on in this study, species will be referred to by their acronym.

Harvesting sites covered a diverse range of terrain (slope), tree characteristics (species, form, individual tree volume) and harvester machine type (excavator based and purpose built) in order to incorporate site conditions and factors that contribute to productivity trends (Table 1). Even though the five individual studies had varying original objectives, the data was collected using a standardised time-study protocol (Ackerman et al. 2014) that enables comparisons between the studies.

The objective of Study 1 was to determine productivity differences between one and three pass debarking and debranching operation in a *G* x *C* clones on even terrain. The objective of Study 2 was to determine productivity differences between excavator based and purpose built machines on varying slope terrain in a *G* x *C* clone. The objective of Study 3 was to determine productivity differences between three and five pass debranching and debarking in a *G* x *U* clone on even terrain. The objective of Study 4 was a pure productivity study of an excavator based harvesting

Fig. 1 Locations of study areas

Table 1 Individual site and stand characteristics of the five studies

Site characteristics	Study 1	Study 2		Study 3	Study 4	Study 5
		Study 2[1]	Study 2[2]			
Species	*Eucalyptus grandis x camaldulensis (G x C)*	*Eucalyptus grandis x camaldulensis (G x C)*	*Eucalyptus grandis x camaldulensis (G x C)*	*Eucalyptus grandis x urophylla (G x U)*	*Eucalyptus smithii (ES)*	*Eucalyptus dunii (ED)*
DBH, cm						
Average	15.5	15.3	16.3	21.6	15.9	16.4
Min.	7.0	9.0	7.3	8.6	5.2	8.0
Max.	21.2	27.2	25.3	29.1	35.7	30.5
SD	2.3	2.7	2.9	3.8	4.6	5.0
Age, y	12	8	8	9	7	12
SPH, n ha^{-1}	987	1001	926	1087	1106	826
Average height, m	16.3	19.88	20.03	25.4	17.4	18.5
Average tree volume m^3 $tree^{-1}$	0.12	0.15	0.15	0.38	0.14	0.15
Slope[a], % (continuous variable)	Level (0–10)	Level – very steep (0–61)	Level – very steep (0–61)	Level (0–10)	Level (0–10)	Level (0–10)
Silvilculture	Planted	Planted-Coppice	Planted-Coppice	Planted	Planted	Coppice
Carrier type	Excavator	Purpose Built	Excavator	Excavator	Excavator	Excavator
Machine manufacturer	Hitachi Zaxis 200	Timberpro TL-725B	Volvo EC-210bf	Hitachi Zaxis 200	Hitachi Zaxis 200	Komatsu PC 200
Head	Waratah H616	Maskiner SP 591-LX	Maskiner SP 591-LX	Waratah H616	Maskiner SP 591-LX	Maskiner SP 591-LX
Location	Zululand	Melmoth	Melmoth	Kwambo	KZN Midlands	Piet Retief
Sample size	297	1156	1099	181	1478	177

[a] Slopes are classified using the National Terrain Classification for Forestry (Erasmus 1994)

machine, felling and processing poor form *ES* on even terrain. The objective of Study 5 was to determine productivity differences between three and five pass debarking and debranching passes operation in *ED* on even terrain. Debarking and debranching passes are defined as the number of times the harvester head travels along the tree stem debarking and debranching. The last pass will entail cross-cutting in log assortments.

2.2 Time study

Different researchers collected time study data at each of the study areas according to the South African Forest Industry Time-study Standard (Ackerman et al. 2014). Field time study observations were recorded using a Trimble GeoXT handheld computer. Time recorded was categorised into one of four elements identified in the standard: fell, process, move and delay (Table 2). All machine operators, although not the same in all studies, were considered trained and capable of operating the harvester in Eucalyptus pulpwood operations consisting of felling, debarking, debranching and crosscutting into assortments. Delay times were recorded regardless of duration. Productivity results were expressed in productive machine hours (PMH). Individual tree volume (m^3) was calculated using the Schumacher and Hall model (Bredenkamp 2012). Individual tree and compartment attributes recorded are reflected in Table 1.

In this study, slope is considered as a continuous variable. Continuous slope data were obtained from Digital Terrain Models (DTMs). These models were derived from large-footprint LiDAR data with approximate 1 m resolution.

Table 2 Time study elements breakdown (Ackerman et al. 2014)

Time element	Description
Fell	Starts when the operator begins moving the head to a tree, ends when the butt end begins to move through the head
Process	Starts when the butt end begins to move through the head, ends when the head has released the last piece of the tree
Move	Starts when the tracks begin moving, ends when the tracks come to a stop
Delay	Starts when the machine unexpectedly stops working, ends when work begins again

2.3 Experimental design

At each of the five study sites, diameter at breast height, measured over bark (DBH), was recorded for every tree using a diameter tape with an accuracy of 0.1 cm. While measuring DBH, each tree was allocated a unique number per study area in order to identify each tree when recording cycle times during the actual harvesting of the samples. Heights of at least 50 representative trees per site, chosen from various locations in the allocated compartment and spanning across the range of DBH available, were measured using a Haglof Vertex laser hypsometer with an accuracy of 0.1 m. The heights and DBH of these representative trees were used to derive a regression, which allowed the heights of the remaining, not measured trees, to be estimated based on the DBH measured for each tree.

Every tree was numbered to facilitate the pairing of tree dimensions with felling and processing times to calculate productivity (m^3 PMH^{-1}). Numbers were painted on tree stems at an angle to ensure visibility during timing. Prior to harvesting, a randomised block experimental design (RBD) (Clewer and Scarisbrick 2001) was applied to each study area to reduce bias.

2.4 Statistical analysis

Basic statistics, correlation analysis and linear regression modelling were performed to determine and clarify variables affecting harvester productivity. Tree volume was used as the continuous predictor for regression models with additional correlation analyses applied to identify the significance of variables, such as species, carrier type, silviculture, slope, and debarking pass on productivity. Where significant factors were identified, additional models were developed.

As a secondary analysis, multiple regression analysis was conducted to better fit the dataset. The pooled dataset was categorised according to potential influencing factors, notably species and carrier type, to determine if these factors were significant to harvester productivity, while using tree volume as the predictive variable. To compensate categorical influencing factors with more than two categories, such as species and carrier type, data was grouped and analysed regarding their respective categories. Multiple regression analysis was conducted as a means to capture residuals, and more accurately represent productivity.

After each multiple linear regression productivity model was developed, an analysis of covariance (ANCOVA) was conducted in order to verify potential significant differences between the individual linear regression models that make up each of the full multiple linear regression. If the results of the ANCOVA show that the individual linear regressions are non-parallel, then the ANCOVA is rejected and the multiple linear regression model is significant.

However, if the test cannot reject that the individual linear regressions are parallel, then significance of the full multiple linear regression is not established. Further testing of intercept equality is conducted in order to establish that the models are not the same. If equal intercept cannot be rejected, the multiple linear regression model developed is not significantly different and a single linear regression model can adequately fit the dataset. However, if intercept equality is rejected, the multiple linear regression productivity model is a better fit for the dataset.

All analysis and models were conducted and developed through Excel and STATISTICA 13 (StatSoft, Tulsa, OK, USA).

3. Results

All five individual datasets were pooled to produce a mean productivity figure of 14.5 m^3 PMH^{-1} (Table 3). Literature and correlation analysis identified tree volume as the most significant contributor to harvester productivity (p<0.001). The pooled harvester productivity was plotted against tree volume and analysed to develop a single linear regression model. The result of the single regression equation was positively correlated with the dataset (r^2=0.64, p<0.001), where the regression equation is y=4.536+63.801x (where x = tree volume) (Fig. 2 and Table 3).

The average productivity for each of the individual studies varied between 13.80 and 27.49 m^3 PMH^{-1}. Regression models were also developed for each of the different studies (Table 3). The productivity models were developed with »x« equal to tree volume.

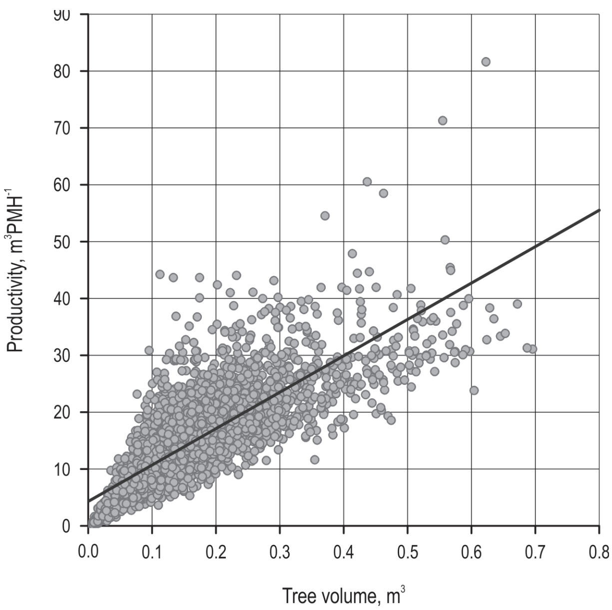

Fig. 2 Single linear regression model of pooled productivity

Table 3 Mean productivity per study

Study	Mean productivity m^3 PMH^{-1}	Equation	R^2	Significance
Overall	14.47 (0.35–69.22)	$y=4.536+63.801x$	0.64	***
Study 1	17.93 (2.92–43.78)	$y=5.800+102.784x$	0.45	***
Study 2	14.45 (1.90–44.32)	$y=4.754+63.611x$	0.61	***
Study 3	23.61 (2.46–58.57)	$y=3.283+53.041x$	0.79	***
Study 4	27.49 (0.35–59.24)	$y=1.073+82.817x$	0.76	***
Study 5	13.80 (1.56–69.22)	$y=1.085+84.778x$	0.75	***

x = tree volume, m^3; *** refers to significance at $p<0.001$

3.1 Multiple linear regression

Along with single linear regression models, multiple linear regression models were developed to better explain variation of the pooled dataset. All multiple linear regression equations, when significant, were developed considering species, carrier type (excavator based verse purpose-built), silviculture (planted or coppice), slope, debarking and debranching harvester head passes and tree volume. In this analysis, slope and tree volume are continuous variables, while silviculture, harvested head passes, carrier type and species are categorical.

3.2 Species

Productivity equations were developed by categorising data by species. Along with species, equations of carrier type, silviculture, slope, debarking pass and tree volume were considered.

Multiple linear regression models were developed for each species. Models for *Eucalyptus smitthii* (*ES*) and *Eucalyptus dunnii* (*ED*) were not significant from each other after an ANCOVA test (p=0.48). As the individual models for *ES* and *ED* were not significant, both species data were pooled to develop a new combined model (*ES+ED*). The overall and three species based models, *ES+ED*; *G* x *C*; *G* x *U* (Table 4), show a positive relationship with increasing tree volume.

Each productivity model was developed with respect to influencing factors. For instance, the influencing factors to *ES+ED* productivity were silviculture, pass and tree volume, while, *G* x *C* productivity was influenced by carrier type, silviculture, slope, pass and tree volume. *G* x *U* productivity was only influenced by pass and tree volume.

As multiple variables were used to develop these models, predicted values versus observed values were plotted (Fig. 3). Each of the productivity models represent the pooled dataset with r^2 greater than 0.60.

3.3 Species and harvester type

As suggested by Sirén and Aaltio (2003) and Spinelli et al. (2010), machine differences may have an effect on productivity. Therefore, the pooled dataset was reanalysed and new productivity equations were developed

Table 4 Regression equation by species

Species	Equation	R^2	Significance
Overall	$y=23.684+(0.497)*x_1+(-0.734)*x_2+(0.027)*x_3+(-3.963)*x_4+(64.430)*x_5$	0.68	***
ES+ED	$y=0.847+(1.189)*x_2+(83.087)*x_5$	0.76	***
G x C	$y=21.246+(0.174)*x_1+(-1.906)*x_2+(-0.052)*x_3+(-2.633)*x_4+(65.652)*x_5$	0.60	***
G x U	$y=3.283+(53.041)*x_5$	0.78	***

x_1 = model type (purpose-built = 1 or excavator = 2); x_2 = silviculture (planted = 1 or coppice = 2); x_3 = slope (percent); x_4 = number of processing passes; x_5 = tree volume (m^3); *** refers to significance at $p<0.001$

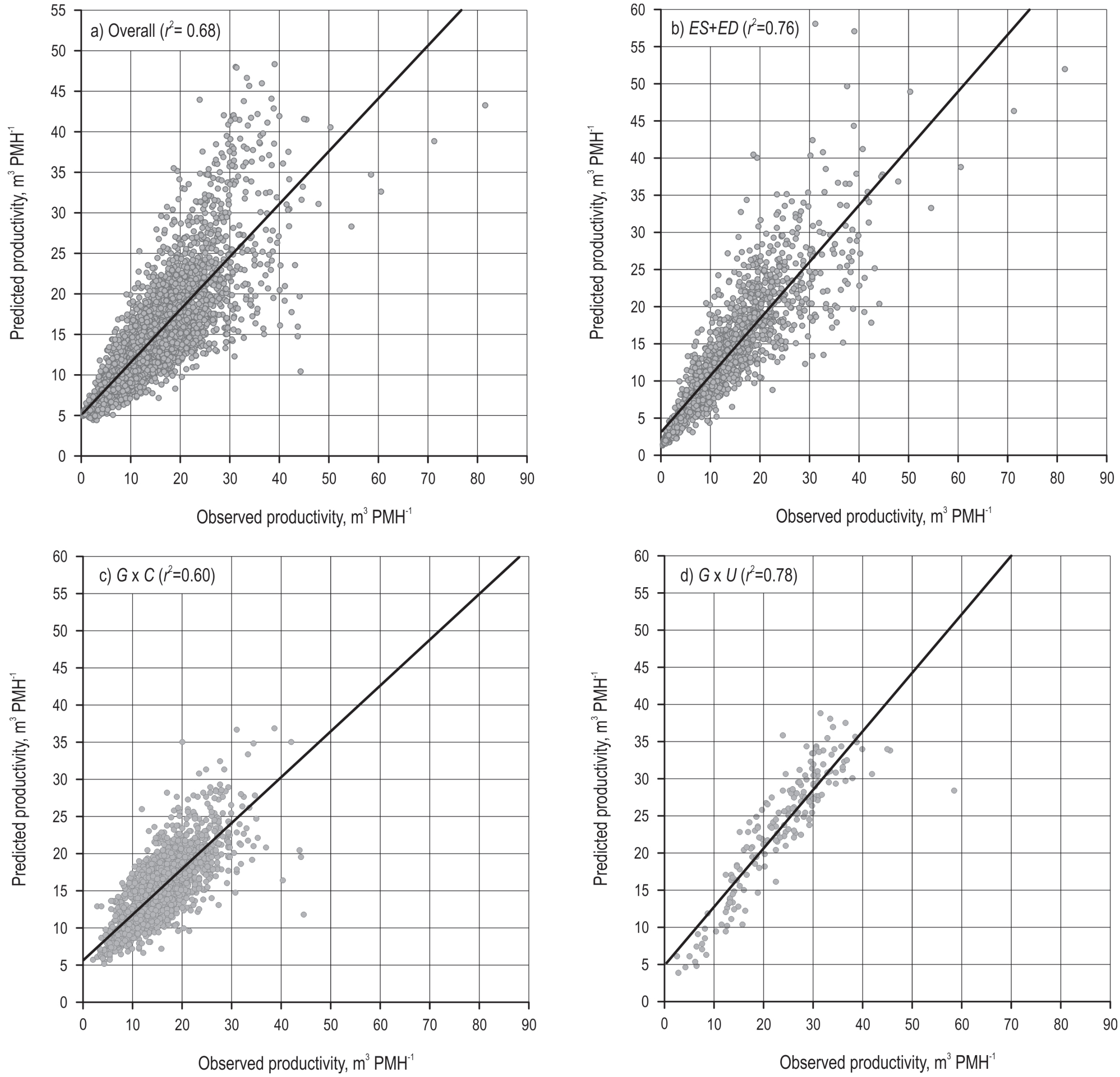

Fig. 3 Productivity regression models per species, including predictive values versus observed values

Table 5 Regression equation based on harvester machine make per species

Machine make	Species	Equation	R^2	Significance
Hitachi	*ES+ED*	y=4.368+(63.286)*x_5	0.65	***
Komatsu	*ES+ED*	y=1.052+(83.114)*x_5	0.76	***
TimberPro	*G* x *C*	y=10.559+(–2.300)*x_2+(–0.094)*x_3+(62.286)*x_5	0.56	***
Volvo	*G* x *C*	y=4.979+(–1.455)*x_2+(0.003)*x_3+(73.665)*x_5	0.64	***
Hitachi	*G* x *C*	y=22.427+(–3.196)*x_4+(52.717)*x_5	0.62	***
Hitachi	*G* x *U*	y=20.197+(–2.064)*x_4+(40.857)*x_5	0.56	***

x_1 = Silviculture (planted = 1 or coppice = 2); x_3 = Slope (percent); x_4 = Number of Processing Passes; x_5 = Tree volume (m³);
*** refers to significance at $p<0.001$

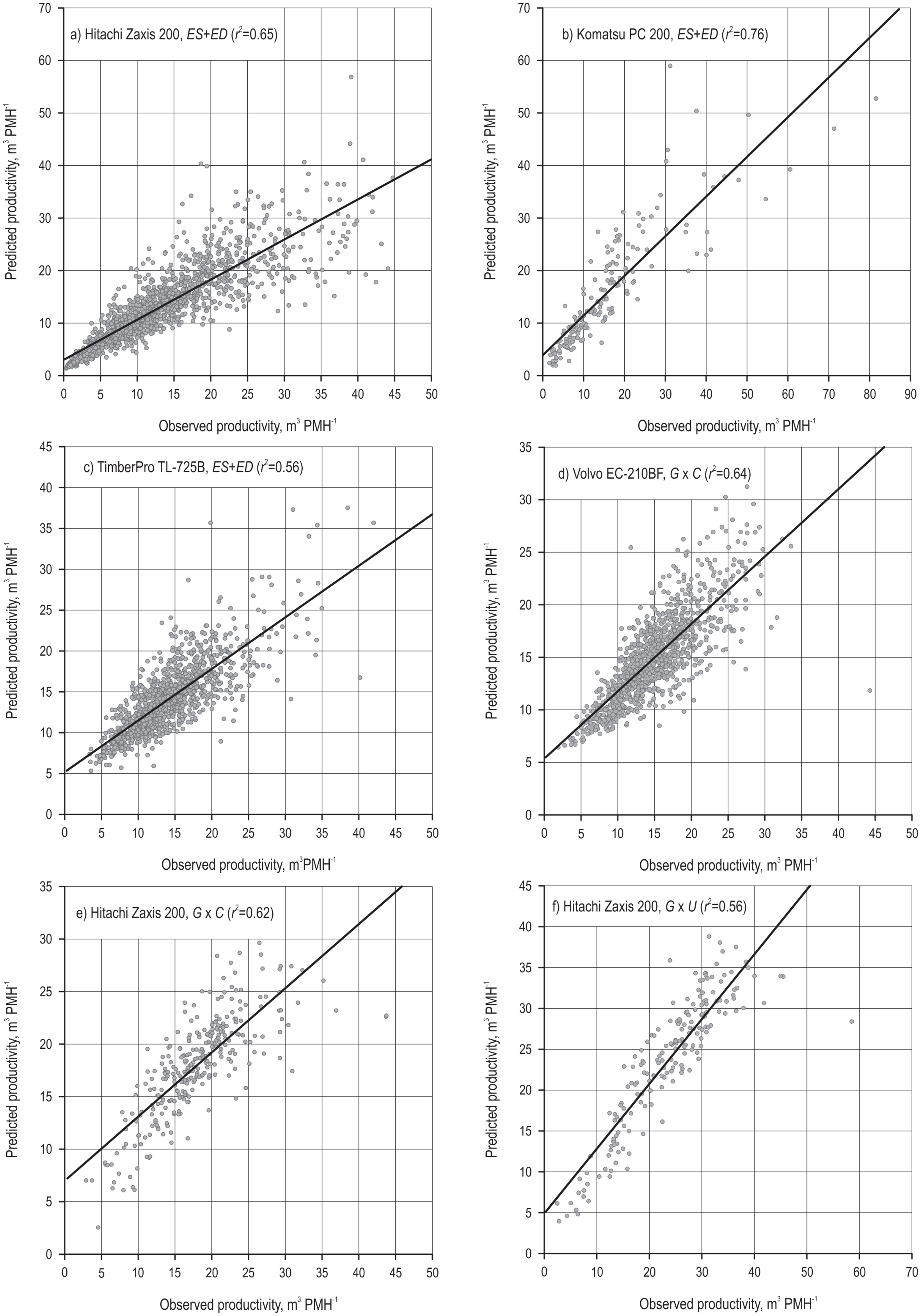

Fig. 4 Productivity regression models per species and harvester manufacturer and model, including predictive values versus observed values

with both species and harvester manufacturer as categorical variables. The TimberPro harvester, used at one site, was the only purpose built machine. All the other sites were harvested using excavator based harvesters. Silviculture, slope, debarking passes and tree volume were each tested for significance and included in the appropriate productivity models. Again, each of the multiple linear regression models was positively correlated with increasing tree volume (Table 5).

The Hitachi and Komatsu *ES+ED* productivity was only influenced by tree volume. The TimberPro *G* x *C* and Volvo *G* x *C* productivity was also influenced by tree volume, but also by silviculture and slope. In the *G* x *C* and *G* x *U* stands with the Hitachi machine, the productivity was only influenced by pass and tree volume.

As previously completed for the species based models, predicted values verses observed values graphs were plotted to demonstrate the accuracy of developed models by plotting the model over the recorded productivity of each carrier make and species (Fig. 4).

4. Discussion

When comparing five original studies using multiple linear regressions, the highest productivity was observed in Study 1, while the lowest productivity was recorded in Study 3. Data collected in Study 4 and Study 5 had the second highest productivity when stem size exceeded 0.19 m^3, regardless of poor tree form. However, as tree volume decreased below 0.19 m^3, productivity recorded in Study 2 and Study 3 exceeded the values of Study 4 and Study 5.

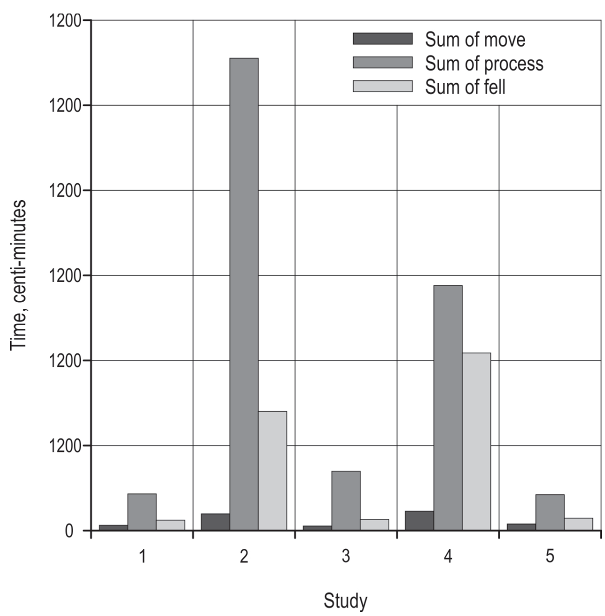

Fig. 5 Individual time consumption per work element per study in centi-minutes

In Study 2, steep and varying slope may be responsible for the high recorded processing time (Fig. 5) and, hence, lower productivity similar to Acuna and Kellogg (2009). Study 3 had the second highest mean productivity as a result of larger and higher volume trees. While productivity would be expected to be even higher on this site based on most published literature, considerable additional time was required for processing each tree, lowering overall productivity similar to the results found in Nakagawa et al. (2007, 2010).

4.1 General productivity models

In previous studies, tree volume was identified as a significant predictor of harvester productivity and, as a result, regression equations were developed based on tree volume (Sirén and Aaltio 2003, Nurminen et al. 2010, Acuna and Kellogg 2009, Strandgard et al. 2013, Standgard et al. 2016).

In order to compare the pooled dataset to the literature data, a single linear regression model was developed based on 21 previously published papers. In order to do this, the mean productivity values and the mean tree volume in each publication were plotted and a new single linear regression model was developed. The literature based model was then overlapped with the single linear regression model developed from the pooled dataset (Table 6). Unfortunately, due to the small sample size from literature data, the comparison was limited.

Specifically, in this comparison, all productivity data in the combined dataset and the literature models associated with tree volumes greater than 0.5 m^3 were removed from the analysis. This process allowed the dataset to stay within an appropriate harvested tree volume range. A typical 10 year old harvested *G* x *C* grown on a high site index South African plantation, would have a volume of 0.23 m^3 (Kotze et al. 2012), with few ever exceeding this 0.5 m^3 limit.

Table 6 Regression model equation of literature based data against dataset

	Regression model	R^2	Significance	N
Current study	$y=4.0582+67.3274x$	0.624	***	4388
Literature	$y=2.4658+52.6189x$	0.623	***	21

x = tree volume in m^3

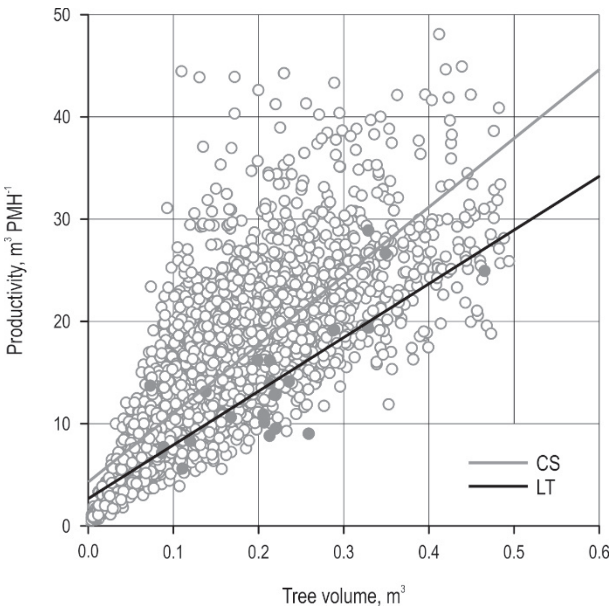

Fig. 6 Combined dataset (CS), published literature (LT) models and data points in respect to tree volume and productivity

Fig. 6 plots the literature and combined dataset models in respect to tree volume and productivity. Additionally, all individual data points are plotted to illustrate the spread of data around the models. Overall, both models show clear productivity increases with increasing tree volumes.

The mean productivity recorded is 14.47 m^3 PMH^{-1}, whereas the productivity recorded for the literature model is 9.91 m^3 PMH^{-1}. When compared to the literature through the least squared method, the mean productivity captured by the combined study data was significantly more productive (p<0.001). Although the ANCOVA was ultimately rejected after testing intercept equality, it could not reject that the models may be parallel. (p=0.28). This may imply that the models have similarities, even though productivity is significantly different, or it could be potentially attributed to systematic error related to the removal of data to limit the effect of the large tree sizes in literature models.

4.2 Other influencing factors

4.2.1 Species

Similar to Nurminen et al. (2010), this study identified species having a significant effect on productivity (p<0.001). The G x C, ED and ES productivity models (Table 4) have a relatively higher spread of productivity values of less than 30 m^3 PMH^{-1}, while the G x U productivity model has a more consistent and regular spread of data with values of less than 45 m^3 PMH^{-1}. As each species-specific model has its own influencing factors, it is difficult to compare the models. For instance, carrier type and slope appear only in the Overall and G x C models, whereas silviculture, number of passes and tree volume appear in all of the models. Overall productivity estimates can be calculated with the basic data on influencing factors. These estimates are an important component in the management of logging crews and the extended forest products supply chain.

4.2.2 Carrier type

In the literature, machine and equipment selection has been considered to make a significant difference on harvester productivity (Sirén and Aaltio 2003, Spinelli et al. 2010). One of the reported potential differences is the influence of harvester head models (Laitila and Väätäinen 2013). This relationship was not confirmed by the current study; it was only able to establish significance for the specific harvester manufacturer and model when tested with a correlation analysis.

Furthermore, no published literature was found on productivity based on machine selection between excavator based machines verses purpose-built machines, especially in relation to Eucalyptus CTL harvesting operations. This study compared the two carrier types and confirmed purpose-built machines as being more productive for most tree volumes, but as tree volume decreased so did the margin of significance. Although less common in South Africa because of the high initial investment cost, purpose-built machines specialise in tree felling and processing, which keeps their production rate stable and less affected than excavator based machines by factors such as terrain changes (Martin 2016).

4.2.3 Slope

Ground slope of the sites in this study ranged from flat to over 60%. In all studies except Study 2, slope was classified as per Erasmus (1994) as level (0–10%) and, after analysis, it was found to be insignificant to production rate (p=0.07). In contrast, Study 2 had varying slopes ranging from level to very steep. The literature suggests that regardless of tree volume, a steeper slope leads to a decrease in harvester productivity (Spinelli 2002, Acuna and Kellogg 2009, Magagnotti et al. 2011, McEwan et al. 2016). The influence of slope, as stated in the literature, was only significant in Study 2, where there were more data on steeper terrain used in the analysis. At the same time, the less steep terrain had very little influence on productivity in the full tree volume range.

4.2.4 Passes for debarking and delimbing

As Eucalyptus trees are typically debarked and delimbed at the stump in CTL operations, these activities are considered in the development of productivity models. Debarking effort is related to the strength of the bark/wood bond; the stronger the bark/wood adhesion, the greater the impact on debarking productivity (Hartsough and Cooper 1999, van de Merwe 2014). The literature has suggested that climatic conditions can significantly affect the barkwood bond of logs due to varying moisture content and, therefore, the productivity rate of immediate in-field debarking (Öman 2000, Araki 2002, Nuutinene et al. 2010, van de Merwe 2014). Two studies did not have the number of passes included in their models. In Study 2, the main focus of the project was to investigate carrier type interactions with productivity on variable terrain, so little to no data was collected on the number of passes required for debarking and delimbing. Likewise, the focus of Study 4 had limited interest in the number of passes and these data fell out of the model as insignificant (p>0.05).

4.2.5 Independent literature models

As previously stated, many studies have shown tree volume to be the most constant variable to determine harvester productivity (Spinelli et al. 2002, Ovaskainen et al. 2004, Jiroušek et al. 2007, Nakagawa et al. 2007, Spinelli et al. 2010, McEwan 2012, Picchio et al. 2012, Seixas and Batista 2012). The strong correlation between tree volume and productivity is confirmed by the analysis in this study, where tree volume was identified as the most significant predictor of harvester productivity (p<0.001). In the general productivity models discussed in the first part of this section, the literature based model was generated using volume and productivity data points from multiple papers to develop a linear regression model. Three additional published studies fully developed productivity models that allow a further comparison with the combined dataset model. All four of these models are plotted in Fig. 7.

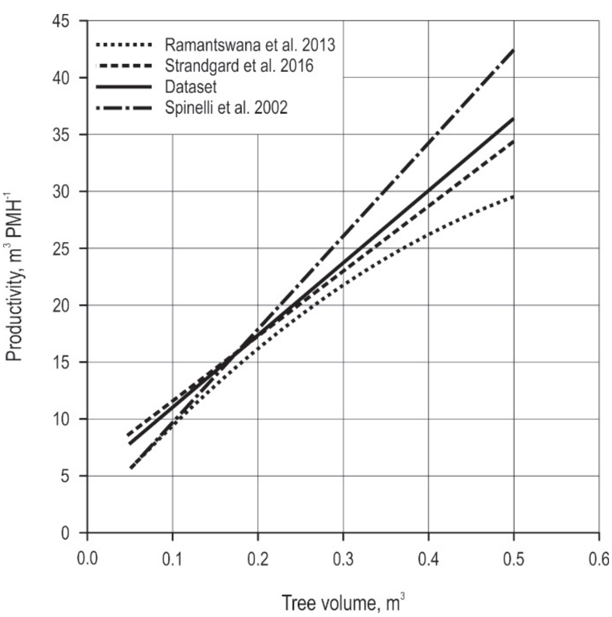

Fig. 7 Harvester productivity (m^3 PMH^{-1}) for three independent literature models and the combined dataset model

The Spinelli et al. (2002) and Strandgard et al. (2016) models focused on developing harvesting productivity models for Eucalyptus with regard to southern Europe and Australia, respectively. Ramantswana et al. (2013) considered harvester productivity effects on differently managed silviculture (coppice verse planted) Eucalyptus plantations. Despite different primary objectives, the models were all based on tree volume as the continuous predictor and thus they were comparable with the combined dataset model. When models were compared, the productivity model developed with the dataset model fits into the existing range and follows the common trend based on literature models (Spinelli et al. 2002, Ramantswana et al. 2013, Strandgard et al. 2016).

These regression models not only reveal, but validate the increase in productivity of the harvester as tree volume increases, regardless of the consideration of additional variables (i.e. terrain, silviculture, carrier type). These equations are the start of a potential productivity equation to help local stakeholders and contractors to determine productivity and cost models for future South African operations.

4.3 Limitations

The main limitations of this study are as follows:

⇒ as this study consists of a combination of discreet datasets with diverse objectives and variables, not necessarily recorded in all studies, analyses and comparisons were complicated

⇒ although considered trained, different operators were used over the two-year data collection period of this study. Operator's efficiency was excluded from analysis

⇒ weather conditions for each of the studies were not included in this combined dataset. The productivity of different tasks, like debarking, can vary between wet and dry weather, so while these data were assumed to be collected during normal dry conditions, actual daily weather could result in productivity differences. Weather effects were not included in this analysis.

5. Conclusions

This study developed general productivity models, specific for South Africa, for mechanised Eucalyptus pulpwood CTL harvesting (felling and processing) operations through the combination of the results of five individual studies. The models considered species, silvicultural practices (planted vs. coppiced), carrier type (purpose built vs. excavator based machines), number of passes for debarking and delimbing and slope.

When studies were combined, the overall mean productivity from the dataset was 14.47 m^3 PMH^{-1} with a range between 0.35 m^3 PMH^{-1} and 69.22 m^3 PMH^{-1}. Through a correlation analysis, tree volume was found to be the most significant predictor of overall productivity, confirming the published results. Based on this result, a single linear regression model was developed with respect to the individual tree volume.

To further strengthen the models, the additional influence of species, silvicultural practices, carrier type, number of passes for debarking and delimbing and slope were incorporated into a general productivity model through multiple linear regression analysis. The dataset was then categorised by species, showing that there were productivity differences for each species groups. As each species group used different contributing factors, it was impossible to make significant comparisons between the groups.

A new model based on existing data points from published literature and three other published complete productivity models were also compared with the models developed in this study. Similarities between the models confirmed that harvester productivity increases as tree volume increases, regardless of the consideration of additional variables (i.e. slope or silviculture).

As the first step in refining a locally relevant productivity model for mechanised CTL systems, these results can help stakeholders and contractors to determine productivity and costs for future operations. This work by no means addresses all aspects of Eucalyptus pulpwood clearfelling productivity, but continued efforts in this field and broadening the database with more and diverse data, will lead to a robust South African specific productivity model.

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