South African Pine Cut-to-Length Harvesting: an Analysis of Fibre Loss and Productivity

Chloe Williams, Pierre Ackerman

Abstract

A study was conducted in Pinus elliottii *and* Pinus patula *clear-felling stands in the Southern Cape and Mpumulanga forestry regions of South Africa. A hybrid harvester was observed over four compartments in a cut-to-length system in order to assess its productivity as well as its precision with regards to potential fibre loss while processing* Pinus elliottii *and* Pinus patula *for sawlog production. Potential fibre loss results show that the harvester contributes minimally through inaccurate cross-cutting, accounting for 1.5% of the total wood volume processed. Converted to a cost, this indicated losses up to € 0.18 m^{-3} for* P. elliottii *and € 1.61 m^{-3} for* P. patula*. Additionally, the machines were found to be more productive when working with* P. elliottii *(32.12 m^3 SMH^{-1}) than* P. patula *(17.55 m^3 SMH^{-1}). Based on these findings, the loss was estimated at up to € 22 650 and € 101 530 y^{-1} for* P. elliottii *and* P. Patula*, respectively. Species showed to have a significant impact on the processing accuracy, with cross-cutting of* P. patula *stems being less precise than* P. elliottii*. This was attributed to the species' tendency to grow thicker branches, although differences in harvesting conditions could have contributed. Results suggest that harvesting* P. patula *stands in a CTL system requires more caution since these can be associated with higher economic losses, and lower productivities. Considering the recent growth of mechanised CTL harvesting, this study hopefully aids in exploring the efficacy of a system, which has gone largely untested to date in South African conditions.*

Keywords: cut-to-length, harvesters, productivity, merchandising, precision, plantations

1. Introduction

Commercial forestry has seen an increase in the use of mechanised harvesting equipment in the past few decades (Jiroušek et al. 2007), making analysis of these systems an important step in maximising yield from South African industrial plantations. Cut-to-length (CTL) timber harvesting, a system that can be fully mechanised, is characterised by trees being processed to log assortments in the stand where they are felled (Holtzscher and Lanford 1997, Nurminen et al. 2006). One of the characteristics of mechanised CTL systems is that cross-cutting is performed by the harvester with the help of on-board computer (OBC) systems, which allow for the measurement and storage of the stem's length, diameter and volume while processing (Marshall et al. 2006). This replaces motor-manual log scaling and cross-cutting (Marshall et al. 2006).

Mechanised harvesting operations are potentially more flexible, safe and more sensitve to environmental conditions than traditional motor-manual or semi-mechanised systems (Nurminen et al. 2006). They may also be more economical in the long run because, compared to typical motor-manual methods that involve multiple workers cross-cutting logs with chainsaws, only two machine are used, thus decreasing fuel consumption, manpower requirements and providing safer, healthier working conditions for the operators (Holtzscher and Lanford 1997, Van der Merwe 2014). However, mechanised CTL use has been limited in South Africa to date. According to Kellogg and Brink (1992) and Holtzscher and Lanford (1997) the reason could be attributed, in part, to high initial investment associated with acquiring the machinery to transition to a mechanised CTL operation. In addition, there are concerns about cost optimisation and potential volume/fibre losses on valuable logs due to potentially inaccurate cross-cutting performed by the harvester (Eggers et al. 2010, Spinelli et al. 2011). Processing essentially aims to produce the best value logs, while minimising fibre loss by staying within allocated log assortment dimensions (Ackerman and Pulkki 2012). If a log exceeds the required assortment length, a portion above and beyond the required assortment length will eventually be trimmed off in the sawmill. Conversely, if a log is cut short of the required assortment length, the log length is downgraded and trimmed to the next lower length assortment; usually a full module of 0.3 m. Typically, a 10 cm log trimming allowance is added to all sawlog assortment lengths in South Africa to accommodate skew crosscutting, mainly associated with motor-manual operations (Ackerman and Pulkki 2012). If computer aided cross-cutting abilities of modern day harvester heads are accurate enough, the trim allowance can potentially be eliminated.

Studies have been conducted to evaluate the extent of losses (both in terms of fibre and economic recoverable value) associated with cross-cutting performed by harvesters (Chiorescu and Gronlund 2001, Nieuwenhuis and Dooley 2006, Eggers et al. 2010, Nuutinen et al. 2010, Spinelli et al. 2011, Marshall et al. 2006, Opferkuch et al. 2014). Most studies have found harvester cross-cutting of high quality saw logs and veneer to be acceptably accurate and comparable to motor-manual methods (Eggers et al. 2010, Spinelli et al. 2011), especially if adequate measures are taken to calibrate the harvester heads so that they can measure while felling, debarking and cross-cutting stems (Chiorescu and Gronlund 2001, Nieuwenhuis and Dooley 2006, Marshall et al. 2006). Nonetheless, measurement errors can be caused by machine vibrations, poor calibration, inappropriate bark thickness functions input in on-board computers, changes in environmental and climactic conditions, as well as factors related to the operator (Spinelli et al. 2011).

Even though many studies report that harvester cross-cutting is comparably accurate to motor-manual methods, the accuracy level typical of these methods may actually be a poor baseline of comparison. A study by Ackerman and Pulkki (2012) showed significant inaccuracies in motor-manual log scaling operations, mostly attributed to poor operator training and attitudes, and supervision. Disregarding comparisons between the two systems, some manufacturers claim that the measurement accuracy of their machines are within 1 mm for diameter and 1 cm for length (Eggers et al. 2010). Other studies have reported that harvester heads achieve 90% of their theoretical accuracy (Conradie 2003), which exceeds that of semi-mechanised opertaions in South Africa (Ackerman and Pulkki 2012, Ackerman et al. 2017). Overall, it is unclear whether manufacturers are perhaps overstating the accuracy of their products and if comparing mechanical to motor-manual cross-cutting methods is appropriate in assessing the accuracy of cross-cutting performed by harvesters.

Prior research has been largely inconclusive about the effects of tree characteristics on harvester cross-cutting accuracy. For instance, in their study of *Pinus spp.* in South Africa, Eggers et al. (2010) found that tree diameter, branch characteristics and the presence of stem defects had no significant effect on the machine's ability to cross-cut as accurately as motor-manual bucking. However, their study compared two scaling systems and did not come to a conclusion on potential individual accuracy. Other studies have indicated the opposite (Nieuwenhuis and Dooley 2006), with stem sweep having the most important impacts on the accuracy of cross-cutting (Richardson 1988).

Although there has been ample research on mechanised CTL systems on a global scale, studies on the accuracy of harvesters working in mechanised CTL systems in South Africa are limited, especially for pine sawlog production species typical to South Africa. Further, research on which factors could potentially contribute to inaccuracy has been largely inconclusive for South African conditions. Therefore, a study was conducted on a CTL system working in a pine sawlog stand with the intention of identifying and analysing the potential fibre loss associated with inaccurate cross-cutting. Research also included a time study of the harvester component of the CTL system to determine productivity. Considering Kellogg and Bettinger (1994) initiated productivity studies on mechanised cut-to-length systems in 1994, similar studies in South Africa are much needed at this time. The findings of this study are aimed at determining which factors are important when considering the amount of fibre lost by harvester cross-cutting in CTL systems and hopefully help harvesting managers and equipment operators address those factors.

1.1 Objectives

The main aims of this study are as follows:

⇒ analyse how much useful wood volume (i.e. the amount of fibre recovered in cross-cut stems) is potentially lost due to inaccurate cross-cutting by the harvester and convert these volumes to potential economic losses

⇒ explore which log characteristics (i.e. log length, tree species and log diameter) influence the accuracy of CTL harvester measurements.

2. Materials and methods

2.1 Study area

The study was conducted in four sawlog producing clear-felling compartments, two in the Southern Cape and two in Mpumulanga, South Africa (Table 1). The Southern Cape is known for its steep coastal escarpment landscape, shallow to moderately deep lithosolic and colluvial soils, and mild climate (Hanekom et al. 1989, Seydack et al. 2011). Temperatures typically range from 12 °C to 20 °C, and annual rainfall is approximately 1140 mm evenly spread throughout the year (Hanekom et al. 1989, Seydack et al. 2011). Comparatively, the Mpumulanga escarpment, located higher in elevation (i.e., 810 to 1930 m asl), is characterised by cool, dry winters and hot, wet summers (Louw and Scholes 2002). Mean annual temperature is approximately 14 °C to 19 °C, while mean annual rainfall is between 840 mm and 1670 mm (Louw and Scholes 2002). Soils are typically ferralitic or podzolic (Louw and Scholes 2002). The species planted in the compartments studied were *P. elliottii* and *P. patula* (Table 1). Otherwise, the compartments were comparable in terms of stand and terrain conditions: stand age, tree size, slope class, ground strength and ground roughness were similar (Table 1). All had low average ground roughness and slope classes. Both machine operators, one in the Southern Cape and one in Mpumalnaga, had more or less the same operating experience, two years and 18 months on the machines and being employed by the same contractor, underwent similar initial and follow-up training. Weather conditions were similar between the study locations; namely sunny and dry.

The harvesters studied were hybrid machines – 179.7 kW tracked John Deere 753 feller-bunchers fitted with a Waratah HTH623C (Southern Cape) or Waratah HTH622B (Mpumulanga) harvester heads. Both harvester heads were equipped with TimberRite measuring systems, but the HTH623C was slightly heavier (3050 kg versus 2300 kg) and had a wider maximum feed roller opening compared to the HTH622B (Waratah 2016a, 2016b). Both systems matched the dimensions of the processed trees.

During processing, it was observed that the first log cut from every stem was maximised for length (up to 6.6 m), while all subsequent assortments were cut to shorter lengths. The log assortments produced only included 2.4 m, 3.0 m, 4.2 m, 6.0 m and 6.6 m. A 0.1 m trimming allowance was permitted on each log length over and above the specified length.

For the purpose of this study, trimming allowance is defined as being »an assortment cut longer than standard lumber lengths because of the impossibility of bucking logs squarely and potential logging damage to log ends« (Bredenkamp 2000, Brink et al 2000, United States Department of Agriculture 2006, Ackerman and Pulkki 2012). This implies that if cross-cutting accuracy is perfect, no trimming allowance is required. In this study, the trimming allowance was not considered

Table 1 Characteristics of the four study compartments and stand cruise details

Compartment	A	B	C	D
Location	Southern Cape	Southern Cape	Mpumulanga	Mpumulanga
Area, ha	8.16	37.29	2.16	8.02
Espacement, stems ha^{-1}	260	437	213	377
SPH, m^3 ha^{-1}	257.1	480.0	304.3	337.3
Species	*P. elliottii*	*P. elliottii*	*P. patula*	*P. patula*
Stand age, years	21	26	24	20
Average height, m	23.13	26.13	27.83	26.76
Average DBH, cm	27.5	35.99	39.47	32.03
Average tree volume, m^3	0.99	1.10	1.43	0.89
Average slope class[2]	1	1	1 and 2	1 and 2
Ground strength[2]	3.4.5, 2.2.3, 2.2.4	2.2.3, 2.3.4	1.3.4	1.3.4
Roughness[2]	1	1	1	1

[1] Soil forms are based on classification in Soil Classification – A Taxonomic System for South Africa (Soil Classification Working Group, 1991)
[2] Slope class, Ground strength and roughness are classified using the National Terrain Classification for Forestry (Erasmus, 1994)

a fibre loss. However, any length of log cross-cut beyond nominal log length plus the 0.1 m trimming allowance was deemed fibre loss. The harvester head processing function was calibrated prior to the study and it is assumed that the processing function was done to produce length specified logs exactly according to the on-board computer system (specified length plus 0.1m trimming allowance).

2.2 Data collection and analysis

To assess harvester productivity, a time study was conducted on harvesters at each compartment. Multiple swaths of trees were delineated and marked with fluorescent paint for ease of recognition from a distance. Each tree's diameter at breast height (DBH) was measured using a DBH tape (n=860). A sub-sample of tree heights was measured using a Vertex (n=88), an electronic Hagloff Hypsometer instrument that uses ultrasound to measure height. The distance between felling positions was estimated using the harvester's track length (4.5 m). WorkStudy+™ 4.0 installed on a Trimble GeoXM handheld was used to collect the time study data. In order to ensure that all the data related to the harvester was collected accurately, a video recording of the time study was taken to serve as a back-up in the case of errors during the study or subsequent analysis. The work cycle was broken up into elements similar to those described in Ackerman et al. (2014), execpt that the »boom-out« and »boom-in« elements were grouped with the »felling« element. All delays were recorded regardless of duration. Standing tree volume was calculated using the following growth model (Eq. 1) (Bredenkamp 2012):

$$lnV = b_0 + b_1 \ln\left(dbh + f\right) + b_2 lnH \qquad (1)$$

Where:

V stem volume, m^3

dbh breast height diameter, cm

H tree height, m

Values for the coefficients b_0, b_1, b_2 and f for the species of interest were derived from Bredenkamp (2012). Productivity per productive machine hour (PMH) (Eq. 2), utilisation (Eq. 3), and mechanical availability (Eq. 4) were calculated according to the equations described by Björheden and Thompson (1995) and Ackerman et al. (2014).

Productivity m^{3}PMH^{-1} =
(Number of trees x Average tree size) /
Productive time *(2)*

Utilisation (%) =
(Productive machine hours /
Scheduled machine hours) x 100 *(3)*

Mechanical availability (%) =
(Available machine hours /
Scheduled machine hours) x 100 *(4)*

To assess the harvester's cross-cutting accuracy, a sample of cross-cut logs was measured (n=224). According to sawlog class specifications (Southey 2012), the log assortments were classified for the purposes of this study as either »short« for 2.4 and 3.0 m logs or »long« for 4.2, 6.0 and 6.6 m logs. Individual log lengths, under-bark small and thick end diameters, were recorded to the nearest centimetre. Sawlogs with small end diameters of 15 cm or over were randomly sampled from log piles produced by the harvester, while all logs <14.9 cm were ignored for the purposes of this study.

To calculate the volumes of log assortments and the associated volume lost resulting from inaccurate cross-cutting, the following formula was used (Eq. 5) (Bredenkamp 2012):

$$V_{\log} = \frac{h}{2}\left(A_{\mathrm{b}} + A_{\mathrm{u}}\right) \qquad (5)$$

Where:

$V_{\log}$ log volume, m^3

A_{b} cross sectional area at the base, m^2

A_{u} cross sectional area at the upper end, m^2

h log length, m.

Log assortments cut to any length between the nominal length and the 0.1 m trimming allowance were, for this study, considered to be cut accurately and were not counted as contributing any fibre loss. However, anything cross-cut above the nominal log length plus the trimming allowance was deemed fibre loss. If the log was cut below the minimum intended length, this fibre loss was assessed according to the next (lower) log assortment length. Saw kerf was not considered as fibre loss in this study. The volume losses were summed within species and within the log assortment classes. This value was then converted to a percentage of the total volume of wood processed by the harvester (i.e. the total volume of all logs measured in the study). In addition, the percentage of logs undercut, cut accurately and overcut was calculated within each of the log classes. The fibre loss volumes were converted to financial losses using weighted average industry log prices as of October 2015 for each of the log classes outlined in Southey (2012). Financial losses were then extended to an annual basis using the machine's average productivity and assuming that it worked two, eight hour shifts per day for 250 days per year, equating to an estimated annual volume harvested of 128 500 m^3 for *P. elliottii* stands on average and 70 200 m^3 for *P. patula* stands.

Statistical analysis, including basic statistics, assumptions tests (Shapiro-Wilk's and Levene's test) and an analysis of covariance (ANCOVA), was conducted using STATISTICA 12.6 software (StatSoft, Tulsa). An ANCOVA, which allows for the inclusion of both categorical and continuous variables, was run on the length lost in order to more clearly analyse the effects of log class assortment, diameter and species on the accuracy of cross-cutting since volume would naturally be affected by the log's size (i.e., diameter and length).

3. Results

The harvester's productivity was calculated to be 28.48 m^3 SMH^{-1} on average, while mechanical availability was 93.3% and utilisation was 90.5% (Table 2). Productivity, as well as utilisation, was significantly higher in *P. elliottii* compartments (p=0.00). Productivity ranged from 32.12 m^3 SMH^{-1} in *P. elliottii* and 17.55 m^3 SMH^{-1} in *P. patula* stands.

In terms of the harvester's cross-cutting accuracy, 1.187 m^3 (or 1.516%) of the total volume processed of 78.28 m^3 was found to be lost due to inaccurate cutting (Table 3) in the sub-sample of logs measured (n=224). Very few logs (0.9%) were undercut. The largest proportion of fibre loss came from short *P. patula* logs (84.5%), with long *P. elliottii* logs contributing the second most with 10.7%. *P. patula* contributed the largest proportion to the inaccurate cuttings (88.4%) in total (Table 3). The fibre loss equated to a value of €1.85 m^{-3} for *P. elliottii* and €1.61 m^{-3} for *P. patula* (Table 4). Extended throughout the year, this was estimated to add up to € 22 650 for *P. elliottii* and €101 530 for *P. patula* (Table 4).

Table 2 Average tree volume, productivity, mechanical availability and utilisation for the harvester in each of the compartments where it was studied. Standard deviations are shown in brackets

Species	Average tree volume, m^3	Productivity m^3 SMH^{-1}	Availability %	Utilisation %
P. elliottii	1.01 (0.22)	32.12 (9.56)	97.74	95.60
P. patula	0.51 (0.18)	17.55 (5.50)	74.52	68.84
Average	0.88 (0.31)	28.48 (10.76)	93.34	90.54

Table 3 The lost volume of wood due to inaccurate harvester cross-cutting in each log assortment class in each species, expressed as a raw volume and as a percentage of the total volume of wood cut

Species	Log assortment class	Sample size, n	Average diameter, cm	Average length, m	Standard deviation in length m ± std dev	Undercut logs, %	Logs cut accurately, %	Logs over cut, %	Volume loss, m^3	Volume loss, %	Contribution, %
P. elliottii	Short	28	28.33	3.07	0.1	0	78.57	21.43	0.01	0.013	0.877
	Long	80	36.24	4.72	0.76	0	45	55	0.127	0.163	10.736
P. patula	Short	89	30.08	2.78	0.29	2.25	17.98	79.78	1.002	1.281	84.475
	Long	27	31.01	6.43	0.63	0	62.96	37.04	0.046	0.059	3.912
Average	All	224	32.17	3.95	1.37	0.89	40.18	58.93	1.187	1.516	100

Table 4 The economic losses associated with potential fibre loss due to inaccurate harvester cross-cutting

Species	Log assortment class	Harvested volume, m^3 $year^{-1}$	Average sample price, € m^{-3}	Estimated revenue, € $year^{-1}$	Value loss % of revenue	Value loss € h^{-1}	Value loss loss € m^{-3}	Value € $year^{-1}$
P. elliottii	Short	128 500	45.4	58 323 40	0.02	2.76	0.09	11 050
	Long	128 500	60.3	77 407 00	0.03	6.32	0.2	25 270
	All	128 500	56.4	72 459 40	0.03	5.66	0.19	22 650
P. patula	Short	70 200	45.6	32 041 70	0.53	42.17	2.69	168 700
	Long	70 200	51	35 538 20	0	2.6	0.2	10 220
	All	70 200	46.8	32 855 50	0.31	25.4	1.61	101 530
Average	All	113 900	51.6	58 791 90	0.14	20.58	0.79	82 320

An ANCOVA was conducted to determine if tree species, the log length class and the log diameter had significant effects on the length of the log lost through inaccurate cross-cutting. The log length class and the average diameter were not found to be significant (p=0.07 and p=0.66, respectively). However, the effect of species was found to be significant (p=0.00). *P. patula* had 0.1018 m of utilisable log length lost on average compared to 0.0237 m for *P. elliottii.* The distribution of lost length was found to be non-normal (Shapiro-Wilk's W= 0.28142 and p=0.0000) and the factors analysed were also all non-homoscedastic (Levene's p=0.000), so findings were confirmed with a Mann-Whitney U-test between species and the lost length (p<0.001).

4. Discussion

Similar to prior studies, the harvesters demonstrated reasonable levels of accuracy in cross-cutting in terms of fibre loss, if accurate cutting can be defined as when there are no fibre losses. Even though only 40% of logs were cut to exact dimension (nominal log length) (Table 3), the volume of fibre lost was 1.187 m^3, which represents 1.516% of the total volume of wood processed (Table 4). This finding is supported by earlier research (Chiorescu and Gronlund 2001, Nieuwenhuis and Dooley 2006, Marshall et al. 2006, Eggers et al. 2010, Nuutinen et al. 2010 and Spinelli et al. 2011). Studies show that length measurement errors, which would lead to fibre losses from harvester cross-cutting, are usually not significant (Marshall et al. 2006). In fact, a study by Eggers et al. (2010) found similar results when comparing value recovery from motor-manual cross-cutting versus various harvesters: there was only a 2.1% difference in the value recovered from logs in the different systems. Similarly, Nieuwenhuis and Dooley (2006) found the harvester's length measurement to be within 2% of the actual length of the log measured using a tape measure and Spinelli et al. (2011) found 98% of logs to fall within a 4 cm range of the prescribed length. The results of this study seem to support earlier research since large errors in length measurements would have caused a greater degree of fibre loss through inaccurate cross-cutting.

Although the fibre loss in this study only equates to €0.18 m^{-3} for *P. elliottii* and €1.61 m^{-3} for *P. patula*, this was estimated to add up to €22 650 (0.31% of total revenue) and €101 530 (3.09% of total revenue) per year, respectively (Table 4). In terms of economics, this study also supports Eggers et al.'s (2010) study, but perhaps these seemingly small effects should not be disregarded since the effects of fibre loss become more important in the longer term. In past research, it has been documented that errors associated with undercutting have more substantial economic impacts due to practice of downgrading compared to overcutting (Spinelli et al. 2011). As such, more wood is lost by downgrading rather than trimming (Spinelli et al. 2011) particularly if the number of length assortments are limited as in this study. This may help to explain the minimal degree of undercutting observed in this study, which only accounts for 0.6% of logs (Table 3). On-board computer system calibration may account for some of the errors in cutting, but it is also possible that operator behavior could contribute to the trends observed (Ackerman and Pulkki 2012). Not only is there is a fairly low likelihood of the operator actually cutting a log under 2.4 m due to the policy of downgrading, but operators may also be trained to err on the side of caution by over-cutting rather than undercutting (or OBC's calibrated to do this), thus reducing fibre loss and maximising economic yield. In fact, slight overcutting is seen as being compliant with industry. Overall, approximately half the logs the harvester cross-cut were within the acceptable 10 cm trimming allowance range for the assortment (40.2%) and half were over cut (58.9%) (Table 3).

Looking at the factors that could potentially affect the harvester's cross-cutting accuracy, this study found that the log assortment class did not have a significant effect on the accuracy of the harvester. The longer log assortment classes in both species had slightly higher standard deviations in length (Table 3), but this was not statistically significant. Past research has shown that the intended log assortment did not affect the volume of wood lost, with similar proportions of inaccurate cuttings in 2.4, 2.7 and 6.6 m log lengths (Eggers et al. 2010). Additionally, the log's diameter did not have a significant effect on fibre loss, which supports Eggers et al.'s (2010) study, in which they found that tree characteristics, including diameter, did not affect the level of cross-cutting accuracy performed by the harvester compared to more manual means. However, it was found that the tree species did have a significant effect on the amount of fibre loss, with *P. patula* having higher levels of associated fibre loss than *P. elliottii*. The volume lost was significantly higher for *P. patula* logs, which contributed 88.39% to the total lost volume (Table 3). In addition, the harvester's productivity was higher when working in *P. patula* stands, although these also had a higher average tree volume (Table 2). *P. patula* is known to have larger branches than other pine species, which proves to be a struggle when processing trees (De Villiers 1965, Van Wyk 1978) and some studies have shown branches to lead to measurement errors by the harvester when cross-cutting because they cause the length measuring device in the harvester head to lose contact with the stem (Richardson 1988). A study by Opferkuch et al. (2014) found, similar to this study, that the harvester's measurement error was greatest for logs originating from higher up on the stem compared to logs cut from the base of the tree, which was attributed to branches. However, more recent research done by Eggers et al. (2010), in which they found that branchiness and stem characteristics of *Pinus patula* and *Pinus elliottii* in South Africa did not significantly affect the accuracy of the harvester, directly contradicts both earlier findings and the results of this study. It should be noted that in this study all *P. patula* logs were cut by the Waratah HTH622B harvester head, while the *P. elliottii* logs were cut by the Waratah HTH623C harvester head, which may be a confounding factor. Although both harvester heads were equipped with identical measuring systems and the maximum tree diameter was well under the maximum feed roller opening on either machine, the heavier weight of the harvester head used on *P. elliottii* stems may have affected the machine's productivity and the occurence of accurate cuttings, which were both higher than those observed for *P. patula*. It is also important to take the operator's level of experience into consideration. The operator working in the *P. patula* stands had two years of experience on the machine, whereas the operator working in the *P. elliottii* stands had only 18 months of experience. Generally, a higher level of experience translates to a higher likelihood that the operator will succeed in cutting assortments accurately (Spinelli et al. 2011). Moreover, the different operators should be noted as other factors about them may affect the accuracy of their work, such as motivation, attitude, skill and level of attention (Spinelli et al. 2011). This could have confounding effects on the analysis results for the species studied.

It would be useful to conduct further studies of this type that allow for the analysis of operator, machine and stand factors to be more fully assessed in terms of their impacts on the accuracy of cross-cutting. In addition, future research could include a more detailed analysis of tree characteristics relating to branches, sweep or other factors. Overall, this study found that the volume of fibre loss was highest for *P. patula* logs. In terms of the machine's productivity, *P. patula* stands were also associated with the lowest average productivity. Taking this into account, it might be advisable to be aware of greater economic challenges when harvesting *P. patula* stands in a CTL system. Depending on the inherent accuracy of mechanised processing, it may be possible to not even apply the 0.1m trimming allowance. In a study by Ackerman and Pulkki (2012), it was shown that on an annual country wide cut of 4.5 million m^3, the fibre lost through the trimming allowance amounted to 80 500 m^3 of potentially utilisable fibre.

5. Conclusions

Since there has been minimal research on the accuracy of harvester cross-cutting in South African pine sawlog mechanised CTL systems and as these studies have had contradicting findings, this study aimed both at assessing the accuracy of a harvester's ability to cross-cut *Pinus spp.* stems as well as exploring the factors that could potentially affect the amount of useful wood lost through inaccurate cross-cutting. In addition, the productivity of the machine, a purpose-built John Deere feller buncher equipped with a Waratah harvester head, was calculated. The machines were found to be more productive when working in *P. elliottii* stands (32.12 m^3SMH^{-1}) than in *P. patula* stands (17.55 m^3SMH^{-1}). The study, which focused on clear-felling stands in the Southern Cape and Mpumulanga forestry regions of South Africa, found a high level of accuracy from the machines when looking at fibre losses. Logs processed by these machines only had 1.187 m^3 of lost utilisable wood (which was 1.516% of the total wood volume) associated with inaccurate cross-cutting. The revenue potentially lost through inaccurate cross-cutting was estimated to add up to €22 650 per year (€0.18 m^{-3}) for *P. elliottii* and €101 530 per year (€1.61 m^{-3}) for *P. patula* in the operations studied. These results support earlier research. Similar to prior South African studies, the results also show that length and diameter did not significantly affect the amount of fibre loss. However, the tree species did have a significant impact on the fibre loss associated with cross-cutting. *P. patula* stems, known to be branchier in general, had a higher level of fibre loss (0.1018 m) compared to *P. elliottii* stems (0.0237 m). However, this finding may be confounded with other factors, such as operator characteristics, operator experience and machine characteristics. The study design unfortunately does not allow for the comparison of these factors and more research is required. Nonetheless, this study suggests that harvesting *P. patula* stands in a CTL system may require more caution and attention since these are associated with potentially more fibre loss and lower productivities.

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Authors' addresses:

Chloe Williams, BSc *
e-mail: chloe.c.williams@hotmail.com
Assoc. prof. Pierre Ackerman, PhD
e-mail: packer@sun.ac.za
Stellenbosch University
Department of Forest and Wood Science
Private Bag X1
Matieland
SOUTH AFRICA

*Corresponding author