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Productivity and cost estimates for incorporating tracked processors into conventional loblolly pine harvesting regimes in the Southeastern United States

Marissa "Jo" Daniel[a], Tom Gallagher[a], Dana Mitchell[b], Timothy McDonald[c] and Brian Via[a]

[a]School of Forestry and Wildlife Science, Auburn University, Auburn, AL, USA; [b]USDA Forest Service, Southern Research Station, Auburn, AL, USA; [c]Bio-systems Engineering, Auburn University, Auburn, AL, USA

ABSTRACT

Due to the recent encouragement for loggers to integrate tracked processors into their conventional harvest equipment regime in the Southeastern United States, this study aimed to provide loggers with an estimate of the additional productivity and operating costs that could be incurred. Since tracked processors have rarely been operated in this region, a comparison study was conducted to determine differences in productivity and operating costs between a less experienced operator versus a more experienced operator. The study indicated the less experienced operator was able to produce 67 green tonnes/hour while the more experienced operator produced 80 green tonnes/hour. Costs per tonne for the less experienced operator were approximately $2.18/tonne at the end of year 1 and decreased to $1.92/tonne at the end of year 5, depicting a $0.26/tonne difference within 5 years. The more experienced operator incurred costs of $1.82/tonne at the end of year 1 and $1.61/tonne at the end of year 5 for a total difference of $0.21/tonne. A sensitivity analysis demonstrated that extreme fluctuations in fuel or maintenance/repair prices had less than a $0.20 increase in the final cost/tonne. An increase in production rates from 65 to 125 tonnes decreased the cost/tonne $0.90/tonne, and increasing utilization rates from 50% to 85% decreased the cost per tonne of the processor by $0.78 per tonne. These results indicated that operators should be less concerned with changes in fuel and maintenance costs and be more concerned with their production and utilization rates.

Abbreviations: CTL = cut-to-length, WT = whole tree, less experienced operator = LExOp, more experienced operator = MExOp, Timberland Investment Management Organization = TIMO, manufacturer's suggested retail price = MSRP, productive machine hours = PMH

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KEYWORDS
Forestry swing machine; timber yard; productivity; cost analysis; forestry excavator; sensitivity analysis

Introduction

Conventional logging in the Southeastern United States is typically based around three pieces of equipment; a feller-buncher, skidder, and knuckle-boom loader with a pull through de-limber (Wilkerson et al. 2008). These machines work together to harvest, transport, de-limb, and load tree-length material onto trailers where they are hauled directly to the mill to be manufactured into specific products. While most of the mills in the Southeast still prefer full-length trees, a select few are starting to provide loggers with incentives and subsidies if they haul processed, dimension-length wood to their mills. These mills are encouraging loggers to invest in dangle-head processors attached to a purpose-built forestry excavator, insisting that the increase in overall production for the logger will be significant enough to justify the purchase of this additional piece of equipment (Donnell 2017).

Due to the integration of advanced technologies into the machine, the incorporation of tracks for mobility, and the addition of the attachment head, incorporating a tracked processor into a Southeastern United States harvest system is estimated to be around $500,000 per machine. This is almost double the price for a knuckle-boom loader, which is commonly used in the southeastern region of the United States for both loading and merchandizing. Additionally, although a tracked processor is capable of loading a truck, it is not the most efficient method, therefore an additional loader of some sort would likely need to be purchased to load the logs onto the trailer. Tracked loaders have a similar price tag to the tracked processors, therefore a logger would be spending almost four times more money if they chose to purchase both the tracked processor and tracked loader. Currently, no official cost analysis has been conducted to determine the effects of incorporating a processor into a conventional harvesting system or whether those costs would differ based on the operators experience level.

Unlike with other machines in the forest industry where an operator can become proficient in a relatively short amount of time, a tracked processor operator is predicted to need a full year before becoming competent and almost 3 years before becoming fully proficient in the machine (Sales Representative 2018; Purfurst 2010). This time duration is too long for a logger to wait for increased productivity and oftentimes serves as a deterrent for purchase. Other concerns for tracked processors include limitations to accuracy and precision capabilities when measuring dbh and length in loblolly pine (*Pinus taeda*).

CONTACT Marissa "Jo" Daniel mzd0060@auburn.edu School of Forestry & Wildlife Sciences, Auburn University, Auburn, AL, USA

A better understanding of measurements for diameter inside bark or diameter outside bark is required before dbh measurement accuracy can be determined. Abnormalities along the stem, such as protrusions from stems or disease, have a tendency to create inaccurate readings by the measuring wheel. Processing multiple stems with a single grab is an additional opportunity to misrepresent dbh, length, and even stem count because the machine's software is not designed to recognize more than one stem in the rollers at a time. With all these initial concerns, loggers are hesitant to invest in a processor.

Although little is known about processors in the Southeastern United States, they are being researched more significantly in many other parts of the world (Eggers et al. 2010; Spinelli and Magagnotti 2010). A study conducted in New Zealand analyzed the productivity of two harvesters with Waratah processor heads in larger diameter Radiata pine. This study looked at the machines' functionality on the landing as processors, in the woods harvesting machines, and as de-limbing tools. Results indicated that these machines were very versatile and capable of performing well regardless of the required use (Evanson and McConchie 1996).

One study compared both cut-to-length (CTL) and whole-tree(WT) harvest systems to motor-manual methods and found that both mechanized systems far out-performed the chainsaw, providing loggers with options for harvesting methods. This paper also inferred that CTL optimization may become the preferred method of harvesting in South Africa due to the machine's ability to provide accurate log measurements for *Pinus radiata* and *Eucalyptus spp*. trees (Eggers et al. 2010). Another study comparing the two different processing systems took place in the Italian Alps. Results from this study found that the price that the mill paid for the final product determined which system was preferable. If sawlog prices were not significantly high, CTL systems could not be justified (Spinelli and Magagnotti 2010). While numerous studies are currently being conducted around the world to better understand tracked processors and their potential in the forestry environment, at this time none have been conducted on operators who have little prior experience operating a tracked processor against those who have operated the machine for over 10 years and are considered experts.

The objective of this study was to provide loggers with an educated estimate of the additional productivity and operating costs that could be incurred when incorporating a tracked processor into a conventional loblolly pine harvesting crew in the southeastern United States. Since tracked processors have rarely been operated in this region, a comparison study was conducted to determine differences in productivity and operating costs between a less experienced operator versus a more experienced operator. Objectives for this study also included providing loggers an explanation of what effects a change in fuel prices, maintenance, production, and/or utilization had on the processors' per tonne operating cost.

Materials and methods

A time study was conducted in order to determine the productivity and costs when using a tracked processor. A 2154G John Deere Swing Machine with a 622B Waratah processor head was chosen for the experiment due to its applicability and availability for this experiment (See Table 1 & Figure 1). In order to demonstrate productivity for a logger's initial purchase, as well as actual machine productivity, two operators were analyzed. The first less experienced operator (LExOp) had about 2 months' experience working with this type of machine, however, he did have an extensive history of operating knuckle-boom loaders and other pieces of heavy equipment. This individual simulated the productivity time of switching an operator from

Table 1. Machine specifications for a 2154 JD swing machine.

DRIVELINE	SPECIFICATIONS
Engine manufacturer	John Deere
Engine model	PowerTech PVS 6.8 L
Displacement, ltr (in^3)	6.8 (415)
Engine output, kW (hp)	122 (164)
Engine output – net, kW (hp)	122 (164)
Carrier rollers – Each side	2
Track rollers – Each side	8
Track shoe width, mm (in)	600 (24)
Track shoe width – option, mm (in)	710 (28)
DIMENSIONS	
Overall length, mm (ft/in)	9860 (32 ft 4 in)
Transport height, mm (ft/in)	3730 (12 ft 3 in)
Overall width, mm (ft/in)	3300 (10 ft 10 in)
Overall track length, mm (ft/in)	4450 (14 ft 7 in)
Track length on ground, mm (ft/in)	3660 (12 ft)
Tailswing radius, mm (ft/in)	3130 (10 ft 3 in)
Ground clearance, mm (ft/in)	710 (2 ft 4 in)
Width over tracks, mm (ft/in)	3300 (10 ft 10 in)
Track gauge, mm (ft/in)	2620 (8 ft 7 in)
Horizontal reach, m (ft/in)	8.74 (28 ft 8 in)
Dump height, mm (ft/in)	7260 (23 ft 10 in)
CAPACITIES	
Fuel tank, ltr (gallons (US))	800 (211)
Hydraulic tank, ltr (gallons (US))	136 (36)
PERFORMANCE	
Ground bearing pressure, kPa (PSI)	62.3 (9.04)
Slew torque, kNm (lbf/ft)	74.376 (54,857)
Travel speed, kph (mph)	4.8 (3)
Lift capacity at max reach, kg (lbs)	5860 (12,920)
Pump type	Variable Axial Piston
Pump flow, ltr/min (gallons (US)/min)	236 (62.3) x 2
Relief pressure, kPa (PSI)	34,300 (4975)
Boost pressure, kPa (PSI)	38,000 (5511)
WEIGHTS	
Operating weight, kg (lbs)	28,352 (62,505)

Figure 1. Image of the tracked processor used during the study.

a knuckle-boom loader to a processor for potential loggers interested in operating a tracked processor on their sites. The second more experienced operator (MExOp) was provided by Waratah and had more than 11 years' experience operating harvesters and processors. This individual simulated the potential productivity of the machine.

The experiment was conducted approximately 6.4 kilometers northwest of Rockford, Alabama off highway 22. The property was in the central part of the state and was managed by a Timberland Investment Management Organization (TIMO). The tract was contract harvested by an alternate company who provided the feller-buncher, skidder, and loader which supplied the processor with wood for the project. The entire tract of land being harvested was approximately 261 hectares in size and was comprised of approximately 30-year-old loblolly pine plywood and pulpwood. Although hardwood stems were occasionally intermixed into the loads skidded to the landing, they were not included in the study. Both operators' time studies were conducted using wood from the same geographic location for continuity purposes.

Data for the time studies were manually recorded and included; diameter within a 5-centimeter diameter class, length to the nearest 10 centimeters, product class, and general notes for each tree that was processed. Starting and ending times for each time study, as well as additional times of significance, were recorded with a stopwatch and used later as a reference. Two video recorders were set up inside, one viewing the tree being processed and the other viewing the monitor displaying the tree's dbh, product class, and total length through Waratah's TimberRite 30 Lite software program (Waratah 2018). One video recorder was placed outside the processor. A separate video recording was made for each of the time trials resulting in a total of 33 videos for the study. These videos were used to collect the operator's productivity and verify the tree's dimensions that were manually recorded. An excel based program specifically designed to conduct time studies on processors and harvesters was used to calculate the operator's productivity.

An observation was defined as the time it took to process each tree, with cycle times beginning once the observer could see that the processor had found and picked up the log. A point was designated on the video where the processor's boom intersected with the carrier as the start cycle time. This point was designated to ensure consistency throughout the time study. The start cycle ended when the processing head found the end of the log, which also initiated the next cycle names process log 1. Process log 1 cycle ended when the saw came out to process the first log, initiating process log 2. This cycle also ended when the saw came out to process log 2 which initiated process log 3. Process log 3 ended when the saw came out which initiated the last cycle known as the discard top and swing to deck cycle. The discard top and swing to deck cycle ended once the processor's boom once again intersected with the designated point on the carrier initiating the start cycle time (Table 2).

Fuel usage was collected using John Deere's JD Link System which provided detailed information regarding; the amount of fuel burned when at idle versus when it was working, the average fuel rate for both idle and working, the amount of actual work time, and an overall number of engine hours operated. This information was provided in both visual and table format on an hourly basis which allowed the fuel consumption rate for each operator to be determined for each trial using the weighted average of all the above-mentioned variables (John 2018).

Data analysis

Data were input into an Excel spreadsheet. Diameter breast height (dbh) distribution of the data was calculated in total as well as for each operator. The total number of trees were calculated for each time trial by diameter class as well as by-product class. Total tonnes, volume, the number of logs produced per hour, and the cycle rate (trees/minutes) were automatically calculated in the excel spreadsheet after each trial was completed. Clark and Saucier's tables were used to verify the total tonnes and volumes (Clark and Saucier 1990).

Results were then inputted into Minitab 18 where descriptive statistics were calculated on all variables. Two-sample *t*-tests with confidence intervals were conducted comparing all variables against both operators to determine if there were significant differences between operators. One-tailed *t*-tests were then conducted on all statistically significant variables to determine the strength of the difference. Linear regression models were developed for the total productivity of both operators separately and for each operator by-product class. All models were calculated with delays.

An economic analysis was conducted using Dr. Robert Tufts before/after-tax cash-flow spreadsheet for years 1 through 5 (Tufts and Mills 1982). Five years were included in both the before and after tax comparisons for two reasons. First, the end of year 5 was when the machine became fully depreciated out for tax purposes and second, the cost of ownership was largely based on the operators' productivity. This indicated that throughout the duration of the loan, the operators' productivity had a direct effect on the amount of principle that could be paid off. The higher the operators' productivity, the lower the cost per tonne each year became because an increased percentage of the loan's principal was being paid off with the additional profit.

Table 2. Cycle time designation for the processor's time study.

Processor's cycles	Cycle time initiated	Cycle time ended
Start cycle	When the processor's boom intersected with the carrier	When the processing head found the end of the log
Process log 1	When the processing head found the end of the log	When the saw came out to process the first log
Process log 2	When the saw came out to process the first log	When the saw came out to process the second log
Process log 3	When the saw came out to process the second log	When the saw came out to process the third log
Discard top/swing to deck	When the saw came out to process the third log	When the processor's boom intersected with the carrier

Initial investment price for the 2154 G tracked swing machine with a 622B Waratah head was approximately $575,000 (Warrior Tractor, personal communication, 2018). Trade in value was estimated to be 20% of the manufacturer's suggested retail price (MSRP) or $115,000 but with a book value of $0 at trade-in. For the purpose of the study, a $50,000 down payment was established with an annual percentage rate of 6% for 60 months (Great Western Bank, personal communication, 2018). Insurance and property taxes were combined to equal 6% with a discount rate of 5% for the analysis. Fringe benefits were set at 40%.

Maintenance and repair costs were estimated using Edwin S. Miyata's publication for *"Determining Fixed and Operating Costs of Logging Equipment"* (Miyata 1980; Miyata and Steinhilb 1981). Fuel price for number two off-road diesel was $0.74 per liter during the time of the study (U.S. EIA 2018). Fuel usage rates were collected from the JD Link system within the processor for each productive machine hour (John 2018). An average of 27.44 liters per hour was established and used for the study. Lubrication prices were established as per the time of the study, and Miyata was used to determine the final fuel and lube rate of $22.78. Productivity for both LExOp and MExOp was used in addition to averaging both operators productivity. The expected life of the machine was set at 10 years, 20,000 scheduled machine hours, with inflated fuel and lubrication, maintenance and repair, and labor rates all set at 2% per year. Utilization rate was established at 70% for the analysis.

A sensitivity analysis was conducted to better understand how a change in utilization, productivity, the price of fuel per liter, and the cost of maintenance/repair per productive machine hour affected the annual equivalent cost (AEC) at years 1 and 5 in Dr. Tufts before-tax cash flow spreadsheet. All ranges were chosen based on their opportunity of occurring in real life either on the landing or at a centralized wood yard. Fuel ranged from $0.53 per liter to $1.06 per liter, maintenance/repair ranged from $6.00 per hour to $18.00 - per hour, productivity ranged from 65 to 125 tonnes, and utilization ranged from 55% to 85%. This information was recorded in excel and graphed for visual analysis.

Results

Overall, 1079 observations were made with both operators after removing outliers and incomplete data, with 468 observations being made throughout five-time trials with LExOp and 611 observations from MExOp during six-time trials. Dbh distribution ranged from 15.24 to 45.72 centimeters for both operators with over 70% of the trees classified between 20 and 31 centimeters dbh (Figure 2). MExOp processed a range of 6 to 52 additional trees from each dbh class in comparison to LExOp, however, when basing the comparison against the proportion of trees processed by each operator the range was only a 0% to 5% difference (Figure 3). *T*-tests were conducted to compare differences in dbh, log length, volume, kilograms, number of logs per tree, and tree density between the two operators. None of the variables were found to be statistically different, indicating that differences in productivity could not be associated with the differences in processed trees.

Actual productivity

Measured productivity for LExOp's five-time trials resulted in an average of 67 tonnes of wood, or approximately 217 logs, being processed per hour (Table 3). This operator demonstrated that he was capable of processing approximately two trees per minute with a majority of the trees possessing two logs within each tree. MExOp was able to process on average 80 tonnes of wood, or approximately 250 logs per hour, based on the results of six-time trials (Table 4). This operator demonstrated that they were capable of processing approximately three trees per minute with a majority of the trees possessing two logs within each tree. Overall, MExOp was able to produce 13 additional tonnes of wood an hour.

Two-sample, two-tailed *t*-tests were conducted on the productivity variables to determine if there was a statistical difference between operator productivity (see Table 4). Where:

$$H_0 = MExOp - LExOp = 0$$
$$H_1 = MExOp - LExOp \neq 0$$

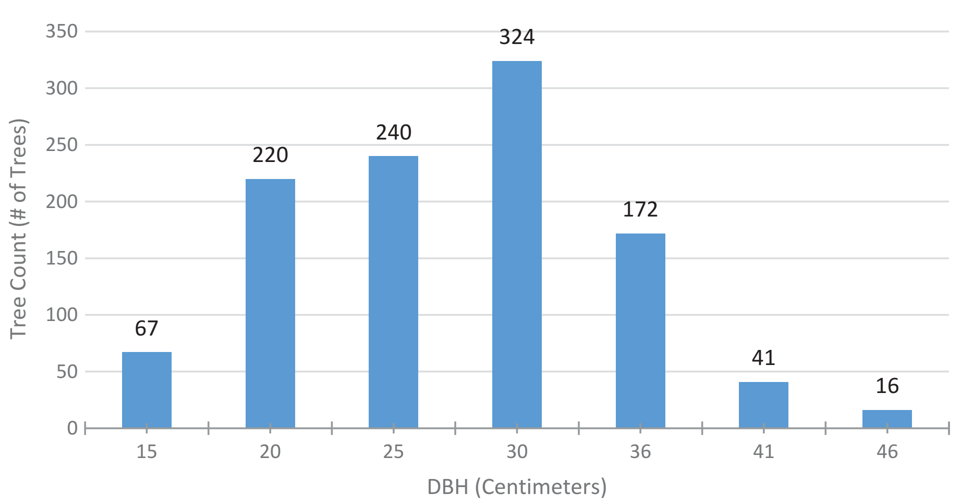

Figure 2. Total dbh distribution (centimeters) of each size class for both operators.

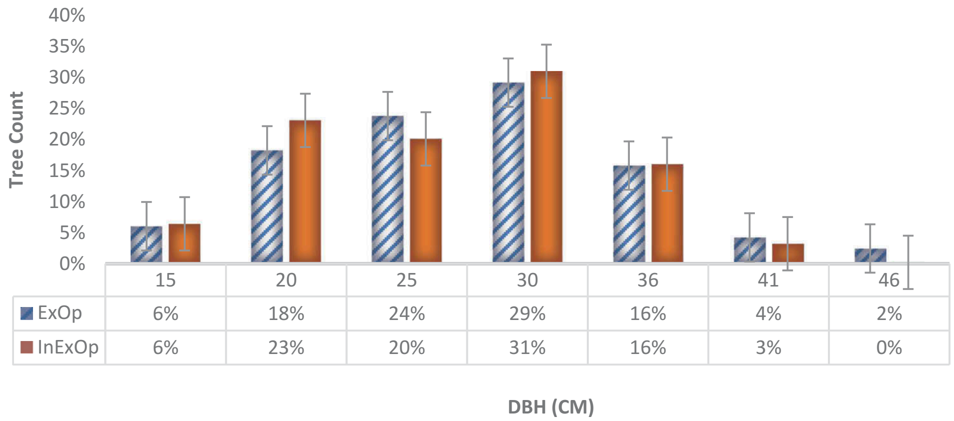

Figure 3. A comparison of dbh distribution (centimeters) at each size class between operators with standard errors included.

Table 3. Actual productivity for LExOp by individual time trial and overall average. Cycle Rate is indicated with a (CR).

Productivity	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Avg.
Total # Trees	118	93	86	74	89	**92**
Tonnes/hr	63	75	67	71	60	**67**
Logs/hr	210	241	231	227	174	**217**
Trees/min (CR)	2	3	2	2	2	**2**

Table 4. Actual productivity for MExOp by individual time trial and overall average. Cycle Rate is indicated with a (CR).

Productivity	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 6	Avg.
Total # Trees	82	128	101	108	88	105	**102**
Tonnes/hr	77	70	78	77	74	105	**80**
Logs/hr	271	258	251	250	225	245	**250**
Trees/min (CR)	3	3	3	3	2	3	**3**

Fuel consumption (L/hr), productivity (m^3/hr), productivity (tonnes/hr), and productivity (logs/hr) were found to be statistically significant at the 95% level or higher and were re-run as a one-tailed *t*-test where:

$$H_0 = MExOp - LExOp = 0$$
$$H_1 = MExOp - LExOp > 0$$

All variables were found to be statistically significant at the 95% level indicating that MExOp's actual productivity was significantly greater than LExOp in all productivity measurements (Table 5).

Predicted productivity

In addition to determining the actual productivity of the processor, multiple linear regression models (MLRs) were developed using cycle time in total seconds as the dependent variable. Both tonnes/tree and logs/tree were used as the independent variables to estimate the predicted productivity of the processor. Two models were developed (Table 6) where the initial model (M1) determined productivity for each operator. This model also had a p-value of <0.001 and had an R-squared of 31.69%.

Table 5. A one-tailed *t*-test comparing productivity variables against operators.

	MExOp mean	LExOp mean	p-Value
Fuel consumption, L/hr	28	27	0.002
Productivity, m^3/hr	81	67	0.028
Productivity, tonnes/hr	80	67	0.028
Productivity, logs/hr	250	217	0.023

Table 6. Linear regression model results.

Model	SS	MS	F-value	P-value	R2	Adj R2
M1	32,530	10,843.5	163.46	<0.0001	31.69%	31.50%
M2	40,807	10,201.7	154.05	<0.0001	36.46%	36.22%

$$\begin{aligned} M1 &= Cycle\ Time\ (in\ secs) \\ &= 9.87 + 2.92\ x\ O\ (operator) \\ &\quad + 15.88\ x\ W\ (tonnes\ /tree) \\ &\quad + 1.61\ x\ N\ (logs/tree) \end{aligned}$$

where *O* was a class variable coefficient (1 = less experienced operator and 0 = more experienced operator). The coefficient *W* represented the weight in tonnes per tree, and the coefficient *N* represented the number of logs cut per tree. No trees were recorded with a weight less than one tonne or possessing less than one log. Coefficient *O* indicated that LExOp was 2.92 seconds slower processing a tree than MExOp given the same tonnage, number of logs per tree, and assuming all product classes are the same. Overall, MExOp's cycle time per tree was approximately 27 seconds per tree compared to LExOp's cycle time of 30 seconds per tree.

The second model (M2) estimated each operator's productivity based on which product class they were processing.

$$\begin{aligned} M2 &= Cycle\ Time\ (in\ secs) \\ &= -11.51 + 2.83\ x\ O\ (operator) \\ &\quad + 10.64\ x\ P\ (product\ class) \\ &\quad + 16.36\ x\ W\ (tonnes\ /tree) \\ &\quad + 12.22\ x\ N\ (logs/tree) \end{aligned}$$

where *P* represented the product class coefficient (1 = plywood and 0 = pulpwood) and *O* once again represented the operator coefficient. This model had an R-squared of 36.46% with a p-value of <0.001. Overall MExOp's cycle time for processing a tree was approximately 17 secondsfor a pulpwood log and 28 seconds for a plywood log. LExOp's cycle time for processing trees was 20 seconds for a pulpwood log and 31 seconds for a plywood log.

Economic analysis

Three before-tax cash flow cost analyses were estimated for the processor using a spreadsheet developed by Dr. Robert Tufts of Auburn University (Tufts and Mills 1982). The processor's annual equivalent cost (AEC), the cost of owning and operating the processor throughout the duration of its life when considering the time value of money, was found to be $251,273 at the end of year 1 and $221,822 at the end of year 5 overall for all studies (Tufts and Mills 1982; Jernigan et al. 2016). Cost per tonne for year 1 was $2.18 for LExOp, $1.99 for the average of the two operators, and $1.82 for MExOp (Table 7). Cost per tonne for year 5 was $1.95 for LExOp, $1.75 for the average, and $1.61 for MExOp. These values were the result of using each operator's green tonne/PMH, 70% utilization, fuel and lube rates of $22.78/PMH, and maintenance and repair rates of $11.36/PMH.

An after-tax cash flow cost analysis was conducted using a marginal tax rate of 28% but leaving all other parameters the same which resulted in an AEC of $215,426 at the end of year 1 and an AEC of $167,889 at the end of year 5 (Table 8). Cost per tonne for year 1 was $1.87 for LExOp, $1.71 for the average of the two operators, and $1.56 for MExOp. Cost per tonne for year 5 was $1.45 for LExOp, $1.32 for the average, and $1.22 for MExOp. This analysis was performed to demonstrate the potential costs of the processor under the government tax rate system.

Table 7. Discounted before-tax cash flow analysis summarized results for 2154G Tracked Processor. AEC indicates the annual equivalent cost.

Before tax	Year 1 cost/tonne	Year 5 cost/tonne
Overall AEC	$ (215,426.00)	$ (167,889.00)
LExOp	$ (2.18)	$ (1.95)
Average	$ (1.99)	$ (1.75)
MExOp	$ (1.82)	$ (1.61)

Table 8. Discounted after-tax cash flow analysis summarized results for 2154G Tracked Processor. AEC indicates the annual equivalent cost.

After tax	Year 1 cost/tonne	Year 5 cost/tonne
Overall AEC	$ (215,426.00)	$ (167,889.00)
LExOp	$ (1.87)	$ (1.45)
Average	$ (1.71)	$ (1.32)
MExOp	$ (1.56)	$ (1.22)

A sensitivity analysis was conducted to better understand how a change in utilization, productivity, the price of fuel per liter, and the cost of maintenance and repair per productive machine hour affected the AEC at years 1 and 5. Overall results depicted an increase in the cost/tonne when both fuel prices and maintenance and repair prices increased while the cost/tonne decreased when production and utilization increased. Cost per green tonne increased from $1.69 to $1.85/gt when fuel prices increased from $0.53 to $1.06/litre at year 5 (Figure 4). Cost per green tonne increased from $1.69 to $1.83/gt when maintenance and repair costs increased from $6.00 to $18.00/PMH at year 5 (Figure 5). Increasing productivity from 59 to 100 gt decreased cost/tonne from $2.19 to $1.13/gt at year 5 while utilization decreased from $2.29 down to $1.51/gt when increasing utilization from 50% to 85% (Figures 6 & 7).

Discussion

Throughout the Southeastern United States, select mills are encouraging loggers to incorporate tracked processors into their operations insisting that the increase in overall production for the logger will be significant enough to justify the machines initial purchase price. The comparison between less experienced operators versus more experienced operators demonstrated that regardless of wood type, LExOp was able to produce approximately 67 tonnes/hour or almost 17 truckloads a day if one truckload weighed 25 tonnes, and each operator had 70% utilization for a 9-hour day. MExOp, on the other hand, produced 80 tonnes/hour or just under 20 truckloads a day given the same conditions.

Typical productivity for more experienced knuckle-boom loaders in the Southeastern United States with the same utilization and productive machine hours range between 13 and 26 tonnes/hour if all other variables are held constant and wood supply is not an issue (Visser and Stampfer 2003). These numbers indicate that even an inexperienced track processor operator would be able to produce double the tonnage of a more experienced knuckle-boom loader operator given the same scenario.

The *t*-test analysis conducted during the study indicated that there was a significant difference between LExOp's and MExOp's productivity. The regression

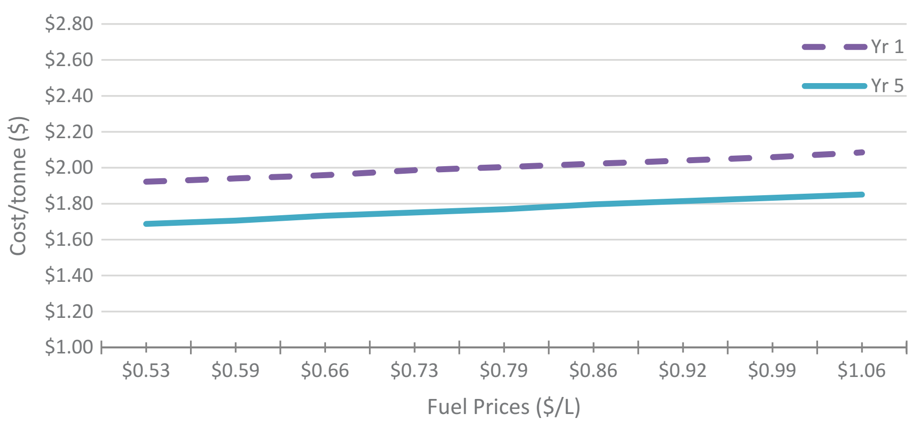

Figure 4. Sensitivity analysis depicting how a change in fuel price affects processor cost per tonne in years 1 & 5 in the United States.

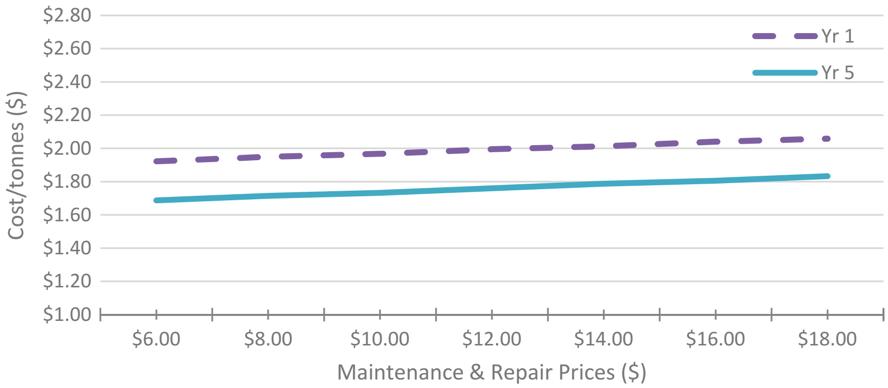

Figure 5. Sensitivity analysis depicting how a change in the price of maintenance and repairs affects processor cost per tonne in years 1 & 5 in the United States.

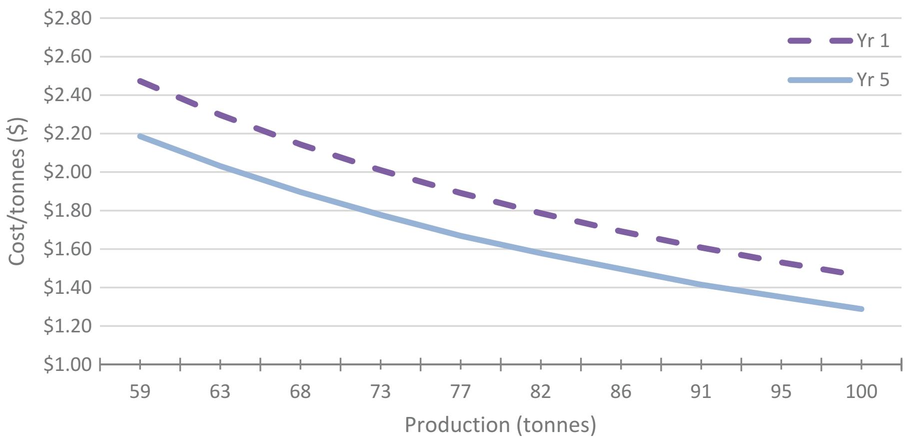

Figure 6. Sensitivity analysis depicting how a change in hourly productivity affects processor cost per tonne in years 1 & 5.

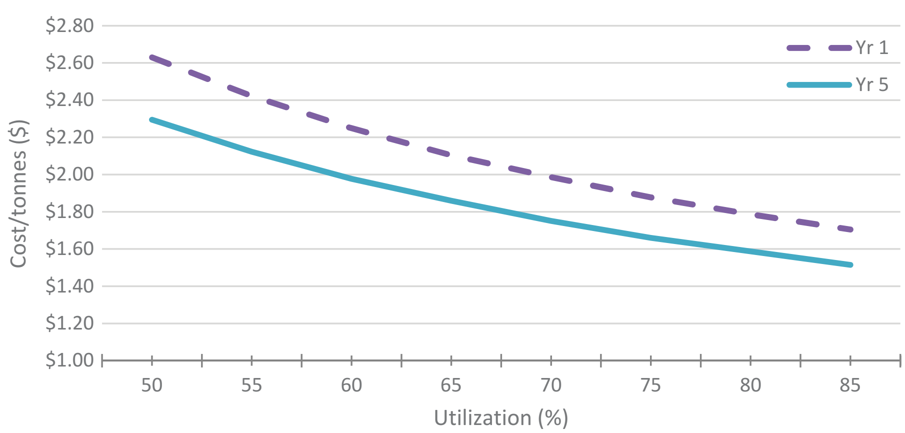

Figure 7. Sensitivity analysis depicting how a change in processor utilization, either in the woods or at a depot, effects processor cost per tonne in years 1 & 5.

analyses for the predicted productivity for M1 and M2 indicated that both the weight of each stem as well as the number of logs produced from each stem were important variables when determining cycle times for each operator as well as each product class. These findings were important to note because site-specific variables such as where the tree was planted on the hillslope, how much moisture the basin had received in the recent past, or how tall the trees were, could all play an important role in determining the operator's productivity when processing stems.

The discounted before-tax cash flow cost analyses conducted depicted a $0.26/tonne difference for LExOp versus a $0.21/tonne difference for MExOp between years 1 and 5. These findings indicated that LExOp's cost/tonne decreased more than MExOps throughout the 5-year timeframe. The analyses results also displayed a difference of $0.36/tonne between LExOp and

MExOp's at year 1 and a $0.31/tonne difference at year 5 indicating that on average MExOp's cost/tonne were cheaper than LExOp's by $0.335/tonne on any given year which was expected given the increased productivity from MExOp.

The sensitivity analysis demonstrated that regardless of the AEC year, extreme fluctuations in both fuel prices and/or maintenance/repair prices had less than a $0.20 increase in the final cost/tonne. An increase in production rates per tonne decreased the cost/tonne $0.90/tonne while increasing utilization rates from 50% to 85% decreased the cost per tonne of the processor by $0.78 per tonne. These results indicated that operators should be less concerned with changes in fuel and maintenance costs and be more concerned with their production and utilization rates.

Ideally, this study could be repeated with additional operators being incorporated into the current comparison study results to offset any effects from only having a single operator in each regime. Results from this study, however, still verified Evanson & McConchie findings of the tracked processor's versatility as both a processor and a delimbing tool (Evanson and McConchie 1996). The machine demonstrated its ability to process stems with minimal effort regardless of dbh or length of the loblolly pine. Further research needs to be conducted with regards to the machine's ability to process hardwood stems as well as whether or not the processor's existence is justified by the price of sawlogs in the area, however, initial observations believe that this machine will not be suitable in a hardwood setting and that Spinelli & Magagnotti's results will be confirmed (Spinelli and Magagnotti 2010).

Additionally, further research needs to be conducted to determine the accuracy of the track processors dbh and length measurements in loblolly pine. Unfortunately, this study did not track mill specifications per stem, so it is unknown how many cuts were made that were outside of the mill's allowable target. Future research is recommended on this topic to better understand the number of mismeasurements that were made from the wheel, the lack of daily calibration, or inaccurate analysis because the diameter outside the bark was missmeasured when the processor was required to run the head up and down the stem multiple times for delimbing purposes.

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Disclosure statement

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Authors' contributions

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