Self-Levelling Feller-Buncher Productivity Based on Lidar-Derived Slope

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Abstract – Nacrtak

The purpose of the study was to examine the ability of LiDAR (Light Detection and Ranging) to derive terrain slope over large areas and to use the derived slope data to model the effect of slope on the productivity of a self-levelling feller-buncher in order to predict its productivity for a wide range of slopes.

*The study was carried out for a self-levelling tracked feller-buncher in a 24-year old radiata pine (*Pinus radiata*) plantation near Port Arthur, Tasmania, Australia undertaking a clear felling operation. Tree heights and diameter at breast height were measured prior to the harvesting operation. Low intensity LiDAR (>3 points m^{-2}) flown in 2011 over the study site was used to derive slope classes. A time and motion study carried out for the harvesting operation was used to evaluate the impact of tree volume and slope on the feller-buncher productivity.*

The results showed the ability of LiDAR to derive terrain slope classes. The study found that for an average tree volume of 0.53 m^3, productivities of 97 m^3 PMH_0^{-1} (Productive Machine Hours excluding delays) and 73 m^3 PMH_0^{-1} were predicted for the moderate slope (11–18°) and steep slope (18–27°), respectively. The difference in feller-buncher productivity between the two slope classes was found to result from operator technique differences related to felling. The productivity models were tested with trees within the study area not used in model development and were found to be able to predict the productivity of the feller-buncher.

Keywords: Tasmania, productivity, self-levelling feller-buncher, LiDAR, mechanised harvesting system, slope

1. Introduction – *Uvod*

The productivity and efficiency of a mechanised harvesting system is affected by a number of factors including forest stand characteristics (stand density, undergrowth), tree characteristics (tree size or piece size, tree form, crown size), terrain variables (slope, rocks, woody debris, ground roughness, ground strength, streams and drainage features, roads, etc.), operators' experience, skill & work technique and machinery limitations or design (Brunberg et al. 1989, Lageson 1997, Nurminen et al. 2006, Visser et al. 2009). Knowledge of the impact of these factors on the productivity and efficiency of forest harvesting machines can assist in predicting their performance under different conditions in a cost-effective way and lead to more productive harvesting operations.

Tree size (volume or weight) has been determined by many studies to be the most influential factor affecting the productivity of forest harvesting machines (e.g. Brunberg et al. 1989, Kellogg and Bettinger 1994, Acuna and Kellogg 2009). However, slope is the primary determinant of travel speed and stability of harvesting machines (Davis and Reisinger 1990). Increasing slope has been shown to be a significant factor in decreasing the productivity of a range of forest harvesting equipment (Stampfer 1999, Stampfer and Steinmüller 2001, Simões and Fenner 2010, Zimbalatti and Proto 2010). In addition, rubber-tyred harvesting machines are generally restricted to slopes <19° whereas tracked machines can operate on slopes up to 27°, with some specialised tracked machines able to operate on steeper slopes (e.g. the Valmet Snake (Stampfer and Steinmüller 2001)).

Previous harvester productivity studies have usually extrapolated stand-level slope information from a limited number of points manually measured with clinometers across the study site or used DTMs (Digital Terrain Models) derived from contours (e.g. Acuna and Kellogg 2009, Oliveira Júnior E. D. de. et al. 2009). LiDAR is a well-recognised technology for the production of high quality DTMs (Ackermann 1999, Wehr and Lohr 1999), which can be used to visualise and calculate slope (Giles and Franklin 1998) and as an input into harvest planning (Reutebuch et al. 2005). LiDAR slope maps have been shown to be very accurate and of high resolution compared with DTMs derived from contour maps (Vaze and Teng 2007). Use of LiDAR to generate accurate, broad area DTMs makes it possible to predict the impact of slope on forest harvesting machine productivity across an entire forest estate using models relating productivity to slope.

Self-levelling feller-bunchers have recently been introduced in parts of Australia and New Zealand for harvesting operations in steep terrain (Acuna et al. 2011). Self-levelling feller-bunchers have advantages over conventional feller-bunchers such as reducing the risk of tilting, increased lifting capacity and increased operator comfort during downhill operations (MacDonald 1999, Acuna et al. 2011). The objective of the study was to use LiDAR-derived slope from readily available low cost LiDAR data to develop a relationship between slope and the productivity of a self-levelling feller-buncher, and then to use this relationship to predict the productivity of the feller-buncher for other areas, where slope had been estimated using similar LiDAR data.

2. Material and methods *Materijal i metode*

2.1 Study site – *Mjesto istraživanja*

The study was located near Port Arthur, Tasmania, Australia (Latitude/Longitude: 43°10′10″ S / 147°47′ 20″ E). The stand was 24-year-old radiata pine plantation of 1057 trees ha^{-1} with no undergrowth. The study site was an area of approximately 1 hectare within a plantation being clearfelled for pulp wood production. Tree spacing was 2.5 m × 4 m and lightly branchy trees were good in forms and quality. The site had never been thinned. The forest floor consisted of moist, soft and clay loamy soils. There were some dolerite rocks that accounted for the ground roughness. Ground slope was between 7–27° with an average of 21°.

One hundred and two trees of normal growth and forms covering the range of heights at the study site were selected and their heights were measured with a Vertex hypsometer and Impulse 200 laser to the nearest 0.1 m. The diameter at breast height (*DBH*, cm) of all trees on the study site was measured with a diameter tape to the nearest 1 cm. A height-diameter model derived from the measured tree heights was used to estimate heights of the remaining trees. Each tree had a unique number painted on the stem to allow it to be identified during the time and motion study. A volume function supplied by Norske Skog, Australia was used to estimate each tree merchantable volume (m^3). Means and value ranges for pre-harvest tree measurements are presented in Table 1.

Table 1 Means and value ranges for pre-harvest tree measurements
Tablica 1. *Raspon i prosječne vrijednosti izmjere stabala prije sječe*

	Mean *Arit. sredina*	Range *Raspon*
Height – *Visina*, m	26.1	10–37
DBH – *Prsni promjer*, m	0.29	0.10–0.46
Basal area – *Temeljnica*, m^2	0.07	0.01–0.16
Volume – *Obujam*, m^3	0.61	0.06–1.84

2.2 Airborne LiDAR system – *Sustav LiDAR*

LiDAR data covering the study site was supplied by Forestry Tasmania, with the specifications presented in Table 2. This LiDAR data was available as it had been collected for the purpose of resource and land management used by Forestry Tasmania that manages native and plantation forests in the region. LiDAR data supplied in .LAS format were classified into ground and non-ground points. LiDAR data accuracy was verified by the data provider.

A DTM was constructed with a cell size of 2 m using ground LiDAR points and slope was derived from the DTM using ArcGIS 10. The terrain slope classification used by the Forestry Commission UK (1996) (Level = 0–6º, Gentle = 6–11º, Moderate = 11–18º, Steep = 18–27º, Very steep = >27º) was adopted in the study because: (i) the classes are based around operational considerations, (ii) there was no widely accepted terrain classification system in use in Australia, (iii) this classification is very similar to that used by the Forest Practices system in Tasmania (Forest Practices Board 2000) of Hilly =12–19º, Steep = 20–26º, Very Steep =27º and above and (iv) it is an internationally recognised classification.

2.3 Time and motion study – *Studij rada i vremena*

An operator with twelve years experience (two years with current machine) carried out the harvesting

Table 2 LiDAR parameters and scanning system settings
Tablica 2. *Parametri LiDAR-a i postavke sustava snimanja*

LiDAR attribute – *Obilježja LiDAR-a*	Values – *Vrijednosti*
Date of flight – *Datum leta*	25/05/2011
System – *Sustav*	ALTM (Airborne Laser Terrain Mapping) Gemini
Beam divergence – *Odstupanje pulsa*	0.20 milliradian
Footprint diameter – *Prostorna rezolucija*	20 cm
Laser mode – *Mod lasera*	Single pulse
Pulse return density (range) – *Gustoća povratka pulsa (raspon)*	>3 m^{-2} (1st , 2nd, 3rd and last) (2.3–3.2)
Horizontal accuracy – *Horizontalna točnost*	0.15 m
Vertical accuracy – *Vertikalna točnost*	0.15 m
Pulse rate frequency – *Frekvencija pulsa*	70 kHz

Table 3 Description of time elements
Tablica 3. *Opis radnih sastavnica*

Time elements – *Radne sastavnice*
Moving time: Begins when the feller-buncher or the boom starts to move to a tree and ends when machine head is clamped on the tree *Premještanje: Započinje kada feler bančer ili dizalica započinje s pomicanjem i završava kada sječna glava zahvati stablo*
Felling time: Starts when the feller-buncher head clamps on to the tree stem and ends when the tree touches the ground *Sječa: Započinje kada sječna glava zahvati stablo te završava kada posječeno stablo dodirne tlo*
Stacking time: Starts when the feller-buncher grabs a log and ends when it drops the log onto the pile *Uhrpavanje: Započinje kada feler bančer zahvati deblo i završava u trenutku kada ga ispusti na složaj*
Cycle time: Starts when the feller-buncher commences moving to a tree and ends when the feller-buncher completes felling the tree *Vrijeme turnusa: Započinje premještanjem feler bančera ka stablu i završava kad feler bančer posječe stablo*
Delay: Any interruption to the harvesting operation spending extra time. The cause of the delay (e.g. operational, personal, mechanical, or study induced) is recorded *Prekidi: Svako prekidanje pridobivanja drva koje izaziva dodatni utrošak vremena. Uzroci su prekida (npr. povremeni radovi, osobni, kvarovi ili izazvani istraživanjem) zabilježeni*

operation with a self-levelling tracked feller-buncher, Valmet 475EXL fitted with a Quadco hotsaw accumulating head. It was manufactured in 2004 and had worked for 7751 hours. The Valmet 475EXL is designed to operate on uneven ground and on steep slopes.

The harvesting operation was recorded using a digital video camera in mainly fine and sunny conditions on the 4th April 2011. Several brief episodes of drizzly rain occurred, but did not disrupt the harvesting operation and filming.

The operator was observed to fell trees in a 4 row swath directly uphill (moving at right angles to the contours) or on side-hill (moving parallel to the contours) on gentle & moderate terrain and downhill on steep terrain. In fact, terrain conditions largely dictated tree harvesting pattern in steep and moderate steep slope areas. Trees were laid out in the previously harvested area at right angles to the direction of harvester movement for subsequent processing into logs. The length of each swath was approximately 100 m. One to three trees were felled at each stop.

To avoid issues associated with GPS (Global Positioning System) accuracy and performance under tree cover, following the harvesting operation GPS locations of 100 stumps along the border of the study site were recorded with a standard GPS measuring device. Coordinates of stump locations were used to locate the harvest area on the LiDAR-derived DTM.

Timer Pro Professional software (www.acsco.com) was used to extract each time element from the video recording (Table 3). Time elements unrelated to tree size and slope including stacking, brushing, clearing and any delays were excluded from the analysis because of their random occurrences.

In order to develop feller-buncher productivity models for each slope class, the following steps were carried out:

⇒ Stump locations on the boundary and tree spacing measurements in the plantation area were used to interpolate the locations of remaining trees using ArcGIS 10.

⇒ One hundred and twenty-six trees in the moderate slope area and 124 trees in the steep slope area of the study site were selected for model development using previously derived LiDAR slope. Trees with normal growth and forms were selected from both slope areas and selection was limited to trees that could clearly be identified as being in the allocated slope class. There was insufficient area of gentle slope at the study site for productivity modelling.

⇒ For estimated location of each tree in the study area, both tree volume and slope class were allocated.

⇒ Time consumptions of each tree for slope classes were estimated from the time and motion study.

⇒ A correlation between tree volumes and time consumptions for each slope class was established, which in turn was used to formulate a productivity model.

⇒ Prior to model development, mean tree sizes for each slope class were compared using a *t*-test ($p<0.05$).

2.4 Data analysis – *Obrada podataka*

Productivity models for the feller-buncher were developed based on the cycle times for the trees se-

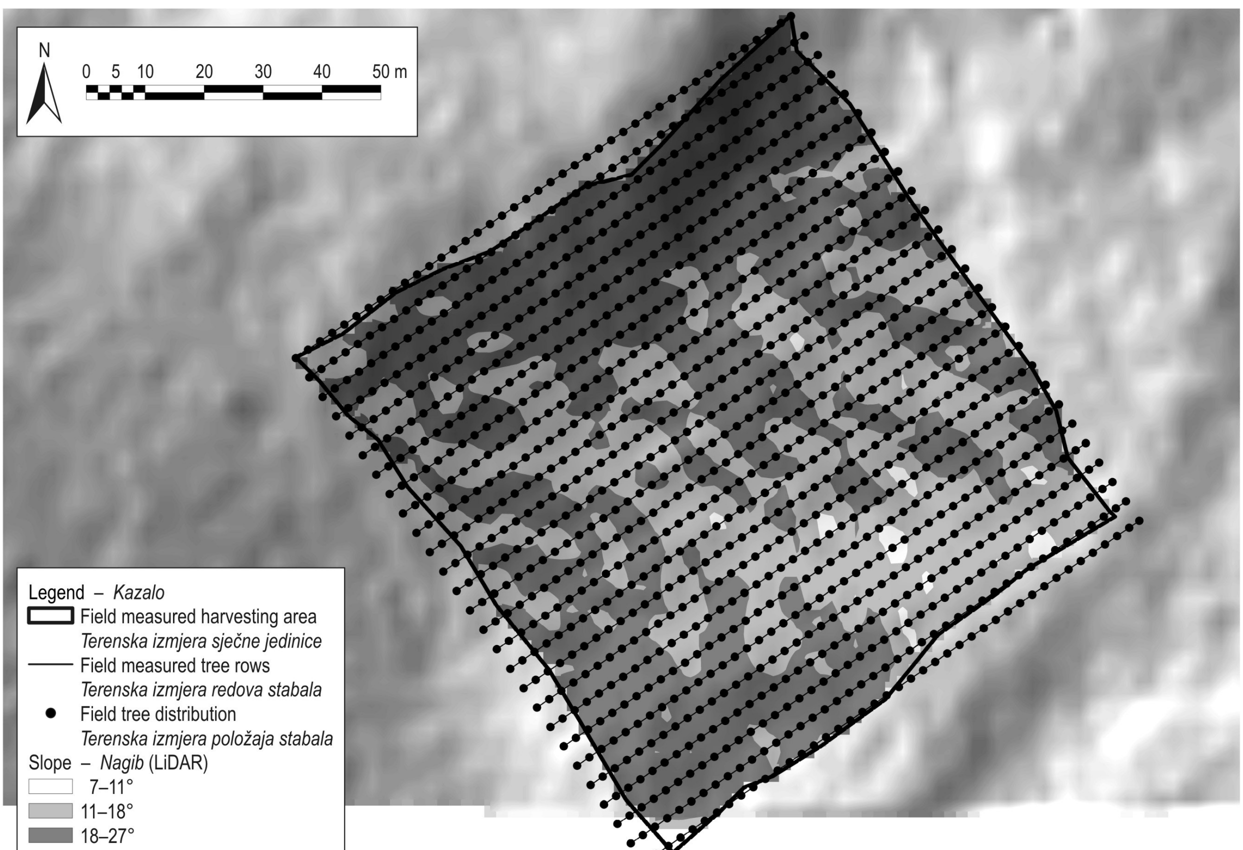

Fig. 1 LiDAR-derived slope class (Field tree distribution and Field measured tree rows refer to approximate locations)

Slika 1. *Razredi nagiba terena izvedeni iz LiDAR-ovih snimaka (terenske izmjere redova i pojedinih stabala odnose se na približne položaje)* lected in each slope area to determine whether slope significantly affected feller-buncher productivity.

Productivity (m^3 PMH_0^{-1}) was estimated using the following formula:

Productivity = (volume / cycle time) * 60

Where,

Volume – tree volume (m^3) estimated from field measurements

Cycle time (min) – refer to Table 3.

PMH_0 – Productive Machine Hours excluding delay time

Regression models were developed for each slope class and tested to determine the best-fit models using their mean Bias, Mean Absolute Deviation (MAD), RMSE (Root Mean Square Error), R^2 and the distribution of the residuals. The best-fit models for each slope class were compared using an F-test ($p < 0.05$) (Motulsky and Christopoulos 2003).

The relationship between tree volume and moving & felling times for each slope class was tested using linear regression to determine whether tree volume was a potential covariate in a one-way Analysis of Covariance (ANCOVA). If it was found not to be, a one-way Analysis of Variance (ANOVA) would be performed. A general linear model was used to analyse the ANCOVA and/or ANOVA models (Minitab 16, Minitab Ltd.). Mean felling and moving times for each slope class were compared by a post hoc analysis of the means using Tukey's test in order to identify the impact of each time element on feller-buncher productivity.

In order to test whether the productivity models developed in the study were able to accurately predict the productivity of the feller-buncher when felling trees elsewhere on the study site, thirty-five trees not used in the model development process were randomly selected from each slope class. Topographic variability and slope ranges of model testing areas were chosen and verified to be similar to those of model development areas. The productivity of the feller-buncher for each of these trees was calculated using cycle time and tree volume and was estimated using the productivity models developed for each slope class. For each slope class, the calculated and estimated productivity values were compared using a paired t-test. Linear regression [$Y = a + b(X)$] analysis was performed to predict productivity of the feller-buncher for each slope class, where X is the independent variable, field measured productivity; Y is the dependent variable, predicted productivity and a & b are the regression coefficients. Statistical software Excel 2007 was used to perform analyses.

3. Results – *Rezultati*

Field measured stump locations (coordinates) were used to locate the harvest area on the LiDAR-derived DTM. The LiDAR-derived slope range for the study site was 7–27° with a mean slope of 19°, which was found to be comparable to field measurements of the study site. The slope of the study site was classified into three classes: gentle slope (7–11°), moderate slope (11–18°) and steep slope (18–27°) (Forestry Commission UK 1996) (Fig. 1). Several small areas (maximum 8 m × 6 m) of over 27° slope were added to the steep slope class as they were too small to affect the productivity of the feller-buncher.

Mean tree volumes in the moderate and steep slope areas were not significantly different (Table 4).

As there were very few instances of stacking time during the study, it was excluded from cycle time. Two trees were cut and accumulated in head in two occasions and they were also excluded from the analysis while developing the model to be consistent with overall tree selection technique. In the steep slope areas, a number of trees had fallen on other trees during harvest operation and the operator was observed to

Table 4 Summary tree volume (m^3) statistics for each slope class
Tablica 4. *Statistički prikaz obujma stabala za svaki razred nagiba terena*

	Moderate slope (11–18°) *Umjereni nagib (11–18°)*	Steep slope (18–27°) *Strmi nagib (18–27°)*
Mean volume – *Srednji obujam*, m^3	0.55	0.51
SD – *Standardna devijacija*, m^3	0.26	0.26
Volume range – *Raspon obujma*, m^3	0.05–1.12	0.13–1.20
Count – *Veličina uzorka*	126	124

Table 5 Model coefficients and goodness of fit statistics for the feller-buncher productivity model for each slope class
Tablica 5. *Koeficijenti modela i dobrota statističke prikladnosti modela proizvodnosti feler bančera za svaki razred nagiba*

	Model coefficients – *Koef. modela*		Goodness of fit statistics – *Dobrota statističke prikladnosti*			
	β_0	β_1	*MBE*	*MAD*	*RMSE*	R^2
Moderate slope – *Umjereni nagib* (11–18°)	12.3	3.8	2.5	24.0	34.7	0.60
Steep slope – *Strmi nagib* (18–27°)	10.8	3.5	2.0	17.7	25.8	0.61

drag them out in the processing areas. The model form that best fitted the data was a natural logarithm transformation of processed volume and the square root of productivity:

$$(Productivity)^{1/2} = \beta_0 + \beta_1 * ln\ (Processed\ volume)$$

As the models were developed based on the square root of the dependent variable, the goodness of fit measures for the productivity models were calculated from back-transformed model outputs (Scott and Wild 1991). Model coefficients and fit statistics are shown in Table 5.

Productivity of the feller-buncher was strongly correlated with tree volume in both slope areas (Fig. 2). Productivity was greater (97 m^3 PMH_0^{-1}) for the moderate slope class (11–18°) than that (73 m^3 PMH_0^{-1}) for the steep slope class (18–27°) at the pooled mean tree volume of 0.53 m^3. The difference between the productivity models was statistically significant (p<0.05).

Feller-buncher moving and felling times were separately found to be poorly related to tree volume and thus a one-way ANOVA was performed. The data for the felling and moving times were found to satisfy the ANOVA assumptions. Mean felling times for each slope class were significantly different, whereas there was no significant difference between mean moving times for each slope class (Table 6).

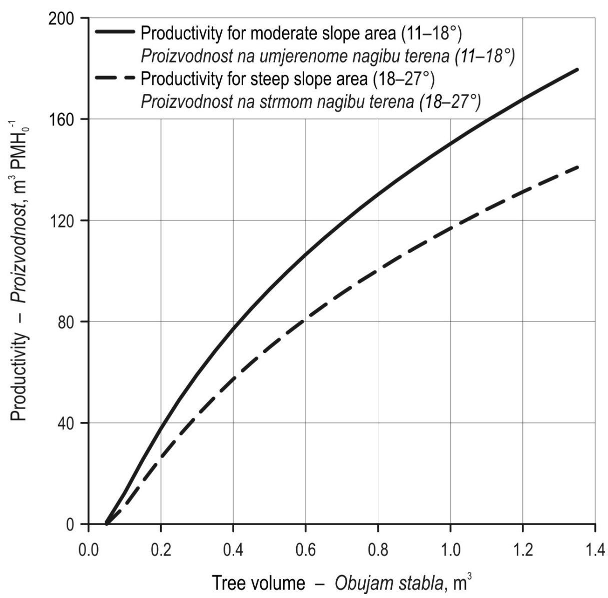

Fig. 2 Productivity of the feller-buncher against tree volume for moderate slope (11–18°) and steep slope (18–27°)
Slika 2. *Ovisnost proizvodnosti feler bančera o obujmu stabla za umjereni (11–18°) i strmi (18–27°) nagib*

The mean feller-buncher productivity, predicted using the slope class productivity models for trees not used in the model development, was not significantly

Table 6 Feller-buncher mean felling and moving times, standard deviations (SD), min. and max. values for slope classes at the study site
Tablica 6. *Deskriptivna statistika vremena sječe i premještanja za razrede nagiba istraživane sječine*

	Felling time, sec – *Vrijeme sječe*, s				Moving time, sec – *Vrijeme premještanja*, s			
	Mean *Aritmetička sredina*	Standard deviation *Standardna devijacija*	Minimum *Najmanja vrijednost*	Maximum *Najveća vrijednost*	Mean *Aritmetička sredina*	Standard deviation *Standardna devijacija*	Minimum *Najmanja vrijednost*	Maximum *Najveća vrijednost*
Moderate slope – *Umjereni nagib (*11–18°)	9.7	5.4	4.9	56.4	11.6	7.7	3.5	44.6
Steep slope – *Strmi nagib* (18–27°)	14.3	8.4	5.9	56.8	12.4	6.6	4.7	45.8

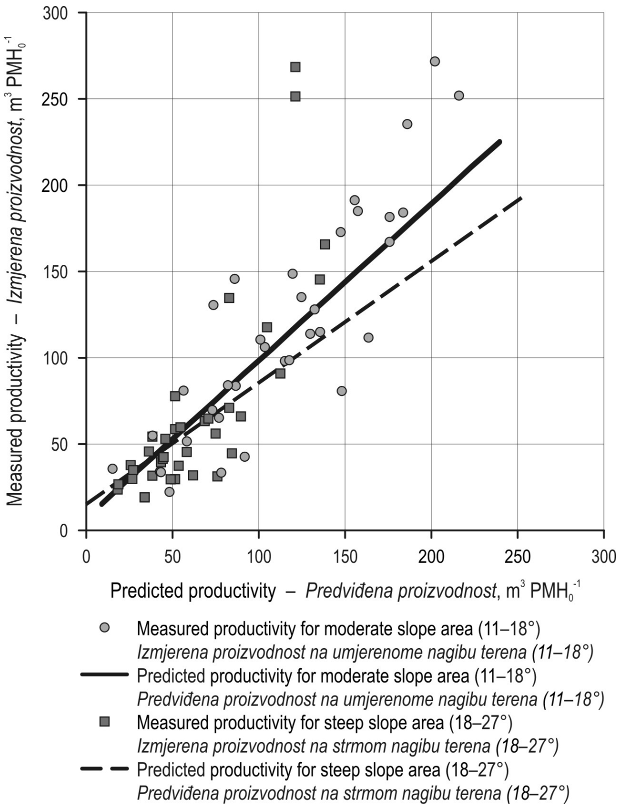

Fig. 3 Predicted productivity as a function of measured productivity for moderate slope (11–18°) and steep slope (18–27°) of the model testing areas

Slika 3. *Predviđena proizvodnost kao funkcija izmjerene proizvodnosti za umjereni (11–18°) i strmi (18–27°) nagib istraživane sječine*

different from the mean feller-buncher productivity calculated from cycle times and tree volumes for the same trees (p<0.05). Measured productivity was found to be strongly correlated with predicted productivity for each slope (Fig. 3).

4. Discussion and Conclusion – *Rasprava sa zaključcima*

The productivity of the feller-buncher in the current study was found to decrease in the steeper slope class, which was consistent with the findings of previous studies (e.g. FPInnovations 2008, Oliveira Júnior E. D. de. et al. 2009). However, there is considerable variation amongst the previous studies in the degree of decrease in productivity with increasing slope, which implies factors other than slope are influencing the results. In the current study, the decrease in productivity between steep slope (18–27°) and moderate slope (11–18°) was 24% whereas Acuna and Kellogg (2009) found no significant difference in the productivity of a feller-buncher across a slope range from <10º to 20º and FPInnovations (2008) showed a 30% reduction in productivity between 6–11º slopes and 11–18º slopes based on modelled results from a number of feller-buncher studies. The greatest decrease in feller-buncher productivity was reported by Oliveira Júnior E. D. de. et al. (2009), who found an 80% decrease in productivity for a tracked feller-buncher between 0 and 27º slopes. This large productivity drop was explained by the difference in soil type (e.g. »agri-loose« soil) and difficulties in handling larger trees on steep terrain. Other potential factors accounting for the variation between the study results may include machine characteristics, operator skill and the number of stems removed per hectare, because travelling time between trees may increase disproportionately with increasing slope. These factors, however, were not investigated in this study.

To isolate the cause of the productivity differences between the slope classes in the current study, the cycle time components (moving and felling times), were further analysed. The study found felling time to be the main driver for the variation in productivity, which was the result of the operator spending significantly more time per tree (over 4 seconds) felling trees in the steep slope area (Table 6). Terrain conditions largely dictated the harvesting pattern and observations indicated it had a greater impact on steeper slopes within the steep slope classification. Since operating the machine on an uphill slope is slightly more comfortable and productive (Howe 2011), the operator was observed to fell trees uphill by predominantly extending the boom and moving the feller-buncher in the moderate slope areas and lay them out for processing primarily using the boom, whereas, in the steep slope areas the operator drove downhill to fell each tree and then back uphill to deposit them in suitable areas, preferably those with moderate slope, for processing. In the steep slope areas, the operator also spent time dragging out a number of trees that had fallen on other trees. The combination of these factors contributed to higher time consumption when felling trees in the steep slope areas.

The study did not investigate whether soil strength was an influential factor affecting the machine's stability and traction in the steep slope areas, although the soil in the steep slope areas was observed to be muddy compared with that in the gentle and moderate slope areas. Stampfer and Steinmüller (2001) demonstrated that the locomotion of the harvester was dependent on the terrain slope and the soil bearing capacity. Therefore, consideration of the soil bearing capacity, while evaluating slope effects on harvester productivity, may be an area for future research.

The models developed in the study were able to predict the productivity of the feller-buncher felling trees from each slope class on the study site where the topographical features and slope ranges were similar to model development areas. This suggests that the models can be used to predict the productivity of the feller-buncher operating in other areas of radiata pine plantation with tree volume between 0.06–1.84 m^3 and slope between 11–27°. The models may not be applicable where topographic variability is significantly different (higher or lower) from the model development areas, because the assignment of trees for each slope class based on the methodology used in the study may not represent the exact locations, which excluded the use of trees on the boundary of the slope classes and where slope was very variable and different slope variability will potentially influence the operator approach. In addition to being able to estimate terrain slope, LiDAR has been demonstrated by a number of researchers to be able to accurately predict tree volume (e.g. Hyyppa et al. 2001, Persson et al. 2002). However, the LiDAR point density in these studies was considerably greater than that for the current study, which targeted using readily available LiDAR data in the interest of exploring a methodology that would be cost-effective for practical application.

Acknowledgement – *Zahvala*

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Sažetak

Proizvodnost feler bančera sa žiroskopskom kabinom temeljena na nagibu terena izvedenom iz LiDAR-ovih snimaka

Cilj je istraživanja bio ocijeniti mogućnost uporabe LiDAR-ovih snimaka za određivanje nagiba terena na velikim površinama te ispitati djelovanje nagiba na proizvodnost feler bančera sa žiroskopskom kabinom.

*Istraživanje je provedeno u čistoj sječi plantaže smolastoga bora (*Pinus radiata*) u Tasmaniji, u blizini Port Arthura (Australija). Plantaža je bila u dobi od 24 godine. Korišten je feler bančer sa žiroskopskom kabinom, opremljen gusjenicama.*

Visina i prsni promjer stabala mjereni su prije sječe. Upotrijebljene su LiDAR-ove snimke niskoga intenziteta (>3 točke po m^2) iz 2011. godine kako bi se odredio nagib terena. Pri sječi i izradbi obavljen je i studij rada i vremena radi određivanja proizvodnosti vozila, a u ovisnosti o obujmu posječenih stabala i nagibu terena.

Rezultati istraživanja dokazuju primjenjivost LiDAR-ovih snimaka za raščlambu nagiba terena. Može se zaključiti da je za stablo prosječna drvnoga obujma od 0,53 m^3 proizvodnost feler bančera sa žiroskopskom kabinom bila 97 m^3/h (ne uključujući prekide rada) na terenu umjerena nagiba (11–18°) odnosno 73 m^3/h (ne uključujući prekide rada) na strmijim terenima (18–27°). Razlika u proizvodnosti vozila zasniva se na različitim postupcima pri sječi i izradi koje je radnik morao obavljati ovisno o nagibu terena. Modeli proizvodnosti temelje se na stvarno posječenom i izrađenom drvnom obujmu.

Ključne riječi: Tasmanija, proizvodnost, feler bančer sa žiroskopskom kabinom, LiDAR, strojna sječa, nagib

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