Unlocking the potential of harvester on-board-computer data in the South African forestry value chain

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DECLARATION

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Abstract

The South African forest industry is in a state of change from motor-manual to fully mechanised harvesting systems. This is predominately driven by health and safety concerns related to motor-manual harvesting systems, and the need to enhance systems productivity and product quality. Through the use of technologically advanced harvesting machinery with on-board computing systems, and standardised and compatible data collection software, all mechanised processing operations are able to produce real-time (time-stamped) data related to almost every action or function of the machine. The software referred to above is the Standard for Forest Communication (StanForD) first developed by Skogforsk in 1987, as a standard for managing the information flow from the forest machines through the value chain. Although most machines in South Africa are compatible with the StanForD systems, the usefulness of the concept remains under-utilised due to limited understanding of the interface between harvester heads and the computing systems. This includes validating the integrity and accuracy of the data emanating from the system, and that is firmly embedded in quality assurance and computer calibration. The objective of this study is to propose and develop an applicable bark deduction method for *Pinus patula* in the Mpumalanga Highveld region of South Africa for more precise log volume calculations.

This was accomplished by modelling historical *P. patula* bark thickness data from the Mpumalanga Highveld region to obtain bark thickness estimates for the two methods of bark deduction to be assessed that are available on the Ponsse Opti OBC system. Three trials were run: T1 (status quo no bark deduction function), T2 (length-based [LB] bark deduction method) and T3 (diameter-class length-based [DLB] bark deduction method). The two bark deduction methods were implemented successfully, and the harvester`s under bark (UB) diameter measurements compared well with manual measured UB diameter measurements which was derived through the novel application of photogrammetry technology.

Results showed that if no bark deduction method is used the harvester over-estimates stem volume by 13.7% and 14.6% for each of two respective bark deduction methods. Furthermore, by the nature of *P. patula* bark being extremely thick at the base of the tree stem, means this over-estimation is even greater for butt logs. The harvester over-estimated the log volume of the first plywood log cut by 20.8% for T1, where through the implementation of a bark deduction method the volume estimation was improved to an under-estimation of only 1.6% and 0.2% for T2 and T3 respectively. The results of this study show that by not implementing bark deduction methods the harvester`s log volume estimations are grossly over-estimated and the usefulness of the harvester`s data for value chain management is lost.

Key concepts: Bark thickness deduction, Harvester calibration, Measurement accuracy, Volume estimation, StanForD, *Pinus patula*

Opsomming

Moderne sny-tot-lengte ontginnings masjiene is ‘n hoogs gesofistikeerd en word beheer deur tegnologies gevorderde aanboord rekenaars. Hierdie rekenaars word bedryf deur `n data format die Standaard for Forest Communication (StanForD) wat aanvanklik in 1987 ontwikkel is deur Skogforsk. Die formaat dien as die data standard vir inligtingsvloei vanaf die ontginnings masjien dwarsdeur die waardeketting tot by die saagmeul. Alhoewel die meeste ontginnings masjiene in Suid-Afrika versoenbaar is met die StanForD data formaat word die bruikbaarheid van die konsep nie ten volle benut nie. Dit is as gevolg van die gebrekkige kennis t.o.v die interaksie tussen die masjien se rekenaar en die ontginnings masjien se sny kop. Dit sluit die bekragtiging van die integriteit en akkuraatheid van die data wat uit die sisteem voortspruit met spesifieke klem op masjien kalibrasie.

Die doel van hierdie studie is om ‘n toepaslike bas-dikte-verminderings-metode vir Pinus patula in die Mpumalanga Hoëveld streek van Suid-Afrika vir meer presiese blok volume berekeninge te ontwikkel. Dit was vermag deur die modellering van geskiedkundige data P. patula bas diktheid vir die Mpumalanga Hoeveld streek om die nodige geskatte waardes van bas diktheid te verkry vir die twee beskikbare metodes van bas vermindering wat op die Ponsse Opti aanboord rekenarsisteem beskikbaar was te assesseer. Drie streekproewe was uitgevoer naamlik; T1 (geen bas vermiderings metode), T2 (lengte gebaseerde bas dikte vermindering) en T3 (diameter-klas lengte gebaseerde bas dikte vermindering). Die twee bas verminderings metodes was suksesvol geïmplimenteer en die masjien se blok onder bas deursnee metings was vergelyk met die fisiese gemeete onder bas deursnee meetings wat verkry is deur die gebruik van fotogrammetrie tegnologie.

Resultate het gewys dat as daar geen bas verminderings metode gebruik word nie oorskat die masjien se volume skatting met 13.68% en 14.59% vir onderskeidelik T2 en T3 oorskat word. P. patula se bas is verskriklik dik op die onderste gedeelte van die stem wat beteken dat die oorskatting nog groter is vir blokke wat onder op die stam hul oorsprong het. Die masjien het die blok volume vir die eerste veneer blok wat vanuit die stam gesny word vir T1 met 20.81% oorskat as geen bas dikte vermindering metode gebruik word nie, en met die implementiering van `n bas dikte vermindering metode is die volume skatting verbeter na ‘n onderkskatting van slegs 1.59% en 0.18% vir T2 en T3 onderskeidelik. Die resultate van die studie beklemtoon dat deur nie bas verminderings metodes te implimenteer nie word blok volumes oorskat waardeur die bruikbaarheid van die ontginnings masjien se data vir bestuur van die bosbou waardeketting verlore gaan.

Sleutelbegrippe:

Bas dikte vermindering, Ontginnings masjien kalibrasie, Meeting akkuraatheid, Volume berekening, StanForD, *Pinus Patula*

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List of Abbreviations

AMSL	Above mean sea level
BT	Bark thickness
CTL	Cut-to-length
DBH	Diameter at breast height
DLB	Diameter-class length-based bark deduction method
LB	Length-based bark deduction method
LED	Large end diameter
ME	Measurement error
MHS	Mechanised harvesting system
OB	Over bark
OBC	On-board-computer
SD	Standard deviation
SED	Small end diameter
StanForD	Standard for forest communications
UB	Under bark

1. Introduction

The South African Industrial forest industry relies on 1.212 million ha of planted forestry land made up of both hard- and softwoods. Softwoods (*Pinus spp.*) total about 601 000 ha, while the remaining area consists of hardwoods (*Eucalyptus* and *Acacia spp.*). Of the 1.212 million ha, 57% is managed for pulpwood production, 37 % for saw logs, 3% for mining timber and 3% for other purposes (Forestry Economic Services CC, 2018). Total plantation round wood production during 2016/2017 was 18.3 million m³, of which 37% was softwood and 63% hardwood. The total plantation round wood sale value was R10.1 billion (Forestry Economic Services CC, 2018). Of the 601 000 ha of softwood, 74% is managed for saw timber and 26% for pulpwood production. Although a number of different softwood species are planted in South Africa, *Pinus patula* remains the most widely planted tree species with an area of around 294 000 ha (Forestry Economic Services CC, 2018). The dominance of *P. patula* is attributed to its preferred wood properties for use in the structural, veneer and pulpwood industries (Vermaak, 2007; Hongwane *et al.*, 2017).

Since the late 20th century there has been a rapid shift toward mechanised harvesting operations internationally, primarily led by the Nordic countries (Längin & Ackerman, 2007; Längin *et al.*, 2010). This is supported by Uusitalo (2010) who found that mechanised CTL harvesting accounted for more than 90% of the wood procured for the forest industry in the Nordic countries. The push towards mechanised forest operations is driven by a decrease in productivity from motor-manual harvesting systems, rising input costs, labour shortages in rural forestry areas and an increased awareness concerning worker safety (Kirk *et al.*, 1997; Axelsson, 1998; Murphy *et al*, 2004; Murphy *et al.,* 2005).

Although still a comparatively recent technology in South Africa, the South African forest industry is following the same trend as mentioned above. A survey conducted by Längin and Ackerman (2007) showed that motor-manual operations accounted for 65% of the harvested volume in South Africa, while fully mechanised harvesting systems (MHS) contributed only 6.4%. By contrast, a recent study by Wenhold (2017) showed that, the use of MHS has increased to 57%, with motor-manual operations accounting for the other 43% of harvesting systems being applied in South Africa. The reason for this shift to MHS in South Africa is similar to the international explanations as mentioned above, but also supported in South African related literature (Steenkamp, 2007; Ramantswana *et al.*, 2013; McEwan & Steenkamp, 2014; Van der Merwe *et al.*, 2015; Norihiro *et al.*, 2018). These factors have created an environment conducive to mechanisation of forest operations as a cost-mitigating factor with the aim of increasing productivity.

Mechanised Cut-To-Length (CTL) timber harvesting is described as the process where a harvester fells, delimbs and crosscuts a tree at the stump into log assortments. A forwarder then transports these assortments to a roadside landing. Once delivered to the landing the assortments can be loaded onto a truck for delivery to a processing plant or mill (Längin *et al.*, 2010). As mechanised CTL systems have developed over the years, so too has the sophistication of the harvester in terms of log measurement and data recording. A key example is the development and advancement of the on-board-computing (OBC) systems integrated into the functioning of the harvester, that collect a vast array of data automatically, and which are available to practitioners and researchers alike (Möller *et al.,* 2011).

Although this is now commonplace globally, it is however still not the case in South Africa, where the value of the data produced has not yet been unlocked. Apart from unlocking the full value there is still a clear ignorance concerning the measurement and data accuracy of even the most basic outputs available from the OBC. The precise estimation of bark thickness is known to have a large impact on volume calculations and log optimisations however, it is often omitted or critically inaccurate (Marshall *et al.*, 2006; Strandgard & Walsh, 2011). As most modern harvesters are of Scandinavian or North-American origin, the implicit bark deduction methods available are not applicable to South African species and conditions, and therefore still need to be developed, validated and applied.

Objectives:

The objective of this study is to propose and develop an applicable bark deduction method for *P. patula* in the Mpumalanga Highveld region of South Africa for more precise under bark log volume calculations.

Based on the objective of this study the following sub-objectives are proposed, to determine:

- The impact of bark deduction method calibration or non- calibration on harvester log diameter calculation.
- Log length measurement accuracy of harvesters when calibrated in the Highveld region of South Africa.
- The impact of actual stump heights vs stump height as set on the harvesters OBC on the harvester OBC system`s interpretation of DBH.

2. Literature Review

2.1. Harvester measuring procedure

Uusitalo (2010) described the term harvester measurement as the measuring of a quantity of timber through a measuring device attached to a harvester head during harvesting work. A harvester`s measurement systems comprises of measurement sensors, a computer controlling the measurement process, control and peripheral devices, and an internal telecommunications network such as a Controller-area network (CAN), which links everything together (Uusitalo, 2010). This measurement system in turn produces, diameter, length and volume measurements. Combined, these parameters drive the harvesters log optimisation and bucking control system.

2.1.1. Diameter measuring procedure

Stem diameter is determined through the utilisation of sensors called angle potentiometers that are located in the feed rollers or delimbing knives of the harvester head (Nordström & Hemmingsson, 2018). Nordström and Hemmingsson (2018) further explain that the OBC calculates stem diameter as the diameter of a circle through triangulation for the three-point measurement method or by averaging the perpendicular measurements in the four-point measurement method. These are then recorded by the machines OBC system.

2.1.2. Length measuring procedure

Length measurements are often, performed by a toothed measuring wheel situated on the body of the harvester head. The measuring wheel, which is connected to an optical or inductive pulse sensor, is pressed into the stems bark by a hydraulic cylinder (Uusitalo, 2010). The head records the distance between the chainsaw`s felling cut and the measuring wheel as the starting length. As the stem is fed through the head, it causes the measuring wheel to turn, which then transmits a pulse value to the harvester`s computer which gets translated into a numerical value (Uusitalo, 2010; Nordström & Hemmingsson, 2018).

2.1.3. Volume calculation

The length and diameter measurements recorded by the machine`s OBC system are used for the volume determination of each log cut from the stem. Stem volume determination is entirely dependent on the accuracy of the harvester's diameter and length measurements. The harvester's OBC system either uses the formula for a cylinder (Equation 1), or a truncated cone (Equation 2), depending on manufacturer specifications (Uusitalo, 2010). The harvester`s computer then calculates the volume of the log by summing the volume of the 10 cm long sections. Depending on the manufacturer's specifications, the OBC uses either the minimum, maximum, or the arithmetic mean diameter of each section when using Equation 1. The volumes of these cylinders are summed to supply the volume of each produced log and the stem total (Arlinger, 2018).

Cylinder:

$$Volume = (\pi * \frac{d}{2})^2 * l \qquad (1)$$

Truncated cone:

$$Volume = \left(\pi * \frac{l}{3}\right) * (r1^2 + r1 * r2 + r2^2) \qquad (2)$$

Where:

Volume = section volume (m^3)

d = minimum, maximum, or arithmetic mean diameter (cm)

l = length of section (cm)

r1 = section large end radius (cm)

r2 = section small end radius (cm)

2.1.4. Harvester Bucking Control System

Bucking or cross cutting is the process whereby a tree is cut into sections or assortments called logs (Uusitalo, 2010). Harvester operators can use the OBC's automated bucking optimisation system or they have the choice of manually selecting the products to be produced from a tree through the pressing of pre-programmed hot keys where each corresponds to a certain product type (Labelle & Huß, 2018). If the operator uses the bucking optimisation system, it works in either of two ways. The OBC can be set-up to either optimise each stem`s monetary value, or to fulfil the market’s product requirements (Marshall, 2005). This bucking optimisation works on a process called adaptive stem prognosis (Arlinger, 2018).

Stem prognosis is the process whereby the computer predicts the taper of the specific stem to determine the cutting points for the specific products that need to be produced according to a price list. The harvester`s OBC needs to know the dimensions of a section of the stem profile to be able to make a prediction on the unknown part. When the harvester head grips the base of the stem and runs it through the feed rollers for the first 3 to 4 m, it measures dimensional data. This new data together with the stem profiles from previously processed trees is used to predict the unknown stem profile of the current stem. The computer then calculates the optimised cutting points for the specific product dimensions to be produced. As the stem moves through the head, the measuring system continually checks if the actual stem profile is within the required range of the predicted stem profile. If the prediction is not within the given tolerance, the computer will run a new optimisation procedure and adjust the cutting points either forwards or backwards, depending on the new product to be cut. If the stem profile is within the allowed tolerance, the stem is crosscut at the original cutting point. Using the new stem profile information measured and the profiles in its history, the OBC predicts the cutting points for the next product to be cut until it reaches the minimum topping diameter of the stem (Arlinger, 2018).

2.2. Measurement accuracy

Harvester heads work in a mechanically demanding and tough environment. This causes a lot of strain on the measuring equipment where many factors can influence measurement accuracy. Skogforsk (Swedish Forestry Research Institute) uses three standard benchmarks for assessing measurement accuracy (Nordström & Hemmingsson, 2018):

- The proportion of measurements within a given range; for diameter measurements this range is within ± 4 mm of the control measurement and ±2 cm for length measurements called the Swedish “Best-5”.

- The dispersion or spread of the measurements; expressed in terms of the measurements standard deviation (SD). A lower SD signifies more precise and consistent measurements.
- Systematic deviation; when the measuring equipment is consistently over- or under-measuring. Strandgard & Walsh (2012a) show that the regular checking and maintenance of measuring equipment coupled with a professional calibration procedure and quality audit can minimise these errors.

2.2.1. Length measurements

Length measurement error can be the result of a variety of factors. A main cause is the slipping or loss of contact of the measuring wheel with the log surface (Strandgard & Walsh, 2012a). This is supported by Nieuwenhuis & Dooley (2006) and Mederski *et al.* (2018) who found that stem crookedness, large branch stubs and loose bark can lead to measurement errors. These factors can lead to the harvester head using multiple delimbing attempts which can cause the measuring wheel to lose its length measurement. (Andersson & Dyson, 2001; Strandgard & Walsh, 2012a; Mederski *et al.*, 2018).

The hydraulic pressure settings also play a key role in measurement accuracy. According to Nordström and Hemmingsson (2018) the length measuring wheel needs to have enough hydraulic pressure to stay in contact with the stem to prevent slippage. In addition, Nordström and Hemmingsson (2018) described that the hydraulic pressure settings of the feed rollers and delimbing knives affects the ease and rate at which the stem is fed through the head. If the feed rollers slips it can lead to errors in length measurement (Nordström & Hemmingsson, 2018). Operators often re-zero the measuring wheel by cutting a small disc off of the end of the stem however, contact between the cutting bar and the stem end can often be narrowly missed, causing the over-estimation of log length (Strandgard & Walsh, 2012a). The clogging of the measuring wheel with soil and bark has also been described as a source of error and should be kept clean (Saathof, 2014).

In a Canadian study on the length measurement accuracy of 83 harvesters and processors, Andersson & Dyson (2001) found the accuracy within the Swedish “Best-5” to range from 23% to 92% of length measurements per machine. The authors explained the large dispersion in measurement accuracy by the fact that some harvesting sites placed a larger emphasis on quality control and calibration of the measuring system and subsequently achieved much better results than sites where this was not the case (Andersson & Dyson, 2001). Leitner *et al.* (2014) found that harvester length-measurement accuracy of a Ponsse H7 harvesting head increased by 30.4% to achieve 97.5% accuracy within the "Best-5" range following a professional calibration procedure. Leitner *et al.* (2014) further found that a regularly calibrated Komatsu 350.1 harvester head achieved a measurement accuracy of 95% within the "Best-5". This is supported by Niewenhuis & Dooley (2006) and Marshall *et al.* (2006), who suggested that the regular calibration and checking, coupled with a systematic maintenance program, is essential to reducing measurement error in harvesters.

Skogforsk periodically conducted tests from 1995 to 2016 on measuring and control systems from different machine manufacturers to monitor their technological development and accuracy. The latest tests in 2016 were conducted on four different harvester units. The length measurement test found John Deere to be most accurate achieving 94% of its measurements within the "Best-5" range, while Ponsse achieved an accuracy of 90%, and Dasa and Komatsu achieved accuracies of 87% and 84%, respectively (Nordström *et al.,* 2018). While this is only a slight improvement from the 2006 test where the average length accuracy for the test units was 84%, the standard deviation decreased by 28% compared with the 2006 tests for all the systems in the trial (Nordström *et al.*, 2018).

2.2.2. Diameter measurements

Full stem contact with the measuring equipment throughout the measurement process is critical to ensure correct diameter measurements. For this reason, characteristics that influence the smooth taper of the stem will have an impact on measurement accuracy. This can be the result of excessively large knots and branch nodes that cause the delimbing knives to deflect, leading to over-estimation of diameter (Strandgard & Walsh, 2012a). The OBC however has a built-in function that assesses every diameter measurement to ensure that the stem diameter decreases towards the tree top and will therefore average out any diameter that indicates an increase towards the top of the tree (Uusitalo, 2010). Furthermore, Strandgard & Walsh (2012a) explain that the hydraulic pressure settings of the delimbing knives and feed rollers play an important role in stem diameter estimation. If these pressures are too high it can lead to the bark being compressed or even removed by the delimbing knives leading to under-estimation of diameter (Strandgard & Walsh, 2012b).

An important assumption regarding harvester diameter measurements is that trees are round. This however is not true, as trees tend to be more oval, especially towards the butt end. This "out of roundness" is known to cause measurement errors (Strandgard & Walsh, 2012b; Nordström & Hemmingsson, 2018). This means that the orientation of the stem shape in the harvester head can lead to discrepancies in the diameter measurement (Strandgard, 2009), since harvesters either use the 3-point triangulation or the 4-point measurement technique.

In a study on 31 harvester and processor heads in Canada, Andersson & Dyson (2001) found that only 34% of logs small end diameter (SED) measurements were within the ± 4 mm range. The authors however did not consider this a representative result of measurement accuracy as the machines were rarely calibrated for accurate diameter measurements (Andersson & Dyson, 2001). More recently in the 2016 Skogforsk diameter tests, John Deere again outperformed its competitors. This unit recorded 84% of its measurements within ± 4 mm of the manual control, while the other three systems averaged between 76% and 79% of their measurements within the target range (Nordström *et al.*, 2018). This was an average improvement of 11% compared with the 2006 diameter test results and a decrease in SD from 4.5 mm to 4.1 mm (Nordström *et al.*, 2018). This clearly illustrates the level of precision that harvester-measuring systems can achieve if the calibration is set as a top priority by the harvesting team, and conducted regularly and methodically.

2.2.3. Quality assurance

The precision of the harvester data is paramount to its use for management related tasks. It has been widely documented that the precision of this data is embedded in the regular maintenance and correct calibration of the measuring equipment (Andersson & Dyson, 2001; Marshall *et al.*, 2006; Nieuwenhuis & Dooley, 2006; Strandgard & Walsh, 2012b; Leitner *et al.*, 2014; Nordström & Hemmingsson, 2018). Andersson & Dyson (2001) noted that there should be buy-in from the whole harvesting team regarding the measuring accuracy programme, and that regular quality checks are essential for this operation. Although this increased quality control will decrease productivity and increase total harvesting cost, this higher cost needs to be incurred by all in the value chain as increased log quality will ultimately increase sawmill lumber recovery, and as such increased harvester log quality should be incentivised (Andersson & Dyson, 2001).

A good example of a strong quality assurance scheme is the Swedish Forestry Organisation BIOMETRIA, which audits harvester measurements on behalf of the Swedish forest industry to ensure data accuracy. Their standards are regarded as the gold standard in harvester measurements accuracy (Arlinger, 2018). They have three levels of measurement accuracy ratings namely: 1) well passed approval, 2) approved (alarm level) and 3) big deviation that are given to a harvesting team (machine and operators) (BIOMETRIA, 2019). Big deviation requirements are a minimum of 35% of diameter measurements within ±4mm and 40% of length measurements within ±2cm. For an approved rating the diameter requirements are a minimum of 55% of measurements within ±4mm and 70% of length measurements within ±2cm. The well passed approval requires at least 65% of diameter measurements within ±4mm and 80 of length measurements within ±2cm (BIOMETRIA, 2019). This standard and process of measurement accuracy auditing ensures the accuracy of harvester data for the entire Swedish forest industry.

2.3. Harvester head Calibration

Harvester calibration plays an integral part in the quality assurance of harvester measurements (Andersson & Dyson, 2001; Nieuwenhuis & Dooley, 2006; Strandgard, 2008; Uusitalo, 2010; Leitner *et al*., 2014). The calibration procedure is the process where the operator checks if the measuring sensor measurements corresponds to the actual stem measurements (Nordström & Hemmingsson, 2018). According to Nordström and Hemmingsson (2018). This process needs to be completed after all maintenance and repairs to the measurement system, or a change in operating conditions. This full calibration procedure coupled with the regular quality checking of measurements on random control stems forms the basis of harvester measurement quality assurance in Sweden (Nordström & Hemmingsson, 2018).

If the operator selects the full calibration procedure on the OBC, he also decides on the number of previously processed stems to be used for the calibration. If the random control check is activated on the system, the OBC will randomly select a stem to be used as the control. When the specific stem is harvested, a pop up message will appear on the OBC screen to notify the operator upon which he needs to complete the control measurements. For both the full calibration and the random checks, the manual measurement procedure stays the same. Log lengths are measured with a logger`s tape which are recorded manually into a digital caliper. Diameter measurements of these logs are then measured at one-metre intervals with the digital caliper. At each diameter measurement position, two perpendicular measurements are taken. Once the control measurements are completed, the caliper is connected to the OBC and the data is automatically transferred to the harvester. The OBC will then propose adjustments to the measuring system, or manually input adjustments can be made based on the data (Nordström & Hemmingsson, 2018).

Length calibration adjustments are usually proposed as a correction factor that will adjust the measuring wheel estimate of the log length, while the diameter measurements have two main types of calibration (Nordström & Hemmingsson, 2018):

- Breakpoint calibration – calibration is conducted according to diameter classes, but adjacent diameter classes do influence each other.
- Regression calibration – converts all the data to a straight line. This method requires data for the entire range of stem diameters in the compartment to prevent the calibration model changing too much on the edges.

Strandgard & Walsh (2012a) found that harvesters tend to be set-up to measure conservatively. Although this approach decreases the number of logs that are out-of-specification, it will also increase timber volume and value loss (Strandgard & Walsh, 2012a).

2.4. Harvester On-Board-Computer systems

The global shift towards mechanised CTL harvesting has also brought along the technological advancement of the OBC systems that these machines use, and as such the use of the vast amounts of data that these systems record. It has been well documented that modern harvesters should be considered as a valuable source of data from which the whole forestry value chain can be managed (Gellerstedt & Dahlin, 1999; Murphy, 2001; Stendahl & Dahlin, 2002; Strandgard, 2009; Möller *et al.*, 2011; Olivera *et al.*, 2014; Olivera & Visser, 2016a,b; Roth, 2016; Brewer *et al.*, 2018).

This technological shift originates from the utilisation of modern technology in forestry machines (Uusitalo, 2010). A modern harvester`s OBC incorporates all the features of a laptop PC, with the addition of cellular telecommunications technology and Global Navigation Satellite Systems(GNSS) (Marshall, 2005; Uusitalo, 2010).

Harvester OBCs record vast amounts of data automatically through the harvester head`s measurement system, GNSS receiver, harvesting directives and records of operator`s decisions (Möller *et al.*, 2011). The measurement system records the diameter, length and volume of every log and stem in detail, as well as the time it takes to be processed by the harvester head (Stendahl & Dahlin,2002). Together with this, the harvester`s GNSS coordinates are also continually recorded. Coupling this spatial information with the machine`s production data adds another layer of depth to this information for use in harvesting management, logistics and silviculture (Möller *et al.*, 2011; Olivera *et al.*, 2015). The use of this information is however entirely dependent on the accuracy and precision of the harvester measurements.

2.4.1. StanForD

The Standard for Forest Communications (StanForD) was developed by Skogforsk in the late 1980s (Skogforsk, 2010). StanForD provides a universal means to communicate with forest machines and management systems, as well as a standard data format for all CTL harvesting information (Skogforsk, 2010; Olivera & Visser, 2016a). This standard is used by most major manufacturers of CTL harvesting machines (Skogforsk, 2010)

Möller *et al* (2011) described the progression of StanForD as follows:

1. 1990’s: Data used only to control the bucking optimisation (dimensions and pricelists).
2. 2000’s: Production data started to be used as a base for planning and logistics.
3. 2010’s: Data is now starting to be used as a base for planning and control of the following processes in the supply chains: the prognosis of forest fuel, regeneration planning after final felling, transparent information to forest owners and updates of forest plans. The standardised individual stem and log information is also widely used.

The latest version, StanForD 2010 uses the XML format for storing data, which is open sourced so there is no unnecessary data type conversion needed to utilise the data (Skogforsk, 2010). However, the complexity of efficiently using this data should not be under-estimated, as illustrated by Purfürst and Erler (2011), and Olivera and Visser (2016). Although, StanForD provides a standardised data format, the automatic parsing of this data remains complex (Purfürst, 2010; Purfürst & Erler, 2011). The reason for this is that different machine manufacturers use their own computer software systems and applications to record and interpret the data, while different harvester models can use different versions of StanForD (Purfürst, 2010; Purfürst & Erler, 2011).

StanForD 2010 records data under four broad functions, each with several file types storing different information as described by (Skogforsk, 2010):

- Production control manages the cutting instructions, log length and diameter specifications, and the mix of products (price matrices) to be cut. It also manages in what geographical location the machine is authorised to cut through GIS applications and map overlays (Skogforsk, 2010; Möller *et al.*, 2011).
- Production reporting files supply feedback on the volumes that are produced. This data supplies individual log level information on volume, product type and dimensions. It can be used for logistics management, contractor and resource owner payments, as well as forest inventory purposes (Skogforsk, 2010).
- Quality control is managed through the harvesting quality control (hqc.) file. This file supplies information regarding the accuracy of the harvester’s measuring system (Skogforsk, 2010).
- Operational monitoring files automatically record the work time process in relation to the harvesting object, machine and operator. This data permits production monitoring and comparisons between different machines and systems. It records all machine time elements. This supplies a holistic picture to assess machine use and calculate key performance indicators regarding production and associated costs (Skogforsk, 2010).

2.4.2. Stem (.stm) files

Stem (.stm) files are a file type under the earlier version of StanForD. Stem files supply detailed diagnostics of each stem processed, from length and diameter measurements to location and time stamps. For these reasons, they are of interest to researchers trying to find innovative ways in which to employ them for system productivity analysis and optimisation. They normally record the following information (Arlinger *et al.*, 2012):

- Site ID (compartment name)
- Species ID
- Stem DBH
- Stem length
- Stem volume
- Diameter measurements at 10 cm length intervals for whole stem
- Log length, OB and UB log end diameters and volume
- GNSS coordinates of the machine (latitude, longitude and altitude)
- Time stamps (year, month, day, hour, minute and second)

Strandgard *et al.* (2013) and Brewer *et al.* (2018) used these data to do automated harvester productivity time studies using stem file time stamp and stem volume data. Wenhold (2017) also used stem files to analyse and model new harvester operator productivity learning curves in clear-felling and thinning operations. In addition, Olivera *et al.* (2015) used the combination of volume and GNSS data from stem files to create volume and productivity maps to assess machine productivity across different site factors. Stem files are also of keen interest for bucking optimisation analyses as they provide a complete stem profile (Uusitalo, 2010). In the new StanForD 2010 version, the information recorded in stem files are reported by the harvester quality control (.hqc) file.

2.5. Bark thickness (BT)

Round wood is usually marketed in terms of its UB volume (Staengle *et al.*, 2016). Although tree bark is fundamental to the health and longevity of a standing tree it has very limited commercial value (Marshall *et al.*, 2006). Herein lies a problem for modern harvesters, as they need to be able to predict UB diameters from over bark (OB) measurements for bucking optimisation and volume calculation. In a study on the impact of BT estimates on optimal log making, Marshall *et al.* (2006) found that not considering bark thickness will inflate produced log volumes and subsequently the value. This study further found that using the incorrect species coefficients in a bark deduction model can cause up to 34% of logs to not meet market specifications (Marshall *et al.,* 2006). Marshall *et al.* (2006) also explained that by not using or using the wrong BT model on a harvester can lead to the potential over or under-payment to the logging contractors and forest owners when using the harvester's volume calculations. This shows the use of the right bark deduction method is essential for optimised value recovery and exact volume calculations. This is supported by Strandgard and Walsh (2012a) who determined that accurate BT estimates are critical if one wants to implement stem optimisation in the bucking procedure. In conclusion, the fact that harvester measurement data is also increasingly being used for management related tasks, it is important to ensure accurate BT estimation.

2.5.1. StanForD bark deduction methods

The StanForD system provides four standard methods for bark deduction to harvester operators (Strandgard & Walsh, 2011):

1. Zacco (1974) function:

$$dbt = b0 + b1 * Dob \tag{3}$$

Where:

dbt = double bark thickness (mm)
b0 and b1 are user-defined coefficients
Dob = stem diameter over bark (mm)

2. The second method is based on German requirements where BT is deducted as a set value for certain diameter classes (Skogforsk, 2012).

Table 1: German bark deduction method

Bark deduction (mm)	Log SED over bark (mm)
30	<=320
20	>320 <=200
10	>200 <=0

3. Scots pine bark deduction function developed by Skogforsk.

$$htg = -ln(0.12/(72.1814 + 0.0789 * DBH - 0.9868 * lat))/(0.0078557 - 0.0000132 * DBH) \tag{4}$$

Double bark thickness below break point (Hmeas< htg)

$$dbt = 3.5808 + 0.0109 * DBH + (72.1814 + 0.0789 * DBH - 0.9868 * lat) * exp(0.0078557 - 0.0000132 * DBH) * Hmeas) \tag{5}$$

Double bark thickness above break point (Hmeas> htg)

$$dbt = 3.5808 + 0.0109 * DBH + 0.12 - 0.005 * (Hmeas - htg) \tag{6}$$

4. Norway spruce bark deduction function developed by Skogforsk

$$dbt = 0.46146 + 0.01386 * dbh + 0.03571 * dob \tag{7}$$

In an Australian study on harvester estimates of *Pinus radiata* BT, Strandgard and Walsh (2011) found that the Zacco function does not take into account the non-linear change in BT from the base to the top of the tree. Further, it could not explain that the same stem diameter at differing tree heights can have different BT (Strandgard & Walsh, 2011). This led to the model severely under predicting BT for the lower section of the tree and over predicting for the higher sections. For these reasons, this model is not applicable for trees whose BT is not proportional to diameter OB.

The second StanForD method is only applicable in Germany for species where BT is proportional to stem diameter. Strandgard and Walsh (2011) also found that the Scots pine function could be applied to *P. radiata* with a diameter of less than 40 cm. Further, Strandgard and Walsh (2011) found the Norway spruce model to be not of any use as it under-estimates BT for larger diameter values. The coefficients for these two models are also hard coded, so the user cannot derive his own coefficients for input into the StanForD system.

Machine manufacturers can also add other bark deduction methods into their own control system. Ponsse`s Opti control system has extra bark deduction methods such as (Ponsse, 2018):

1. Proportional bark deduction method:
   This method first reduces bark from the measured DOB as a millimetre thickness value. It further deducts BT as a percentage thickness of the first DOB measured. This method is useful for species where BT is proportional to stem diameter.
2. Diameter class deduction:
   Bark thickness is reduced according to the DOB measurements. Each diameter class has a set BT value in millimetres that is subtracted from the DOB measurement to calculate the UB diameter.
3. Length-based bark deduction method:
   The whole stem is divided into sections of a certain length starting from the butt end of the stem. Each section has a bark thickness in millimetres assigned to it which is subtracted from the OB diameter measurement to give the UB diameter.
4. Diameter-class length-based bark deduction:
   This method also deducts bark according to length sections from the butt end, but the BT is classified into different DBH classes. This works with the idea that bigger trees will have thicker bark irrespective of the position above the base of the tree. It works with a table where length from the butt end is in the top row and diameter classes are in the first column. Therefore, this method works well for many areas and for most the tree species if there is reliable information to populate the table.

Clearly, there are various bark deduction methods available on modern harvester OBC systems. However, these models have not yet been developed in a South African plantation forestry context, as the methods that do allow users to input these parameters do not exist for South African conditions or species. This will lead to errors concerning harvester diameter estimation, bucking optimisation and volume calculation in the South African context.

2.5.2. *P. patula* bark characteristics

P. patula bark is thick, rough and scaly with large elongated plates and deep, longitudinal fissures, especially on the lower part of the stem (Perry, 1991). The bark is dark grey-brown in colour on the lower trunk but becomes more reddish-brown or orange up the stem (Vidakovic, 1991). Perry (1991) and Vidakovic (1991) both describe the rapid change from large thick scaly bark at the base of the stem to a thin papery bark between 3-4m up the stem or in relative terms between 10-20% of tree height. This is supported by Van Laar (2007) who illustrated this change in bark thickness up the stem, where relative bark thickness (the fraction of BT and diameter OB) dropped from 0.3 to around about 0.1 at 0.2 relative tree height (BT measurement height as fraction of total tree height). For these reasons, the thick bark on the lower stem section of *P. patula* can lead to complications during mechanised stem processing.

Owing to this, it is necessary to use a bark deduction method that considers the decrease in bark thickness with an increase in tree height of *P. patula*. As mentioned previously the current four StanForD bark deduction methods do not offer this ability. However, two Ponsse bark deduction methods do. Therefore, we will develop the necessary parameters and evaluate the length-based (LB) and diameter-class length-based (DLB) bark deduction available to us on the Ponsse Opti system.

2.6. Conclusion

Internationally the Nordic countries remain at the forefront of harvester measurement accuracy and data use. The Swedish company BIOMETRIA is a good example of using information gathered by the harvester`s head during the bucking process to manage a forestry supply chain (BIOMETRIA, 2019). This whole system relies on accurate data which is produced through an integrating quality assurance scheme to which all harvester operators prescribe (Strandgard & Walsh, 2012a).

Earlier harvester measurement accuracy studies have mostly compared harvester OB log diameters with manual control OB measurements. The few published studies that have investigated the accuracy of harvester bark thickness estimates have all highlighted the fact that one cannot input a new model on the StanForD system for a specific country`s species or regions as a major obstacle. In Australian plantation forestry none of the bark deduction methods currently available are suitable for their

P. radiata plantations (Strandgard & Walsh, 2011). However, as these machines are increasingly more prevalent around the world, studies of this type are important to be able to realise the full log-making and information gathering potential of these modern harvesting machines.

In the South African context recent studies of mechanised CTL harvesting systems have mostly focused on machine productivity and fuel consumption (Ramantswana *et al.*, 2012; Ramantswana *et al.*, 2013; Ackerman *et al.*, 2016; Williams & Ackerman, 2016; Ackerman *et al.*, 2018; Brewer *et al.*, 2018; Norihiro *et al.*, 2018). A study by Eggers *et al.* (2010) did however compare the value recovery of manual log scaling methods with harvester/processor head log optimisation in pine saw timber operations in South Africa and found no difference between methods. This is the only earlier study on mechanised CTL saw timber log making in South Africa. Although it showed that mechanised CTL log making compared favourably to traditional manual methods. This study did not look at harvester measurement accuracy and the impact this can have on stem optimisation. This illustrates the limited understanding of harvester head-measurement accuracy and calibration in South African forestry plantation conditions, as there are currently no published studies that investigate these aspects.

As previously mentioned, various international studies have shown that correct BT estimates are critical for the optimisation of saw logs, exact volume calculations and subsequently more accurate harvester data. This plays an essential role if one wants to use the automatically generated harvester data to better manage the forestry value chain. This study aims to address these gaps in the South African forest industry.

3. Materials and Method

3.1. Study Site

The study compartment was situated in the Jessievale Plantation near the village of Warburton, in the Mpumalanga Highveld region of South Africa. The plantation falls under the summer rainfall area of South Africa with a mean annual rainfall of 844 mm. Jessievale Plantation has a mean annual midday temperature of 15˚C and is situated at an altitude of 1670 amsl. The compartment from which data was gathered was harvested in winter.

Table 2: Compartment characteristics

Site Attributes	
Species	*Pinus patula*
Age (years)	20.1
Initial planting espacement (m)	3.0 x 3.0
SPH (stems/ha)	372
Average DBH (cm)	30.9
Average height (m)	25.9
Average tree volume (m^3)	0.90
Ground roughness	Even
Ground strength	Firm
Average slope	<5%

3.2. Research Design

The flow of the research is shown in Figure 1.

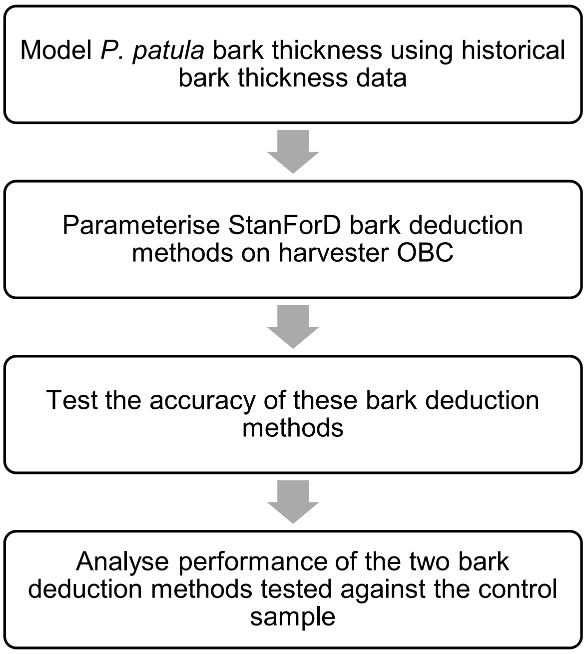


Figure 1: Research flow chart

A 3x4 factorial design was applied for factors A and B (Table 3) and two-way main interactions were analysed between factors.

Table 3: Research design.

Factor A – Bark deduction method	T1 – Control Status quo - no bark deduction (40 trees)				T2 – Length-based (LB) bark deduction method (40 trees)				T3 – Diameter-class length-based (DLB) bark deduction method (40 trees)			
Factor B – Log Assortment	Long Saw log	Plywood log	Hewsaw	Pulp log	Long Saw log	Plywood log	Hewsaw	Pulp log	Long Saw log	Plywood log	Hewsaw	Pulp log

3.2.1. Factor A – Bark deduction treatment

Factor A (Table 3) investigated the effect that the bark deduction treatments had on the accuracy of the harvesters diameter and length measurements. Current harvester heads have no bark deduction functions in use, hence T1 was used as the status quo or control. Since T1 used no bark deduction function, the harvesters OBC assumed OB and UB diameter measurements are the same. T2 used the LB bark deduction method and T3 the DLB bark deduction method. These three factors were tested using the same harvester machine with the same operator throughout the study.

3.2.2. Factor B – Log Product

Factor B (Table 3) investigated the accuracy of the harvester`s diameter and length measurements on each log assortment produced. Log assortments produced were long saw logs, plywood logs, and hewsaw, and pulp logs (Table 4).

Table 4: Log assortment specifications.

Assortment	Log length (cm)	Harvester log target length (cm)	Log minimum small end diameters (cm)
Plywood log	255	265	55 - 25
Long Saw log	600	612	25 - 15
Hewsaw	300	312	21 - 11
Pulp log	240	240	11 - 8

3.3. Research Instruments

3.3.1. Bark thickness modelling

Historical *P. patula* bark thickness data was obtained from a study by Kotze (1995). The Kotze (1995) study produced merchantable volume and tree taper equations from a dataset of 284 trees from all major *P. patula* growing sites of South Africa. The data set collected by Kotze (1995) consisted of diameter UB and OB at specific heights along the tree above ground level (H_{ag}). The difference between these two measurements produced an estimate of bark thickness (BT) at specific H_{ag} levels.

3.3.1.1. Bark thickness data classification

The Kotze (1995) dataset was stratified by region to provide only the Mpumalanga regions data due to the location of the current study. The data was further filtered by age class, extracting data in the age range of 18-32 years. This range represents trees of clear-felling age. Ultimately, a sample 117 trees was available for bark thickness modelling. BT change was modelled over relative tree height (RHt) (i.e., H_{ag} of the BT measurement as a fraction of total tree height) rather than actual tree height, which differed for all 117 trees in the sample.

$$RHt = \frac{H_{ag}}{H} \qquad (8)$$

Where:

$RHt =$ Relative tree height

$H_{ag} =$ Height above ground level (m)

$H =$ Total tree height (m)

For the LB bark deduction method modelling, data from all 117 trees were used. For the DLB bark deduction method, subsets of the original 117 trees were used based on each trees` Diameter-at-Breast Height (DBH) OB measurement. The different models and categories are summarised in Table 5.

Table 5: Description of all the bark thickness models used to populate the two bark deduction tables.

Bark deduction method	Tree grouping	Model name	Number of trees
Length-based	All trees	LB	117
Diameter-class length-based	15-24.9 cm DBH OB	15-DLB	13
Diameter-class length-based	25-29.9 cm DBH OB	25-DLB	28
Diameter-class length-based	30-34.9 cm DBH OB	30-DLB	21
Diameter-class length-based	35-39.9 cm DBH OB	35-DLB	25
Diameter-class length-based	40-44.9 cm DBH OB	40-DLB	16
Diameter-class length-based	>45 cm DBH OB	45-DLB	14

3.3.1.2. Bark thickness data modeling

The change in BT up the stem of *P. patula* was modelled using the statistical software package STATISTICA 13 (TIBCO Software Inc., 2018). These models were developed to calculate the parameters needed for the bark deduction tables on the Ponsse harvesters OBC system. BT was plotted on the Y-axis with RHt on the X-axis. The data of each model was fitted with an exponential decay function (Equation 9) and by using Non-Linear Estimation the coefficients of the non-linear regression (Equation 9) was estimated.

$$Bark\ Thickness = a + exp(b + c * RHt) \tag{9}$$

Where:

BT = Bark thickness (cm),

a, b & c = coefficients, and

RHt = Relative tree height (Equation 8)

The accuracy in the prediction ability of each model was analysed with the following two statistics; The R-squared for each model expressed as the percentage of variation explained and the mean bias.

Length-based bark thickness deduction

The RHt required for the equation was calculated at the following heights above ground level (H_{ag}): 2 m, 4 m, 6 m, 8 m, 12 m, 20 m and 25 m. This was done by using the average tree height for the data set as total tree height. This relative height was used to calculate the BT for that RHt that will be entered onto the harvesters` OBC. These initial two-metre intervals were selected as they represented the cutting points between plywood logs cut from lower part of the stem where bark thickness changes rapidly.

Diameter-class length-based bark thickness deduction

The same process was followed for the DLB bark deduction method. Each individual DBH class model was analysed separately. The calculated BT was entered onto the harvesters OBC in the DLB bark deduction method matrix.

3.3.2. Photogrammetry analysis

To increase accuracy and reduce bias of log-end OB and UB diameter estimates, a novel photogrammetry approach was used in this context. Strandgard (2009) suggested that diameter tapes are the best instrument to measure log diameters for harvester accuracy studies, but the operational difficulty in putting all the logs ends on bearers drove us to investigate the possibility of using photogrammetric analysis. An open sourced image processing software ImageJ 1.26 (Rasband, 2002) was therefore used to analyse log ends and stump photos for more precise UB diameter estimates.

3.3.2.1. Photography rig

A Samsung J5pro cellphone camera was used to capture the images. It features a 13 megapixels rear camera with LED flash, f/1.7 aperture and an auto-focus function

(Samsung, 2018). This cellphone was attached to a selfie-stick fitted to a wooden plank with the following dimensions 10 mm x 60 mm x 1000 mm (Figure 2).

Figure 2: Photography rig used to take photos of the log small ends and stumps.

3.3.2.2. Photogrammetry test

Prior to the fieldwork, this apparatus and methodology were tested in order to quantify the effect of distortion and hence potential error from the images. For this a black and white checkerboard (Figure 3a) with cells of 25 mm x 25 mm was used. These cells were arranged into 11 columns and eight rows and printed on an A4 page. The printed sheet was mounted on a black background which was placed vertically against a wall. Three photographs were taken at varying distances from the checkerboard (i.e., 50 cm, 70 cm and 90 cm). This was done to mimic actual circumstances where the distance of the camera from the log end will vary depending on the log end diameter in order to get the whole log end to fit in the photo frame.

Once the three images were uploaded into the ImageJ software package, they were analysed as follows. Firstly, the images were processed with the built-in ImageJ 1.26 “find edges” function. This algorithm highlights sharp changes in intensity on the active image (Ferreira & Rasband, 2012) to highlight the edges of the rectangles (Figure 3b). Secondly, the scale and units of measure for each photograph were set with the built-in “set-scale” function that uses a known distance on the image as a reference length. Lastly, using the line segment function, a line was drawn from the edge of one cell to the edge of the next with the distance measured in centimetre with the “measure” function (Figure 3b). Repeated length measurements were then taken on each photo: eight horizontally, five vertically and seven diagonally for a total of 60 measurements on the three photos. Measurement distances ranged from 10.0 - 27.5 cm for the horizontal images, 10.0 - 20.0 cm for the vertical images and 7.0 - 28.0 cm for the diagonal images.

3.3.2.3. Analysis

The difference between the actual and measured distances was used to calculate the measurement error (Equation 10).

$$ME = Actual - Measured \tag{10}$$

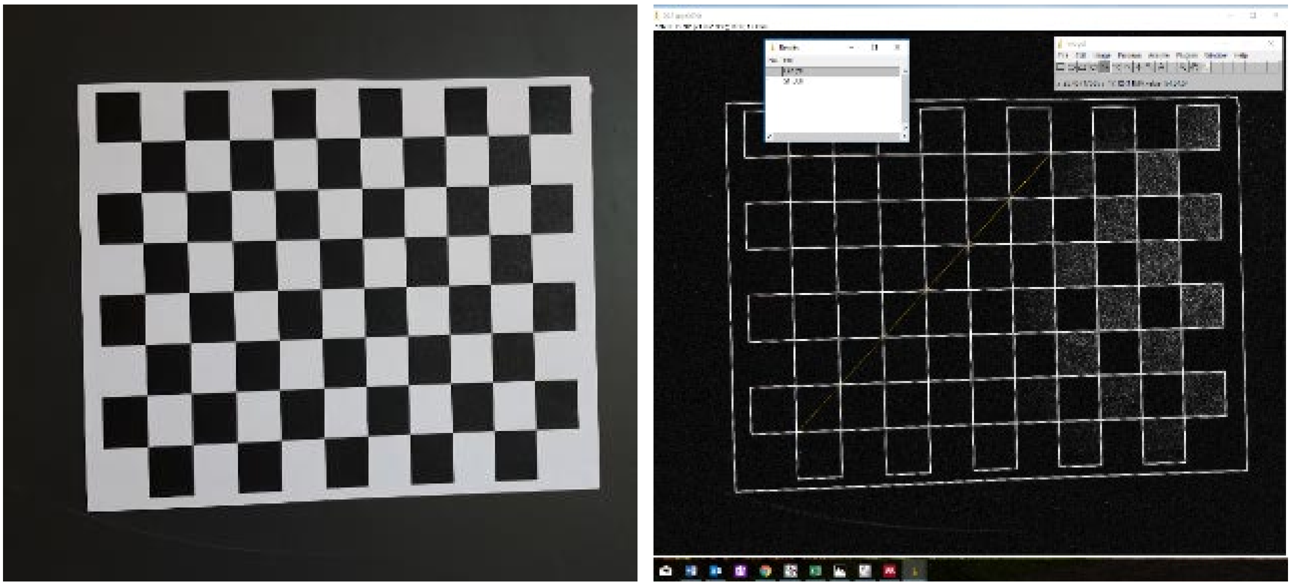
Where:

ME = Measurement error

Actual = Correct distance of the blocks measured

Measured = Photogrammetric measured distance of blocks

This ME for all the measurements was analysed through descriptive statistics in STATISTICA 13 (TIBCO Software Inc., 2018) to calculate the bias of this measurement method.



(a) (b)

Figure 3: (a) Checkerboard used in the photogrammetry test procedure, (b) Example of the length measurement procedure used on a processed photograph using the ImageJ software package.

3.3.3. Pre-Harvesting

3.3.3.1. Felling corridor layout

Each treatment (T1, T2 and T3) was assigned a harvesting corridor consisting of 40 trees, two tree rows wide. Each corridor was laid out adjacent to a previously felled seventh row that was removed in a commercial thinning. Felling adjacent to the open seventh row allowed enough space for the processed logs to be placed separately for each tree. The trees were numbered with from 1 - 120 in such a way as to allow for easy identification during the harvesting process.

3.3.3.2. Individual tree measurements

Each trees' DBH OB (1.3 m) was marked on individual trees, measured in cm using a diameter tape and recorded. The height (m) of every fourth tree was measured with a Vertex hypsometer, three height measurements were taken for each tree from different positions and averaged to one measurement. All the measurements were recorded.

3.3.4. Harvesting

3.3.4.1. Harvester characteristics and harvesting method

A Ponnse Bear harvester fitted with a H8 harvester head on a Ponnse C6 knuckle-boom crane and Opti 4G computer system was used in the study (Table 6 and Figure 4). Both bark-deduction methods were tested using this machine.

Table 6: Harvester machine specifications

Model	Ponsse Bear
Output (kW)	240
Torque (Nm)	1 300
Number of wheels	8
Machine mass (including head)(kg)	24 500
Harvester head	Ponsse H8
Computer system	Ponsse Opti 4G
Harvester crane	C6
Max boom reach (m)	10
Ground clearance (mm)	700
Fuel tank volume (l)	400

Figure 4: Ponsse bear harvester.

As noted above, the harvester operator proceeded to fell the numbered trees, placing the logs of each tree sequentially in distinct piles for ease of identification and to aid the manual measurement procedure for each log. Care was taken to record the order in which these trees were harvested since it was important for matching the manual data with the harvesters stem file data. After each tree was processed, the harvester operator brought the machine to idle to allow the numbering of the stump and logs with each specific trees number. This ensured that all tree, harvester and manual log measurements matched up.

3.3.4.2. Harvester head calibration procedure

Prior to the harvesting of the corridors, the harvesting head was calibrated for length and diameter precision according to the manufacturer's procedures. The process involved felling and processing five trees across the range of diameters (DBH) expected to be encountered during the study. The operator was instructed to place each felled tree separately but in sequence of felling. Once the five trees were on the ground the manual calibration procedure was selected on the OBC for the calibration to proceed. The operator selected the number of processed logs to be used for the calibration procedure, after which the OBC sent the diameter and length measurements of the processed logs to the digital caliper connected to the OBC.

The next step involved measuring the lengths and diameters of the processed logs using the digital caliper starting with the butt log of the first stem harvested. The digital caliper displays the product and length of the log to be measured. Length was measured with a logger's tape along the top of the log (Figure 5a). This measurement is then recorded in the digital caliper. Next, the caliper tells the operator at what distance from the large end of the log the diameter control measurements need to be taken.

Two perpendicular diameter measurement were made at each of these positions moving from the large end to the small end of the log tree (Figure 5b). If the measurements are accepted by the caliper, it will beep once. If there is a problem with the measurement, the caliper will beep twice upon which the operator can decide if he wants to re-measure that diameter or move onto the next one. It is important to avoid large branch stubs or sections where bark is missing from the logs as this will lead to inaccurate measurements.

The length measurements can then be adjusted with a correction factor. It is important to be sure that the corrections proposed by the computer are not due to random errors during the measuring procedure. Therefore, the operator can choose to accept the adjustments or he can otherwise input his own. For the diameter calibration, there are different adjustments for different diameter classes as stem diameters play a role in these measurement accuracies. During this study the proposed computer adjustments were accepted.


(a) (b)

Figure 5: The manual length (a) and diameter (b) measurements done for the calibration process.

Finally, another three trees were felled for the purpose of validating the calibration procedure and checking that the adjustments were correct. Once this was deemed accurate, the three experiments commenced.

3.3.4.3. T1 - Control treatment – no bark deduction method in place.

Prior to the start of the first (control) treatment, a full harvester head calibration was conducted. The harvester operator then harvested the whole control corridor. When the corridor was complete, the stem file was extracted from the machine`s OBC.

3.3.4.4. T2 - Length-based bark deduction method

For the second treatment, the bark thickness parameters for the LB deduction method were entered onto the OBC system. The harvester operator then repeated the harvesting procedure as mentioned earlier. After completion of the corridor, the stem file was again extracted from the machines computer as well as the production summary report. This was necessary to verify if the machine produced OB and UB volumes (Vob and Vub) for in-field validation of the treatment.

3.3.4.5. T3 – Diameter-class length-based bark deduction method

The same procedure as for T2 was followed. The bark thickness parameters for T3 were entered onto the OBC. After completion of the harvesting process, the stem file and production summary were again extracted from the machine`s OBC.

3.3.5. Post Harvesting

3.3.5.1. Log Identification Code

The SED of each log was marked with a unique identification code representing the tree and log sequence number for each log within the tree. For example, the first log from the first tree was marked as 1-1 (Figure 6). All subsequent measurements were recorded against each logs unique code.

Figure 6: Log end photograph with the log ID code and ruler used to scale photograph for photogrammetric analysis.

3.3.5.2. Log length measurements

Length measurements were recorded for every log using a calibrated loggers tape to the nearest centimetre. Length was measured on the top of the log in the same manner as was done during the calibration process. The distance from the marked DBH point on the butt log to the large end of the butt log was also measured. This distance was used to calculate the stump height of the tree by subtracting it from 1.3 m (DBH).

3.3.5.3. Log end and stump diameter photos

A photo of the SED of every log was taken for later photogrammetric diameter analysis. Only the SED was photographed as the SED of one log is the large end diameter (LED) of the subsequent log. The stump of each tree was photographed for LED calculation of the butt logs. If the harvester heads measuring wheel was re-zeroed following felling of the tree, the off-cut was photographed for the LED calculation of the butt log. Each photograph was labelled with the unique ID for that specific log.

3.4. Data processing

3.4.1. Stem (.stm) file parsing

Each treatments stem file was imported into an Excel-based stem file decoder developed in-house by the Department of Forest and Wood Science at the University of Stellenbosch. The variables contained in these files were decoded and arranged in a tabular format sorted per log.

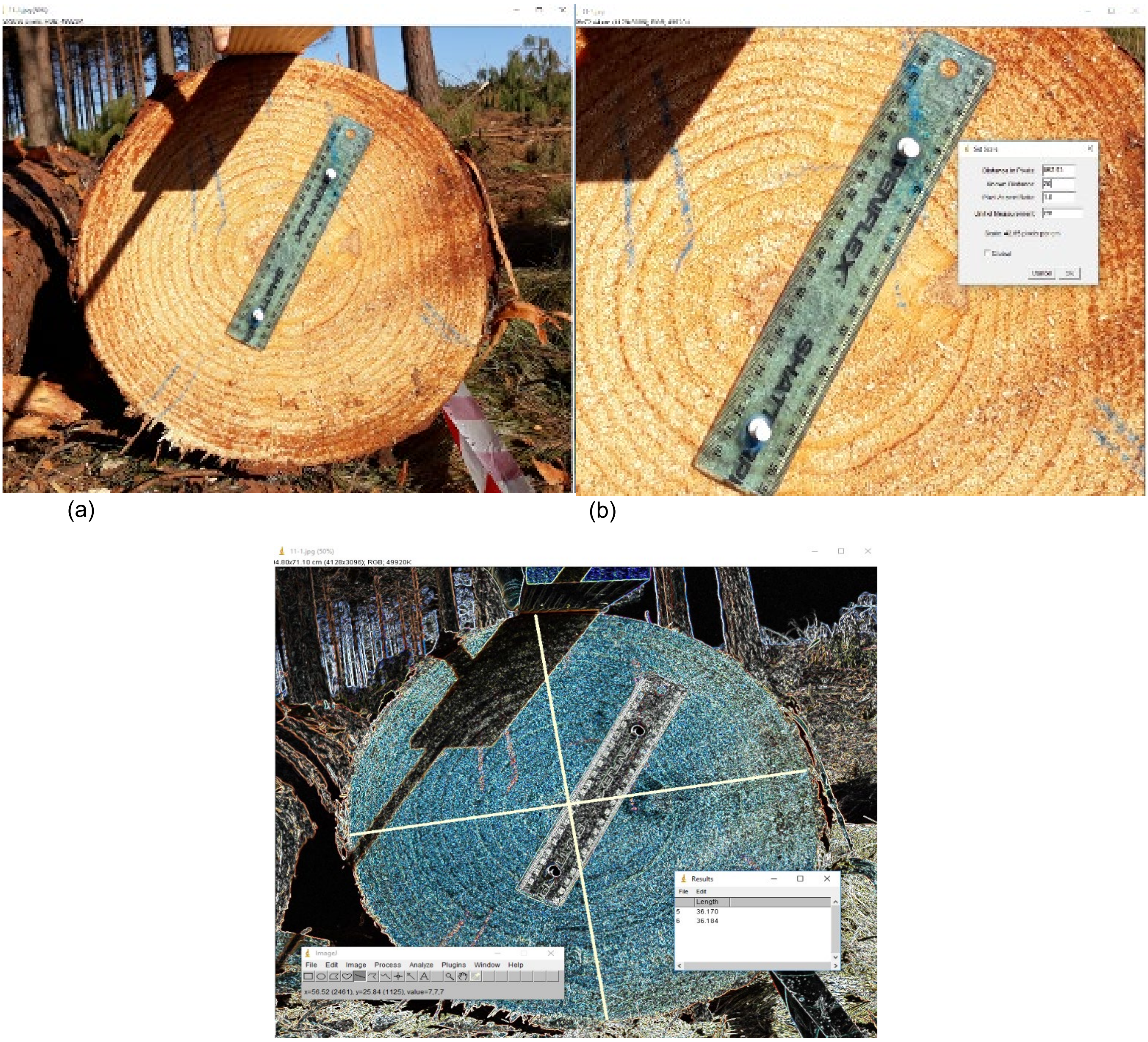
Information extracted and used from the stem files included the following:

- Stem ID
- Stump diameter
- DBH
- Stem length
- Number of logs from stem
- Stem volume under bark
- Stem volume over bark
- Time stamp
- Log ID
- Log product type
- Log length
- Log volume over bark
- Log volume under bark
- Small end diameter over bark
- Small end diameter under bark
- Large end diameter over bark
- Large end diameter under bark

The time stamp at which each stem was felled as recorded by the harvester in the stem file together with the number and order that the products cut from each stem were used to match harvester data with the manual control measurement. Each stem file stem and log were subsequently assigned a number corresponding to the treatment it underwent as well as the tree and log number. The stem files also contained records of the reject sections processed by the harvester head which were removed from the data set.

3.4.2. Log end photogrammetry analysis

Each photograph was imported and analysed individually in the ImageJ software package (Figure 7a). To begin, the scale of each image was set to ensure accurate measurements (Figure 7b), the reason being that the whole log end needed to fit in the frame and be clear in the photograph. This caused the distance between the log end surface and the camera to change for each log, which also caused the scale for each photograph to change. After the scale of the image was set, it was processed (Figure 7c) with the built in ImageJ function “find edges”. This made it easier to distinguish between wood (blue) and bark and background (grey & black). Once this was done, using the line segment function, a line was drawn across the log-end making sure to bisect the pith. The length of this line was measured to 1/10th of a millimetre accuracy and taken as one log end diameter. Another line was then drawn perpendicular to the first, using the same procedure to measure the other diameter of the log (Figure 7c). These two measurements were made for each log and recorded in Microsoft Excel. The measurements were averaged to acquire the log end and stump diameters for each log.



(a)

(b)

(c)

```
11-1.jpg (50%)
4.80x71.10 cm (4128x3096); RGB; 49920K
```

```
     Length
5    36.170
6    36.184
```

```
x=56.52 (2461), y=25.84 (1125), value=7,7,7
```

Figure 7: Clockwise from top left: (a) Log SED photo imported into ImageJ software, (b) setting the measurement scale for the photo and (c) determining the UB diameter measurements of the log small end.

3.4.3. Measurement Error

The manual measurements for diameter and length were compared with the harvester measurements through the analysis of the difference between the two measurements. The difference is expressed as the measurement error, which is calculated with the following equation:

$$ME = Y - \acute{Y} \tag{11}$$

ME = Measurement error

Y = Manual (Control) measurement

$\acute{Y}$ = Harvester measurement

If the measurement error is negative, it means that the harvester over-estimated the actual dimensions of the log. If the measurement error is positive this then means that the harvester under-estimated that log`s dimensions. All results are presented according to this over- or under-estimation of log dimensions. Measurement error was calculated for the log LED, SED, Plywood log diameter and length error (Table 8).

Table 7: Summary of the different dependant and independent variables in the study.

Independent variables	**Description**
Treatment	T1 - Control treatment
	T2 - LB bark deduction
	T3 - DLB bark deduction
Log Products	Long Saw logs
	Plywood logs
	Hewaw
	Pulp log
Dependant variables	**Description**
Measurement Error	Large End Diameter
	Small End Diameter
	Log Length
	Plywood log diameter

Table 8: Summary of analysis parameters

Analysis	**Measurement Error (ME)**	**Control measurement (Y)**	**Harvester measurement (Ý)**
Log large end error analysis	Large End Diameter	Manual (Photogrammetry) LED diameter	Harvester UB diameter
Log small end error analysis	Small End Diameter	Manual (Photogrammetry) SED diameter	Harvester UB diameter
Log length error analysis	Log Length	Manual length	Harvester length
Plywood log diameter error analysis	Plywood log end diameters	Manual (Photogrammetry) diameter	Harvesters UB diameter

3.4.4. Plywood log diameter analysis

P. patula bark is thickest on the base section of the stem (Vidakovic, 1991). It was therefore deemed important to investigate how the two bark deduction methods performed for plywood log since they essentially originate at the base (pruned section of the tree) of the stem, as opposed to the other assortments which are not as impacted by bark thickness due to their position on the tree. To do this, the first four diameter cuts for the plywood log measurements were extracted from the full dataset for further analysis (Figure 8). These first four cuts represent the initial 8 m of the stem.

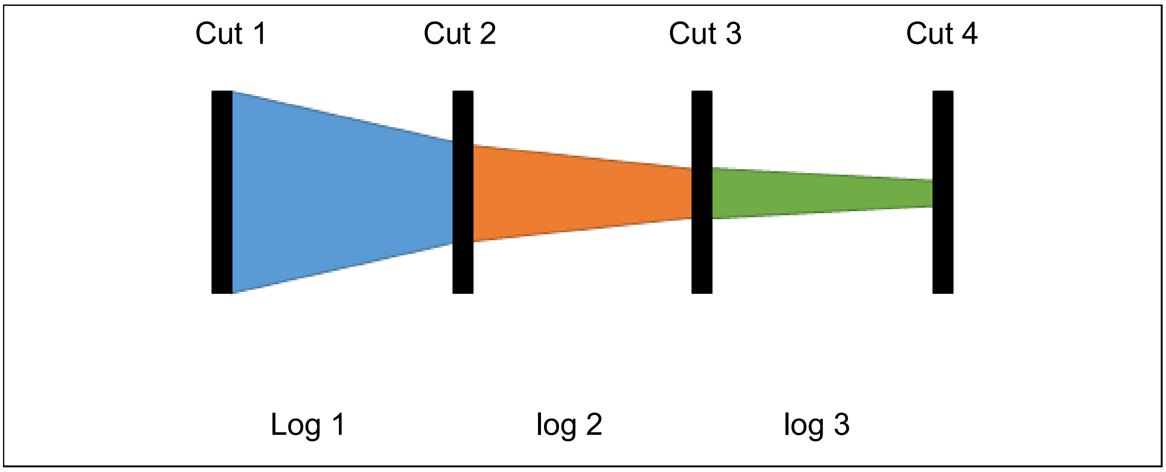


Figure 8: Illustration of first three plywood logs and their four diameter cut positions used during the plywood log diameter measurement and volume analysis

The measurement error was analysed with the factorial ANOVA procedure already mentioned. The means of these first four diameter measurements for each treatment were tabulated for the manual and harvester UB diameter measurements respectively. These mean diameter measurements were compared by calculating the percentage difference (Equation 12) between the manual and harvester measurements. The percentage difference was calculated by subtracting the harvester`s measurement from the manual measurement and calculating the percentage as the percentage of the manual measurement.

$$Percentage\ difference\ (\%) = \frac{Control\ measurement - Harvester\ measurement}{Control\ measurement}\ x\ 100 \qquad (12)$$

3.4.5. Log length measurement error

The log mean length measurement error (MLME) was also assessed with the same factorial ANOVA procedure used for the log end diameter analysis. Length measurement errors are assessed according to the Swedish “Best-5” standard which measures the percentage of measurements within the five adjacent one-centimeter classes ±2 cm.

3.4.6. Volume comparison

The volume comparisons were done in four parts; stem and log volume, log volume as a percentage of total stem volume and plywood log volume.

3.4.6.1. Stem volume comparison

The difference between the harvesters UB and OB volume calculations was assessed with Equation 12. This percentage difference was used as a measure of how the bark deduction methods influenced the harvester’s volume calculations compared with the control treatment – T1.

3.4.6.2. Log volume comparison

Further analysis of how the two bark deduction methods affected the volume calculation of logs per product was done. The mean OB and UB log volume for each group of product x treatment was calculated. The percentage difference between these two measurements was calculated using Equation 12 and the changes were analysed.

3.4.6.3. Log volume as a percentage of total stem volume

The mean log volumes contribution towards total stem volume was quantified for the position from where that log was cut from the stem (e.g. the first log cut will be log numbered one and so on until the last log is cut from that tree). This was done to quantify the mean log cut from the base of the stems volume contribution towards total stem volume. As stem diameter and bark thickness is greatest on the lower section of the stem, logs cut from this section will contribute more towards total stem volume than logs cut from higher up the stem. Accordingly, if the tree bark is thickest for these logs the potential for volume over-estimation is greater on this section of the stem compared to logs cut from higher up the stem where *P. patula* bark is thinner. This calculation and comparison will only be done on the results from T2 and T3 as T1 did not have UB log volumes.

3.4.6.4. Plywood log volume comparison

The harvesters log volume calculations cannot be compared with manually calculated log volumes because of inherent differences in how these two volumes are calculated. For this reason, to be able to compare the impact of the harvesters UB diameter measurements on volume calculations with the manual diameters and volumes, we applied the harvester`s diameter measurements in the Smalian`s log volume equation 13 (Bredenkamp & Upfold, 2012). Using the diameter measurements for the first four cuts of plywood logs together with the product length, we calculated the volume for the average first three plywood logs cut for each treatment.

$$V = (d_t^2 + d_T^2)\ x\ \frac{\pi}{8}\ x\ l \qquad (13)$$

Where:

V = Log Volume (m^3)

d_t^2 = Log SED (cm)

d_T^2 = Log LED (cm)

l = Log length (m)

This manually calculated harvester volume was then compared with the log volumes calculated with the manually measured log end diameters. This was done to get a better understanding of how the differences between the manual and harvester log end diameter measurements influence the logs volume calculation.

3.4.7. Statistical Analysis

Two-way factorial ANOVA was used to analyse the data in STATISTICA 13 (TIBCO Software Inc., 2018). The first hypothesis tested was for no treatment interaction effects. If this null hypothesis was rejected, then the interaction means were compared with an appropriate comparisons procedure. If the null hypothesis was not rejected then the treatment interactions were not significant, although the main effects can be interpreted, the treatment interactions can still be interpreted (Milton & Arnold, 1999). Significance was measured to a $\alpha = 0.05$. When significant differences were found between treatments or treatment interaction effects, significant differences between individual means where determined with post hoc tests. If the Levene`s test for homogeneity of variances was significant the treatment means were compared with the Games-Howell multiple comparisons procedure, otherwise if insignificant, the LSD multiple comparisons procedure was used. If the factorial design was unbalanced, the LSD multiple comparisons procedure was also used.

4. Results

4.1. Bark thickness modeling

The data set used to model the estimates for T2 – Length-based (LB) bark deduction method is shown in Figure 9. Both the combined data (LB model) and the subsets (DLB models) show the same bark pattern observed for *P. patula* (Figure 9). Bark is thick at the base of the stem after which thickness rapidly declines with an increase in relative tree height.

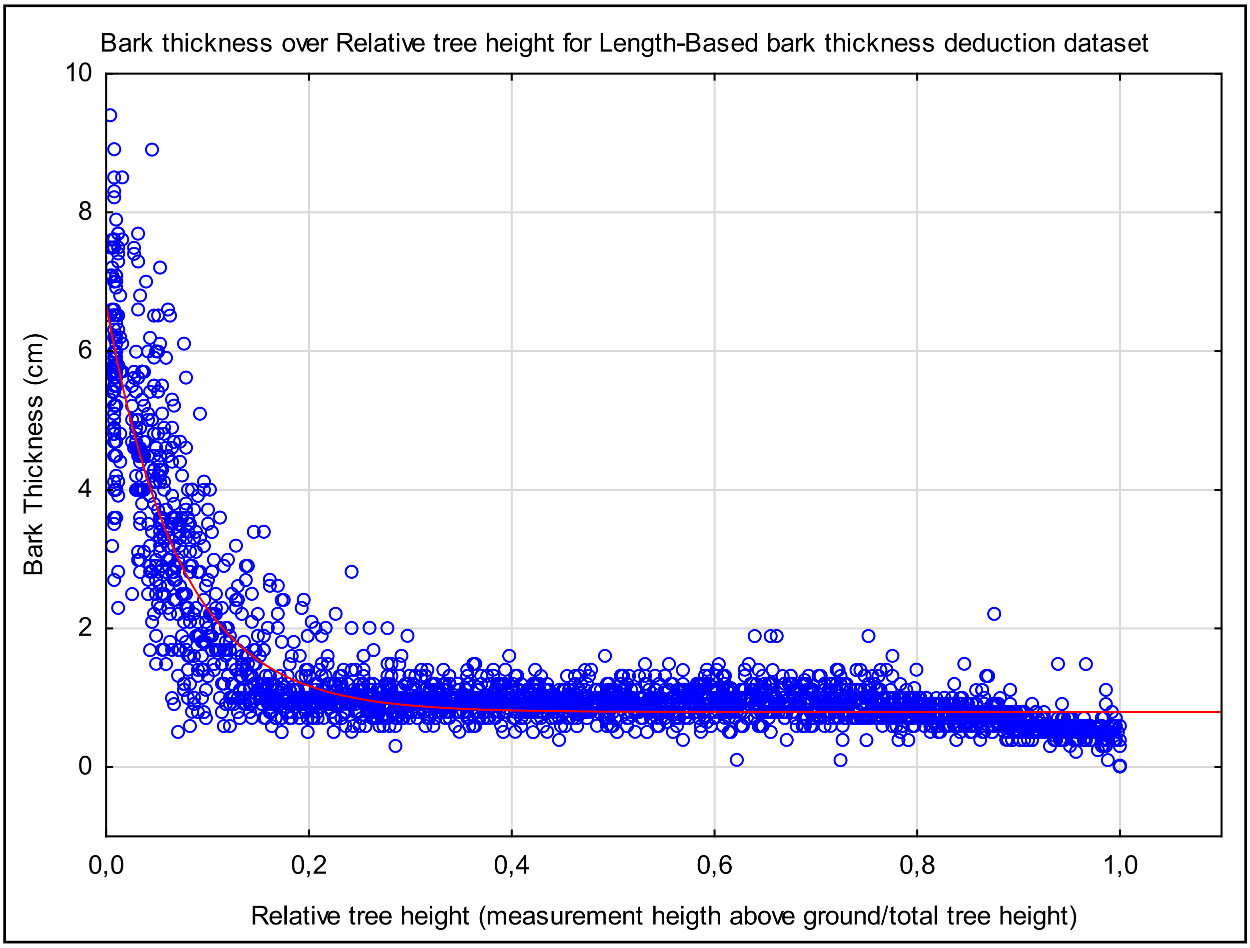


Figure 9: Change in *P. patula* bark thickness with change in relative tree height observed for the length-based bark deduction dataset.

The coefficients a, b and c for each of the seven bark deduction models (as categorised in Table 5 – 1 LB and 6 DLB bark deduction models) were found to be significant with p-values = <0.001 to a 95% confidence level (Table 9).

Table 9: Bark thickness modelling statistical results

Aggregate Results
Model is: V10 = a + EXP(b+c*v11)
Dependant Variable: Bark Thickness
Level of confidence: 95.0% (alpha=0.050)

Model Name	Coefficient	Estimate	Standard error	Degrees of freedom	t-value	p-value	Lo. Conf limit	Up. Conf limit
LB	a	0.787	0.014	2743	57.615	0.000***	0.760	0.814
	b	1.770	0.011	2743	161.741	0.000***	1.748	1.791
	c	-13.729	0.276	2743	-49.678	0.000***	-14.271	-13.187
15-DLB	a	0.642	0.030	351	21.437	0.000***	0.583	0.701
	b	1.550	0.033	351	46.334	0.000***	1.484	1.616
	c	-16.706	0.992	351	-16.839	0.000***	-18.659	-14.754
25-DLB	a	0.720	0.022	351	32.656	0.000***	0.677	0.763
	b	1.752	0.019	351	93.763	0.000***	1.715	1.789
	c	-14.964	0.505	351	-29.643	0.000***	-15.956	-13.973
30-DLB	a	0.793	0.028	351	28.818	0.000***	0.739	0.847
	b	1.705	0.025	351	66.903	0.000***	1.655	1.755
	c	-15.431	0.708	351	-21.809	0.000***	-16.821	-14.040
35-DLB	a	0.831	0.028	351	30.138	0.000***	0.776	0.885
	b	1.777	0.021	351	85.464	0.000***	1.736	1.817
	c	-12.447	0.483	351	-25.792	0.000***	-13.395	-11.499
40-DLB	a	0.853	0.038	351	22.443	0.000***	0.779	0.928
	b	1.890	0.027	351	70.771	0.000***	1.837	1.942
	c	-13.413	0.665	351	-20.167	0.000***	-14.720	-12.105
45-DLB	a	0.846	0.042	351	20.149	0.000***	0.763	0.928
	b	1.913	0.026	351	74.359	0.000***	1.862	1.963
	c	-11.441	0.564	351	-20.280	0.000***	-12.551	-10.332

(From here on significant tabulated p-values will be referred to as *, highly significant tabulated p-values will be referred to as ** and very highly significant tabulated p-values will be referred to as ***)

The comparison of the observed and fitted values for each developed model show that the range of percentage of variance explained ranged between 82.70% and 88.06% with the mean bias results for each model being smaller than 0.0014 cm (Table 10).

Table 10: Comparison statistics between the observed and fitted BT values for each data set.

Model	No. of observations	% of Variance explained	Mean Bias (cm)
LB	2746	82.7	-0.000001
15 - DLB	292	83.6	0.000459
25 - DLB	615	88.1	0.001347
30 - DLB	482	83.9	0.000829
35 - DLB	611	85.4	0.000918
40 - DLB	392	85.0	0.000800
45 - DLB	354	86.5	0.001443

4.1.1. T2 – Length-based bark thickness deduction

The bark thickness estimates calculated with Equation 9 using the parameters modelled for the LB model are shown in Table 11.

Table 11: Length-based bark thickness deduction table

Length (cm)	200	400	600	800	1200	2000	2500
BT (mm)	63	27	14	10	9	8	8

4.1.2. T3 – Diameter-class length-based bark thickness deduction

The bark thickness estimates calculated with Equation 9 using the parameters modelled for each of the DLB-models are shown in Table 12.

Table 12: Diameter-class length-based bark thickness deduction table (bark thicknesses in mm)

DBH Class (mm)	**Length (cm)**							
	0	**200**	**400**	**600**	**800**	**1200**	**2000**	**2500**
150-249	50	18	9	7	7	6	6	6
250-299	61	23	11	8	7	7	7	7
300-349	60	23	12	9	8	8	8	8
350-399	64	30	16	11	9	8	8	8
400-449	71	32	17	12	10	9	9	9
>450	73	38	21	14	11	9	9	9

4.2. Photogrammetry test results

The photogrammetry test results showed that there was a mean under-estimation of the distance measurement on the checkerboard of 0.08 cm with a standard deviation of 0.08 cm (Table 13).

Table 13: Photogrammetry test descriptive statistics for distance measurement on checkerboard.

Sample number	Mean (cm)	Standard Deviation (cm)	Confidence -95% (cm)	Confidence 95% (cm)	Minimum (cm)	Maximum (cm)
60	0.08	0.08	0.06	0.1	-0.14	0.24

4.3. Measurement Error

4.3.1. Final log sample size

Table 14 summarises the number of logs per product and treatment that were used during the final measurement error analysis.

Table 14: Number of logs per treatment and product used in final analysis.

Product	Treatment			Total
	1	2	3	
Plywood log	92	75	74	241
Long saw log	37	53	43	133
Hewsaw	28	26	38	92
Pulp log	9	14	20	43
Total	166	168	175	509

4.3.2. Log Large End Diameter Measurement Error

The interaction between treatment and product was significant ($F_{6, 497} = 8.847$) with p = <0.001 (Table 15 and Figure 10) for Log LED ME, therefore the interaction effects are interpreted.

Table 15: ANOVA table for log LED ME two-way experiment.

Source of variation	Log LED ME				
	SS	Df	MS	F	p
Intercept	97.44	1	97.439	32.488	0.000***
Treatment	215.08	2	107.541	35.856	0.000***
Product	79.29	3	26.429	8.812	0.000***
Treatment*Product	159.20	6	26.534	8.847	0.000***
Error	1490.62	497	2.999		

Levene's test for homogeneity of variance was significant ($F_{11, 497} = 23.974$) with p = <0.001 (Table 16) for log LED ME.

Table 16: Levene`s test for homogeneity of variances for Log LED ME.

Effect: "Treatment"*Product Degrees of freedom for all F's: 11, 497			
MS	MS	F	p
26.002	1.085	23.974	0.000***

Significant differences were determined through the LSD multiple comparison procedure for the treatment and product interaction for LED ME (Figure 10).

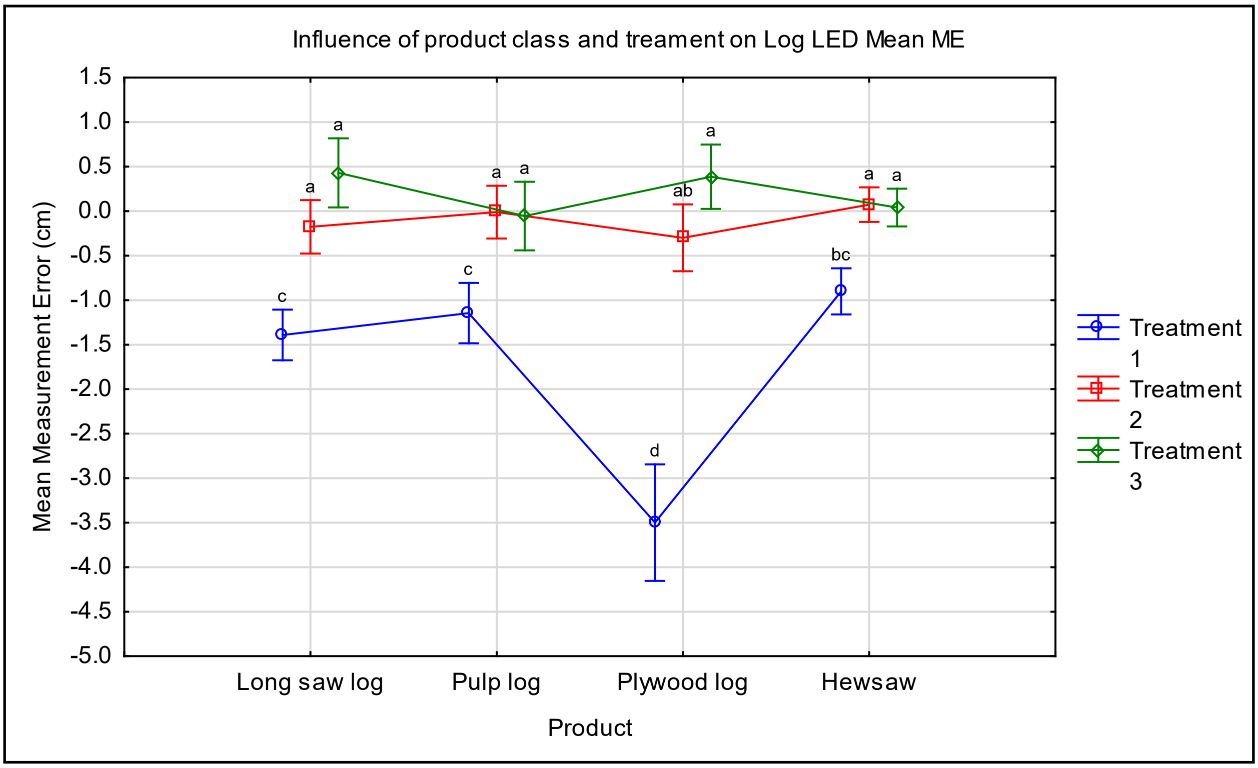


Figure 10: Influence of bark deduction treatment and log product on log LED ME (treatment means that do not significantly differ from each other are marked with the same letter, i.e. a, b, c etc.).

The descriptive statistics for log LED ME are summarised in Table 17. Plywood logs had the largest measurement error for T1 with the harvester head over-estimating the log end diameter by 3.50 cm. T2 was also over-estimated by 0.30 cm while T3 was under-estimated by 0.39 cm.

Table 17: Descriptive statistics for log LED ME.

Product	T1		T2		T3	
	No. of logs	Mean ME (cm)	No. of logs	Mean ME (cm)	No. of logs	Mean ME (cm)
Long Saw log	37	-1.39	53	-0.18	43	0.43
Plywood log	92	-3.50	75	-0.30	74	0.39
Hewsaw	28	-0.90	26	0.07	38	0.04
Pulp log	9	-1.14	14	-0.01	20	-0.06

The LED for long saw logs for T1 was over-estimated by 1.39 cm. This over-estimation in log end diameter for long saw logs was reduced to 0.18 cm for T2, while the mean diameter for T3 was under-estimated by 0.43 cm. The Hewsaw log end diameter for T1 was over-estimated by 0.90 cm, although this error was reduced to a slight under-estimation of 0.07 cm and 0.04 cm for T2 and T3, respectively. The mean log end diameter for pulp logs for T1 was over-estimated by 1.14 cm. This error margin was reduced to an under-estimation of only 0.01 cm for T2 and an over-estimation of 0.06 cm for T3.

4.3.3. Log Small End Diameter Measurement Error

The interaction between treatment and product was significant ($F_{6, 497} = 6.328$) with p = <0.001 (Table 18 and Figure 11) for Log SED ME, therefore the interaction effects are interpreted.

Table 18: ANOVA table for log SED ME two-way experiment.

Source of variation	Log SED ME				
	SS	Df	MS	F	p
Intercept	79.40	1	79.398	107.419	0.000***
Treatment	67.30	2	33.650	45.526	0.000***
Prod	10.61	3	3.537	4.785	0.003**
Treatment*Prod	27.66	6	4.610	6.238	0.000***
Error	367.35	497	0.739		

Levene`s test for homogeneity of variance was significant ($F_{11, 497} = 2.019$) with p = 0.025 (Table 19) for log SED ME.

Table 19: Levene's Test for Homogeneity of Variances of log SED ME.

Effect: "Treatment"*Product Degrees of freedom for all F's: 11, 497			
MS	MS	F	p
0.605	0.300	2.019	0.025*

Significant differences were determined through the LSD multiple comparison procedure for the treatment and product interaction for SED ME (Figure 11).

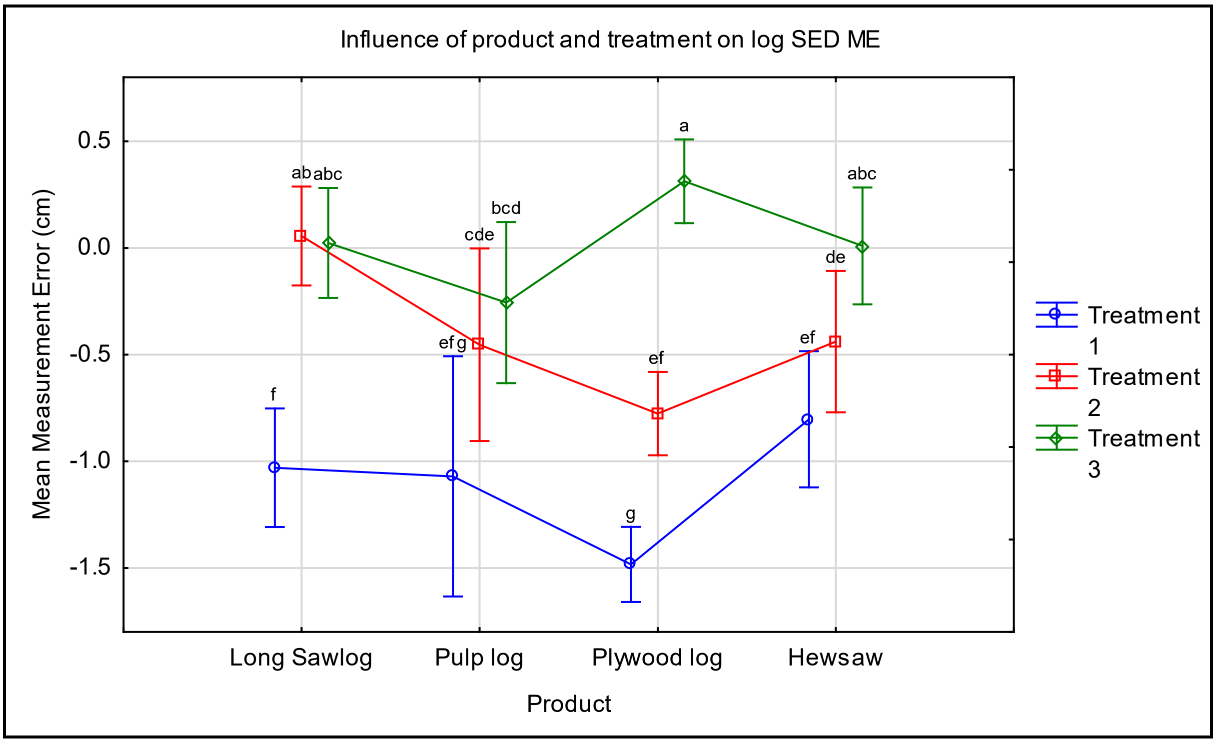


Figure 11: Influence of bark deduction treatment and log product on log SED ME (treatment means that do not significantly differ from each other are marked with the same letter, i.e. a, b, c etc.).

Table 20: Descriptive statistics for log SED ME.

	T1		T2		T3	
Product	No. of Logs	Mean ME (cm)	No. of Logs	Mean ME (cm)	No. of Logs	Mean ME (cm)
Long Saw log	37	-1.03	53	0.06	43	0.02
Plywood log	92	-1.48	75	-0.78	74	0.31
Hewsaw	28	-0.80	26	-0.44	38	0.01
Pulp log	9	-1.07	14	-0.45	20	-0.26

Plywood logs had the largest mean measurement error for the log SED with an over-estimation of 1.48 cm for T1. T2 was over-estimated by 0.78 cm while the diameter for T3 was under-estimated by 0.31 cm. Long saw log SED for T1 was over-estimated by 1.03 cm, however this error margin was improved to a slight under-estimation of 0.06 cm and 0.02 cm for T2 and T3, respectively. The Hewsaw log diameter was over-estimated by 0.80 cm for T1 and 0.44 cm for T2, while the diameter for T3 was under-estimated by 0.01 cm. The pulp log mean SED was over-estimated by 1.07 cm for T1 which was reduced to an over-estimation of 0.45 cm and 0.26 cm for T2 and T3, respectively.

4.3.4. Plywood Log Diameter Measurements

The interaction between treatment and measurement was significant ($F_{6, 285} = 59.108$) with p = <0.001 (Table 21 and Figure 12) for the Plywood log diameter measurements. Therefore, the interaction effects was interpreted.

Table 21: ANOVA table for plywood log diameter error two-way experiment.

Source of variation	Plywood log diameter ME				
	SS	Df	MS	F	p
Intercept	298.69	1	298.688	161.626	0.000***
Treatment	518.45	2	259.227	140.273	0.000***
Measurement	183.01	3	61.003	33.010	0.000***
Treatment*Measurement	655.39	6	109.232	59.108	0.000***
Error	526.69	285	1.848		

Levene`s test for homogeneity of variance was significant ($F_{11, 285} = 7.618$) with p = <0.001 (Table 22) for Plywood log diameter measurements.

Table 22: Levene's Test for Homogeneity of Variances of Plywood log diameter ME.

Effect: "Treatment"*"Measurement" Degrees of freedom for all F's: 11, 285			
MS Effect	MS Error	F	p
5.763	0.756	7.618	0.000

Significant differences were determined through the LSD multiple comparison procedure for the treatment and product interaction (Figure 12). The descriptive statistics for these mean values are summarised in Table 23. Measurement one of Treatment one has a ME of -7.39cm, this is because it is a comparison between the manual UB vs the harvesters OB log end diameter on the base of the stem where BT is at its thickest.

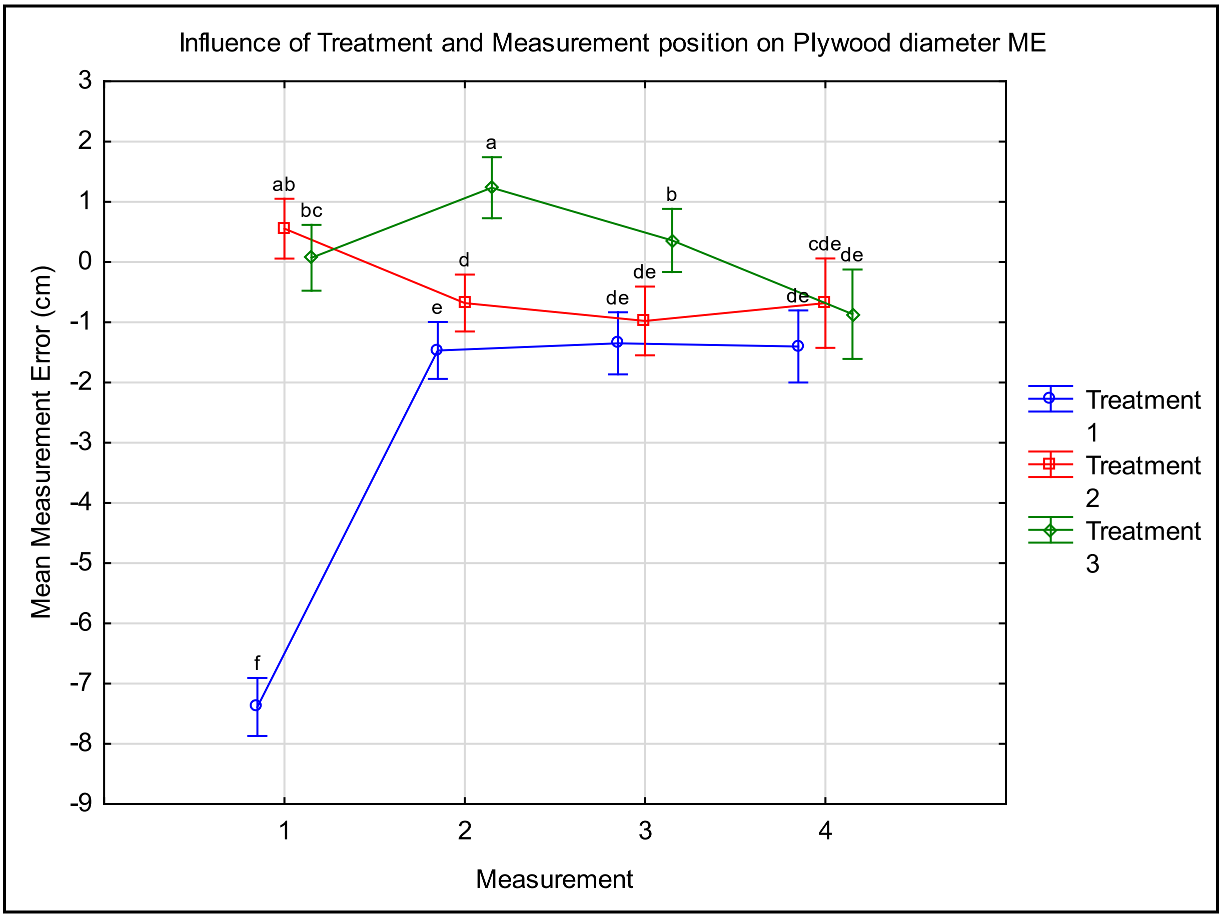


Figure 12: Influence of bark deduction treatment and measurement position on plywood log end diameter ME (treatment means that do not significantly differ from each other are marked with the same letter, i.e. a, b, c etc.).

Table 23: Plywood log diameter ME descriptive statistics for the first four crosscutting positions from the butt end of the stem as illustrated in figure 8.

Position of cut from base of the stem	T1 – No bark deduction		T2 – LB bark deduction		T3 – DLB bark deduction	
	# Logs (n)	Mean ME (cm)	# Logs (n)	Mean ME (cm)	# Logs (n)	Mean ME (cm)
1	31	-7.39	29	0.55	24	0.07
2	32	-1.47	32	-0.68	28	1.23
3	27	-1.35	22	-0.98	26	0.36
4	20	-1.40	13	-0.68	13	-0.87

The percentage difference between the mean manual and harvester diameter measurements was used as a measure of how the bark deduction methods improved harvester measurement accuracy compared to the status quo (Table 24).

Table 24: Percentage difference between the mean manual UB and harvester diameter measurements (Harvester measurements – T1-OB, T2-UB and T3-UB).

Cut position	Treatment	Mean measurement height from base of stem (m)	Mean manual UB diameter Measurement (cm)	Mean harvester diameter Measurement (cm)	Percentage difference
1st	T1	0.17	35.50	42.89	-20,8%
	T2	0.14	34.84	34.29	1,6%
	T3	0.11	39.72	39.65	0,2%
2nd	T1	2.81	30.02	31.49	-4,9%
	T2	2.78	28.63	29.31	-2,4%
	T3	2.75	32.50	31.26	3,8%
3rd	T1	5.45	29.41	30.76	-4,6%
	T2	5.42	27.90	28.99	-3,9%
	T3	5.39	31.25	30.90	1,1%
4th	T1	8.09	28.33	29.74	-5.0%
	T2	8.06	27.22	27.90	-2,5%
	T3	8.03	31.70	32.56	-2,7%

4.3.5. Log Length Measurement Error

The interaction between treatment and product is insignificant ($F_{6, 497} = 0.283$) with p = 0.945 (Table 25) for length error. Length ME almost differs over treatment ($F_{2, 509} = 2.176$) with p = 0.115 (Table 25). Length ME differed significantly for each product $F_{(4, 509)} = 5.46$ with p = <0.001 (Table 25 and Figure 13).

Table 25: ANOVA table for length measurement Error two-way experiment.

Source of variation	Log length ME				
	SS	DF	MS	F	p
Intercept	368.38	1	368.384	156.840	0.000***
Treatment	10.22	2	5.111	2.176	0.115
Prod	46.16	3	15.388	6.551	0.000***
Treatment*Prod	3.98	6	0.664	0.283	0.945
Error	1167.35	497	2.349		

Levene`s test for homogeneity of variance was significant ($F_{3, 505} = 14.585$) with p = <0.001 (Table 26) for log length ME.

Table 26: Levene`s Test for Homogeneity of Variances for log length ME.

Effect: Product Degrees of freedom for all F's: 3, 505			
MS Effect	MS Error	F	p
13.063	0.896	14.585	0.000***

Significant differences between products means were determined through the LSD multiple comparison procedure for log length ME (Figure 13).

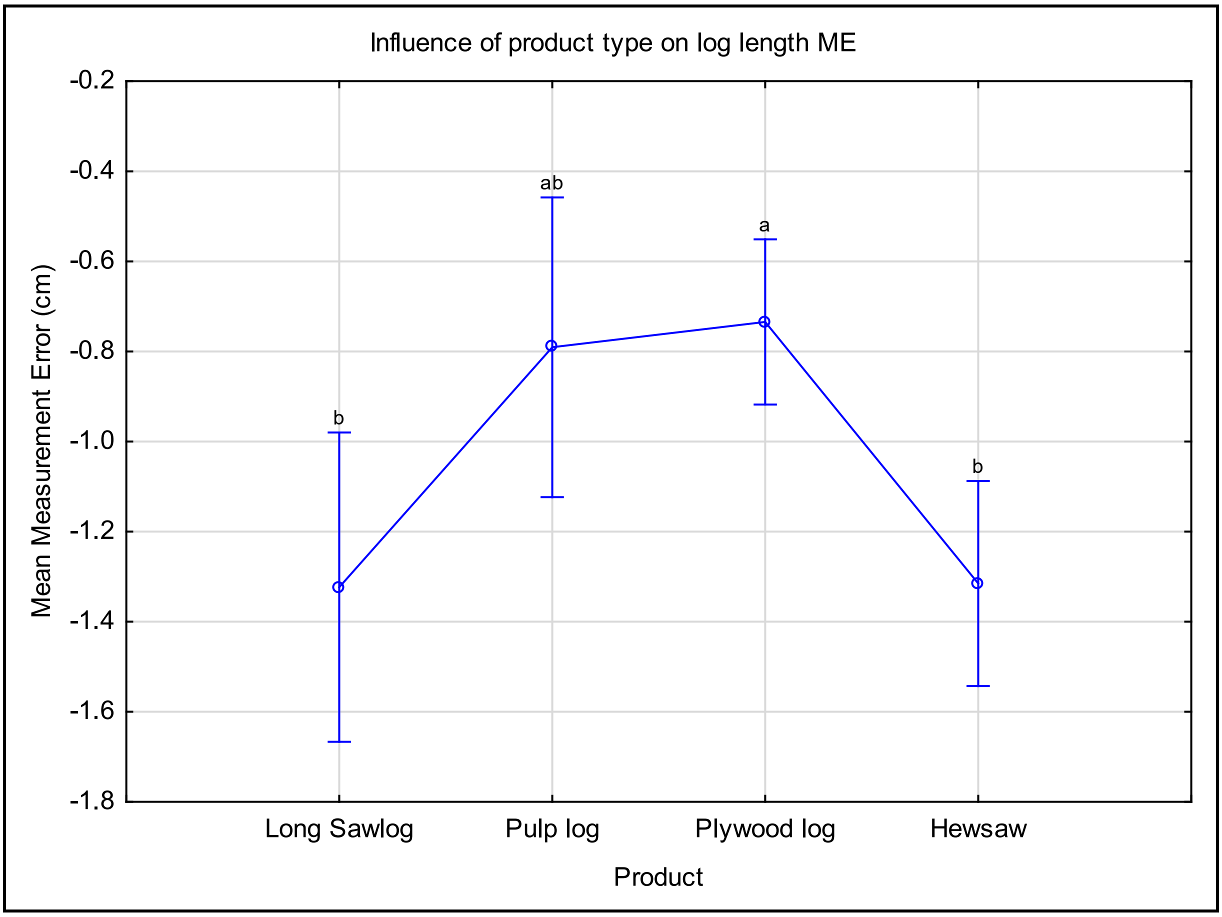


Figure 13: Influence of log product on log length ME (treatment means that do not significantly differ from each other are marked with the same letter, i.e. a, b, c etc.).

Mean log length measurement error was on average over-estimated for all product classes. For all the products combined (n=509) log length was over-estimated by 1.0 cm with a standard deviation (SD) of 1.6 (Table 27 and Figure 13). Measurement error ranges from -8 cm to 3 cm which demonstrates that although on average log lengths are typically over-estimated, they can also be under-estimated on occasion. Log length for long saw logs (n=133) were over-estimated by 1.3 cm on average with a SD of 2. The measurement error ranged from -8 cm to 3 cm. Plywood log length (n=241) were over-estimated by 0.7cm on average with a SD of 1.4. The measurement error ranged from -6 cm to 3 cm. The log length for Hewsaw (n=92) was over-estimated by 1.3 cm on average with a SD of 1.1. While the measurement error ranged from -5 cm to 1 cm. Pulp log length (n=43) was over-estimated by 0.8 cm on average with a SD of 1.1. The measurement error ranged from -5 cm to 2 cm.

Table 27: Log length measurement accuracy descriptive statistics, manual control measurements vs harvester length measurements.

	All Logs	Long saw logs	Plywood logs	Hewsaw logs	Pulp logs
Count	509	133	241	92	43
Mean (cm)	-1.0	-1.3	-0.7	-1.3	-0.8
Standard Deviation	1.6	2.0	1.4	1.1	1.1
Minimum (cm)	-8	-8	-6	-5	-5
Maximum (cm)	3	3	3	1	2

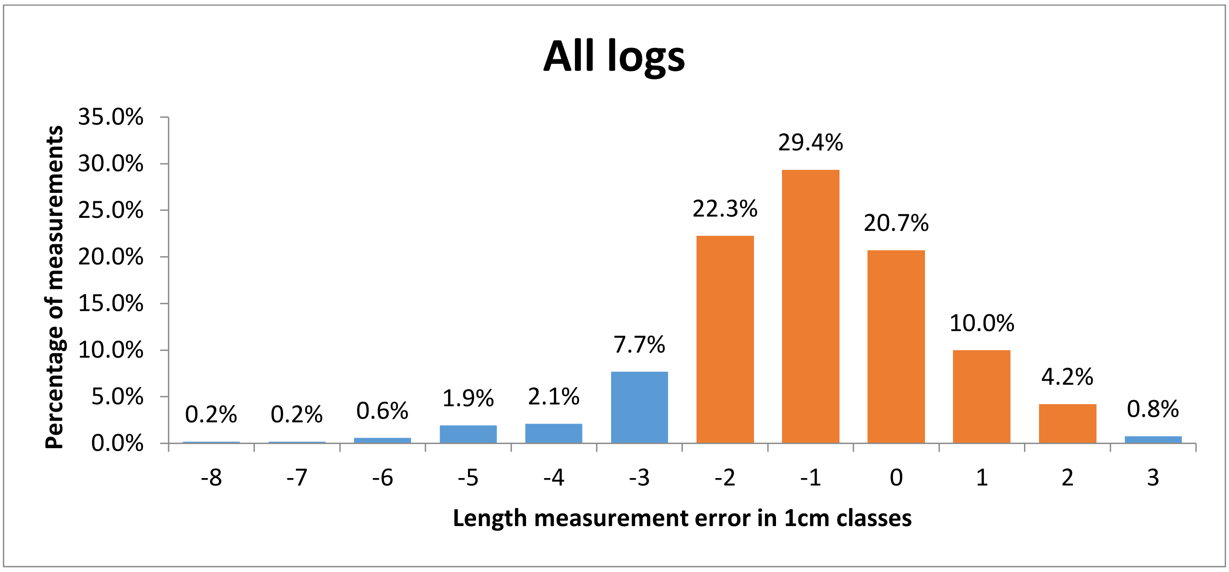


Figure 14: Length measurement error distribution for all logs (Swedish “Best-5” range illustrated as orange bars).

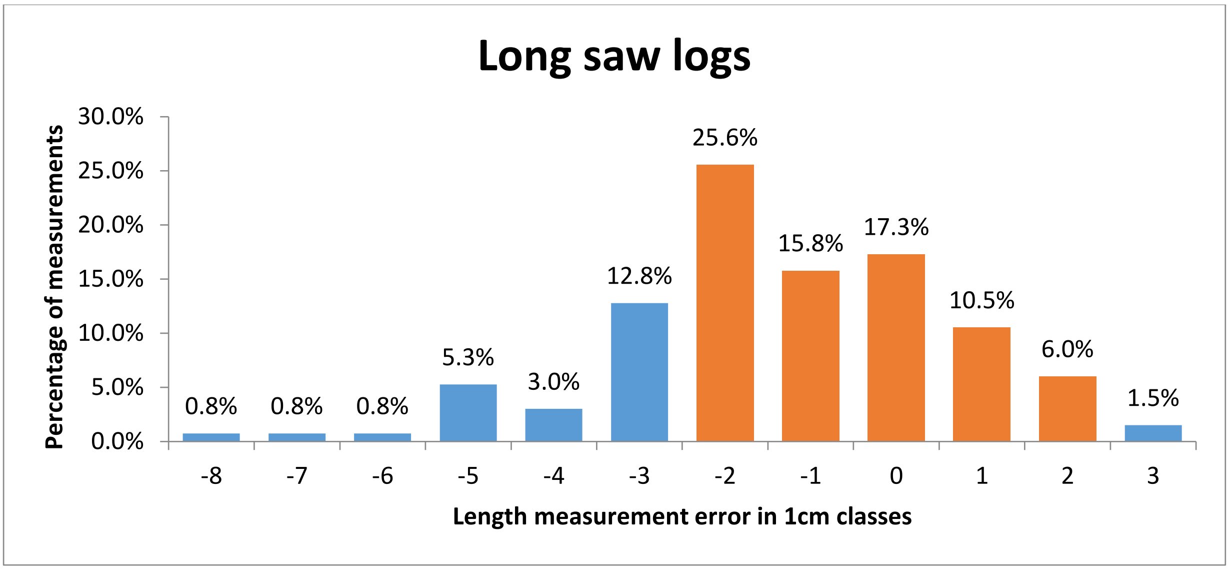


Figure 15: Length measurement error distribution for long saw logs (Swedish “Best-5” range illustrated as orange bars).

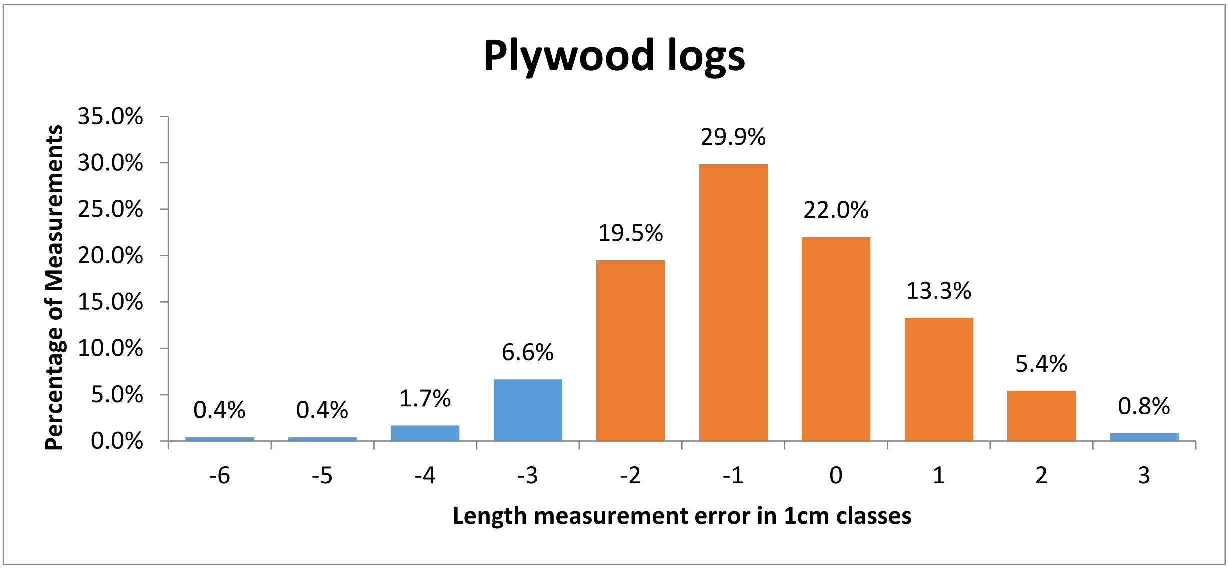


Figure 16: Length measurement error distribution for Plywood logs (Swedish “Best-5” range illustrated as orange bars).

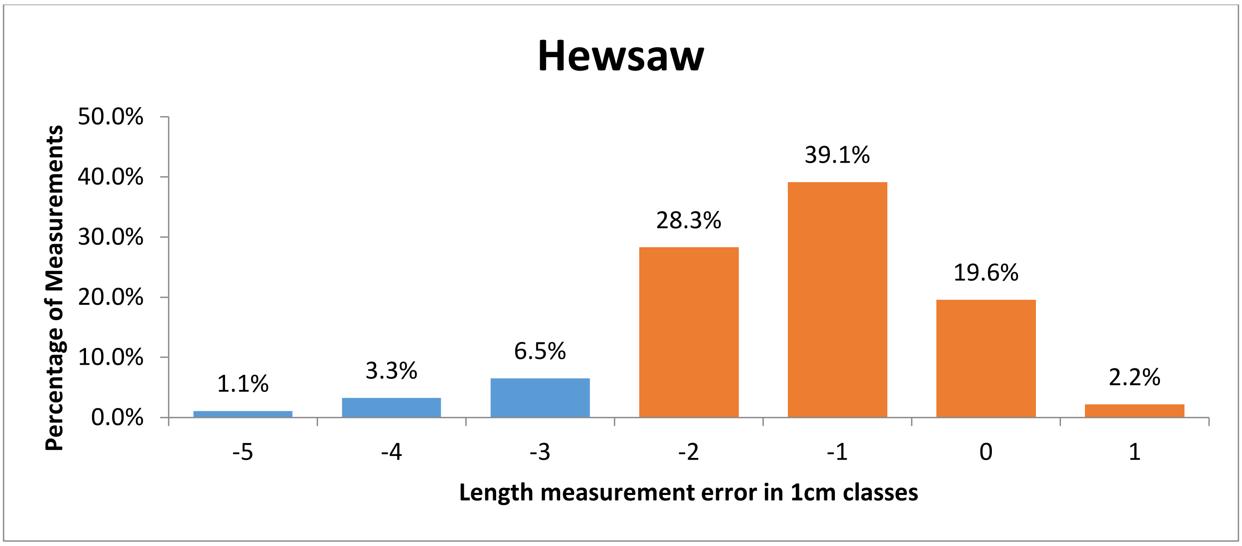


Figure 17: Length measurement error distribution for Hewsaw (Swedish “Best-5” range illustrated as orange bars).

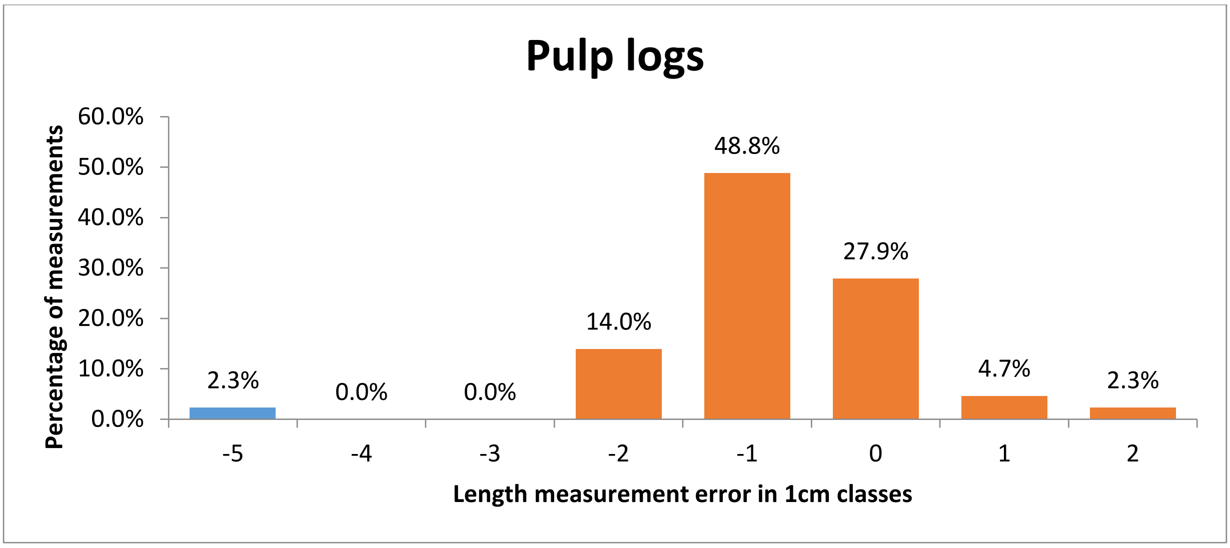


Figure 18: Length measurement error distribution for Pulp logs (Swedish “Best-5” range illustrated as orange bars).

All product groups achieved a measurement accuracy of 86.6% which is within the Swedish “Best-5” standard (Table 28 and Figure 14). Pulp logs achieved the highest accuracy of 97.7% (Table 28 and Figure 18), while long saw logs achieved the lowest measurement accuracy of only 75.2% within the “Best-5” range (Table 28 and Figure 15). Plywood logs and Hewsaw achieved 90.0% and 89.1% within the Swedish “Best-5” standard respectively (Table 28 and Figures 16 and 17).

Table 28: Harvester log lengths within length tolerance classes of actual log length as a percentage of the total number of logs for the product.

Product	0cm	±1cm	±2cm	±3cm	±4cm	±5cm	±6cm	±7cm	±8cm	Total no. logs
All	20.8%	60.1%	86.6%	95.1%	97.2%	99.2%	99.6%	99.8%	100.0%	509
Long Saw logs	17.3%	43.6%	75.2%	89.5%	92.5%	97.7%	98.5%	99.2%	100.0%	133
Plywood logs	22.0%	65.1%	90.0%	97.5%	99.2%	99.6%	100.0%	100.0%	100.0%	241
Hewsaw	19.6%	60.9%	89.1%	95.7%	98.9%	100.0%	100.0%	100.0%	100.0%	43
Pulp logs	27.9%	81.4%	97.7%	97.7%	97.7%	100.0%	100.0%	100.0%	100.0%	92

4.4. Volume Results

4.4.1. Stem Volume Comparison

T1 (control) had the same total stem volume calculation for both volume calculations as no bark deduction method was applied (Table 29). For T2, there was a difference of 4.4 m^3 between the harvester's total OB and UB volume calculations, while for T3 this difference was 5.8 m^3 (Table 29). This means that by applying the LB bark deduction method in T2, the OB volume calculation over-estimated the total stem volume by 13.7% and 14.6% for T3 using the DLB bark deduction method (Table 29).

Table 29: Differences between total harvester OB and UB volume calculations.

Parameters	Treatment		
	T1 - No bark deduction	T2 - LB bark deduction	T3 - DL based bark deduction
Total harvested volume UB (m^3)	40.0	32.20	40.0
Total harvested volume OB (m^3)	40.0	36.6	45.8
Volume difference (m^3)	0.00	4.4	5.8
Total number of stems	40	40	40
Percentage difference between harvester`s UB and OB volumes as percentage of UB volume	0.0%	-13.7%	-14.6%

4.4.2. Log Volume Comparison

Plywood log volumes were over-estimated by the largest margin with 15.5% and 15.8% respectively for T2 and T3 (Table 30). The volume for long saw logs was over-estimated by 8.9% and 10.4% for T2 and T3 respectively. The log volume for Hewsaw was over-estimated by 8.7% for T2 and 8.7% for T3. The volume of pulp logs for T2 was over-estimated by 9.7% while the volume for T3 was over-estimated by 9.6%.

Table 30: Comparison between mean harvester UB and OB log volumes for each product and treatment.

Treatment	Product	Mean Harvester UB Volume (m^3)	Mean Harvester OB Volume (m^3)	Difference between Manual and Harvester log volume as % of Manual log volume
T1	Long Saw logs	0.27	0.27	0.0%
T2		0.25	0.27	-8.9%
T3		0.27	0.30	-10.4%
T1	Plywood logs	0.22	0.22	0.0%
T2		0.17	0.20	-15.5%
T3		0.22	0.26	-15.8%
T1	Hewsaw	0.08	0.08	0.0%
T2		0.07	0.08	-8.7%
T3		0.08	0.09	-8.7%
T1	Pulp logs	0.05	0.05	0.0%
T2		0.04	0.04	-9.7%
T3		0.04	0.05	-9.6%

4.4.3. Log volume as a percentage of total stem volume

Table 31 compares the average volume contribution of each product to total stem UB merchantable volume as measured by the harvester, depending on where that log is cut from in the stem. The lower the log is cut from the stem the greater contribution it has towards the total stem volume. Table 31 shows the mean volume contribution of the combination of a specific product and the position from where in the stem that product is cut has towards the total stem volume for that specific tree. The percentages does not total to a 100% as there are endless combinations for what products and in which sequence they are cut from a tree. This provides insight into the volume contribution that logs cut from the lower sections of the stem has towards total stem volume.

Table 31: Mean log volumes as a percentage of total stem volume per treatment, product and the position of that specific log in the stem (Table does not total to a 100% as this is only an illustration of a specific logs contribution to total stem volume).

Treatment	Log no.	Plywood logs	Long Saw logs
T1 – No bark deduction	1	23.9%	51.3%
	2	18.5%	39.7%
	3	16.8%	31.5%
	4	14.6%	27.7%
	5	11.4%	23.1%
	6		17.3%
T2 – LB bark deduction	1	19.7%	46.4%
	2	19.4%	41.1%
	3	18.2%	32.3%
	4	15.8%	27.8%
	5	12.1%	24.6%
	6		19.0%
T3 – DLB bark deduction	1	18.8%	42.0%
	2	17.5%	36.9%
	3	17.0%	36.0%
	4	15.0%	24.9%
	5	12.8%	24.4%
	6	11.4%	17.9%

Table 32 shows the average contribution of the mean log by assortment and treatment towards total stem UB merchantable volume.

Table 32: The means of the average log volume as a percentage of total log stem volume per treatment and product.

Treatment	1	2	3
Plywood logs	19.2%	18.9%	17.1%
Long saw logs	31.3%	33.6%	31.8%
Hewsaw	9.1%	11.0%	12.3%
Pulp logs	6.0%	6.7%	5.3%

4.4.4. Plywood log volume comparison

The impact that the differences between manual and harvester diameter measurements has on the volume calculations are illustrated in Table 33. By using the mean diameter measurements for each of the cuts in Table 26 it is possible to calculate the mean Plywood log volume for the first three logs cut for each of the three treatments.

Table 33: Comparison of the mean manual and harvester volumes for the first three plywood logs cut from the stem.

Treatment	Log Position	Mean Manual Log Volume (m^3)	Mean Harvester Log volume (m^3)	Difference between Manual and Harvester log volume as % of Manual log volume
T1 – No bark deduction	1st	0.22	0.29	-31.0%
	2nd	0.18	0.20	-9.7%
	3rd	0.17	0.19	-9.8%
	Total	0.58	0.68	-17.9%
T2 – LB bark deduction	1st	0.21	0.21	-0.1%
	2nd	0.17	0.18	-6.3%
	3rd	0.16	0.17	-6.6%
	Total	0.53	0.56	-3.9%
T3 – DLB bark deduction	1st	0.27	0.26	3.2%
	2nd	0.21	0.20	5.0%
	3rd	0.21	0.21	-1.7%
	Total	0.69	0.67	2.3%

4.5. Stump heights and DBH

The effect of treatment mean stump height was not significant ($F_{2, 110} = 2.119$) with p = 0.125 (Table 34). Therefore, the data for all three treatments were grouped and analysed together.

Table 34: ANOVA table for stump heights one-way experiment.

Source of variation	Stump heights				
	SS	Df	MS	F	p
Intercept	24837.28	1	24837.28	250.908	0.000***
Treatment	419.58	2	209.79	2.119	0.125
Error	10888.87	110	98.99		

Mean stump height was 14.9cm with a SD of 10.1cm, stump heights ranged from 2.0 to 68.0 cm (Table 35).

Table 35: Stump height descriptive statistics.

Treatment	N	Mean (cm)	SD (cm)	Std. Err	Min (cm)	Max (cm)
Combined	113	14.9	10.1	0.95	2	68
1	39	17.0	8.6	1.38	6	56
2	36	15.0	10.4	1.74	2	68
3	38	12.4	10.7	1.74	4	66

There was a significant difference between manual and harvester DBH measurements with p = 0.01 (Table 36).

Table 36: T-Test table for differences between manual and harvester DBH measurements.

Variable	Mean (cm)	SD (cm)	N	Diff. (cm)	SD (cm)	t	Df	p
Manual DBH	34.74	5.27						
Harvester DBH	32.82	5.33	120	1.92	2.59	8.10	119	0.00

The mean difference between the manual and harvester DBH measurements was 1.92 cm (Table 37). This mean error had a large variation with a range of between - 9.40 cm and 13.70 cm (Table 37).

Table 37: Descriptive statistics for manual and harvester DBH measurements and the difference between the two.

Variable	Descriptive Statistics (DBH)				
	Valid N	Mean (cm)	Minimum (cm)	Maximum (cm)	SD (cm)
Manual DBH (mDBH)	120	34.74	22.30	51.10	5.27
Harvester DBH (hDBH)	120	32.82	21.50	48.70	5.33
Difference between mDBH and hDBH	120	1.92	-9.40	13.70	2.59

5. Discussion

5.1. Bark thickness modelling

The historic *P. patula* bark thickness data from Kotze`s (1995) thesis used to model the change in bark thickness in this study showed that despite large bark thickness variations at the base of the stem between trees, *P. patula* bark is generally thick at the base of the tree, becoming thinner with an increase in tree height. *P. patula* bark thickness decreases rapidly between 0.2 and 0.3 of relative tree height from where it stays relatively constant towards the top of the tree. These findings are supported by results from earlier studies (Perry, 1991; Vidakovic, 1991; Van Laar, 2007)

This shows that *P. patula* BT decreases hyperbolically up the stem, which is described as Grosenbaugh`s (1967) second pattern of tree bark. This bark pattern is also observed in *P. radiata* grown under plantation conditions in Australia and New Zealand (Sands, 1975). This type of bark pattern has caused problems for researchers in Australia trying to improve harvester bark thickness estimates for *P. radiata* as the various bark deduction methods available to them on harvester OBCs cannot account for the dramatic decrease in bark thickness with change in tree height (Strandgard & Walsh, 2011). This supports the decision to evaluate two bark deduction methods that consider a decreasing bark thickness with an increase in tree height.

This study developed specific bark thickness deduction models for *P. patula* in the Mpumalanga Highveld region of South Africa from historic data. The bark thickness data sets were modelled with an exponential decay function due to the bark pattern observed, for the purpose of determining the coefficients needed to develop the bark deduction tables to be evaluated. The same equation was modelled on the seven different data sets; one for the length-based bark deduction method and six for the DLB bark deduction method.

Significant p-values (<0.001) were observed for all coefficients for each of the seven models. When comparing the observed values to the fitted values, the percentage of variance explained by the models varied between 82.7% and 88.1% between the seven datasets. This equation explained the thick bark on the lower stem and thin bark observed higher up the tree better than the Zacco straight-line equation available on the harvester`s OBC (Strandgard & Walsh, 2011; Roth, 2016). For the above-mentioned reasons, the models were deemed to be appropriate to use in the development of the LB and DLB bark thickness deduction tables available on the harvester`s OBC.

5.2. Photogrammetry test results

Before the field tests, it was important to assess the photogrammetric method of measuring the log end diameters for two reasons. Firstly, we needed to see if a mobile phone camera and photogrammetry rig would take photographs of sufficient quality. Secondly, we needed to determine the accuracy of the measurement technique. The photogrammetry test results showed that there was a mean length measurement under-estimation of 0.08 cm with a SD of 0.08 cm and an error range of -0.14 cm to 0.24 cm. Considering that the International benchmark for harvester diameter measurement accuracy as set by Skogforsk is the percentage of measurements within ±4 mm of the reference diameter (Nordström & Hemmingsson, 2018), this measurement method was deemed acceptable to calculate log end diameters for the purposes of this study.

5.3. Measurement Error

The harvester’s measurement accuracy and improvements in measurement accuracy of the UB diameter were assessed through the calculation of the measurement error: i.e., the difference between the manual (control) and harvester measurements. This was done for the log LED, SED, plywood log diameter measurements and the log length.

5.3.1. Log Large End Diameter Measurement Error

The interaction between treatment and product had a significant effect on log LED mean ME. Therefore, LED mean ME was compared within each product across the three different treatments. Plywood log mean ME for T1 was the largest of all products with the harvester head over-estimating the diameter by 3.50 cm. This value was significantly different from the mean ME observed for T2 and T3, between which there was no significant difference. The use of the respective bark deduction methods reduced the mean ME to an over-estimation of 0.30 cm and 0.39 cm for T2 and T3, respectively. For long saw logs the mean ME for T1 was over-estimated by 1.39 cm, while this over-estimation was improved to 0.18 cm for T2 and 0.43 cm for T3. The mean log ME for T1 was significantly different from both T2 and T3, between which there was no significant difference.

Hewsaw log mean ME for T1 was over-estimated by 0.90 cm; this mean ME was significantly different from the mean ME observed for T2 and T3 which was reduced to a slight under-estimation of 0.07 cm and 0.04 cm for T2 and T3, respectively. No significant difference was seen between T2 and T3 for Hewsaw. The pulp logs mean log ME for T1 was over-estimated by 1.14 cm with this error margin reduced to an under-estimation of 0.01 cm for T2 and an over-estimation of 0.06 cm for T3. Not one of these mean ME values differed significantly from each other. This could be because of the small sample size for pulp logs within each treatment leading to high variability within each group. It is to be expected that the largest improvement in measurement accuracy occurred for plywood logs and long saw logs as these products are cut from the thicker base section of the stem as compared with hewsaw and pulp logs which are produced from the top half.

5.3.2. Log Small End Diameter Measurement Error

The interaction between treatment and product had a significant effect on log SED mean ME. Therefore, SED mean log ME was compared within each product group across the three different treatments. As with the LED mean log ME, Plywood logs also had the largest mean ME for log SED with an over-estimation of 1.48 cm for T1, which was reduced to an over-estimation of 0.78 cm for T2, and an under-estimation of 1.03 cm for T3. The mean log ME for all three treatments of plywood logs differed significantly from each other. Long saw log mean ME for T1 was over-estimated by 1.03 cm. This value differed significantly from both T2 and T3, which did not differ from each other. The mean log ME for T2 and T3 improved to a slight under-estimation of 0.06 cm and 0.02 cm, respectively.

The mean log ME for Hewsaw was over-estimated by 0.80 cm for T1 which was improved to an over-estimation of 0.44 cm for T2. These two values did not differ significantly from each other. The Hewsaw mean log ME for T3 was improved to an under-estimation of 0.01 cm which differed significantly from both T2 and T3, respectively. The pulp logs mean log ME for T1 was over-estimated by 1.07 cm. This value differed significantly for the mean ME for T2 which was improved to an over-estimation of 0.45 cm. The mean log ME for T3 for pulp logs was improved to an over-estimation of 0.26 cm, which differed significantly from T1, but not from T2. As with the log LED the greatest improvements occurred for long saw logs and plywood logs.

5.3.3. Plywood Log Diameter Measurement Error

As found with the log LED and SED analysis, products produced from the base of the stem had the greatest potential for measurement improvement which underlines the importance of this section of the stem with regards to measurement accuracy and bark thickness estimates. These findings support our intention to assess the plywood log diameter measurements separately to establish a better understanding of how the bark deduction methods performed at the base of the stem.

As with both the log LED and SED mean ME, the interaction between treatment and product had a significant effect on plywood log ME. Therefore, the treatments were compared within each cut position. The mean log ME of the first cut for T1 had the largest ME for all cases and was over-estimated by 7.39 cm. This value differed significantly from the mean log ME`s for both T2 and T3, between which no difference was found. The mean log ME for these two treatments was improved to an under-estimation of 0.55 cm and 0.07 cm for T2 and T3, respectively. For the second cut, T1 was over-estimated by 1.47 cm, with the mean log ME for T2 being improved to an over-estimation of 0.68 cm, while the ME for T3 was under-estimated by 1.23 cm. The mean log ME for all three treatments differed significantly from each other.

The mean log ME of the third cut for T1 was over-estimated by 1.35 cm, which was slightly improved to 0.98 cm for T2. No significant differences were observed between T1 and T2, but both these two values differed from T3, whose mean log ME was improved to an under-estimation of 0.36 cm. The mean log ME for T1 of the fourth cut was over-estimated by 1.40cm, with the mean log ME being improved to an over-estimation of 0.68 cm and 0.87 cm for T2 and T3, respectively. No significant differences were observed between the mean ME for any of the three treatments of the fourth cut. To bring these mean diameter measurement errors into context, we will analyse the percentage difference between the manual and harvesters' diameter measurements.

The largest improvement in measurement accuracy occurred at the first cut, where the harvester diameter measurement was over-estimated by 20.8% for T1. This was improved to an under-estimation of only 1.6% and 0.2% for T2 and T3, respectively.

For the second cut T1 and T2 was over-estimated by 4.9% and 2.4%, while T3 was under-estimated by 3.8%. For the third cut, T1 and T2 was over-estimated by 4.6% and 3.9% respectively, while T3 was under-estimated by 1.1%. For the fourth cut, T1 was over-estimated by 5.0% with T2 and T3 over-estimated by 2.5% and 2.7%, respectively. This shows that through the implementation of bark thickness deduction methods harvester diameter measurements can be improved (Marshall, Murphy & Lachenbruch, 2006; Strandgard & Walsh, 2011; Roth, 2016).

Harvester diameter measurement accuracy in this study is not relatable to earlier harvester measurement accuracy studies, as most of these compared manual OB measurements with harvester OB measurements (Strandgard & Walsh, 2012a ; Saathof, 2014; Nordström *et al.*, 2018). Furthermore, none of these studies were done on *P. patula*. The mean diameter measurement error results however clearly showed that by the implementation of bark deduction methods, harvester diameter measurement accuracy can be improved. This is especially true for the large diameter logs such as the plywood logs and long saw logs produced from the base of the stem.

5.3.4. Length Measurement Error

Interactions between treatment and product had no significant impact on the mean log length ME, this was also true for treatment on its own. Product type did however have a significant effect on log length ME. Long saw logs had the lowest measurement accuracy within the Swedish “Best-5” with only 75.2% of measurements within ±2 cm of the log’s actual length, while the mean length was over-estimated by 1.3 cm with a SD of 2.0 cm. Long saw logs are the longest assortment produced at 612 cm and are also cut from the middle section of the stem which is unpruned and generally has the largest branches. The presence of large thick branches have been reported to lead to increased harvester length measurement inaccuracy (Saathof, 2014). These branches can cause problems during the delimbing process since they lead to repeated back and forth movements of the harvester head, which causes the measuring wheel to lose its position on the stem (Strandgard & Walsh, 2012a). Large branch stubs can also cause the measuring wheels to travel further over the defects, leading to an incorrect length estimation as stated by Nieuwenhuis & Dooley (2006), who found that an increase in branch size and frequency leads to a decrease in length measurement accuracy.

Pulp logs achieved the highest measurement accuracy of 97.7% of length measurements within the Swedish “Best-5” range, with a mean length over-estimation of only 0.8 cm and a SD of 1.1 cm. As pulp logs are the shortest assortment cut at 240 cm, there is less room for measurement error. Since they are also cut from the top of the tree where branches are at their smallest, this will have less of an impact on log length measurement accuracy (Nieuwenhuis & Dooley, 2006).

Plywood logs achieved a measurement accuracy of 90.0% within the Swedish “Best-5” range, the mean length for Plywood logs was over-estimated by 0.8 cm with a SD of 1.4 cm. Plywood logs are cut at 265 cm from the pruned lower section of the stem, which supports the theory that the absence of large branches leads to increased measurment accuracy. Hewsaw logs achieved 89.1% of length measurements within the Swedish “Best-5” range with a mean log length over-estimation of 1.3 cm and a SD of 1.1 cm. Hewsaw logs are 312 cm long and cut from the top half of the stem where branch size tends to decrease. This further supports Nieuwenhuis & Dooley (2006) and Saathof`s (2014) claim that increased frequency and diameter of branches leads to increased length measurement error.

Log length accuracy is very important for lumber mills due to the value loss associated with logs that are out of specification (Marshall *et al.*, 2006). For this reason sawmills prescribe an overcut or log trimming allowance of a certain length, which in most cases is 100 mm, to ensure that logs are within length specification to minimise these losses (Leitner *et al.*, 2014). In the case of the company on who’s land these investigations were done, this log trimming allowance ranges from 100mm to 120 mm depending on the assortment. However, various international studies have shown that modern harvesters can measure log length very accurately, so this trimming allowance can be reduced.

Strandgard & Walsh (2012b) found that three Australian harvesters working in *P. radiata* plantations achieved more than 80% of log-lengths within the Swedish “Best-5” range. The Skogforsk wood value trials in 2016 found harvester length measurement accuracies for four different manufacturers of between 84% and 94% with an overall SD of 1.8 cm (Nordström *et al*, 2018). In this study a Ponsse H7 harvesting head with Opti 4G bucking computer measured 90% of log lengths within the “Best-5” range with a SD of 1.6 cm. Leitner *et al.* (2014) found that a Ponsse H7 harvester head can achieve a log length measurement accuracy of 97.5% after a professional calibration procedure. Thus the grouped accuracy of 86.6% of length measurements within the Swedish “Best-5” range with a SD of 1.6 cm achieved by the Ponsse H8 harvester head in this study is in-line with international standards. Therefore, this high level of log length measurement accuracy warrants an investigation into the sawmill practice of log overcuts which could be over cautious and leads to unneccessary wood fibre loss.

5.4. Stem Volume

Using the log end-diameter ME and specifically the plywood log diameter ME, we see that the use of bark thickness deduction methods improves harvester diameter measurement accuracy. This is especially true for the first log cut from the base of the stem where *P. patula* bark is thickest. By not implementing a bark deduction method, this over-estimation in diameter measurements will translate into an over-estimation of the produced log volumes as calculated by the harvester’s OBC (Marshall*et al.*, 2006).

The percentage difference between the harvester’s mean OB and UB volumes show that by not implementing a bark thickness deduction method, the total UB stem volume for T2 will be over-estimated by 13.7%, while for T3 this over-estimation is 14.6%. This portion of total stem volume attributed to bark is similar to what Marshall *et al* (2006) found for *P. Radiata* (16%), *Douglas Fir* (17%) and *Ponderosa Pine* (27%).

5.5. Log Volume

The percentage volume over-estimation per product and treatment combinations were compared by analysing the differences between the harvester mean OB and UB volumes. T1 which was the control treatment (no bark deduction method) has the same values for both the OB and UB volumes. For this reason, the investigation only considered the differences for T2 and T3. Plywood log volumes were over-estimated by the largest margin with 15.5% for T2 and 15.8% for T3. These logs are cut from the base of the stem, where stem diameter and bark thickness are at its thickest and bark will accordingly contribute more towards total log volume. The percentage over-estimation for each of the other products were similar. Long saw logs volumes were over-estimated by 8.9% for T2 and by 10.4% for T3. Hewsaw log volumes were over-estimated by 8.7% and 8.7% for T2 and T3, respectively, while pulp log volumes were over-estimated by 9.7% and 9.6% for T2 and T3, respectively.

It is important to note that although the percentage of volume over-estimation for each product is quite similar, the volume that each log contributes to total stem volume differs by product class and from which section of the stem that log is cut. Naturally, the products cut from the base of the tree will contribute more towards total stem volume because this is where the stem diameter is largest. This is especially true for long saw logs, which when cut from the butt section contributed 46.4% and 42.0% towards total stem volume for T2 and T3 respectively, because not only are they cut from the section with the largest diameter they are also the longest assortment produced. In addition, the first plywood log cut from the stem contributed 18.8% and 19.7% towards the total stem volume for T2 and T3, respectively.

By contrast Hewsaw and pulp logs are short assortments and cut from the thinner tops of the stems and contributed less towards total stem volume. The average Hewsaw log contributed 11.0% and 12.3% of total stem volume for T2 and T3, respectively, while the average pulp log contributed only 6.7% of the total stem volume for T2 and 5.3% for T3. This shows that in the context of total harvested volumes long saw logs and plywood logs cut from the lower part of the tree with the thickest bark will contribute the largest proportion of the over-estimated log volumes UB. This further highlight the importance of this section of the stem with regards to correct harvester bark thickness estimates.

5.6. Plywood log volume comparison

By extracting the dimensions of the first three plywood logs cut for each treatment it was possible to build the mean stem for each of these groups of measurements. This provided a detailed analysis on the impact and improved accuracy of the bark deduction methods on this section of the stem. Also, these three logs contribute a large proportion of total stem volume. For T2 the average contribution of the first three plywood logs was 57.3% of total stem volume and 53.3% for T3.

Through the comparison of the OB and UB log volumes for the extracted plywood log measurements, we see that when not using a bark thickness deduction method (T1), plywood log volume is grossly over-estimated. This is especially apparent for the first log cut from the stem, whose volume was over-estimated by 31.0%. The second and third log's volumes were over-estimated by 9.7% and 9.8%, respectively, which gives a total volume over-estimation of 17.9% for the first three Plywood logs cut from the stem if no bark-thickness deduction method is applied.

The UB volume calculation is significantly improved by the implementation of a bark deduction method. The volume for the first plywood log cut for T2 was over-estimated by only 0.1%, while the second and third log's volume was over-estimated by 6.3% and 6.6%, respectively. This gives a total UB volume over-estimation of only 3.9% for the first three logs cut for T2. The volume of the first two logs cut for T3 was over-estimated by 3.2% and 5.0%, respectively, while the third log`s volume was under-estimated by 1.7%, which gave a total log volume over-estimation of 2.3% for T3.

5.7. Stump heights and DBH

The height from ground level at which trees are felled is referred to as the stump height. High stumps have frequently been described as an unnecessary source of fiber loss (Kewley & Kollegg, 2001; Ackerman & Pulkki, 2012). In modern harvesters, this height is pre-set on the machine's OBC, which in this study was set at 20cm. Brewer *et al.* (2018) speculated that this fixed harvester stump height could be one of the causes for the significant differences observed between the harvesters' and manually measured tree DBH. This study unfortunately did not measure stump height to substantiate this claim.

In the current study we observed a mean stump height of 14.9 cm which is more than 5 cm lower than the stump height set on the harvester's OBC. However, the variation in stump heights was large, ranging from 2 cm to 68 cm. The preset 20 cm stump height means that the harvester will measure the stems DBH at 1.1 m from the butt end of the first log to get the diameter at 1.3 m. The lower mean stump height (other than the pre-set mean) means that the harvesters' DBH value will on average not be measured at 1.3 m but at 1.25 m and with the large variation in stump height the harvester DBH measurement will also have a large variation. The manual and harvester DBH measurements seen in this study differed significantly from each other. When calculating the difference between these two DBH measurements, we see an error range of between -9.4 cm to 13.7 cm, which can be attributed to the large variation in stump heights.

5.8. Bark deduction method evaluation

Exact bark thickness measurements play an important role in harvester head log diameter measurement accuracy and subsequently log UB volume calculations. Both T2 and T3 improved harvester UB diameter measurement. Although each of the bark deduction methods performed with different margins of accuracy for different sections of the stem and different assortments. The analysis of the plywood log diameter measurements provides insight into the performance of the various bark deduction methods, on the most dynamic section of bark on the base on the stem. The felling cut is the most important measurement position for bark thickness estimations as illustrated by the over-estimation of this diameter by 7.39 cm when not taking bark thickness into account for T1. This ME was greatly improved through the implementation of a bark deduction method with the ME for T2 being under-estimated by 0.55cm, while T3 was over-estimated by 0.07cm.

Looking at the results of Table 23 (Plywood log descriptive statistics) we can see that although there is still error in the diameter measurements for T2 and T3 there is an overall improvement in the measurement accuracy when compared to T1. This also translated into a substantial improvement in the precision of the harvester UB volume calculations, with T2 over-estimating the volume of the first three plywood logs by 3.9% and with T3 under-estimating this volume by only 2.3% compared to the over-estimation of 17.9% for T1. Considering that this base section of the stem contributes to a substantial proportion towards total stem volume, improved measurement accuracy in this section will provide a far more accurate harvester total UB volume estimation than what is currently achievable.

As mentioned, each bark deduction method is more accurate for different sections of the stem. T2 tends to over-estimate diameters except for the first plywood log cut, while T3 tends to under-estimate log diameters except for the fourth plywood log cut. Taking all these factors into account and the fact that the first measurement plays a significant part in overall measurement accuracy, we suggest that T3 is the best solution for the bark thickness estimation problem. T3 is more accurate for the first cut of the plywood logs and the volume difference for the first three plywood logs is the closest to zero out of the two bark deduction methods assessed.

6. Conclusion

The main objective of this study to develop and propose an applicable bark deduction method for *P. patula* in the Mpumalanga Highveld region of South Africa for more precise harvester volume calculations was achieved. This was accomplished through the modelling of historical *P. patula* bark thickness data from the Mpumalanga Highveld region to obtain the necessary bark thickness estimates for the two methods of bark deduction to be assessed, which were available on the Ponsse Opti OBC system. The two bark deduction methods were implemented successfully, and the harvester's UB diameter measurements compared with manual UB measurements which was derived through the novel application of photogrammetry technology.

With increasing prevalence of mechanised CTL harvesting systems globally and in South Africa, the need to understand more than just system productivity is important. Harvesters and forwarders automatically collect a variety of valuable information which can be used for improved management of the forestry value chain. Theoretically, harvester data allows for near real time tracking of log volume from stump to the mill gate. However, the use of this data is underpinned in its accuracy, which is where the implementation of bark deduction methods for precise UB diameter estimation comes into play.

Results from the diameter measurement accuracy analysis show that through the implementation of a bark deduction method, harvester UB diameter measurement accuracy is improved, especially on the lower section of the stem, where *P. patula* bark is at its thickest. The base (or felling cut) cut has the largest potential for improved UB diameter measurement accuracy, with the over-estimation of diameter by 20.8% for T1 being reduced to an under-estimation of only 1.6% and 0.2% for T2 and T3, respectively. This increased UB diameter measurement accuracy also leads to more accurate harvester UB volume estimations.

The difference between the harvester total stem UB and OB volumes translates into a volume over-estimation of 13.7% and 14.6% for T2 and T3, respectively. This means that when not using a bark deduction method (as in T1), harvester volumes will be grossly over-estimated. The first three plywood log volumes were over-estimated by 17.9% for T1, where through the implementation of a bark deduction method this was improved to an over-estimation of 3.9% for T2 and an under-estimation of 2.3% for T3.

Harvester log length measurement accuracy compared favourably to International best practice with 86.6% of length measurements within the Swedish “Best-5” standard. Long saw logs had the lowest length measurement accuracy with only 75.2% of length measurements within the Swedish “Best-5”, while pulp logs had the best measurement accuracy with 97.7% of its length measurements within this range. This level of length measurement accuracy may warrant a rethink of the log trimming allowance prescribed by sawmills.

The measured stump heights after harvesting were on average 5.2cm lower than the set stump height on the harvesters’ OBC. Coupled with the large variation in stump height, this explains the significant differences observed between the harvester and manually measured tree DBH.

Modern harvester heads are powerful data collection tools. However, to unlock their full potential one needs to understand all the idiosyncrasies that underpin their efficient and correct utilisation. The data from these machines holds vast potential for the more efficient management of the forestry value chain, and for this reason this work will add to the limited knowledge base regarding harvester data use in the South African forest industry. The findings of this study should serve as a basis for future work on harvester measurement accuracy and specifically the development and implementation of bark deduction methods for improved UB log diameter determination and UB volume estimation.

Study limitations

The following factors constitute the main limitations of this study:

1. The limitation in country wide applicability of the bark deduction methods developed due to regional differences in *P. patula* bark thickness.
2. Not being able to apply a custom bark thickness model onto all the StanForD systems used by modern harvesters.
3. The two bark deduction methods developed can only be used on the Ponsse Opti computer system.
4. Setting a fixed bark thickness for a certain section of the stem. As bark thickness is dynamic across the length of the tree.

Future work

This work should form the basis of improving harvester data accuracy in South Africa for use in the forestry value chain as has been implemented in the Scandinavian countries.

Future work should look at the following concepts:

- Assess the current applicability of the historical *P. patula* bark thickness data used in this study.
- Expand on the species specific bark deduction methods available for the South African forest industry.

7. References

Ackerman, P. & Pulkki, R. 2012. Fibre volume losses of eight softwood clearfell harvesting systems in South Africa. *Southern Forests*. 74(2):133–149.

Ackerman, P., Williams, C., Ackerman, S. & Nati, C. 2016. Diesel Consumption and Carbon Balance in South African Pine Clear-Felling CTL Operations : a Preliminary Case Study. *Croatian Journal of Forest Engineering*. 38(1):65–72.

Ackerman, P., Martin, C., Brewer, J. & Ackerman, S. 2018. Effect of slope on productivity and cost of Eucalyptus pulpwood harvesting using single-grip purpose-built and excavator-based harvesters . *International Journal of Forest Engineering*. 29(2):74–82.

Andersson, B. & Dyson, P. 2001. Log Measuring Accuracy of Harvesters and Processors. In Snowshoe: Council of Forest Engineering *Council on Forest Engineering (COFE) Conference Proceedings: "Appalachian Hardwoods: Managing Change"*.

Arlinger, J. 2018. Personal Communication. Uppsala.

Arlinger, J., Möller, J.J., Sorsa, J. & Räsänen, T. 2012. *Introduction to StanForD 2010*. Uppsala. [Online], Available: https://www.skogforsk.se/contentassets/1a68cdce4af1462ead048b7a5ef1cc06/stanford-2010-introduction-121221.pdf.

Axelsson, S.-Ă. 1998. The Mechanization of Logging Operations in Sweden and its Effect on Occupational Safety and Health. *Journal of Forest Engineering*. 9(2):25–31.

Bredenkamp, B. & Upfold, S. Eds. 2012. *South African Forestry Handbook*. 5th ed. Menlo Park, South Africa: South African Institute of Forestry.

Brewer, J., Talbot, B., Belbo, H., Ackerman, P. & Ackerman, S. 2018. A comparison of two methods of data collection for modelling productivity of harvesters: Manual time study and follow-up study using on-board-computer stem records. *Annals of Forest Research*. 61(1):109–124.

Eggers, J., McEwan, A. & Conradie, B. 2010. Pinus saw timber tree optimisation in south africa: A comparison of mechanised tree optimisation (harvester/processor) versus current manual methods. *Southern Forests*. 72(1):23–30.

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.

Ferreira, T. & Rasband, W. 2012. *ImageJ User Guide v1.46r*.

Forestry Economic Services CC. 2018. *REPORT ON COMMERCIAL TIMBER RESOURCES AND PRIMARY ROUNDWOOD PROCESSING IN SOUTH AFRICA 2016/2017*. Pretoria.

Gellerstedt, S. & Dahlin, B. 1999. Cut-To-Length: The Next Decade. *Journal of Forest Engineering*. 10(2):17–25. [Online], Available: https://journals.lib.unb.ca/index.php/IJFE/article/viewFile/9956/10180 [2019, January 21].

Grosenbaugh, L.R. 1967. *STX -- FORTRAN - 4 PROGRAM for estimates of tree populations from 3P sample-tree-measurements*. Berkeley, California.

Hongwane, P.C., Mitchell, R.G., Kanzler, A., Verryn, S.D. & Chirwa, P.W.C. 2017. Growth and dynamic modulus of elasticity of Pinus patula × Pinus tecunumanii hybrids in Mpumalanga, South Africa. *Southern Forests*. 79(4):277–285.

Instruktion för kvalitetssäkring av längd- och diametermätning med skördare. 2019. Uppsala. [Online], Available: https://www.biometria.se/wp-content/uploads/2019/04/Nationell-instruktion-för-Kvalitetssäkring-av-skördare-version-20190404-slutv.pdf.

Kewley, S. & Kollegg, L. 2001. Mechanical feller-buncher felling: An example study on timber value recovery in south africa. *Southern African Forestry Journal*. 192(1):59–64.

Kirk, P.., Byers, J.., Parker, R.. & Sullman, M.. 1997. Mechanisation Development within the New Zealand Forest Industry: The Human Factors. *Journal of Forest Engineering*. 8(1):75–80.

Kotze, H. 1995. Merchantable Volume and Taper Equations for Pinus Patula. University of Stellenbosch. [Online], Available: http://hdl.handle.net/10019.1/54788.

Van Laar, A. 2007. Bark thickness and bark volume of Pinus patula in South Africa. *Southern Hemisphere Forestry Journal*. 69(3):165–168.

Labelle, E.R. & Huß, L. 2018. Creation of value through a harvester on-board bucking optimization system operated in a spruce stand. *Silva Fennica*. 52(3):22.

Langin, D. & Ackerman, P. 2007. *South African Forest Engineering Survey 2006/2007*. [Online], Available: file:///C:/Users/17621194/Downloads/FESurvey2006-2007.pdf [2019, January 17].

Längin, D., Ackerman, P., Krieg, B., Immelmann, A., Potgieter, C., Van Rooyen, J. & Upfold, S. 2010. *South African Ground Based Harvesting Handbook*. 1st ed. D. Längin, P. Ackerman, B. Krieg, A. Immelmann, C. Potgieter, J. Van Rooyen, & S. Upfold (eds.).

Leitner, T., Stampfer, K. & Visser, R. 2014. Analysing log length measurement accuracy of harvester and processor heads. *Austrian Journal of Forest Science*. 131(3):129–146.

Marshall, H.D. 2005. An Investigation of Factors Affecting the Optimal Output Log Distribution from Mechanical Harvesting and Processing Systems. Oregon State University.

Marshall, H., Murphy, G. & Lachenbruch, B. 2006. Effects of bark thickness estimates on optimal log merchandising. *Forest Products Journal*. 56(10123):87–92. [Online], Available: http://ir.library.oregonstate.edu/xmlui/handle/1957/17956.

Marshall, H.D., Murphy, G.E. & Boston, K. 2006. Evaluation of the economic impacts of length and diameter measurement error on mechanical harvesters and processors operating in pine stands. *Canadian Journal of Forest Research*. 36(7):1661–1673.

McEwan, A. & Steenkamp, J. 2014. Silviculture Modernization in the South African Forestry Industry. *Proceedings of the Second International Congress of Silviculture*. (November 2014):822–826.

Mederski, P.S., Bembenek, M., Karaszewski, Z., Pilarek, Z. & Lacka, A. 2018. Investigation of Log Length Accuracy and Harvester Efficiency in Processing of Oak Trees. *Croatian Journal of Forest Engineering*. 39(2):173–181. [Online], Available: file:///C:/Users/17621194/Downloads/mederski (1).pdf [2019, January 30].

van der Merwe, J.P., Pulkki, R. & Ackerman, P. 2015. Fibre losses during debranching and debarking of Eucalyptus pulp logs using a single-grip harvester. *Southern Forests*. 77(4):309–313.

Milton, J.S. & Arnold, J.C. 1999. *Introduction to probability and statistics: principles in the application for engineering and the computing sciences*. 2nd ed. New York: McGraw-Hill.

Moilanen, T. 2018. *Methods to estimate bark and get under bark diameter of the logs*. Vieremä, Finland: Ponsse.

Möller, J., Arlinger, J., Hannrup, B., Larsson, W. & Barth, A. 2011. Harvester data as a base for management of forest operations and feedback to forest owners. In *4th Forest Engineering Conference: Innovation in Forest Engineering – Adapting to Structural Change*. 31–35.

Murphy, G. 2001. The Future of Forest Engineering. In Snowshoe *2001 Council on Forest Engineering (COFE) Conference Proceedings: "Appalachian Hardwoods: Managing Change"*. [Online], Available: https://www.cofe.frec.vt.edu/documents/2001/COFE_2001_Murphy.pdf [2019, January 22].

Murphy, G., Marshall, H. & Bolding, M.C. 2004. Adaptive control of bucking on harvesters to meet order book constraints. *Forest Products Journal*. 54(12):114–121. [Online], Available: https://search.proquest.com/docview/214629748?pq-origsite=gscholar.

Murphy, G.E., Marshall, H.D. & Evanson, A.W. 2005. Production speed effects on log-making error rates and value recovery for a mechanized processing operation in radiata pine in new zealand. *Southern African Forestry Journal*. 204(1):23–35.

Nieuwenhuis, M. & Dooley, T. 2006. The Effect of Calibration on the Accuracy of Harvester Measurements. *International Journal of Forest Engineering*. 17(2):25–33.

Nordström, M. & Hemmingsson, J. 2018. *Measure Up! A Skogforsk Guide to Harvester Measurement*. [Online], Available: http://www.measureup.gov.au/internet/abhi/publishing.nsf/content/home.

Nordström, M., Arlinger, J., Hannrup, B., Rikard, J., Jönsson, P. & Möller, J.J. 2018. *Wood Value Trials 2016*. Uppsala. [Online], Available: https://www.skogforsk.se/cd_48e5db/contentassets/01cde0f5ca494ddf88aef03b410f93a1/virkesvardestest-2016-low.pdf [2019, February 04].

Norihiro, J., Ackerman, P., Spong, B.D. & Längin, D. 2018. Productivity Model for Cut-to-Length Harvester Operation in South African Eucalyptus Pulpwood Plantations. *Croatian Journal of Forest Engineering*. 39(1):1–13.

Nurminen, T., Korpunen, H. & Uusitalo, J. 2006. Time Consumption Analysis of Harvesting System. *Silva Fennica*. 40(2):335–363.

Olivera, A. & Visser, R. 2016a. Using the harvester on-board computer capability to move towards precision forestry. *New Zealand Journal of Forestry Science*. 60(4):3–7. [Online], Available: https://www.researchgate.net/profile/Alejandro_Olivera_Farias/publication/301469843_Using_the_harvester_on-board_computer_capability_to_move_towards_precision_forestry/links/5770649f08ae0b3a3b7b92a6.pdf.

Olivera, A. & Visser, R. 2016b. Development of forest-yield maps generated from Global Navigation Satellite System (GNSS)-enabled harvester StanForD files: preliminary concepts. *New Zealand Journal of Forestry Science*.

Olivera, A., Visser, R., Morgenroth, J. & Acuna, M. 2014. Integration of GNSS in harvesters as a tool for site-specific management in plantation forests. *Technical reports*. (July 2014):14.

Olivera, A., Visser, R., Acuna, M. & Morgenroth, J. 2015. Automatic GNSS-enabled harvester data collection as a tool to evaluate factors affecting harvester productivity in a Eucalyptus spp. harvesting operation in Uruguay.

Perry, J.P. 1991. *The Pines of Mexico and Central America*. 1st ed. Portland: Timber Press, Inc.

Purfürst, F.T. 2010. Learning curves of harvester operators. *Croatian Journal of Forest Engineering*. 31(2):89–97. [Online], Available: file:///C:/Users/17621194/Downloads/02_purfuerst.pdf [2019, January 17].

Purfürst, F.T. & Erler, J. 2011. The Human Influence on Productivity in Harvester Operations. *International Journal of Forest Engineering*. 22(2):15–22.

Ramantswana, M., McEwan, A. & Pauw, J. 2012. Determining the effect of tree size, bark-wood bond strength and tree form on the productivity of an excavator-based harvester in Acacia mearnsii in the KwaZulu-Natal forestry region of South Africa. *Southern Forests*. 74(3):151–157.

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*. 75(4):239–246.

Rasband, W.S. 2002. [Online], Available: http://imagej.nih.gov/ij/.

Roth, G. 2016. StanForD as a data source for forest management : a forest stand reconciliation implementation case study. University of Canterbury.

Saathof, D.A. 2014. An Investigation of the Measurement Accuracy and Productivity of a Waratah HTH 625c Processor Head. University of Canterbury.

Samsung. 2018. *Galaxy J5/J7 2017: What is new with the Camera in the device?* [Online], Available: https://www.samsung.com/za/support/mobile-devices/galaxy-j5-j7-2017-what-is-new-with-the-camera-in-the-device/ [2019, March 15].

Sands, R. 1975. Radiata pine bark - aspects of morphology, anatomy and chemistry. *New Zealand Journal of Forestry Science*. 5(1):74–86. [Online], Available: https://www.scionresearch.com/__data/assets/pdf_file/0014/31028/NZJFS51975SANDS74_86.pdf [2019, August 01].

Skogforsk. 2010. *StanForD 2010 – modern communication with forest machines*. Uppsala.

Skogforsk. 2012. *Standard for Forest Data and Communication*. Uppsala.

Staengle, S.M., Weiskittel, A.R., Dormann, C.F. & Bruechert, F. 2016. Measurement and prediction of bark thickness in Picea abies: assessment of accuracy, precision, and sample size requirements. *Canadian Journal of Forest Research*. 46(1):39–47.

“Statistica”. 2018. [Online], Available: http://tibco.com.

Steenkamp, J. 2007. THE EFFECT OF HIV AND AIDS ON THE VIABILITY AND MANAGEMENT OF FORESTRY CONTRACTING BUSINESSES IN SOUTH AFRICA. Nelson Manedela Metropolitan University.

Stendahl, J. & Dahlin, B. 2002. Possibilities for Harvester-based Forest Inventory in Thinnings. *Scandinavian Journal of Forest Research*. 17(6):548–555.

Strandgard, M. 2008. Best practice harvester calibration. 2:3. [Online], Available: https://docs.google.com/folderview?pli=1&id=0B7Ng9CzHbCSQUy03V0VtOXBKRXc#list.

Strandgard, M. 2009. Evaluation of Manual Log Measurement Errors and Its Implications on Harvester Log Measurement Accuracy. *International Journal of Forest Engineering*. 20(2):9–16.

Strandgard, M. & Walsh, D. 2011. Improving harvester estimates of bark thickness for radiata pine (Pinus radiata D.Don). *Southern Forests*. 73(2):101–108.

Strandgard, M. & Walsh, D. 2012a. *Assessing measurement accuracy of harvester heads in Australian pine plantation operations*. Hobart, Tasmania.

Strandgard, M. & Walsh, D. 2012b. *Maintaining harvester measurement accuracy to maximise value recovery*. Hobart, Tasmania.

Strandgard, M., Walsh, D. & Acuna, M. 2013. Estimating harvester productivity in Pinus radiata plantations using StanForD stem files. *Scandinavian Journal of Forest Research*. 28(1):73–80.

Uusitalo, J. 2010. *Introduction to Forest operations and Technology*. Tampere, Finland: Tampere, Finland : JVP Forest Systems.

Vermaak, J.A. 2007. Genetic variation for growth , wood and fibre properties of Pinus patula families grown on six sites in South Africa. University of Stellenbosch.

Vidakovic, M. 1991. *Conifers: morphology and variation*. Zagreb, Yugoslavia: Grafičko Zavod Hrvatske.

Wenhold, R.M. 2017. Skills development of mechanised softwood sawtimber cut- to-length harvester operators on the Highveld of South Africa. University of Stellenbosch.

Williams, C. & Ackerman, P. 2016. Cost-productivity analysis of South African pine sawtimber mechanised cut-to-length harvesting. *Southern Forests*. 78(4):267–274.