Harvesting and operations

Technical Report 225

# Assessing measurement accuracy of harvester heads in Australian pine plantations

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CRC for Forestry

Researching sustainable forest landscapes

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## Assessing measurement accuracy of harvester heads in Australian pine plantation operations

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Public report

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## Executive Summary

Incorrect harvester log length measurements are the main cause of non-quality related log rejections by customers. Log length measurement errors result from the harvester measurement wheel slipping or losing contact with the stem and, thus, are more frequent when branching is heavy and the bark is easily detached from the stem. The main sources of harvester diameter measurement errors in Australian radiata pine plantations are stem out-of-roundness and bark thickness estimation errors. Systematic harvester length or diameter measurement errors can be reduced by regular calibration of the harvester head.

There are no universal standards for harvester measurement accuracy, although two Swedish standards (at least 90% of sawlogs in the "Best-5" adjacent 1 cm length classes and at least 90% of sawlog small end diameters (SEDs) within ±4 mm of manual measurements) have been used in a number of studies. Australian harvesters in radiata pine plantations performed poorly against these standards, although the Australian results were comparable to results from overseas studies. However, most sawlogs in the Australian studies met customer specifications for sawlog length and SED. This reflects the ±5 cm tolerance allowed for harvester length measurements and the fact that the minimum allowable SED is only relevant to the minority of logs. There is also evidence that harvesters, both in Australia and overseas, have been set to measure conservatively, (i.e. biased towards larger length and diameter measurements). This approach reduces the risk of logs being rejected by customers at the cost of increased volume and value losses.

Harvester log measurement inaccuracies can reduce value recovery by causing:

- optimisers to make incorrect decisions about which products to cut
- downgrading or docking of logs that do not meet customer specifications.

In Australian radiata pine harvesting, the emphasis has been on addressing the latter issue because few forest growers have implemented bucking optimisation, although many are considering its implementation. The wider implementation of optimisation would require consideration of mechanisms to improve harvester measurement accuracy, particularly diameter measurement accuracy, as this is critical to correctly predicting the price category each log falls into and, thus, the optimum value log combination for each stem.

## *Introduction*

In order to improve worker safety and productivity, there has been a worldwide shift from manual log bucking to mechanical harvesting (Murphy *et al.*, 2004). Errors in harvest machine measurements can significantly reduce value recovery through poor selection of product combinations from each stem. Logs outside size specification may also need to be downgraded to lower value products, or docked, resulting in further losses (Murphy *et al.*, 2005). Murphy (2003) reported average value losses of 20% from 39 mechanised harvesting operations, with the worst performing operation losing 68% of potential value.

Estimating harvester measurement accuracy requires knowledge of the true stem dimensions. However, uncertainty is always present in log measurements. The literature generally assumes manual log measurement values to be the true measurements (or significantly closer to them than the machine measurements) (Andersson and Dyson, 2002; Murphy *et al.* 2005). However, until errors associated with manual measurements are known, differences between manual and machine measurements cannot be assumed to be solely due to errors in machine readings.

The objectives of this report are:

- to quantify typical levels of uncertainty present in forest harvester measurements of length, diameter and bark thickness, under field conditions in Australian radiata pine plantations
- to draw conclusions about the likely impact of machine and manual measurement errors on value recovery.

Logs are primarily classified on the basis of their length and diameter; this report examines errors in these measurements. Although often used in conjunction with dimensions to specify log products, stem quality and form are not explicitly covered in this report, except where they influence length and diameter measurements.

# Measurement Error Sources

Errors in the measurement of log dimensions can result from instrument limitations, inaccuracies in the measurement process and human errors. Although potentially significant (e.g. Melson *et al.*, 2002), human errors, such as misreading an instrument scale or incorrectly entering data, are not covered in this report.

## *Length Measurement*

### *Harvester length measurement*

Forest growers and harvest contractors often place greater emphasis on achieving harvester length measurement accuracy than diameter accuracy, as incorrect log length is the most common cause of non-quality related log rejection. This is because length accuracy is important for every log, whereas diameter accuracy is only critical for logs whose diameters are close to minimum or maximum diameter limits. Murphy *et al.* (2005) reported that 41% of the log rejections in their study were due to incorrect length, whereas only 20% were rejected because of incorrect diameter.

Harvesting heads measure length by using an encoder, usually driven by a toothed wheel or, less commonly, by the feed rollers (Figure 1) (Andersson and Dyson, 2002; Uusitalo, 2010). The toothed wheel is pressed against the stem by a spring or hydraulic arm. The encoder generates a fixed number of pulses for each revolution of the wheel or roller. The measuring wheel's resolution is commonly about 0.5 cm/pulse, which suggests a maximum accuracy of 1 cm (Makkonen, 2001).

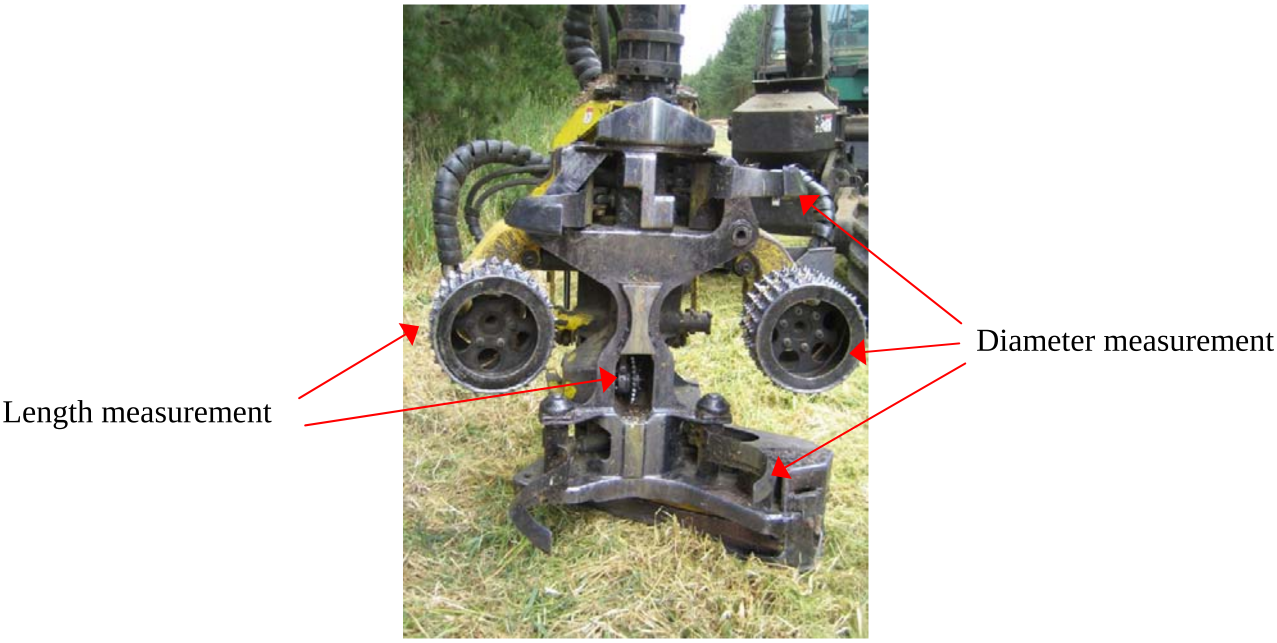


**Figure 1.** Single-grip harvester head showing length and diameter measurement sensor locations

Inaccuracy in harvester length measurement can result from the measurement wheel slipping or losing contact with the stem. Feed rollers are particularly prone to slippage and, thus, are less commonly used for length measurement. Knots and other form defects on the stem can lead to overestimation of length, as the sensors have to travel further over the defect (Makkonen, 2001). Larger diameter wheels are less prone to errors caused by defects (Makkonen, 2001).

Reduced length measurement accuracy has been associated with heavy branching (Plamondon, 1999; Nieuwenhuis and Dooley, 2006) and loose or easily detached bark. The increased errors result from the harvester losing its position on the stem during repeated delimbing passes or losing stem contact. Andersson and Dyson (2002) reported that, occasionally, operators miss the end of the stem, resulting in inaccurate length measurements. Photocells are used in some cases to identify the stem end but these can be damaged and are often obscured by dirt and sawdust. Operators can also reset the length measurement by cutting a narrow disc from the stem end. Cutting a larger disc than required can also occur, potentially reducing value recovery.

Mechanical harvester head sensors are exposed to damage during stem processing. For example, length measurement wheels can be clogged by bark and debris (Myhrman, 2000). The wheels can also be damaged if hit by the stem or by the stem twisting against them (Myhrman, 2000).

Systematic errors in length measurement can be reduced by calibrating harvester length measurements against manual length measurements of the same logs. Although regular calibration has been shown to improve log length measurement accuracy (Nieuwenhuis and Dooley, 2006), Andersson and Dyson (2002) found the most effective overall strategy to ensure length measurement accuracy was quality control procedures to detect and remedy measurement errors at an early stage through calibration or maintenance (statistical process control).

Non-contact length (and diameter) measurement approaches, such as 3D laser scanning and machine-vision (Miettinen et al., 2010), are being tested to overcome some of the limitations of existing approaches. No non-contact methods are currently in use on production harvesters.

There is no universally accepted standard for harvester length measurement accuracy. Two measures that have been used in published studies are:

- Sweden's "Best-5" standard. This is the percentage of sawlogs within the five adjacent 1 cm error classes with the highest number of logs (Figure 2). The desired minimum is 90% of sawlogs in the five classes. Andersson and Dyson (2002) suggested that the "Best-10" (ten adjacent 1 cm classes with the most logs) would be a more appropriate measure in Canada.
- the proportion of sawlogs that meet customer specifications, although variations in customer tolerances can make comparisons difficult.

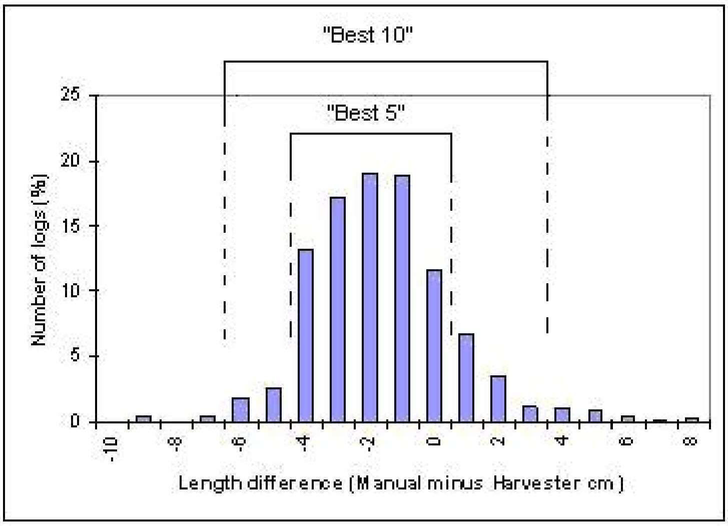


**Figure 2.** Example of the "Best-5" and "Best-10" length classes

A number of overseas studies have found significant errors in harvester length measurements (compared with manual measurements). None of five new single-grip harvesters tested in Sweden was able to achieve 90% of logs in the "Best-5" (Sondell *et al.* 2002). Similarly, only one of 83 harvesters in a trial in western Canada achieved a "Best-5" score of 90%. However, 48 of the harvesters in the Canadian trial achieved 90% or more of their sawlogs in the "Best-10" (Andersson and Dyson 2002).

A greater proportion of the tested harvesters was able to achieve customer length specifications. Andersson and Dyson (2002) reported that, of 83 harvesters tested, 23 cut 95% of sawlogs to customer requirements (typically ±5 cm length tolerance) and 41 harvesters cut 90%. Evanson (1995) reported that, of six harvesters working in

New Zealand radiata pine clearfell operations, four achieved 90% of their sawlogs meeting customer specifications. The two poorer performing harvesters had customer length tolerance specifications of ±3 cm, whereas the remainder were ±5 cm.

There is little information available for harvester length measurement performance in Australian pine plantations. Unpublished studies of three harvesters in South Australia and one in Western Australia found that only one of the four harvesters was able to achieve at least 90% of sawlogs in the “Best-5”. This machine was performing a second thinning and it is unknown if the good result was caused by the tree or machine characteristics. All four harvesters achieved at least 90% of sawlogs in the “Best-10”.

The harvesters achieved better results meeting customer length requirements (±5 cm length tolerance) in the Australian studies, with three of the four harvesters meeting the requirements for at least 90% of the sawlogs they cut. The other harvester cut more than 80% of sawlogs within customer length requirements.

Modern sawmill scanners provide another means of testing harvester length measurement accuracy. Typically, they estimate log length from the log speed and the interruption of a laser beam, to determine the beginning and end of the log. An analysis of sawmill scanner length measurements from over 14 000 sawlogs, cut by 11 harvesters in New South Wales (NSW) radiata pine plantations, found over 90% met customer length measurement requirements. A similar study of 2500 sawlogs from South Australian radiata pine plantations found that 88% met customer length measurement requirements. In both cases, harvesters appear to have been set to cut logs slightly longer (1–2 cm) than the nominal log length. This was probably done to reduce the frequency of logs being rejected by customers for being too short.

#### *Manual length measurement*

Log length is usually measured manually with a tape measure. Tape measures generally have a smallest scale unit of 1 millimetre. The process of using manual length measurements to assess harvester measurement accuracy implicitly assumes that logs are regular in shape. However, in reality, stem irregularity and poor use of the tape measure can be potential sources of errors (Table 1) that may then be ascribed to the harvester.

**Table 1.** Manual log length measurement error sources

| Error source | Effect on measurement (relative to harvester measurement) |
|---|---|
| Logs sawn off-square | Overestimation of length |
| Insufficient tape tension | |
| Tape at angle to stem axis | |
| Tape running over branch stubs and bumps | |
| Metal tape temperature less than 20 ºC * | |
| Stretched tape measure | Underestimation of length |
| Metal tape temperature greater than 20 ºC * | |
| Sweep (stem curvature) | |

*Length of metal tape measures is standardised at 20 ºC

The potential impact of most of these error sources is estimated to be quite low if careful length measurement procedures are followed (Strandgard 2009). The exception is when large butt logs have not been crosscut perpendicular to the centre line of the log, which can cause length differences of over 80 mm between different faces of the log. To address this, manual log length measurements should be made on the same face as that measured by the harvester, if possible. This side can generally be identified by the marks made by the teeth of the length measurement wheel (Strandgard 2009).

### *Diameter Measurement*

Assessment of diameter measurement accuracy assumes that stem cross-sections are circular or, if not, that harvester and manual measurement methods are comparable. However, harvesters measure diameter using three contact points, which cannot be reproduced by any manual measurement method. This may result in differences between manual and harvester diameter measurements, caused by stem out-of-roundness (eccentricity or ovality) being classified as harvester measurement errors.

#### *Harvester diameter measurement*

Harvesters estimate stem diameter using pulse encoders or potentiometers that measure the deflection of the feed rollers or delimbing knives (Figure 1) on the harvesting head as the stem is processed (Andersson and Dyson, 2002; Makkonen, 2001; Uusitalo, 2010). Harvesting heads contact the stem at three points—two movable and one fixed (Figure 3). Some machines measure the deflection of each movable side independently and average the measurements to remove some effects of stem eccentricity.

**Figure 3.** Cross-section of an eccentric stem being gripped at three points by a harvesting head (Uusitalo, 2010)

In order to obtain an accurate estimate of diameter, the feed rollers or delimbing knives that the diameter sensors are attached to need to be pressed against the stem with sufficient pressure to maintain contact (Myhrman, 2000). The degree of pressure can vary with time and use, or be varied by the machine in response to changes in stem diameter or by the operator. Certain bark types can be compressed by this pressure, leading to underestimation of diameter. Teeth on feed rollers can be driven through the bark into the wood. Feed rollers can also strip the bark from the log, potentially leading to diameter measurement errors if the log is fed repeatedly through the harvesting head.

Knots and other form defects on the stem can lead to overestimation of diameter as the feed rollers or delimbing knives are deflected by the defect (Makkonen, 2001). However, most harvesters filter diameter measurements by averaging measurements every 10 cm along the stem, and by rejecting diameter measurements where the diameter has increased towards the tree tip (Peltola *et al.*, 2011). This could lead to discrepancies between harvester and manual diameter measurements if the filtered harvester diameter measurement is compared with a manual measurement taken over the defect.

Systematic errors in length are a fixed proportion, regardless of log length. However, systematic errors in diameter can vary across the diameter range, (i.e. each diameter can have a different systematic error). To address this, most harvester manufacturers recommend calibrating against manual measurements across the full range of diameters encountered at a site, making diameter calibration more complicated than length calibration.

There is no universal standard for harvester diameter measurement accuracy. The Swedish standard is to achieve a minimum of 90% of logs within ±4 mm of manual measurements. Andersson and Dyson (2002) reported diameter measurement accuracy against ±2 mm (common sawmill accuracy standard), ±4 mm and ±8 mm. In

Australia, harvester diameter measurement accuracy is only routinely checked at minimum and maximum diameter limits. Diameter accuracy tolerance is ±0.5 mm (*pers. comm.* ForestrySA staff).

International studies of harvester diameter measurement accuracy have found it to be poor, compared with manual measurements. Sondell *et al.* (2002) reported that none of the five harvesters in their study was able to meet the Swedish standard for diameter accuracy (average performance was 64% of logs within ±4 mm), although they noted that accuracy had improved by 12% from an earlier trial. The worst performers were those using feed rollers to measure diameter. Subsequent diameter calibration substantially improved diameter accuracy measurement in all but one case. Table 2 presents the overall results for the 31 harvesters checked for diameter measurement accuracy in the study by Andersson and Dyson (2002).

**Table 2.** Percentage of harvester diameter measurements within ±2 mm, ±4 mm, and ±8 mm of manual measurements

| Tolerance | Andersson and Dyson (2002) | ForestrySA harvesters | | | Western Australian harvester |
|---|---|---|---|---|---|
| | | 1 | 2 | 3 | |
| ±2 mm | 19% | 50% | 11% | 16% | 14% |
| ±4 mm | 34% | 77% | 20% | 26% | 22% |
| ±8 mm | 57% | 95% | 39% | 50% | 35% |

Andersson and Dyson (2002) suggested that if the relationship between manual and harvester diameter measurement *differences* and harvester diameter *measurements* was statistically significant, it would indicate that the harvester may have benefited from diameter calibration. Applying this procedure showed 23 of the 31 harvesters checked for diameter accuracy in their study should have been calibrated. Correcting the harvester diameter measurements using these relationships suggested calibration would have increased the number of logs within ±2 mm of manual measurements, from 19% to 33%, and within ±4 mm, from 34% to 55%.

Unpublished studies of the diameter measurement accuracy of four harvesters in South Australian and Western Australian radiata pine plantations found none was able to achieve the Swedish standard (Table 2). The aforementioned procedure used by Andersson and Dyson (2002) showed a potential improvement for two of the four harvesters.

*Manual diameter measurement*

The choice of diameter measurement instrument (diameter tape or callipers) can significantly affect manual diameter measurements, primarily because tree stems are rarely circular in cross-section (Biging and Wensel, 1988). Diameter tapes estimate diameter from circumference, assuming the tree stem to be circular. A circle has the smallest circumference for a given area, thus, any deviation from circular in a stem results in diameter tapes overestimating both diameter and cross-sectional area (Clark *et al.*, 2000). Callipers only measure on one axis, thus, single measurements can overestimate or underestimate non-circular stem diameters (Clark *et al.*, 2000). Averaging two calliper measurements taken at right angles to each other will reduce the degree of the error (Chacko, 1961).

McArdle (1928) found that diameter tape measurements were more precise than calliper measurements, by having two people make repeated measurements of diameter at marked breast height points with these two instruments. In the light of these differences, Gregoire *et al.* (1990) cautioned against changing instruments when remeasuring tree diameter.

Pressure applied to the stem with callipers can cause a significant underestimation of the diameter, depending on the operator and the bark properties (Loetsch *et al.* 1973). Wear or damage can cause the moveable arm of a set of callipers to be no longer perpendicular to the scale, resulting in underestimation of diameter (Loetsch *et al.*, 1973). A deviation of 1 ° can result in a 1% underestimation of diameter.

## *Bark Thickness Measurement*

### *Harvester bark thickness estimation*

Log specifications are generally expressed in terms of underbark diameter (James, 2001), which requires harvesters to estimate bark thickness in order to estimate underbark diameter (DUB) from overbark diameter (DOB) measurements. DUB is then used by the harvester's onboard computer (OBC) to estimate log volume and value cut by product for the stand and as an input to optimisation decisions. Errors in bark thickness estimation can result in significant errors in DUB estimation, in turn leading to value losses (Marshall, 2006).

Bark thickness is estimated by the harvester's OBC using a bark thickness model. Most modern harvesters estimate bark thickness using the four built-in StanForD models (Skogforsk, 2007). Two StanForD models allow user input; the others apply to species commercially insignificant in Australia (Scots pine and Norway spruce). The model developed by Zacco (1974) is probably the most suitable for radiata pine and is the only function known to be used in Australia:

$$dbt = b_0 + b_1 * \mathrm{DOB} \qquad \text{(Eq. 1)}$$

where:

$b_0$ and $b_1$ = user-defined coefficients
dbt = double bark thickness (mm)
DOB = diameter over bark (mm)

Strandgard and Walsh (2011) found that, on mature trees, this model underestimates radiata pine bark thickness on the lower trunk and overestimates it on the upper trunk. This is caused by the equation modelling bark thickness as a constant proportion of DOB, whereas radiata pine provenances grown from seed in Australia have thicker bark on the lower stem when mature. The best solution would be to introduce another bark thickness model that more accurately models Australian radiata pine bark thickness.

As bark thickness is modelled rather than measured, errors in DOB measurements could potentially affect the accuracy of bark thickness estimates. However, Strandgard and Walsh (2011) found this source of error to be insignificant in practice in radiata pine plantations.

### *Manual bark thickness measurement*

Bark thickness is generally measured manually using a narrow, pointed bark gauge to penetrate the bark through to the wood. Bark gauges are notoriously difficult to use, particularly in judging when they have completely penetrated the bark. Gauges can be driven a short distance into sapwood, therefore overestimating bark thickness (Gordon, 1983). As bark thickness can vary around the trunk, Avery and Burkhart (1983) suggested taking two measurements at each point to reduce the effect of bark thickness variability.

Gordon (1983) found that bark thickness measurement errors increased with increasing bark thickness and operator inexperience. Strandgard and Walsh (2011) reported that analysis of bark thickness measurements made by two observers of the same log small ends found measurement differences were mainly between ±2 mm, although a small number were larger. Using a single, experienced operator and taking multiple measurements around the stem at each measurement point would minimise these errors.

## Value Recovery

The theoretical maximum value recovery for a stand is achieved rarely, if ever, due to market constraints and losses from damage and measurement errors. Murphy (2003) reported that value losses from all sources ranged from 1% to 68% in 39 mechanised harvesting operations.

Harvester log measurement inaccuracies can reduce value recovery by causing:

- optimisers to make incorrect decisions about which products to cut
- downgrading or docking of logs that do not meet customer specifications.

Diameter measurement inaccuracy has been found to have a greater impact on value recovery than length measurement inaccuracy (Marshall, 2005; Chiorescu and Gronlund, 2001). Under-measurement of length and diameter has a greater impact on value recovery than over-measurement, as under-diameter logs can fall into a lower price category and under-length logs may need to be docked to the next acceptable size. The greater value loss for under-measurement of log dimensions can result in harvesters being adjusted to cut logs slightly over length and diameter specifications, to minimise the number of rejected logs. This effect was apparent in the sawmill scanner length measurements from South Australia and New South Wales (refer 'Harvester length measurement' section). Boston and Murphy (2003) reported similar results for both length and diameter in a final harvest operation in the south-eastern United States.

The impact of harvester log length and diameter measurement inaccuracies on value recovery is dependent on:

- the magnitude of the length and diameter measurement errors
- the specified log product dimensions, tolerances and price categories.

The second point makes it difficult to draw general conclusions about the impact of harvester measurement inaccuracy on value recovery, because the same errors applied to different product mixes could produce very different value recovery outcomes. For example, value losses from docking under-length logs will be less if there are smaller length gaps between adjacent log length classes. Smaller differences between log price categories will have a similar effect on the impact of harvester measurement errors on value recovery, because they will reduce the value difference between the optimum and near-optimum solutions. Published examples of value losses from log measurement inaccuracy show they range from less than 2% (Conradie et al., 2003) to over 40% (Boston and Murphy, 2003).

## Discussion

From the limited number of harvester log measurement accuracy studies available, it appears that harvesters overseas and in radiata pine plantations in Australia rarely meet Swedish standards for harvester length measurement accuracy (at least 90% in "Best-5") and diameter measurement accuracy (at least 90% within ±4 mm). The Australian harvesters were better able to meet customer log specifications. This was due, in part, to customer log length specifications including a tolerance (typically ±5cm). Diameter measurement accuracy is less critical for customer acceptance as it mainly applies to small end diameter limits, which affect a minority of logs.

The current low standard of log measurement accuracy in radiata pine plantations in Australia reflects the general lack of use of bucking optimisation in Australia. Levels of measurement accuracy are targeted at achieving a high level of logs meeting customer length and minimum small end diameter specifications. There does not appear to be any consistent method of process control or a standard calibration procedure employed across the country to ensure accurate measurements by harvesters. In many cases, the correction of measurement errors appears to occur as a reaction to customer complaints rather than as part of normal work practices.

For optimisation to be successfully implemented in Australian radiata pine plantations, an improvement is needed in harvester log measurement accuracy—particularly diameter measurement accuracy—and, therefore, also bark thickness prediction. This is because log SEDs are generally used to determine radiata pine log price categories and are, therefore, critical to the optimiser making correct decisions. In order to achieve this improvement in harvester log measurement accuracy, harvest contractors' standard procedures need to incorporate the regular checking of measurement accuracy and the correction of any problems found, through calibration and maintenance. This may also include checks of harvester log measurement accuracy by the forest grower or by an external agency. The StanForD data standard (Skogforsk, 2007), used by most harvesters, has the ability to randomly select trees to be measured manually by both the operator and the harvester, to monitor harvester measurement accuracy. This feature has been incorporated into quality assurance schemes in Scandinavia and Germany. A similar scheme could be established in Australia.

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