Silva Balcanica, 20(2)/2019

MACHINE PRODUCTIVITY EVALUATION FOR HARVESTERS AND FORWARDERS IN THINNING OPERATIONS IN AUSTRALIA

Mohammad R. Ghaffariyan, Mauricio Acuna, Mark Brown
Forest Industries Research Centre, University of the Sunshine Coast, Queensland

Abstract

Investment in thinning as part of forest management is generally for one of three purposes: improved future stand growth and quality to produce higher value products for later final harvest, removal of fuels to reduce fire risk or to meet ecological goals such as increasing biodiversity. The focus of this paper is on the thinning operations in Australian pine and eucalypt plantations, which are almost exclusively conducted by harvester-processors and forwarders. The Australian Forest Operations Research Alliance (AFORA) has conducted research projects on assessing the productivity of harvester-processors and forwarders in pine and eucalypt plantations in different sates/regions. All-time study data collected in different case studies have been consolidated into a data base called ALPACA (Australian Logging Productivity and Cost Appraisal). The data were used to develop the general productivity predicting models for harvester and forwarder based on multiple regression modelling. Harvester productivity was mainly a function of tree volume. Forwarder productivity was primarily a function of extraction distance. Slope has been included in the models as a weighting factor based on three classes and namely <15%, from 15% to 25% and >25%.

Key words: Thinning, Time study, Productivity, Forwarder, Harvester

INTRODUCTION

Australia's industrial plantations consist of softwood species (1.03 million ha, mostly pine) and hardwood plantations (0.98 million ha, mostly eucalypt) (ABARES, 2013). Thinning within forest management is generally done for one of three purposes: improved future stand growth and quality to produce higher value products for later final harvest, removal of fuels to reduce fire risk or to meet ecological goals such as increasing biodiversity. Thinning materials are usually small size woods, such as pulp logs, large branches and tops with limited industry uses. Pulp logs are used for pulp and paper making purposes or, where bioenergy markets are strong, they can be used for bioenergy. Large branches and tops generally do not meet industrial wood standards, thus are only recovered for bioenergy applications. Because profit margin in thinning operations is low, then it is essential to control the cost of operations. One of the suitable approaches to control the cost is developing machine productivity and cost-predicting models for the expected range of operating conditions. The focus of this research is on the thinning operations in Australian pine and eucalypt plantations, which are almost exclusively conducted by harvester-processors and forwarders.

Studies on the application of the cut-to-length (CTL) system have been carried out in commercial thinning in North America (Kellogg, Bettinger, 1994; Hossain, Olsen, 1998; Turner, Han, 2003; Kellogg, Spong, 2004) and Europe (Glode, 1999; Hanell et al., 2000; Spinelli et al., 2002; Nurminen et al., 2006; Rottensteiner et al., 2008). In Australia, the efficiency of a harvester-processor on a per-tonne basis was found to be higher than the combination of feller-buncher and processor in native forest thinning (Acuna, Kellogg, 2009).

Many factors can affect productivity of harvesters and forwarders; they are summarised in Table 1.

Table 1. Available knowledge on harvesters and forwarders productivity.

Machine	Impacting factors on productivity	Range of productivity (m^3/PMH_0)	Source of information
Harvester	tree size, forking	5.6 to 50	Kärä et al. 2004; Visser and Spinelli 2012; Walsh and Strandgard 2014; Acuna et al. 2017; Baek et al. 2017
Forwarder	type of logs (pulpwood, sawlog or mixed loads), volume per load, travel distance to where loading begins, travel distance during loading and travel distance to landing, stand type, average extraction distance, timber density on the strip road, load volume and size of forwarder and slope of the skid trail	8 to over 36 m^3/PMH_0	Horvat et al. 1990; Kellogg and Bettinger (1994); Tufts and Brinker 1993; Kuitto et al. 1994; UK Forestry Commission 1995; Gullberg 1997; Martin dos Santos et al. 1995; Saunders 1996; Geolia et al. 1999; Spinelli et al. 2003; Cordero et al. 2006, Nurminen et al. 2006; Baek et al. 2017

Although several research projects have been conducted on assessing the productivity and cost of harvester-processors and forwarders in pine and eucalypt plantations in different states/regions in Australia (Acuna et al., 2017; Walsh, Strandgard, 2014; Ghaffariyan et al., 2012; Ghaffariyan, Brown, 2013), there is still no general model which merges all information to provide users with a benchmarking and predicting tool for productivity estimation in thinning operations in Australia. This paper aimed to develop a general productivity-predicting model for harvesters and forwarders in thinning operations and test the significance impact of operational factors (tree size, extraction distance, etc.) on machine productivity using multilinear regression modelling.

MATERIALS AND METHODS

Modelling of thinning operations with ALPACA

The tool ALPACA (Australian Logging Productivity and Cost Appraisal), developed by the Australian Forest Operations Research Alliance (AFORA), was used to generate a productivity model for a harvester and a forwarder, which are commonly used in softwood and hardwood thinning operations. ALPACA is an Excel-based tool used to model and estimate harvest productivity and costs under different scenarios, assist planners to match harvesting systems to forest conditions, assess the impact of factors on productivity and cost and as a control tool to compare planned and actual productivity of harvesting systems, among others. The structure of the ALPACA tool is the same as that of the tool IRLPACA described in Murphy et al. (2010). Input parameters include harvest area, relocation distance, stand details (merchantable volume and trees to be removed per hectare, species), harvest type (e.g. clearfelling, thinning), working hours per year, harvesting system (e.g. cut-to-length, tree length) and machine hourly productivity and costs (Figure 1). As outputs, the tool provides daily production (m^3 and tonnes), cost per m^3 and cost per tonne by machine and for the whole system, as well as days to log the harvest unit. In addition, the tool allows the user to balance the system, i.e. to find the mix of felling/processing and extraction equipment that achieves the least harvesting cost (Acuna, Strandgard, 2017).

Productivity models in ALPACA have been developed for the most common ground-based harvesting systems existing across Australia from more than 200 time

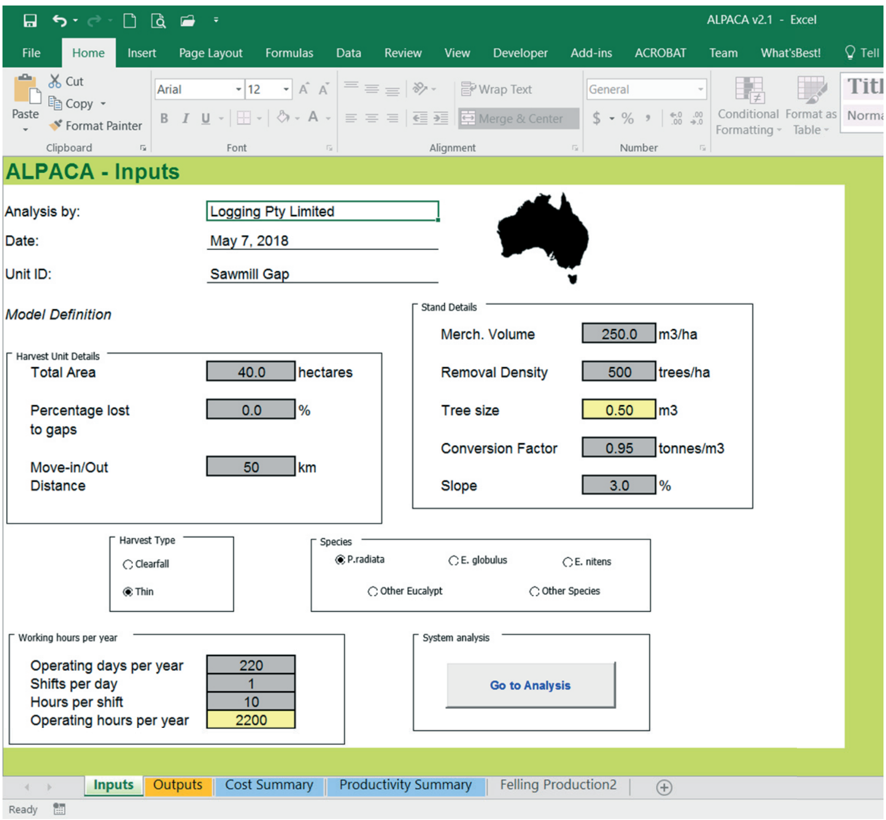

Fig. 1. Data input interface to model a thinning operation in ALPACA.

studies. Table 1 shows the ground-based systems included in the ALPACA tool, including the equipment for felling, processing, extraction and loading. Softwood and hardwood thinning operations are usually conducted using a harvester for felling the trees and processing the stems into logs (Figure 2), a forwarder to collect, load and extract the logs to roadside (Figure 3) and a dedicated loader to load the logs onto trucks (last system in Table 2 which is the one considered in this study). Eventually, the forwarder also can do the loading, although this option was not considered in the study.

Table 2. Ground-based systems and corresponding equipment included in the ALPACA tool.

*Felling (cutover), **Felling/ Processing (cutover)	Extraction (cutover to roadside)	Processing (roadside)	Loading (roadside)
*Feller-buncher	Skidder	Processor	Loader
*Feller-buncher	Skidder	In-field chipper	In-field chipper
**Harvester	Forwarder	NA	Forwarder
**Harvester	Forwarder	NA	Loader

Fig. 2. Harvester. Harvesters fell the trees, process them into logs and sort the logs in small piles.

Fig. 3. Forwarder. Forwarders are used to collect/ load logs into bins and extract them to roadside. At roadside, logs are stacked into piles.

Models for thinning operations developed with ALPACA

Productivity models in ALPACA, including those for thinning operations, are derived mainly from piece count studies but also from detailed time studies. In piece count studies, the number of trees, stems or logs produced in a certain period of time (e.g. one hour), along with their average volume, are recorded. These figures are then used to compute the productivity of harvesting equipment in m^3 or tonnes per productive machine hour (PMH). In this study, all delays that occurred during data collection were not considered as part of the productive time, which in harvesting studies, is referred as to PMH_0. Piece and count studies represent a quick way to estimate the productivity of a piece of harvesting equipment and system, as they can easily be replicated across a range of forest and operational conditions (Acuna et al., 2012). These data points can then be plotted and used to develop predictive models mainly by means of simple or multilinear regression techniques.

In the case of detailed time studies, the goal is to describe the relationship between the time required to perform a particular phase of work (time or work element) and the factors, e.g. tree volume, slope, tree form, etc.), influencing the work (Acuna et al., 2017). This relationship is usually expressed in the form of a simple or multilinear regression model. In addition, detailed time studies are used to compare the productivity of two or more different work methods and machines (Acuna, Kellogg, 2009). They provide elemental detail, can link results to site and operating conditions (e.g. piece size, terrain slope) and they can pinpoint inefficiencies.

Data in detailed time studies are recorded at cycle level and include all work elements in each cycle. In the case of harvesters, some common work elements collected during these studies are moving, positioning to cut a tree, felling, processing, clearing debris and travelling. Likewise, work elements for the forwarder include travelling empty, travelling loaded, loading and unloading. Once a regression model is developed for each work element, these are added up to get a model by cycle, which is then converted to a productivity model.

All time study data collected by the Australian Forest Operations Research Alliance (AFORA) in different case studies across Australia have been consolidated into a data base, which includes, among others, the time and location of data collection, machine type, place of data collection, site specifications (e.g. slope, average tree size, etc.) and measured machine productivity (from piece count or detailed time studies). The data base is the basis of general productivity-predicting models for harvesters and forwarders based on multilinear regression modelling included in ALPACA. For harvesters and forwarders, it is assumed that machine productivity is primarily a function of tree volume and extraction distance, respectively. Slope has been included as a productivity-reduction factor based on three classes including: <15%, from 15% to 25% and >25%. When working on ground slope varying from 15% to 25%, the productivity will drop by 15%, while for slopes exceeding 85%, the productivity is estimated to decrease by 25%. The productivity-predicting models are presented in tables and Excel-based graphs for further spatial analysis at a national level.

For determining the cost per tonne, hourly machine costs (AUD$/PMH) were obtained from ALPACA and AFORA's standard machine-costing models, which use standard costing methodologies used in harvesting studies (Miyata and Steinhilb 1981, Ackermann et al. 2014). The input parameters to calculate hourly costs in ALPACA are shown in Figure 4.

RESULTS

Harvester's productivity and cost prediction

For harvesters, the machine productivity as a function of tree volume (over bark) is presented in Equation 1:

$$\textit{Productivity}\ [m^3/PMH_0]=48.971*\textit{Tree volume}\ [m^3]^{0.6245} \qquad (1)$$

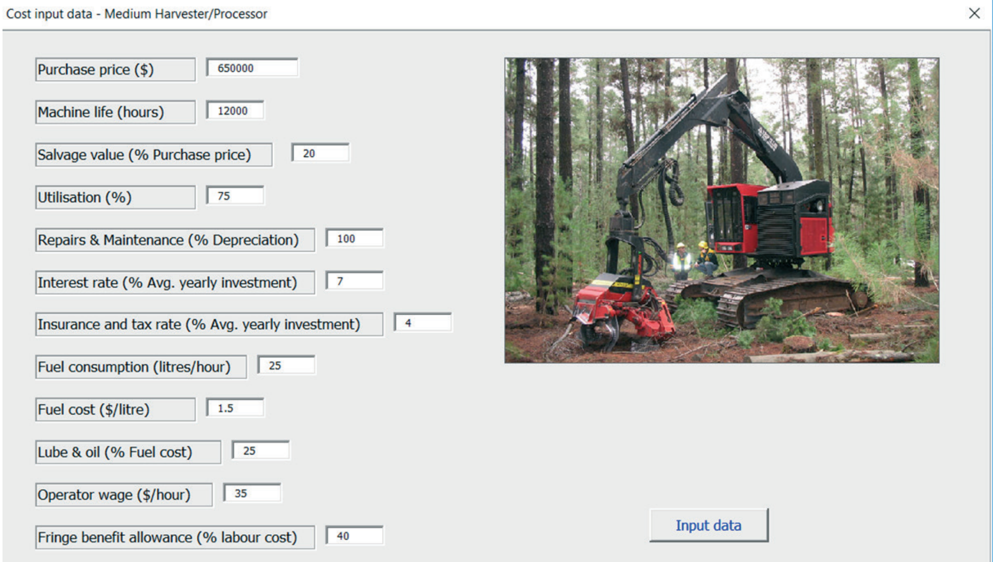

Fig. 4. Input parameters used in ALPACA to calculate machine hourly costs.

The predicted productivity and cost for felling and processing trees using a medium-sized harvester working on slopes less than 15% is presented in Table 3. Larger tree size will result in higher machine productivity and reduced costs. As an indicator, if tree size increases from 0.5 m^3 to 1.0 m^3 the machine productivity will increase from 32.1 m^3/PMH_0 to 48.2 m^3/PMH_0 (free delay productive machine hours), which consequently would drop the cost from 7.4 $\$/m^3$ to 4.9 $\$/m^3$ (34% cost reduction assuming an hourly cost of 236.9 $/PMH).

Table 3. Predicted productivity and cost of medium harvester in thinning operations (slope <15%) for different tree sizes.

Tree volume (m^3)	Predicted productivity (m^3/PMH_0)	Cost ($\$/m^3$)
0.1	11.4	20.7
0.5	32.1	7.4
1.0	48.2	4.9

Harvester productivity can also be impacted by slope. When harvesters work on steeper slopes (above 15%), the movement between trees and positioning the machine will require more time to be done safely, which will impact productivity negatively (Figure 5).

These models are implemented in the ALPACA tool (Figure 6). Additional factors (such as tree form, terrain and operator) can be included to adjust the productivity predictions made by the tool. In the figure, the bands correspond to variations in productivity of +-10% around the prediction curve.

Forwarder's productivity and cost prediction

Two general models are included in the ALPACA tool, one for small forwarders (14 t capacity) and one for large forwarders (20 t capacity). Large-sized forwarders (12-18 t capacity) are commonly used in Australian native forest thinning operations to transport some of the large trees that are removed during the operations (Acuna, Kellogg, 2009).

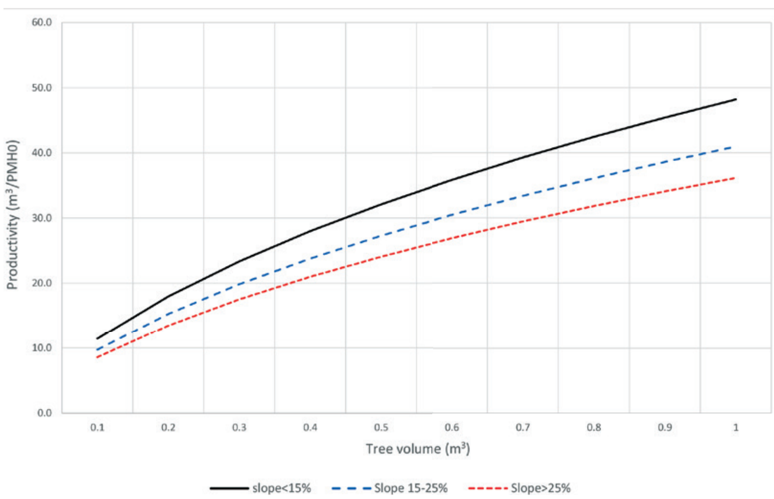

Fig. 5. Predicting harvester productivity depending on tree volume and ground slope.

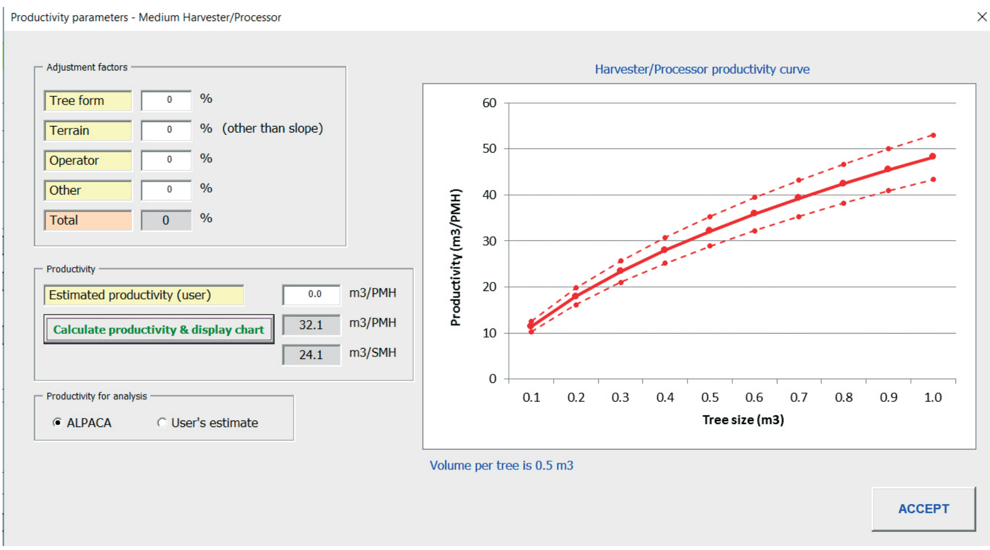

Fig. 6. ALPACA's Productivity model for harvesters in thinning operations.

Model small forwarders

$$Productivity\ [m^3/PMH_0]=44.32-2.72*LN(Extraction\ distance\ [m]) \qquad (2)$$

Model large forwarders

$$Productivity\ [m^3/PMH_0]=87.65/Extraction\ distance\ [m]^{0.126} \qquad (3)$$

Forwarding distance is the most significant factor impacting forwarder's productivity based on the model. Increasing forwarding distance increases the travel time of the machine, resulting in lower productivity for the forwarder. In addition, larger machines (20 t) have higher hourly operating cost than smaller machines (14 t) but can be more productive with larger load sizes.

Table 4 presents the summary of predicted productivity and cost of two forwarders for forwarding distances ranging from 100 m to 800 m on flat terrains (slope< 10%). From the table, the productivity and cost of a large forwarder for extracting logs at average distance of 100 m is predicted as 49.1 m^3/PMH_0 and 5.6 $\$/m^3$, respectively. As extraction distance increases to 400 m the productivity is reduced by up to 16% (41.2 m^3/PMH_0) increasing the cost to 6.7 $\$/m^3$.

Slope of forwarding trails may impact the travelling time between the stand and road side (landing). When forwarding on ground with slope increasing from 10% to 20%, the productivity drops by up to 75% and up to 85% as slopes increase beyond 20%. Figures 7 and 8 illustrate the impact of forwarding distance on the productivity of forwarders for three different slope classes.

Table 4. Estimating productivity and cost of forwarders in thinning operations (slope <10%) for different forwarding distances.

Forwarding distance (m)	Predicted productivity for small forwarder (m^3/PMH_0)	Predicted productivity for large forwarder (m^3/PMH_0)	Cost ($\$/m^3$) for small forwarder	Cost ($\$/m^3$) for large forwarder
100	31.8	49.1	7.4	5.6
200	29.9	45.0	7.9	6.1
300	28.8	42.7	8.2	6.4
400	28.1	41.2	8.4	6.7
500	27.4	40.1	8.6	6.9
600	26.9	39.1	8.8	7.0
700	26.5	38.4	8.9	7.2
800	26.2	37.8	9.1	7.3

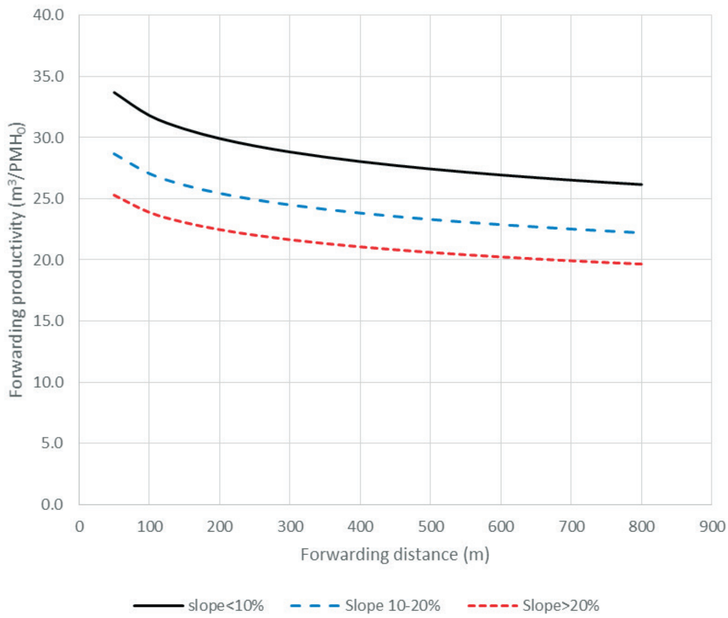

Fig. 7. Predicting productivity of small forwarders, depending on forwarding distance and ground slope.

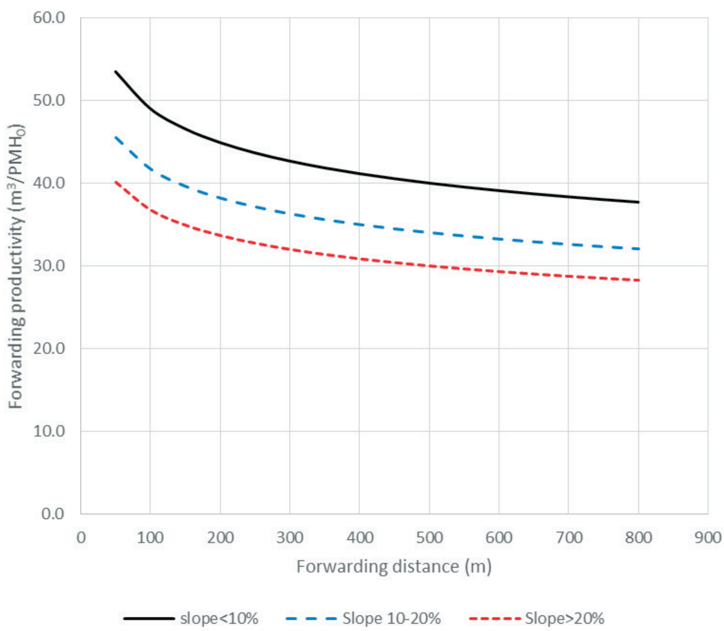

Fig. 8. Predicting productivity of large forwarders, depending on forwarding distance and ground slope.

DISCUSSION

The harvester productivity models in this study are based around the most common productivity-influencing variable for harvesters: tree size. Consistent with previous studies, the developed model shows a non-linear increase in productivity with increasing tree size (Kärä et al., 2004; Visser, Spinelli, 2012; Walsh, Strandgard, 2014; Ghaffariyan et al., 2015; Baek et al., 2017; Acuna et al., 2017). Given the shape of the harvesting productivity model and the fact that it shows an ongoing increasing trajectory, it is understood that the tree sizes included in the study area were well within the technical limits of the harvester.

The difference between predicted productivity in this general model versus other studies is likely influenced by the range of tree sizes included in the study area, tree form, operator experience and other site conditions, e.g. slope and roughness. Because forking of the stem did not present as a significant variable, like it did in the Acuna et al. (2017) case study, it is expected that the trees in the trial had significantly better form with less forking of the stems present. Given there were no specific issues observed during the study, operator experience and terrain conditions re likely to have had minimal, if any impact on the general model.

The productivity-predicting model of forwarders in this study is consistent with other studies (Tufts, Brinker, 1993; Kuitto et al., 1994; Nurminen et al., 2006) where extraction distance was used as an independent variable. As expected, increasing distance resulted in increased extraction time and reduced productivity. The predicted productivity for small forwarder falls within the range (from 8 to 36 m^3/PMH_0) reported by previous studies (Gullberg, 1997; Martin dos Santos et al., 1995; Saunders, 1996; Geolia et al., 1999; Horvat et al., 1990; Cordeo et al., 2006, Baek et al., 2017).

The productivity predicted by model for large forwarders is slightly higher than published international studies, which might be due to the larger size of machine (or other opreational factors, such as larger load volume, flatter terrains, etc.) assumed in our modelling. For both the small forwarders and the large forwarders, slope was found to have a significant impact on the productivity. For both, the productivity was typically reduced by 8 to 15 m^3/PMH_0 with the forwarder likely having to travel slower either due to climbing the reverse slope or to operate safely across the slope. The size of some of the trees removed during thinning operations in Australian native forests, calls for large-capacity (18-20 t) forwarders. These operations require careful planning to ensure productive and safe harvesting and extraction operations. Commercial thinning is normally conducted using an “outrow and bay” method. In this method, a whole row (~4.5 m strip) or access track is removed. For ease of working, thinning machinery often requires that outrows are at right angles to the contour. In natural regrowth, outrows are a maximum of 4.5. m wide and bays a minimum of 12 m wide (Acuna, Kellogg, 2009).

The general productivity-predicting models in this study are useful tools to harvesting managers and contactors for controlling and predicting the forwarders’ and harvesters’ productivity (and cost) in their operations. The size of the machine (forwarder studied in this trial) would impact the productivity and cost which needs to be considered by industry users in operation planning. Care should be taken because these predicting-productivity models were developed based on limited time studies. There is an error of estimation of regression models which needs to be considered when applying these models. In addition, to the error of regression models, the models' application should be limited to the range of the parameters (tree size, extraction distance, etc.) used in this study. If operations/stands conditions are different, one would need to collect further time study data and update the predicting models to match with the working conditions.

CONCLUSIONS

The results of this study indicated that statistically it is possible to merge different time study data to develop a general model. The general models, developed for predicting productivity of harvesters and forwarders, were significant and provided consistent and reasonable outcomes. These models could be used for benchmarking work productivity of similar harvesting operations in Australia. In addition to tree size and forwarding distance, the slope factor was added to the developed models, which may be useful for industry users operating in various terrains.

REFERENCES

ABARES (Australian Bureau of Agricultural and Resource Economics and Sciences). 2013. Australia's state of the forests report – executive summary. Canberra: Department of Agriculture, ABARES, 12 pp.

Ackerman, P., H. Belbo, L. Eliasson, A. De Jong, A. Lazdins, J. Lyons. 2014. The COST model for calculation of forest operations costs. International Journal of Forest Engineering, 25 (1), 75-81. Available from: http://www.forestenergy.org/pages/costing-model-machine-cost-calculation/

Acuna, M., M. Bigot, S. Guerra, B. Hartsough, C. Kanzian, K. Kärhä, O. Lindroos, N. Magagnotti, S. Roux, R. Spinelli, B. Talbot, E. Tolosana, F. Zormaier. 2012. Good Practice guidelines for biomass production studies. Cost Action FP-0902 WG2 Operations research and measurement methodologies. Publisher: CNR IVALSA, ISBN 978-88-901660-4-4, 51 pp.

Acuna, M., L. ellogg. 2009. Evaluation of alternative cut-to-length harvesting technology for native forest thinning in Australia. – International Journal of Forest Engineering, 20, 19-27.

Acuna, M., M. Strandgard. 2017. Impact of climate change on Australian forest operations. – Australian Forestry, 80 (5), 299-308.

Acuna, M., M. Strandgard, J. Wiedemann, R. Mitchell. 2017. Impacts of Early Thinning of a *Eucalyptus globulus* Labill. – Pulplog Plantation in Western Australia on Economic Profitability and Harvester Productivity. Forests, 8, 145. DOI:10.3390/f8110415.

Akay, A., J. Sessions. 2001. Minimizing road construction plus forwarding costs under a maximum soil disturbance constraint. – The International Mountain Logging and 11th Pacific Northwest Skyline Symposium, December 10-12, Seattle, Washington, USA, 268-279.

Baek, K-G, J. Bisson, H.-S. Han. 2017. Productivity and Cost of a Cut-To-Length commercial thinning operation in a Northern California Redwood Forest. – In: Proceedings of the Council of Forest Engineering 2017 Annual Meeting, July 30-August 2, 2017, Bangor, Maine, USA.

Cordero, R., O. Mardones, M. Marticorena. 2006. Evaluation of forestry machinery performance in harvesting operations using GPS technology. – In: Symposium Proceedings IUFRO Precision Forestry Symposium, Stellenbosch, 163-173.

Goglia, V., D. Horvat, S. Sever. 1999. Technical characteristics and test of the forwarder Valmet 860 equipped with a Cranab 1200 crane. University of Zagreb, Faculty of Forest Sceince, Internal Report, Zagreb, 23 pp.

Ghaffariyan, M. R., M. Brown. 2013. Selecting the efficient harvesting method using multiple criteria analysis: A case study in south-west Western Australia. – Journal of Forest Science, 59 (12), 479-486.

Ghaffariyan, M. R., J. Sessions. 2012. Comparing the efficiency of four harvesting methods in a blue gum plantation in south-west Western Australia. CRC for Forestry. Bulletin 29, 4 pp.

Ghaffariyan, M. R., J. Sessions, M. Brown. 2012. Machine productivity and residual harvesting residues associated with a cut-to-length harvest system in southern Tasmania. – Southern Forests: a Journal of Forest Science, 74 (4), 229-235.

Ghaffariyan, M. R., K. Stampfer, J. Sessions. 2007. Forwarding productivity in Southern Austria. – Croatian Journal of Forest Engineering, 28 (2), 169-175.

Glode, D. 1999. Single- and double-grip harvesters – productive measurements in final cutting of shelterwood. – International Journal of Forest Engineering, 10, 63-74.

Goglia, V., D. Horvat, S. Sever. 1999. Technical characteristics and test of the forwarder Valmet 860 equipped with a Cranab 1200 crane. University of Zagreb, Faculty of Forest Sceince, Internal Report, Zagreb, 23 pp.

Gulberg, T. 1997. Time consumption model of off-road extraction of shortwood. – Institutionen foer Skogsteknik, Sveriges Lantbruksuniversitet, Uppsatser och Resultat, 297, 29 pp.

Hanell, B., T. Nordfjell, L. Eliasson. 2000. Productivity and costs in shelterwood harvesting. – Scandinavian Journal of Forest Research, 15, 561-569.

Horvat, D., V. Goglia, S. Sever. 1999. Technical characteristics and test of the forwarder Timberjack 1410 and Timberjack 1710. University of Zagreb, Faculty of Forest Science, Internal Report, Zagreb, 32 pp.

Hossain, M. M., E. D. Olsen. 1998. Comparison of commercial thinning production and costs between silvicultural treatments, multiple sites, and logging systems in Central Oregon. – In: Proceedings of the Council of Forest Engineering 1998 Annual Meeting, 19-23 July 1998, Portland, Oregon.

Kärä, K, Ö. Rönkk, S. Gumse. 2004. Productivity and cutting costs of thinning harvesters. – International Journal of Forest Engineering, 15 (2), 43-56

Kellogg, L. D., P. Bettinger. 1994. Thinning productivity and cost for a mechanized cut-to-length system in the Northwest Pacific Coast region of the USA. – International Journal of Forest Engineering, 5, 43-54.

Kellogg, L. D., B. D. Spong. 2004. Cut-to-length thinning production and costs: experience from the Willamette Young Stand Project. Research Contribution 47. Corvallis: Forest Research Laboratory, Oregon State University.

Kuitto, P. J., S. Keskinen, J. Lindroos, T. Oijiala, J. Rajamaeki, T. Rasanen, J. Terava. 1994. Mechanized cutting and forest haulage. – Mestaeteho Report, 410, 38.

Martin dos Santos, S., C. Machado, H. Leite. 1995. Techno-economical analysis of eucalyptus extraction with forwarder in flat terrain. – Revista Arvore, Vicosa 19 (2), 213-227.

Miyata, E. S., H. S. Steinhilb. 1981. Logging system cost analysis: comparison of methods used. USDAForest Service Research Paper NC-208. North Central Forest Experiment Station, St. Paul, MN.

Nurminen, T., K. Heikki, J. Uusitalo. 2006. Time consumption analysis of the mechanized cut-to-length harvesting system. – Silva Fennica, 40 (2), 335-363.

Rottensteiner, Ch., G. Affenzeller, K. Stampfer. 2008. Evaluation of the feller-buncher Moipu 400E for energy wood harvesting. – Croatian Journal of Forest Engineering, 29, 117-128.

Spinelli, R., P. M. Owende, S. M. Ward. 2002. Productivity and cost of CTL harvesting of Eucalyptus globulus stands using excavator-based harvesters. – Forest Products Journal, 52 (1), 67-77.

Saunders, C. 1996. West Argyll Valmet 890 forwarder trial 1996. Forestry Commission Research Division-Technical Development Branch, Internet Project Information, Note 7/96, 9 pp.

Spinelli, R., P. Owende, S. Ward, M. Torneo. 2003. Comparison of short-wood forwarding systems used in Iberia. – Silvia Fennica, 38 (1), 85-94.

Tufts, R. A., R. W. Brinker. 1993. Productivity of Scandinavian cut-to-length system while second thinning pine plantations. – Forest Product Journal, 43 (11-12), 24-32.

Turner, D. R., H. S. Han. 2003. Productivity of a small cut-to-length harvester in northern Idaho, USA. – In: Proceedings of the 2003 Annual Council of Forest Engineering Meeting, 7–10 September 2003, Bar Harbor, Maine. UK Forestry Commission. 1995. Terrain classification. Technical, Note 16/95, 5 pp.

Visser, R., R. Spinelli. 2012. Determining the shape of the productivity function for mechanized felling and felling-processing. – Journal of Forest Research, 17, 397-402.

Walsh, D., M. Strandgard. 2014. Productivity and cost of harvesting a stemwood biomass product from integrated cut-to-length harvest operations in Australian *Pinus radiata* plantations. – Biomass and Bioenergy, 66, 93-102.

E-mail: mghaffar@usc.edu.au