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A comparison of excavator-based harvester productivity among different machine operators in a clear-cut *Eucalyptus* plantation forest, South Africa

Kylle Schwegman[1]*, Raffaele Spinelli[2], Natascia Magagnotti[2], Muedanyi Ramantswana[1] and Andrew M. McEwan[1]

[1] School of Natural Resource Management, Forest Engineering, Nelson Mandela University, George, South Africa
[2] Institute of Bioeconomy (IBE), Italian National Research Council (CNR), Sesto Fiorentino, Italy

*Corresponding author: kylleschwegman@gmail.com

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Abstract

Background: Recent studies have identified the machine operator as a potential bottleneck to increased machine productivity. Machine productivity variations between 20% and 40% have been observed among different machine operators engaged with wood harvesting under similar working conditions. Most factors (site, climate and terrain) affecting worker productivity have already been analysed and they are described in the existing literature. However, very little information is available regarding the impact of operator selection on the productivity of South African excavator-based harvesters.

Methods: Operator performance was assessed by analysing work study data collected from nine different harvester operators over a three-week period. The experimental conditions were approximately the same for each operator, since all crews worked in clonal *Eucalyptus* plantations clear-cut at the age of 6 to 7 years.

Results: Mean cycle time, which was the time needed to fell, delimb, debark and crosscut one eucalypt tree, varied from 26 to 51 s. Tree size accounted for approximately 25% of the total variation in cycle time and operator proficiency for 40%.

Conclusions: Significant operator variability can be found even within a relatively small pool of operators, and that variability is strong enough to emerge over the well-known dominant effect of tree size. Such variability might be reduced through pre-selection tests and training, both conducted in a simulated environment.

Keywords: Harvester operator; productivity; time study; cut-to-length harvesting

Introduction

Cut-to-length (CTL) harvesting machines require large capital investments which, in turn, demand high output productivity to guarantee investment profitability (Purfürst & Erler 2011). The productivity of CTL harvesters can be influenced by numerous variables, with stem size (piece volume) being the most recognised (see, for example, Eriksson & Lindroos 2014; Jiroušek et al. 2007; McEwan et al. 2016; Ramantswana et al. 2013). In addition to stem size, recent studies show that operator skill and competence strongly affect machine productivity (Häggström 2015; Kärhä et al. 2004; Ovaskainen 2005; Purfürst 2010).

A study conducted by Ovaskainen (2005) found that the variation in machine productivity (m^3 per productive machine hour) among different harvester machine operators can be as large as 40% —a finding confirmed by Kärhä et al. (2004) and Purfürst & Erler (2011). The reason for these differences has been attributed to different skills and abilities, or a combination thereof. Malinen et al. (2018) also observed a large variation in operator productivity and concluded that this

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was independent of age and experience. Therefore, it is difficult to define the indicators that would aid in selecting a good operator, and which factors could be managed to reduce the productivity variation among harvester operators.

An operator's learning curve normally has a sigmoidal shape that describes the "slow beginning", the "steep progress" and, finally, the "plateau" (Purfürst 2010). This corresponds to the slow progress when learning the basics on to the automation of movements, and finally to reaching what could be considered a full professional level of expertise (Purfürst 2010). A study conducted by Parker et al. (1996) showed that during the first phase of the operator's learning curve, the impacts associated with system changes (for example computer systems and/or harvesting systems), stand characteristics, operational instructions (for example specific work techniques or methods) and work method were far greater than in the later stages. Where new machine operators have received "on the job training" or have learned "by doing", it has been observed that there is also an increase in repair and maintenance cost when compared to pre-selection and formal training (Stirling 1990). This is due to the operators constantly pushing machines to run at maximum performance, or at the top of their capacity curve, which can strain joints and cause equipment to fail prematurely ("working the machines too hard"). Studies conducted in Europe show that in the first week of their careers most harvester operators perform at between 50% and 60% of their mature potential, which is reached within eight months on average (Purfürst 2010). However, further small improvements in performance continue to occur for at least five years (Gellerstedt 2002). While experience brings about productivity increases, there comes a time when such increases become negligible (Skirbekk 2004). The South African harvester machine operator pool generally consists of rural unskilled labour that has been selected by the company to operate a harvester machine. They are taught how to operate the machine through informal methods, generally on the job and with the assistance of a more experienced machine operator. This is the same method used in many other countries in the past, due to the high cost of formal training and the general absence of training facilities accessible within a convenient distance (Gaskin et al. 1989; Houghton 1995). Recent studies show that experienced operators develop specific felling techniques that make them more productive than their less experienced colleagues when handling difficult multi-stemmed trees (McEwan et al. 2016; Ramantswana et al. 2017). Although these studies did not specifically focus on the variation among different harvester machine operators, they do indicate that experience may make a difference. However, no studies specifically address the variability found among harvester operators when it comes to their productivity in typical clearcut operations in South African *Eucalyptus* plantations.

Therefore, the aim of this paper was to estimate the approximate size of productivity differences between South African harvester operators. In particular, the study aimed to test: 1) whether and by how much, productivity differs among individual machine operators once the other main effects (such as tree size/volume and terrain) have been removed or accounted for, and 2) whether and by how much operator age, work experience and previous training explain these differences, if any. By providing additional information relating to operators ("the human element") and what may cause variation in machine productivity, future research could be concentrated towards the development of a successful pre-selection and training model which could be tailored to the needs of any contractor or company.

Methods

Study site and design

The field data for this study were collected on a plantation north of Mtubatuba in KwaZulu-Natal, South Africa, managed by the SiyaQhubeka. The species planted consisted mainly of *Eucalyptus grandis* W.Mill ex Maiden *x Eucalyptus urophylla* S.T.Blake hybrid clones (Table 1). At the time of harvesting, the trees were between six and seven years old, with the volume of individual stems between 0.025 m^3 to 0.25 m^3. Terrain conditions were described according to the National Terrain Classification System using the code 321.2.1. This code represents: ground conditions = 321 which is moderate in dry state, good in moist state, very good in wet state; ground roughness = 2 which is slightly uneven; and slope class = 1 which means the ground is level (Erasmus 1994). The study covered operators working for two different contractors active in the area.

Data collection

A pilot study was conducted in the same area, allowing time study data collection and factors to be studied. This was essential to a first observation of operator working techniques; if any major differences where noticed, they would be included in the actual data collection. In addition to this, the pilot study data were used to determine whether there were any differences in operator performance while being observed. No differences were found between productivity in the pilot study and in the main project which took place some months apart. Prior to data collection, consent was requested from all operators involved, who were also asked to complete two questionnaires. The first questionnaire contained a mixture of open and closed questions relating to personal demographics (age, education). The second questionnaire made use of open and closed questions about the working techniques used by the operators, and whether the operators had developed techniques of their own to better cope with local conditions and/or improve productivity. Both questionnaires were completed in accordance with all ethical requirements such as consent, risk, privacy, anonymity, confidentiality, and autonomy. Since all operators used the same work technique, and this was the standard semi-herringbone work technique used in South African eucalypt plantations, this subject was not explored any further.

TABLE 1: Site information for work study trials on harvester operators in Zululand, South Africa.

Forest zone	**Zululand**	
Elevation (m a.s.l.)	~70	
Mean annual precipitation (mm)	~1150	
Mean annual temperature (°C)	21.5	
Tree spacing (m)	3 × 2	
Stand density (stems/ha)	1 667	
Site information specific to contractors	**Contractor A**	**Contractor B**
Mean DBH (cm)	15.4	13.0
Mean tree height (m)	22.8	20.4
Mean volume per tree (m^3)	0.170	0.109
[1]Compartment size (ha)	8-25	5-25
Completed [2]plots per operator	3-4	3-4

[1]Compartment = management unit
[2]Plot = experimental unit on which study measurements were conducted.

Prior to the collection of time study data, supervisors were asked to indicate which of the operators they were currently managing would be considered their best and their average operators in terms of productivity. A time study was then conducted. The aim of this study was to complete 400 trees for each participating machine operator, which would be marked in the test stand in such a way that the productivity and/or technique of each operator was not affected, and each plot would be separated by a buffer zone of three tree rows (five trees per row equating to 15 trees). All data collection for each operator, starting in the morning shift (one shift length is 9 hours), was completed in the same compartment on the same day. For the the machine operators who commenced work in the afternoon shift, data collection would be completed the following day in the same compartment. The workload of each operator was not influenced by this research study, although unforeseen problems (such as strike action for a local mining company) occurred during the data collection process which meant that not all machine operators were able to complete the planned 400 trees. The actual number of trees completed by each operator is provided in Table 2 under the individual operator breakdown.

During the data collection period no other work was recorded as all observed machine operators handled their work flows accordingly (no logs were dropped or incorrectly processed) and major downtimes were not recorded. For each operator, four plots were selected, each consisting of 100 trees (5 trees per row with 20 rows). Operator competence was also included as a subjective ranking system obtained from the shift supervisor prior to observations being made and recorded for each operator. Each tree in a plot was identified with

TABLE 2: Summary information for the nine individual operators who participated in this study.

Operator	No. of compartments[1] worked	No. of plots completed	No. of trees	Total time observed (minutes)	Gender	Harvester head	Ave. tree size (m^3)
1	1	3	294	266	M	Waratah	0.173
2	1	2	223	164	M	Waratah	0.170
3	2	2	217	181	F	Waratah	0.158
4	1	1	118	75	M	Waratah	0.192
5	1	4	415	175	M	SP	0.112
6	2	4	392	228	M	SP	0.101
7	1	4	397	184	M	SP	0.115
8	1	3	303	134	M	SP	0.117
9	2	2	221	134	M	SP	0.095
Overall	-	25	2580	1541	-	-	0.129

[1] A compartment is a contiguous area of the same species and age class and typically has a radius <400 m

a clearly visible numerical code, and its diameter at breast height was measured with a digital calliper and recorded in the study database. Furthermore, the height of 15 trees per plot was determined, to build a diameter-height curve and predict the height of the remaining 85 trees. The DBH and height of each tree was entered into proprietary volume tables available at the company to estimate its stem volume (Figure 1). This meant that the stem volume and time taken to harvest each individual tree could be recorded. Before the harvester felled each plot, the overall bark adhesion was tested with an axe. Sample standing trees were ring-barked with an axe at the base and rip-stripped from the base to the top of the tree to test bark wood bond strength. This simple test was carried out to provide an indication that the degree of bark adhesion was not an additional factor influencing harvester productivity. The bark adhesion was found to be similar across all the study areas; the bark could be removed in very long length strips (>10 m) (Ramantswana et al. 2013). Each participating operator was then monitored while harvesting their four plots. All data collected from each operator was obtained within the same compartment (usually the same day if the operator started first thing in the morning and over two days if the operator started in the afternoon as there would be insufficient daylight to continue the study). A video camera was then placed in the best possible position to record the harvester machine as a safeguard in case of any uncertainties. The time study data were collected by the researcher capturing the data as the marked trees were harvested.

Contractors, machine operators and machine specifications

A total of nine operators participated in the study and successfully completed all steps. The participants differed by age and work experience, with the oldest operator having the most work experience (15 years work experience, over the age of 53 years). The youngest operator was 27 years old and had just over four years of experience. In general, all the operators made use of the semi-herring bone felling technique, whereby the operators felled all trees (in a 5-row swath) to the right-hand side, processed the trees in front of the cab and stacked logs on the left-hand side of the machine. Each operator worked 9-hour shifts. The harvester-head specifications used by the two different contractors who participated in the study are illustrated in Table 3 along with average tree size felled and which operator (Numbered 1 to 9) operated under which contractor.

Data capture and analysis

The questionnaire data were recorded manually, then transcribed into categories and later coded and transferred into an Excel spreadsheet. The work study data were recorded using a Trimble Nomad Handheld computer with UMT plus time study app. Three work study elements were created, namely: Move, Fell and Process, with the total time of all three elements completing one cycle. ”Move” commenced when the harvester’s tracks were turning (distance >1m) and ended when they stopped. “Fell” commenced when the harvester head was swung by the boom in the direction of a specific tree and ended when the feed rollers were activated to feed the tree as the tree fell to the ground. The ”Process” element commenced once the feed rollers began to feed the tree whilst falling to the ground and ended when the harvester head was swung in the direction of the next tree or the harvester started moving. These data were imported into an Excel worksheet for processing and analysis. All data were organised into a master data set, and immediately checked for any clear and obvious outliers. Additional variables were then calculated, including tree volume (m^3 per tree), cycle time (s per tree), fell time as a percent of total work time, and processing time as a percent of total work time. The production of a single integrated master data set allowed checking the possible association between productivity (m^3 PMH^{-1}), work experience (years), age (years), method of training received, machine type, and a subjective competence ranking provided by the onsite supervisor, if applicable.

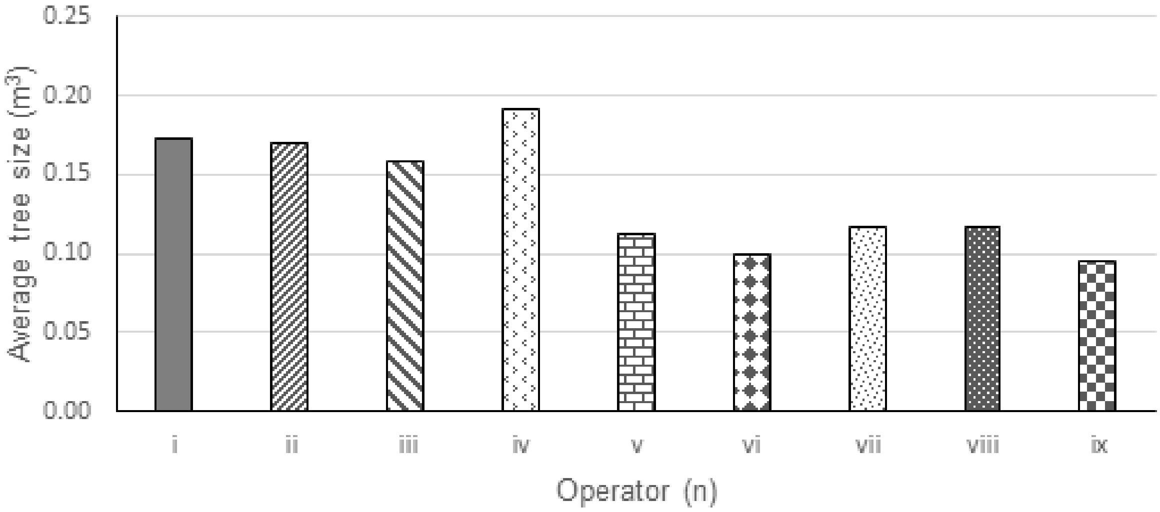

FIGURE 1: Mean tree size (m^3 per tree) harvested by each studied operator.

TABLE 3: Harvester head, carrier type specifications and individual operator information for Contractor A and B

Contractor	**A**	**B**
Make	Waratah	SP
Model	HTH 616	591 LX G3
Service hours (carrier)	12 000-12 500	10 000- 11 000
Maximum diameter capacity (cm):	<68	<60
Weight (kg)	1680	1800
Maximum feed speed (m/s)	5	7
Type of rollers	45 degree double-edged debarking	45 degree double-edged debarking
Computer type	Timbermatic 10	Timbermatic 30
Bar type	Carlton ¾”	Carlton ¾”
Chain type	Oregon ¾”	Oregon ¾”
Carrier Type	20 ton Track-based Hitachi excavator	20 ton Track-based Hitachi excavator
Operator	#1-4	#5-9

Descriptive statistics were used to summarise the data set and provide guidance for further inferential statistics. The statistical program (Statview for Windows 5.01) was used to determine whether there were significant differences in productivity and other factors among operators and groupings of operators based on experience, training, etc. (SAS Institute Inc. 1999). Standard tests for normality and homoscedasticity of the data were carried out (Ryan Noyer’s and Levene’s tests, respectively). Where data were not normally distributed, non-parametric tests were used. Differences among three or more groups were tested using the Kruskal-Wallis test, while differences between two groups were tested using the Mann-Whitney U test. If significant differences were found using an ANOVA, the Tukey-Kramer's test was used to determine which specific pairs of groups caused the difference. Statistical significance was assumed for $\alpha < 5\%$.

Results

Differences among operators

Ideally one would like to make use of machine productivity (m^3 PMH^{-1}) to determine differences among operators. However, productivity (m^3 PMH^{-1}) is related to tree size (m^3 per tree) and, therefore, differences in productivity among operators will be confounded due to differences in tree sizes in the plots that they harvested. It was decided that focusing on cycle time (seconds per tree) would provide a better measure of differences among operators. The mean cycle time for each operator is shown in Figure 2, with an overall mean cycle time across all operators of 35.8 seconds per tree.

The data, for mean cycle time were normally distributed and therefore a general linear model (GLM) was used to analyse differences in time consumption (cycle time) among the nine machine operators. There was a positive

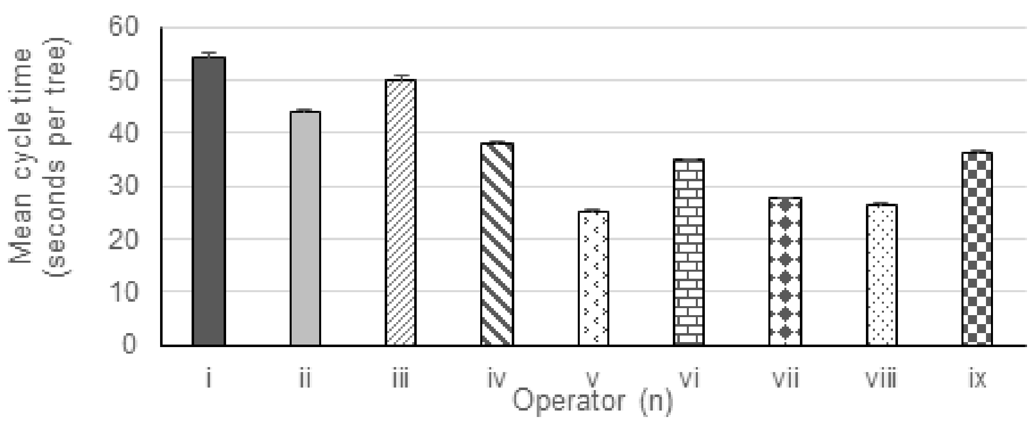

FIGURE 2: Mean cycle time (seconds per tree) with standard error bars for each operator.

relationship between tree size and total cycle time (Table 4). There were also significant differences in total cycle time among operators (p<0.001). Overall, tree size and operator explained approximately 66% of the variation in cycle time. Approximately 26% of the variation in cycle time (s per tree) was associated with tree size (m^3 per tree), while operator competence accounted for ca. 40%. A Tukey-Kramer's test showed that the cycle times recorded for almost all operators were significantly different from each other, except between operators 5 and 8, and 7 and 8.

Effect of experience, training, and supervisor ranking

Two categories were created for each of the following three factors: experience (years), training (type) and supervisor ranking (Table 5).

The Mann-Whitney U test showed that there were significant differences (p-value < 0.01) in operator performance between the categories. Although the sample sizes for the two groups created were small, results clearly showed that operators with >5 years of experience were faster than those with less experience. Furthermore, operators who were ranked top performers by their supervisors were significantly faster than those that were ranked as average. However, the results obtained for experience and training were confounded by significant differences in tree size, which was difficult to control during the experiment (Table 6). When it comes to the effect of training type, it is important to note that the group size was likely too small for reliable general conclusions, although the results were quite suggestive. No significant differences in trees sizes were found for rankings within contractor (Table 6).

Therefore, the results obtained for the effects of experience and training are inconclusive because they may depend on the influence of tree size differences. In contrast, it is safe to say that this study confirms that the supervisors were aware of the most productive operators—at least for the supervisors who participated in the study.

An analysis of covariance (ANCOVA) was done to investigate the effects of experience and training on productivity, after accounting for the effect of tree volume per stem. The ANCOVA results showed that over 35% of the variation in productivity could be attributed to tree size, which confirmed it as the main factor in determining productivity. Experience and training accounted for approximately 10% and 5% of the total productivity variation, respectively. Therefore 50% of

TABLE 4: Results from the ANOVA for total cycle time.

Source	DF	Sum of Squares	Adjusted Sum of Squares	Adjusted Mean Square	F-value	P-value	Effect Strength (%) aka (η^2)
Tree size	1	112054	24140	24140	424.4	<0.0001	26 %
Operator	8	168693	168693	21087	370.7	<0.0001	40 %
Error	2570	146156	146156	57			34 %
Total	2579	426904					

TABLE 5: Categorisation of the nine operators based on experience, training and supervisor ranking.

Factor	Description	Categories	Abbreviation	No. of operators n = 9
Experience	Refers to work experience. Years spent operating a harvester	More than 5 years	Exp>5 years	5
		Less than 5 years	Exp<5 years	4
**Training	Refers to the type of training undertaken prior to becoming a harvester operator	Operators that learnt by doing	Self-taught	6
		Operators that received formal training	Trained	3
Ranking	Rankings of operator productivity provided by their supervisors	Considered to be above average	Top	5
		Considered to be average	Average	4

**The data collected for training were through a questionnaire and did not require operators to supply the authors with a training certificate to validate the type of formal training received.

TABLE 6: Productivity and tree size differences between operators based on experience, type of training and supervisor ranking.

Factor	Category	Productivity (m^3 PMH^{-1})	Mean Rank	Tree size (m^3)	Mean Rank
Operator Experience	⩾ 5 Years	15.0	1495	0.136	1384
	< 5 Years	11.9	1058	0.121	1184
	Z-Value	-	-14.848	-	-6.814
	P-Value	-	<0.0001	-	<0.0001
Operator Training	Self-taught	14.4	1420	0.143	1468
	Course	11.9	1052	0.104	965
	Z-Value	-	-12.003	-	-16.395
	P-Value	-	<0.0001	-	<0.0001
Operator Ranking by Supervisor	Top	15.7	1600	0.129	1299
	Average	10.7	886	0.129	1279
	Z-Value	-	-24.123	-	-0.68
	P-Value	-	<0.0001	-	0.4965

Notes: Mean Rank, Z-Value and P-Value as obtained from the Mann-Whitney U test.

the productivity variation could not be explained by the three main factors that were tested in the experiment and that were found to have a significant effect on its outcome.

Harvester head analysis

No productivity differences were observed between the Waratah HTH 616 and SP591 LX G3 harvester heads although each harvester handled different tree sizes (Figure 3).

However, once tree size was accounted for through the ANCOVA analysis, significant productivity differences were found. Once again, the effect of tree size was dominant as it accounted for approximately 47.3% of the total variation in productivity. Harvester head model accounted for another 15.8%. The balance (36.9%) remained unexplained and must be attributed to factors other than the ones covered by this experiment. Both SP and Waratah heads were used by operators who achieved high and low productivity (higher performing operators were not associated with the use of a specific head).

Multiple linear regression was used to further refine the productivity estimate, introducing tree size as the main independent variable, accompanied by an indicator (dummy) variable that would account for the fixed effect of the harvester head model (Equation 1). Both independent variables were significant ($p<0.05$), and the model explained 56% of the variation in productivity (Figure 4).

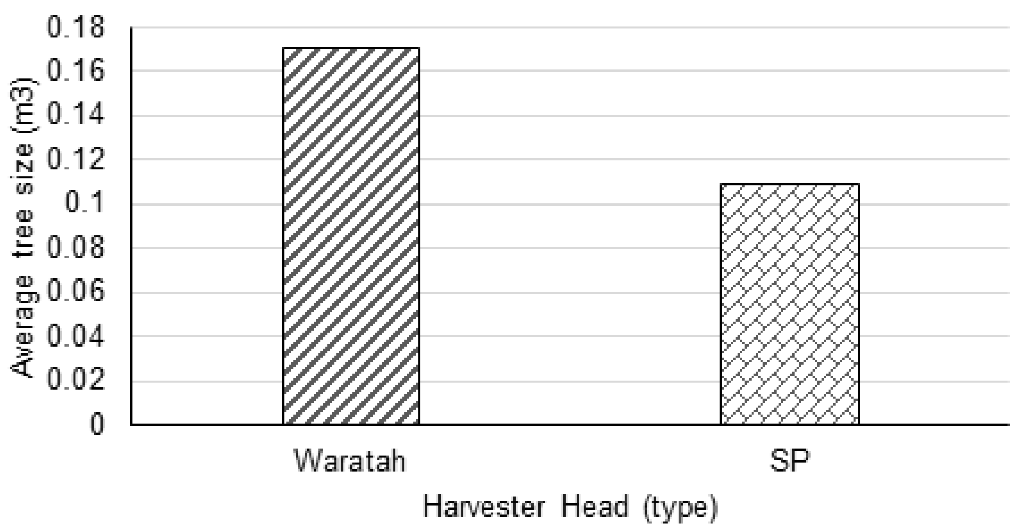

FIGURE 3: Comparison of the mean tree size processed using the Waratah and SP harvester heads.

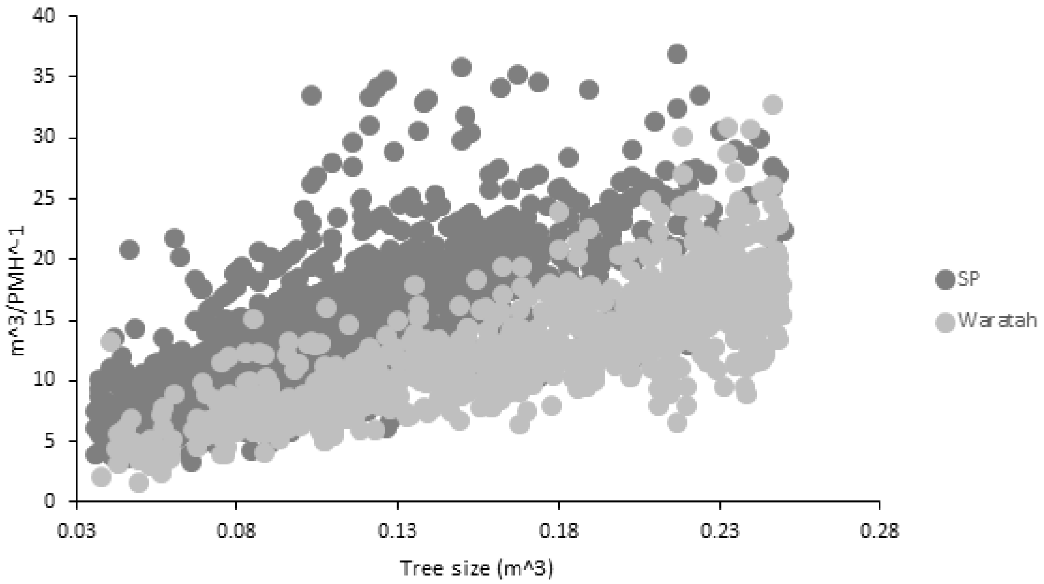

FIGURE 4: Relationship between machine productivity and tree size for the SP and Waratah harvester heads.

$$\text{Productivity} = \beta_0 + \beta_1 \text{ x TreeSize} + \beta_2 \text{ x HeadType} \quad [1]$$

where Productivity is machine productivity (m^3 PMH^{-1}), TreeSize is the size of an individual tree (m3), HeadType is a dummy variable representing the type of head (= 1 if SP head; 0 if Waratah head) and β_0, β_1, and β_2 are model parameters estimated from the data. The final fitted model is given by Equation 2:

$$\text{Productivity} = -1.365 + 85.324 \text{ x Tree size} + 5.788 \text{ x HeadType} \quad [2]$$

When the regression analysis included two indicator variables—one for harvester head model and the other for supervisor ranking—the coefficient of determination R^2 (adjusted) increased to 0.687. This further regression showed again that the SP591 LX G3 head was more productive than the other. Therefore, in future research there could be potential to include informed operator ratings for predicting operator performance and/or productivity.

Discussion

Prior to discussing the main findings of this study, it is important to highlight its main limitations, to create a valid frame of reference for the following discussion and conclusions. The main limitations for this study are the relatively small number of operators that took part in it, and the selection of a specific region in South Africa in which to conduct the investigation—both of which limit the wider generalisation of results, especially those concerning the specific productivity figures. A further and important limitation is the exclusive focus on cycle time and productivity. This study did not investigate operator effects on other performance indicators, especially on work quality (including value recovery, measurement accuracy, stand damage etc.), time management and production cost. Additional performance indicators would be fuel consumption and machine maintenance, on the assumption that productivity gains could also be obtained at the expense of a higher fuel consumption and higher machine/stand damage rates. However, the final number of participants (n=9) was sufficient for answering the specific research questions, although a larger number of participants would have been ideal for gaining deeper insights into topics such as experience and training. Unfortunately, that proved difficult to achieve. The authors did work with a slightly larger pool of operators, but not all the operators that were selected at the beginning were able to consistently complete all the steps in a relatively complex study. The final number of valid operators (n=9) in this study falls well within the range reported for similar peer reviewed studies, which often include as few as six operators (Freedman 1998; Ovaskainen 2005; Wenhold et al. 2020). Ideally, the study could have included some indicator of work quality, such as log size accuracy (length and diameter), log damage or log pile arrangement. However, including such indicators would have required significant additional work that would have strained the resources allocated to the project. In fact, subject literature generally focuses on productivity alone (Ovaskainen 2005); Wenhold et al. 2020)., and that was also the main focus of this study.

The study found a significant operator effect on cycle time, and this effect accounted for approximately 40% of the total variation in mean cycle time (seconds per tree). This level of variation among operators is consistent with results from similar studies, (Kirk et al. 1997; McEwan et al. 2016; Ovaskainen & Heikkilä 2007; Purfürst & Erler 2011). The primary focus of this study was to quantify differences in productivity among individual operators, rather than the factors such as experience, training and ranking that could potentially explain these differences. However, the latter was also tentatively explored and suggestive information was gathered. This component of the study supported the assertion that operator performance can be correctly assessed by experienced supervisors, which may restore some credibility to the much-debated practice known as "operator rating" (Magagnotti et al. 2013). On the other hand, the results of this study offer little insight when trying to determine the specific factors behind operator competence, because statistical analysis failed to find a significant association between productivity and work experience or training history. While these factors are found to have a significant effect on productivity, the effect seems quite modest. Obviously, this is partly the result of the dominant effect of tree volume on work productivity. Further explanations for the weak effect of experience and training on productivity may be the relatively limited variation in their levels encountered within the study, as well as the small sample size and the use of productivity as the only performance indicator. Experience and training are very general descriptors, which include a large variability in components. For instance, formal training can be administered in many different forms and with different emphasis on productivity (as mentioned earlier this study did not formally quantify the level/ degree of formal training received).

While the main aim of this study was not to compare different harvester heads, we found that after accounting for the effect of tree size higher productivity was achieved by operators using the SP head than those using the Waratah head. The results were obtained with both heads using similar carriers, but the heads were operated by different drivers and therefore the recorded differences might also be related to a systematic lower proficiency of the drivers equipped with one of the heads, or with a poorer machine-operator adaptation. A strict comparison of the two heads would require that the same operators are tasked with running both of them, which still would not resolve the uncertainty associated with adaptation.

By describing the variability in operator performance, this study stresses the importance of operator selection and training, in order to fully exploit the large potential of modern forest machinery (Pagnussat & Lopez 2017). In fact, it also supports the value of modern technology aimed at assisting operators, which may also contribute to reduce performance variability, bringing new operators to speed in a shorter time (Hartsch et al. 2022).

Conclusions

This study was able to determine that, even within a small region and between two contractor companies, one can find significant operator variability. Under similar work conditions, different operators can perform their tasks at a significantly different pace. Cycle time variability clearly emerges despite the well-known dominant effect of tree size. It is also clear that the qualities that make one operator better than the others are likely to be a complex combination that goes beyond pure tree cutting pace and are likely gained as a of the result of training and experience.

In conclusion, this study serves mainly to indicate the large productivity gap that could potentially be filled by managing operator selection and training when trying to increase productivity in the absence of further technology advances.

Competing interests

The authors have no competing interests to declare.

Authors' contributions

KS: conceptualisation, project administration, investigation, methodology arranging resources and writing original draft. RS: supervision, formal analysis, visualisation and review and editing. NM: supervision, formal analysis, visualisation, and review and editing. MR: supervision, methodology and review and editing. AMcE: supervision, validation and review and editing.

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References

Erasmus, D. (1994). *National terrain classification system for forestry* (Vol. 11/1994). Pietermaritzburg, South Africa: ICFR.

Eriksson, M., & Lindroos, O. (2014). Productivity of harvesters and forwarders in CTL operations in northern Sweden based on large follow-up datasets. *International Journal of Forest Engineering, 25*(3), 179-200. https://doi.org/10.1080/14942119.2014.974309

Freedman, P. (1998). *Forestry machine simulators: looking for added value in training.* Paper presented at the Canadian Woodlands Forum Annual Meeting, Quebec, Canada.

Gaskin, J., Smith, B., & Wilson, P. (1989). *The New Zealand logging worker-A profile*. [Project Report PR44]. New Zealand: Logging Industry Research Association. https://fgr.nz/documents/download/4160

Gellerstedt, S. (2002). Operation of the single-grip harvester: motor-sensory and cognitive work. *International Journal of Forest Engineering, 13*(2), 35-47. https://doi.org/10.1080/14942119.2002.10702461

Häggström, C. (2015). *Human factors in mechanized cut-to-length forest operations.* (PhD), Swedish University of Agricultural Sciences, Umeå.

Hartsch, F., Dreger, F.A., Englund, M., Hoffart, E., Rinkenauer,G., Wagner, T., Jaeger, D. (2022). Positive and negative work practices of forest machine operators: interviews and literature analysis. *Forests*, *13*:2153, 17 p. https://doi.org/10.3390/f13122153

Houghton, R. (1995). *Injury to forestry workers: Summary Report*. Dunedin, NZ: University of Otago Consulting Group.

Jiroušek, R., Klvač, R., & Skoupý, A. (2007). Productivity and costs of the mechanized cut-to-length wood harvesting system in clear-felling operations. *Journal of Forest Science, 53*(10), 476-482. https://doi.org/10.17221/2088-JFS

Kärhä, K., Rönkkö, E., & Gumse, S.-I. (2004). Productivity and cutting costs of thinning harvesters. *International Journal of Forest Engineering, 15*(2), 43-56. https://doi.org/10.1080/14942119.2004.10702496

Kirk, P., Byers, J., Parker, R., & Sullman, M. (1997). Mechanisation developments within the New Zealand forest industry: the human factors. *Journal of Forest Engineering, 8*(1), 75-80.

Magagnotti, N., Kanzian, C., Schulmeyer, F., & Spinelli, R. (2013). A new guide for work studies in forestry. *International Journal of Forest Engineering, 24*(3), 249-253. https://doi.org/10.1080/14942119.2013.856613

Malinen, J., Taskinen, J., & Tolppa, T. (2018). Productivity of cut-to-length harvesting by operators' age and experience. *Croatian Journal of Forest Engineering: Journal for Theory and Application of Forestry Engineering, 39*(1), 14-22.

McEwan, A., Magagnotti, N., & Spinelli, R. (2016). The effects of number of stems per stool on cutting productivity in coppiced Eucalyptus plantations. *Silva Fennica, 50*(2), 1-14. https://doi.org/10.14214/sf.1448

Ovaskainen, H. (2005). Comparison of harvester work in forest and simulator environments. *Silva Fennica, 39*(1), 89-101. https://doi.org/10.14214/sf.398

Ovaskainen, H., & Heikkilä, M. (2007). Visuospatial cognitive abilities in cut-to-length single-grip timber harvester work. *International Journal of Industrial Ergonomics, 37*(9-10), 771-780. https://doi.org/10.1016/j.ergon.2007.06.004

Pagnussat, M.B., & Lopes, E.S. (2017). The behavioural profile of harvester operators. *Revista Arbore, 41*(2), e410210, 7 p. https://doi.org/10.1590/1806-90882017000200010

Parker, R., Kirk, P., & Sullman, M. (1996). *Learning curves of mechanised harvester and forwarder operators*. [LIRO Report *21*(29)], 6 p. New Zealand: Logging Industry Research Association https://fgr.nz/documents/download/4404

Purfürst, F. (2010). Learning curves of harvester operators. *Croatian Journal of Forest Engineering: Journal for Theory and Application of Forestry Engineering, 31*(2), 89-97.

Purfürst, F., & Erler, J. (2011). The human influence on productivity in harvester operations. *International Journal of Forest Engineering, 22*(2), 15-22. https://doi.org/10.1080/14942119.2011.10702606

Ramantswana, M., Mcewan, A., & Spinelli, R. (2017). The effect of coppice management on stump volume recovery in mechanized operations. *Annals of Forest Science, 74*(3), 1-8. https://doi.org/10.1007/s13595-017-0656-8

Ramantswana, M., McEwan, A., & Steenkamp, J. (2013). A comparison between excavator-based harvester productivity in coppiced and planted Eucalyptus grandis compartments in KwaZulu-Natal, South Africa. *Southern Forests: a Journal of Forest Science, 75*(4), 239-246. https://doi.org/10.2989/20702620.2013.858213

Skirbekk, V. (2004). Age and individual productivity: A literature survey. *Vienna Yearbook of Population Research*, 133-153. https://doi.org/10.1553/populationyearbook2004s133

Stirling, J. (1990). The economies of skill. *Logging and Sawmilling Journal, 3*, 72-81.

Wenhold, R., Ackerman, P., Ackerman, S., & Gagliardi, K. (2020). Skills development of mechanized softwood sawtimber cut-to-length harvester operators on the Highveld of South Africa. *International Journal of Forest Engineering, 31*(1), 9-18. https://doi.org/10.1080/14942119.2019.1578561