Original scientific paper

Impact of Slope on Productivity of a Self-levelling Processor

Martin Strandgard, Muhammad Alam, Rick Mitchell

Abstract

Slope is a major factor affecting forest harvesting machine productivity. As ground-based harvesting methods are generally cheaper than the alternatives, forest managers need to know when ground-based harvesting equipment can be used on sloping sites.

The study objective was to determine the effect of slope on the productivity, cycle time and elemental times of a Valmet 450 FXL self-levelling processor processing a 24 year-old, unthinned radiata pine plantation previously felled and stacked by a feller-buncher. The study site slope was estimated using a LiDAR (Light Detection and Ranging) derived digital terrain model and classified using the regional terrain classification system. Study trees were selected from areas predominantly in the hilly (12–19°) and steep (20–26°) slope classes, as these classes made up the majority of the study site area.

In contrast to previous research, no significant differences were found between the processor productivity, cycle time and elemental times (moving/positioning, swinging and processing) between the slope classes. This was believed to result from the processor working well within its capabilities processing the relatively small trees on the study site. Other important factors may have included that the trees were pre-felled by a feller-buncher and placed in high density rows with their butt ends aligned, which minimised the processor boom and track movements, and that steep slope trees were selected from areas at the lower end of the steep slope class (20–23°). Further research is needed to determine whether the processor productivity would be significantly lower when processing larger trees on steeper slopes.

Keywords: self-levelling, processor, slope, productivity, radiata pine, LiDAR, Australia

1. Introduction

Single-grip harvester productivity is affected by many factors related to stand (tree size, form and spacing), terrain (slope, ground strength and roughness), machine (type, size, boom reach, etc) and operator (experience, technique and attitude) characteristics. Tree size has been shown in numerous studies to be the most important factor affecting harvester productivity, with productivity increasing with increasing tree size (Kellogg and Bettinger 1994, Acuna and Kellogg 2009, Visser and Spinelli 2012, Ghaffariyan et al. 2012). Operator performance is the other major factor in determining harvester productivity. Variability in productivity between skilled operators can be over 40% (Kärhä et al. 2004, Ovaskainen et al. 2004, Hogg et al. 2011).

Of the other factors affecting harvester productivity, slope has an important role in both the selection and productivity of harvesting equipment, as it is a major determinant of machine travel speed and stability (Davis and Reisinger 1990). Given good soil conditions, tracked harvesters with self-levelling cabins can operate on slopes up to 60% (31°), whereas specialised steep slope harvesters (such as the Komatsu 911.3 X3M) or cable-tethered harvesters can operate on slopes up to 70% (35°) (Stampfer and Steinmüller 2001) (wheeled harvesters are restricted to less steep slopes). However, in practice harvester slope constraints are generally set lower to maintain safety and reduce soil damage (MacDonald 1999, Sutherland 2012). On steeper slopes (>35°) or with poorer soil conditions, other, more expensive harvesting methods, such as cable-harvesting, must be used. As ground-based harvesting systems can generally deliver logs more cheaply to roadside than the alternatives, forest owners aim to maximise the use of ground-based equipment in steep terrain (Fight et al. 2006). In order to determine when it is both technically feasible and cheaper to use ground-based harvesting equipment, more research into its performance on steep slopes is required.

Harvesters in *Pinus radiata* (radiata pine) ground-based harvesting operations, either fell and process trees at the stump or process trees felled and stacked by a feller-buncher. The latter approach is typically used on sites where trees need to be extracted from steeper sections and stream reserves to minimise or eliminate machine movements in these areas (Spinelli et al. 2002). Differences in the type and relative duration of the activities performed by a harvester in these two roles may affect the impact of slope on its productivity. Evanson and McConchie (1996) reported that a harvester processing radiata pine at roadside was considerably more productive than when felling and processing trees in the stand because of the time saved not felling trees. Previous research on the impact of slope on harvester productivity has largely focused on machines harvesting rather than processing. A number of trials of both thinning and clearfell harvesting operations have reported that increasing slope decreases harvester productivity. However, Stampfer (1999) found that only the harvester movement was significantly affected by slope, whereas Bolding and Lanford (2002) found slope also affected tree swing time and Spinelli et al. (2010) found that it also affected felling and processing times. Acuna and Kellogg (2009) found increasing slope significantly decreased the productivity of a harvester processing trees felled by a feller-buncher because the processor spent more time positioning the machine and ensuring the logs were piled correctly when operating on steep slopes. In contrast to these findings, Robert et al. (2013) reported that slope had no impact on the productivity of a Komatsu 911.3 X3M steep slope harvester operating on slopes from less than 20° to over 27°.

Assessing the slope experienced by an operating harvester is difficult. Traditionally, the slope of study sites has been estimated using a clinometer, though this approach is limited to measuring the slope between a small number of points. Recently, LiDAR (Light Detection and Ranging) has become more commonly used to estimate slope for harvest planning as it can provide accurate »wall-to-wall« slope maps of a harvesting area (Sessions et al. 2006). However, Berkett and Visser (2013) suggest that the actual slope experienced by a harvesting machine can vary significantly from that predicted from digital slope maps, though this may depend on the resolution of the digital map.

The objective of this study was to compare the productivity, cycle time and elemental times of a self-levelling processor processing trees felled by a feller-buncher when operating on 12–19° slopes and on 20–26° slopes. The hypothesis was that the processor productivity would be significantly lower and its cycle times and elemental times significantly longer when operating on 20–26° slopes compared with when it was operating on 12–19° slopes.

2. Materials and Methods

2.1 Study site

The study was located approximately 6 km west of Port Arthur, Tasmania, Australia. The study site was an area of approximately 1 ha within a radiata pine plantation being clearfelled for pulp wood production (Table 1).

Diameter at breast height (1.3 m) over bark (DBHOB) of all trees on the site was measured with a diameter tape to the nearest 0.1 cm. The heights of 100 trees spread across the site and covering the range of DBHOB values at the site were measured with a Vertex hypsometer and Impulse 200 laser to the nearest

Table 1 Description of study site

Attribute	Value
Species	Pinus radiata
Plantation age at harvest, years	24
Tree form	Good
Branchiness	Light branching
Merchantable stocking, trees/ha	1,057
Thinning	Unthinned
Undergrowth	None
Soil composition	Clay loam
Ground strength	Moderate
Ground roughness	Even with scattered small rocks
Mean slope range, degrees	21 (18–25)
Mean tree height range, m	26.1 (15.8–37.0)
Mean DBHOB range, cm	29.0 (10.3–61.0)
Mean merchantable tree volume range, m^3	0.63 (0.04–3.47)

0.1 m. An individual tree volume function supplied by the forest owner (Norske Skog Australasia) was used to estimate the merchantable volume of each tree. Merchantable tree volume is referred to as tree volume in the paper. A unique number was painted on each tree to identify it during the study. Tree measurements are summarised in Table 1.

2.2 Slope derivation

The slope over the study site was derived from LiDAR data supplied by Forestry Tasmania, Australia with the following specifications (Table 2).

Table 2 LiDAR parameters and scanning system settings

LiDAR attribute	Value
Date of flight	25 May 2011
System	ALTM (Airborne Laser Terrain Mapping) Gemini
Beam divergence, milliradian	0.20
Footprint diameter, cm	20
Laser mode	Single pulse
Pulse return density range, m^{-2}	>3 (1st, 2nd, 3rd and last) (2.3–3.2)
Horizontal accuracy, m	0.15
Vertical accuracy, m	0.15
Pulse rate frequency, kHz	70

LiDAR data were supplied in .LAS format and were classified into ground and non-ground points. LiDAR data accuracy was verified by the data provider.

Slope was derived from a digital terrain model with a 2 m cell size constructed from the ground LiDAR points. The slope of the study site was classified into Flat-rolling = 0–11°, Hilly = 12–19°, Steep = 20–26°, Very Steep = >27° slope classes using the Tasmanian Forest Practices Code terrain slope classification (Forest Practices Board 2000), which is applicable to all Tasmanian timber production forests (Fig. 1).

2.3 Time and motion study

The harvesting system consisted of a feller-buncher, a processor and a forwarder. Immediately prior to the processor study, the feller-buncher felled the trees on the study site and placed each tree across the slope with their butts aligned to form rows of felled trees running

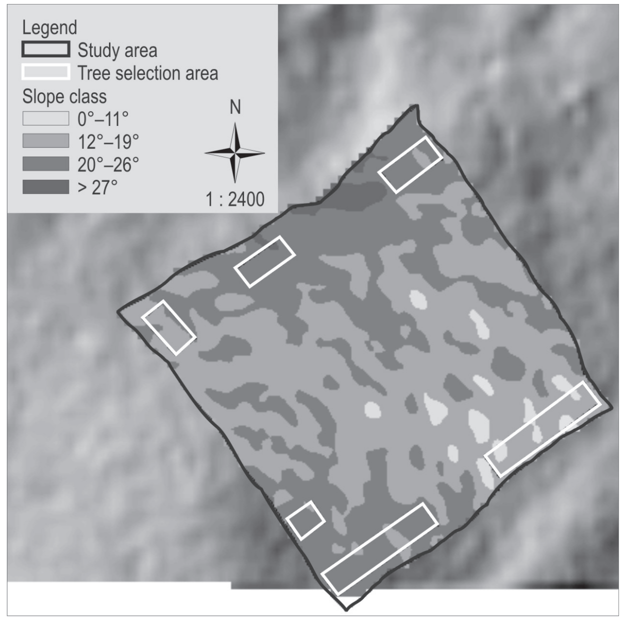

Fig. 1 Processor study area showing slope classes and tree selection areas

up and down the slope (Alam et al. 2013). The processor used in the study was a Valmet 450 FXL self-levelling processor with a 224 kW engine manufactured in 2010 with 2,408 engine hours. It was equipped with a Southstar 585 felling and processing head. The operator had four years experience in operating processors.

The processor worked uphill processing felled trees on the right of the processor to logs (predominantly 5.4 m in length with a minimum small end diameter of 100 mm) piled to the left. At the completion of each strip of felled trees, the processor travelled down the slope to commence the next strip. Processing took place from the fourth to the sixth of April 2011 in overcast conditions and was filmed using a digital video recorder. Cycle time commenced when the processor or boom started to move towards a felled tree and ended when the processor had completed processing the tree and was about to move to the next felled tree. Cycles were divided into the following time elements: moving/positioning, swinging, processing, stacking/bunching, brushing/clearing and delays (Table 3). Elemental times were recorded from the video recordings using TimerPro Professional software (www.acsco.com). The time elements stacking/bunching, brushing/clearing, travel and delays were excluded from the analysis as they occurred infrequently and were unrelated to tree volume and slope.

Trees used in the study were selected from sections of the site which were predominantly in the 12–19° or

Table 3 Description of processor time elements

Time element	Definition
Moving/positioning	Starts when the processor begins to move and/or swing its boom towards a felled tree and ends when the head clamps onto the tree
Swinging	Starts when head clamps onto a felled tree and ends when feed rollers are activated, or the first cut is made to reset the processor length measurement (whichever occurs first)
Processing	Starts when feed rollers are activated, or the first cut is made to reset the processor length measurement (whichever occurs first) and ends when the last log is cut and dropped on the log pile
Brushing/Clearing	Any interruption to other elements to remove unmerchantable trees or clear processing debris
Travel	Time taken to turn around to start new stack or move to and from break. Starts when wheels/tracks begin to rotate. Ends when boom begins its swing towards first tree on new stack
Stacking/Bunching	Starts when the boom commences a swing to retrieve move or »stack« any processed logs. Ends when the boom moves to perform some other activity
Delay	Any interruption to the previous time elements. The cause of the delay (e.g. operational, personal, mechanical, or study induced) is recorded

20–26° slope classes as these slope classes accounted for the majority of the study site area (Fig. 1). To improve the representativeness of the sample, trees were selected from several sections in each slope class and across all three days of the trial. Trees were excluded from the study when the tree number could not be identified during processing or the tree had multiple leaders and each leader was processed separately. Seventy trees were selected for analysis in the 12–19° slope class and sixty-nine in the 20–26° slope class. Trees in the >27° slope class had been moved by the feller-buncher to adjacent, less steep areas.

2.4 Data analysis

Regression models were developed for each slope class for processor cycle time against tree volume, for moving/positioning, swinging and processing times against tree volume and for processor productivity against tree volume using Microsoft Excel 2007 and Minitab 16 Ltd. Various model forms and variable transformations were tested to identify models with the best goodness of fit (R^2, root mean square error (RMSE), and mean absolute error (MAE) which also achieved homogeneity of variance of the residuals. To determine whether processor cycle time, elemental times or processor productivity differed between slope classes, the best-fit models for each slope class were compared using an F-test (p<0.05) (Motulsky and Christopoulos 2003) if the models were significant or with a Mann-Whitney test ($p < 0.05$) if they were not.

3. Results

The processor work elements, cycle times and productivity are summarised in Table 4. With the exception of processing time, the relationships between

Table 4 Mean, Standard Deviation (SD) and range of processor time elements, cycle times, productivities and tree volumes for the 12–19° and 20–26° slope classes

	Slope class			
	12–19°		20–26°	
Time element, minute	Mean (SD)	Range	Mean (SD)	Range
Moving/positioning time	0.11 (0.04)	0.03–0.32	0.11 (0.05)	0.04–0.37
Swinging time	0.11 (0.04)	0.05–0.28	0.09 (0.03)	0.04–0.16
Processing time	0.3 (0.13)	0.10–0.74	0.31 (0.12)	0.09–0.64
Cycle time, minute	0.51 (0.14)	0.24–0.98	0.51 (0.13)	0.27–0.86
Productivity, m^3 PMH_0^{-1}	69.4 (35.8)	14.0–167.1	59.5 (31.5)	15.7–154.0
Tree volume, m^3	0.63 (0.42)	0.09–1.75	0.53 (0.35)	0.09–1.57

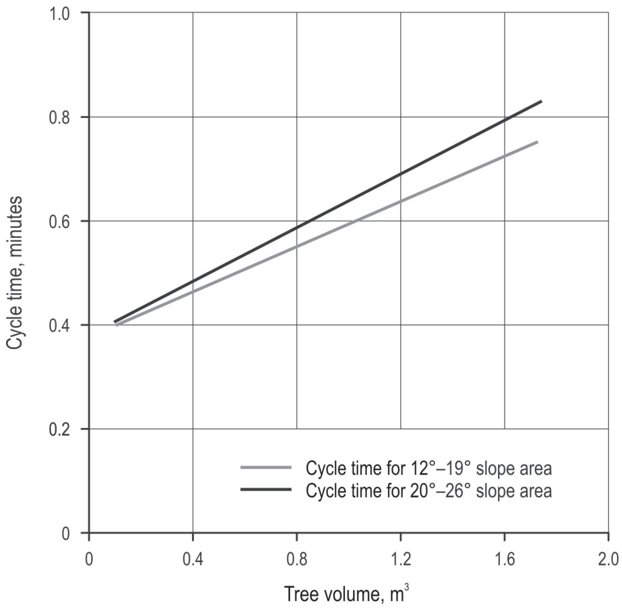

Fig. 2 Processor cycle time (minutes) against tree volume (m^3) for the 12–19° and 20–26° slope classes

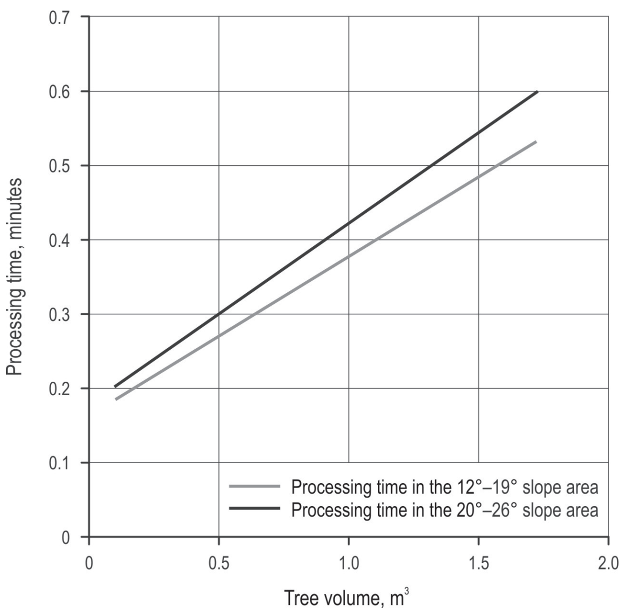

Fig. 3 Processing time (minutes) against tree volume (m^3) for the 12–19° and 20–26° slope classes

each time element and tree volume were not significant. No significant differences were found between mean processor moving/positioning time for each slope class and between mean swinging time for each slope class.

The model form which best fitted the data for cycle time and processing time against tree volume for both slope classes was a linear regression of the dependent variable (Cycle time (minutes) or Processing time (minutes)) and Tree volume (m^3) (Fig. 2 and Fig. 3, respectively):

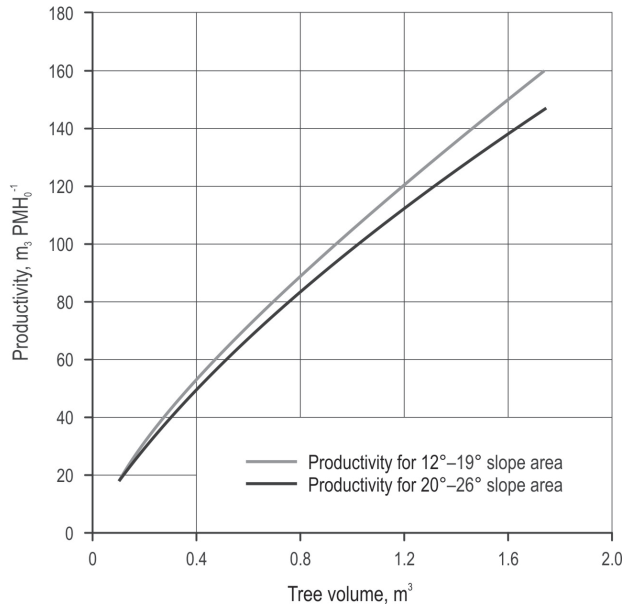

Fig. 4 Productivity ($m^3\ PMH_0^{-1}$) against tree volume (m^3) for the 12–19° and 20–26° slope classes

$$\text{Cycle time} = \beta_0 + \beta_1 \times \text{Tree Volume} \quad (1)$$

$$\text{Processing time} = \beta_0 + \beta_1 \times \text{Tree Volume} \quad (2)$$

Model coefficients and fit statistics are in Table 5. There was no significant difference between the models for each slope class.

The model form which best fitted the data for both slope classes for productivity against tree volume was a natural logarithmic transformation of productivity ($m^3\ PMH_0^{-1}$) and of tree volume (m^3) (Fig. 4):

$$\ln(\text{Productivity}) = \beta_0 + \beta_1 \times \ln(\text{Tree Volume}) \quad (3)$$

Model coefficients and fit statistics are in Table 5. There was no significant difference between the Productivity models for each slope class. As logarithmic transformation of the dependent variable introduces a negative bias, the predicted productivity values were corrected following back-transformation using the method of Snowdon (1991). The correction factors were 1.011 (12–19° slope class) and 1.018 (20–26° slope class).

4. Discussion

Significant relationships were found between the cycle time and productivity of the processor and tree

Table 5 Processor cycle time, processing time and productivity model coefficients and goodness of fit statistics for each slope class

Model	Slope class	Model coefficients		Goodness of fit statistics			
		β_0	β_1	Mean bias	MAE	RMSE	R^2
Cycle time	12–19°	0.377	0.219	0	0.08	0.1	0.42
	20–26°	0.377	0.259	0	0.08	0.1	0.43
Processing time	12–19°	0.168	0.21	0	0.07	0.09	0.47
	20–26°	0.177	0.244	0	0.07	0.08	0.50
Productivity	12–19°	4.639	0.777	0	11.2	15.1	0.82
	20–26°	4.571	0.736	0	9.5	13.4	0.81

volume (Table 5), with the productivity of the processor increasing with increasing tree size (Fig. 4), as found in numerous previous studies (Kellogg and Bettinger 1994, Acuna and Kellogg 2009, Visser and Spinelli 2012, Ghaffariyan et al. 2012). However, in this study the productivity of the processor was not significantly different when operating in the 12–19° slope class and in the 20–26° slope class. This is in contrast to the findings of previous research trials, which found (with the exception of a trial of a specialised steep slope harvester (Robert et al. 2013)) that productivity decreased as slope increased (trial slope ranges shown) (Stampfer 1999 (6–26°), Bolding and Lanford 2002 (0–25°), Acuna and Kellogg 2009 (0–20°), Spinelli et al. 2010 (0–27°)). The near linear relationship between productivity and tree volume for trees with a volume greater than 0.5 m^3 in the current study (Fig. 4) suggests the volume and weight of the majority of the trees were well within the capabilities of the machine. This is the probable cause of the lack of significant difference in the processor productivity between the two slope classes. Spinelli et al. (2010) noted that engine power has a significant effect on the productivity of a harvester, but no interactions between slope and engine power were reported in that study. The divergence of the cycle time and productivity models for each slope class with increasing tree volume (Fig. 2 and Fig. 4) suggests that a site with a larger mean tree size may have resulted in a significant difference between the processor productivity in each slope class. The relatively small sample size and observation time in the study may also have been insufficient to detect differences in the performance of the processor between the slope classes. Any »observer« effect on the operator's performance was believed to be insignificant as the observations were made over a period of three days whereas Makkonen (1954) reported that the observer effect did not last beyond the first day.

The majority of previous trials have reported moving time to be significantly affected by changes in slope (e.g. Stampfer 1999, Bolding and Landford 2002, Spinelli et al. 2010). However, these trials were mostly of harvesters felling and processing trees whereas the current trial was of a processor processing trees felled and stacked by a feller-buncher. Typical operation of a harvester is to fell and process one or more trees from a stationary position and then move to a new position, with the number of trees felled and the distance moved depending on the density of trees and the proportion of trees being removed. In contrast, the processor in the current study performed most movements of its tracks while simultaneously swinging the boom to pick up the next tree for processing (the moving and positioning time element). The proportion of time spent moving and positioning was low (~21–22%) because the stand was unthinned with little mortality resulting in a high density of felled trees along the stacks created by the feller-buncher.

Slope has also been reported in previous trials to have a significant effect on swinging (Bolding and Landford 2002), felling and processing time elements (Spinelli et al. 2010) and the time taken to position logs (Acuna and Kellogg 2009). In the study, felling was not performed by the processor and positioning logs was a rare event. Mean swinging and processing times were not significantly different between the slope classes. However, operating the machine on steeper slopes or with larger trees than in the current study may increase the swinging time because of the increased difficulty in swinging trees from the felled pile to be processed.

In the study, slope was classified into broad classes defined by the Tasmanian Forest Practices Board (2000). However, the majority of the area in the steep slope class from which the study trees were selected was at the lower end of this class (20–23°), which may be another factor explaining the lack of significant impact of slope on the performance of the processor in the study.

At the mean pooled tree volume for this study, the productivity of the processor was greater than that reported by Strandgard et al. (2012) for three harvesters felling and processing radiata pine on relatively flat sites (48.4–55.9 m^3 PMH_0^{-1}). This was expected as the processor in the current study did not have to fell trees and had a high density of trees in the stacks minimising the boom and track movements required to reach each tree. However, the processor in the study also had a greater productivity than a processor processing radiata pine infield on gentler slopes (41 m^3 PMH_0^{-1}) at the mean pooled tree volume for the current study (Ghaffariyan et al. 2012). The lower productivity of the harvester in that operation may be due to it being an excavator-based machine with a less powerful engine (180 kW). The high density of trees along each stack and the arrangement of the felled trees in rows with their butt ends alongside the processor made processing in the current study more analogous to roadside processing than infield processing. FPInnovations (2007) reported the productivity of a processor at roadside to be 48.4 m^3 PMH_0^{-1} (logs <8 m) and 72.4 m^3 PMH_0^{-1} (logs >8 m) for trees at the mean pooled tree volume. Log length clearly had a significant impact on the productivity in these trials and may have been a factor in the high productivity of the processor in the current trial because most trees were processed into several logs of the longest allowable length (5.4 m) with only an occasional shorter log being cut.

5. Conclusion

The lack of a significant impact of slope on the cycle time and productivity of the processor and on the individual time elements in the study suggests that the tree size at the site was well within the capabilities of the processor. Other important factors may have included that the trees were pre-felled by a feller-buncher and placed in high density rows with their butt ends aligned, which minimised the processor boom and track movements, and that the steep slope trees were selected from areas at the lower end of the steep slope class. Further research is needed to determine whether the productivity of the processor would be significantly lower when processing trees with a larger mean volume on steeper slopes.

Acknowledgements

The authors would like to thank the staff of Norske Skog, Australasia and their harvesting contractor BR & KF Muskett and Sons for their assistance in ensuring the success of this trial and the assistance of David Mannes (Forestry Tasmania) in providing the LiDAR data.

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Received: December 24, 2013
Accepted: March 14, 2014

Authors' address:

Martin Strandgard*
e-mail: mstrandg@usc.edu.au
Australia Forest Operations Research Alliance (AFORA)
University of the Sunshine Coast
500 Yarra Boulevard
3121 Richmond
AUSTRALIA

Muhammad Alam, PhD.
e-mail: mmalam@student.unimelb.edu.au
University of Melbourne
500 Yarra Boulevard
3121 Richmond
AUSTRALIA

Rick Mitchell
e-mail: rmitchel@usc.edu.au
Australia Forest Operations Research Alliance (AFORA)
University of the Sunshine Coast
35 Shorts Place
6330 Albany
AUSTRALIA

* Corresponding author