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Production Rates of Mechanized Tree Felling Operations at Sao-Hill Forest Plantation, Tanzania

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ABSTRACT

With the advancement of technology in forest operations, utilization of advanced machines in timber harvesting has been increasing in the last decades. However, in order to understand their contribution in harvesting operations, it is important to quantify their production rates. The findings will assist the development of timber harvesting plans. Therefore, this study was conducted at Sao-Hill Forest Plantation in Tanzania to determine time consumption and production rates of whole tree harvesting system using feller buncher. Regression models for predicting time consumption and production rates were also developed. The results showed that average productive felling time was 0.7 minutes per tree and production rates was 32.6 m^3/h respectively. The production rates varied among tree size classes. For trees with diameter at breast height (*dbh*) of 10-19.9 the average production rates was 19.07 m^3/h while for *dbh* class of 30-39.9 the production rate was 75.48 m^3/h. Time consumption and production rates models were having Adjusted-R^2 of 50% and 56 % respectively. Their relative root mean square errors (RMSEr), computed based on the predictions from 10 - fold across validation results, were 28.69% and 45.37%, respectively. Applicability of the models should be limited within the ranges from which they have been developed.

Key words: Forest operations - whole tree - feller buncher – productivity - regression models.

INTRODUCTION

Timber harvesting operation includes all the activities to fell trees and remove them from the forest to the roadside for loading, and transport from the forest (Sessions *et al*. 2007). In the past most of these activities were done using manual and semi mechanized based methods (Dykstra 1983, Migunga and Kabuka 1996, Silayo *et al*. 2010, Ghaffariyan 2021). But in the recent decades, the use of mechanized timber harvesting operations has increased globally (Bilici *et al*. 2019), where feller bunchers, harvesters and grapple skidders have been used for felling and skidding operations (Mauya *et al*. 2011b, Gülci *et al*. 2021). The increasing use of mechanized based timber harvesting methods is mainly due to its superiority over manual and semi mechanized operations in terms of production, worker safety and less waste (Kärhä et al. 2005, Bilici *et al*. 2019, Gülci *et al*. 2021). However, mechanized harvesting is a costly operation that should be well planned and managed efficiently. Thus, estimating equipment productivity based on a time and motion study can assist logging managers to effectively plan their mechanized harvesting operations (Bilici *et al*. 2019). This had attracted interests among researchers to study and quantify production rates and costs of mechanized timbers harvesting machines in order to plan cost-effective mechanized systems and to make the right selection of equipment for optimal operational efficiencies (Miyajima *et al*. 2021).

Furthermore, in forest operations management there has been a tradition to develop and refine productivity prediction models over time. This is because prediction models are generally based on empirical data, which are often varying depending on methodology and required precision. As such developing new models is an important aspect in management of timber harvesting operations and machineries. Accurate models may also be utilized in different kinds of simulations that aim to find new or more efficient work methods, optimize complete operations or develop machines that are more efficient. However, majority of studies on modelling and predictions of mechanised timber harvesting productivity (e.g. Strandgard and Mitchell 2010, Bilici *et al*. 2019, Gülci *et al*. 2021, Miyajima *et al*. 2021) are from global north where there is high adoption and applications rates of these technologies. But in the global south, particularly in the sub Saharan Africa, there is limited number of studies which have attempted to quantify operational efficiency of mechanized timber harvesting operations, irrespective of preliminary use in some countries like Tanzania and Malawi (e.g. Mauya *et al*. 2011b, Ngulube *et al*. 2014)

Considering that the productivity and efficiency of these machinery is affected by local based factors such as forest stand characteristics, terrain variables, operator skills and machine limitations, development of predictive models is apparently important for accurate estimation of production rates and operational costs for timber harvesting operations in a given environment and economic condition. Therefore, identifying the factors that may interfere with the productivity—and, consequently, the cost—of the felling operation is crucial, because these wood harvesting costs represent a considerable share of the final product cost (Melemez *et al*. 2014, Schweier *et al*. 2019), and are essential for achieving economic balance within the operation (Cambero and Sowlati 2014).

The present study was conducted at Sao Hill Forest Plantation in Tanzania where mechanized timber harvesting operations using feller buncher is being applied since the early 2000s. However, to date there are limited number of studies which have attempted to quantify the productivity and costs of these advanced machines. More specifically the study intended to: 1) determine the time consumption and productivity of feller buncher; 2) develop and validate statistical models for predicting time consumption and production rates of feller buncher.

MATERIALS AND METHODS

Study area

This study was conducted at Sao Hill forest plantation (SHFP) located in Mufindi District, Iringa Region within the Southern highlands of Tanzania (Figure 1a). SHFP is the largest forest planation in the country, which accounts over 55% of the total planted area of the government forest plantations. This forest is the supplier of round woods to, among others, Sao Hill Sawmills Limited and Mufindi Paper Mill Company. Geographically SHFP is located between 8˚ 18'S to 8˚ 33'S and 35˚ 06'E and 35˚ 06'E with an altitude ranging from 1,700m to 2,000m above the sea level. Large part of plantation is located within the Mufindi circle road, Tazama Highway and the little in Ruaha River. Administratively, SHFP is divided into four blocks or divisions, namely; Irundi (1), Ihefu (2), Ihalimba (3) and Mgololo (4) (Figure 1 b). This study was conducted at Irundi block i.e., division 1 (Figure 1 c).

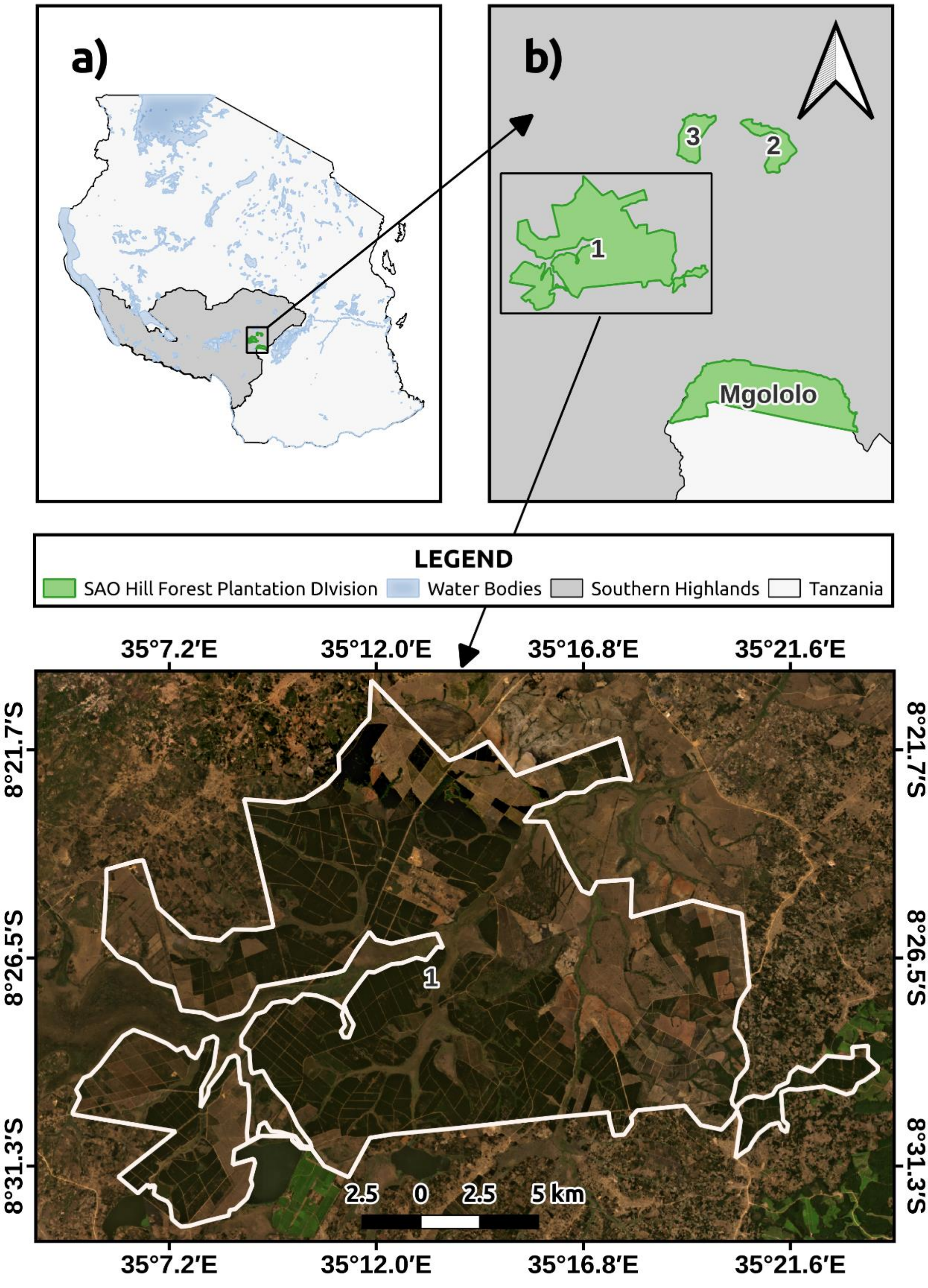

Figure 1. a) Location of SHFP in Tanzania, b) administratively divisions of SHFP, and c) location of division 1, the study area.

Climate

The rainfall pattern in Mufindi district and at SHFP is unimodal with single rainy season from November through May and a dry season during the rest of the year. The area receives between 600 mm to 1,300 mm of rainfall annually. Temperatures are fairly cool, reaching close to freezing point between June and August. The mean monthly minimum and maximum temperatures are 10 °C and 23 °C respectively.

Vegetation

The natural vegetation is characterized by mosaic of open grassland with scattered trees and shrubs dominated by species such as *Brachystegia* and *Jubernadia*. Other species include *Erythrina*, *Parinari cussonia*, *Apodytes* and *Albizia*. The exotic tree species planted in the area include *Pinus patula*, *Pinus elliottii*, *Eucalyptus maidenii*, *Eucalyptus saligina* and at small-scale *Cupressus lusitanica*.

Data collection

In this study feller buncher was used for performing felling in the *pinus patula* plantation. Three types of data were collected: Time consumption, tree variables and topographical data.

Time consumption data

Time and motion studies techniques described by Scott (1973), (Magagnotti *et al*. 2013), were used to record and collect data on work place time (WPT), which essentially refers to the time spent in performing a task at the workplace. It is made up of productive or effective time (i.e., work elements contributing directly to production) and delay times (i.e., interruptions in the working cycle). Delays were further subdivided into necessary delay (inevitable interruption due to the nature of the work) and unnecessary delays (those which could theoretically be eliminated by improved supervision and training). Delays were recorded together with the work element during which they occurred in each of the logging operations by stopwatch. Timing was started at the beginning of each work-element and the stopwatch was snapped back to zero at the end of the work element, elapsed time was read directly from the stop watch and recorded on the study form. The section below explains in detail how the work elements of the feller buncher machinery was referred to in this study.

i. **Moving to tree**: starts when the feller-buncher finishes the previous cycle and begins moving to the next tree to be cut and ends when forward movement has stopped.

ii. **Cutting**: begins when the cutting head is positioned on the tree, cuts and ends when the tree is completely severed from the stump.

iii. **Moving to dump**: begins when the feller-buncher moves from the stump area with the felled tree and ends when movement is stopped at the dumping site.

iv. **Dumping**: begins when movement to dump has stopped and the felled tree is tilted by the felling head into dump position and ends when the tree or tree bunch hits the ground.

v. **Delay times**: This was classified into necessary and unnecessary delays. Necessary delays included the following times: brushing around the tree, freeing the feller buncher saw head when it became pinched and cooling the machine. These were the times related to the continuation of the immediate operations. Unnecessary delays were those delays that were judged to be avoidable and thus could be eliminated by improved supervision and training. Unnecessary delays included times such as taking unauthorized rest breaks, talking to persons not directly involved in production process through mobile phone or any other means and giving instruction to feller buncher operator.

Finally, total felling time was obtained as the summation of time consumption for all the individual work elements. On other hand Productive Machinery Hourly (PMH), was obtained as the summation of the productive time of all the work elements, excluding the delays. The descriptive statistics for each of the work elements as well as the PMH are presentment in Table 1.

Table 1. Summary statistics for time consumption of different work elements independent variables

Work elements	Statistics parameter			
	Minimum	**Maximum**	**Mean**	**Standard deviation**
Moving to tree	0.07	0.82	0.35	0.16
Cutting	0.002	0.10	0.03	0.02
Moving to dump	0.05	0.67	0.28	0.15
Dumping	0.02	0.08	0.03	0.01
Necessary delay	0.00	15.00	0.10	0.97
Unnecessary delay	0.00	2.00	0.02	0.14
Total Work Place Time	0.22	1.41	0.70	0.27
Total time including delays	0.2	16.2	0.80	1.0

Single tree variable data

Prior to felling operations, each of the tree identified for felling was measured for stump Diameter and Diameter at breast height (Dbh) using diameter tape. Likewise, for each of the tree, total tree height (height) was measured using clinometer. *Dbh* and total tree height were then used to compute total tree volume (vol) using the equation by Malimbwi *et al*. (2016).

$$vol = exp(-9.04925 + 1.14781 \times \ln(height) + \ln(dbh)) \qquad (1)$$

Topographical variables

Distance to tree, distance to and slope were the only topographical variable which were recorded. Distance was measured using measuring tape and slope was measured using clinometer. Summary statistics of the independent variables are presented in Table 2.

Table 2. Summary statistics for key independent variables

Variable	Statistics parameter			
	Minimum	Maximum	Mean	Standard deviation
Dbh (cm)	10.00	32	19.97	4.86
Height (m)	15.88	18.00	16.83	0.38
Stump diameter (cm)	13.00	35.86	23.40	5.03
Distance to tree (m)	2.00	41.00	17.56	8.5
Distance to dump (m)	5	50	21.05	9.52
Slope	0.00	0.04	0.03	0.01

Statistical analyses

Feller buncher production rates were estimated using two approaches. In the first case, production rates were computed based on the total cycle time (i.e., including necessary delays). In the second case, the computation considered only PMH (i.e., delay free cycle time). Equations 2 and 3, were used to compute the two types of production rates, respectively. A paired t-test between the production rates with and without necessary delays were employed for testing the significance impact of delays on the production rates of the feller buncher.

$$P_{\text{With delays}} = \frac{(T_{vol})(F)(60)}{T} \qquad (2)$$

Where $P_{With\ delays}$ is production rates (m^3/h), T_{vol} is total tree volume harvested per cycle, T is total cycle time, *F* proportional measuring productive minutes per work place hour, where:

$$F = \frac{100 - D}{100} \qquad (3)$$

D is delay time expressed as percentage of workplace time %. In the second case, productivity was estimated using equation 3 following the approach described by Sessions *et al*. (2007), (Gülci *et al*. 2021, Miyajima *et al*. 2021):

$$P = \frac{(T_{vol})(60)}{PMH} \quad (3)$$

Where P is the production rates in m^3/ha, 60 is used to convert the time from minutes to hours and PMH is the productive machine hour (i.e., delay free).

Model development

Production rates models were developed using the variables selected based on the past studies (e.g. Li *et al*. 2006, Strandgard and Mitchell 2010, Mauya *et al*. 2011a, Bilici *et al*. 2019), logging literatures, as well as on initial testing of all the possible combination of tree and terrain variables. Models relating PMH time as well as production rates with candidate predictor variables were developed using ordinary least square regression (OLS). This approach had commonly been widely applied in feller buncher based studies (Wang *et al*. 2004, Strandgard and Mitchell 2010, Mauya *et al*. 2011b, Bilici *et al*. 2019, Gülci *et al*. 2021, Miyajima *et al*. 2021), with promising results. Thus, in this study it was also adopted considering that, similar types of variables were used in the model fittings. Only PMH and production rates without delays were considered in modelling processes. The standard form of the OLS model as applied in this study is:

$$y_j = \beta_0 + \beta_1 x_{j1} + \cdots + \beta_2 x_{jk} + \varepsilon_j \quad (4)$$

Where y_j stands for either, total PMH (min) or production rates in m^3/h. In fitting the OLS models for both time consumption and production rates, the selected best subsets of the variables were further assessed based on their significance (i.e., $p<0.05$) and variance inflation factor (VIF). Predictor variables with VIF value greater than ten (Soman *et al*. 2019) were considered to be an indicative of multicollinearity, that might give cause of concern on the quality of the parameter estimates. Thus, such variables were trimmed from the model. As part of model fitting procedure, adjusted-R^2 was also calculated and residual diagnostic plots were further examined for each of the fitted model.

Model validation

According to Howard (1992), the utility of production equations is questionable when they are published without documented validation. In this study, to enable comparison of the precision and accuracy of our models with other studies and to understand the model's performance on other datasets, the models were cross-validated. Ideally, the independent datasets of the model validation should be drawn from the population in which the model will be applied. However, due to the limitations in field data availability in this study area, *ten*-fold cross validation was implemented. The ten-fold cross-validation involves splitting the dataset into ten-subsets. In each fold, one subset is held out for checking the model performance (i.e., the validation set), while the model is trained on all other subsets (i.e., nine) (James *et al*. 2013). The process is done repeatedly until all the subsets have been used once as the validation dataset. The predicted values from all the folds were finally compiled into a table and used to estimate root mean square error (RMSE) and its relative value (RMSEr) , which were then computed using the equations below:

$$RMSE = \sqrt{\sum_{I=1}^{n} \frac{(y_i - \hat{y}_i)^2}{n}} \quad (5)$$

and

$$RMSE_r = \frac{RMSE}{\bar{y}} \times 100\% \quad (6)$$

Where y_i and $\hat{y}$ denote field observed and predicted time consumption or production rates for observation i, respectively, and $\bar{y}$ denotes mean field observed time consumption or production rates for all work cycles observations.

RESULTS

Time consumption

A total of 535 feller buncher cycles were observed over the entire period of the study. Total work place time i.e., felling time without delays, ranged from 0.22 to 1.4 minutes with the average of 0.7 minutes.

When necessary delays is included the total felling time per tree ranged from 0.22 to 16.23 minutes with the average of 0.8 minutes. Among the work elements, moving tree consumed a substantial part of total felling time for about 50% of the total work place time and 45% of the total time.

Production rates

Production rates were estimated using the two approaches described in the methodology. In the first approach, when considering the PMH only, the minimum production rate was 6.7 m^3/h and maximum was 156.8 m^3/h, with an average of 32.6 m^3/hr. In the second approach, when including the necessary delays the minimum production rate was 1.0 m^3/h and maximum was 141.2 m^3/h, with the average of 29.0 m^3/h. A paired t test results, indicated that there is significance deference's between the two approaches ($p<0.05$). The results showed further that, for both of the approaches the production rate was higher for the trees in the Dbh Class of 30-39.9, where for the first approach the average production rate was 84.77 m^3/h and for the second approach was 75 m^3/h respectively (Figure 2).

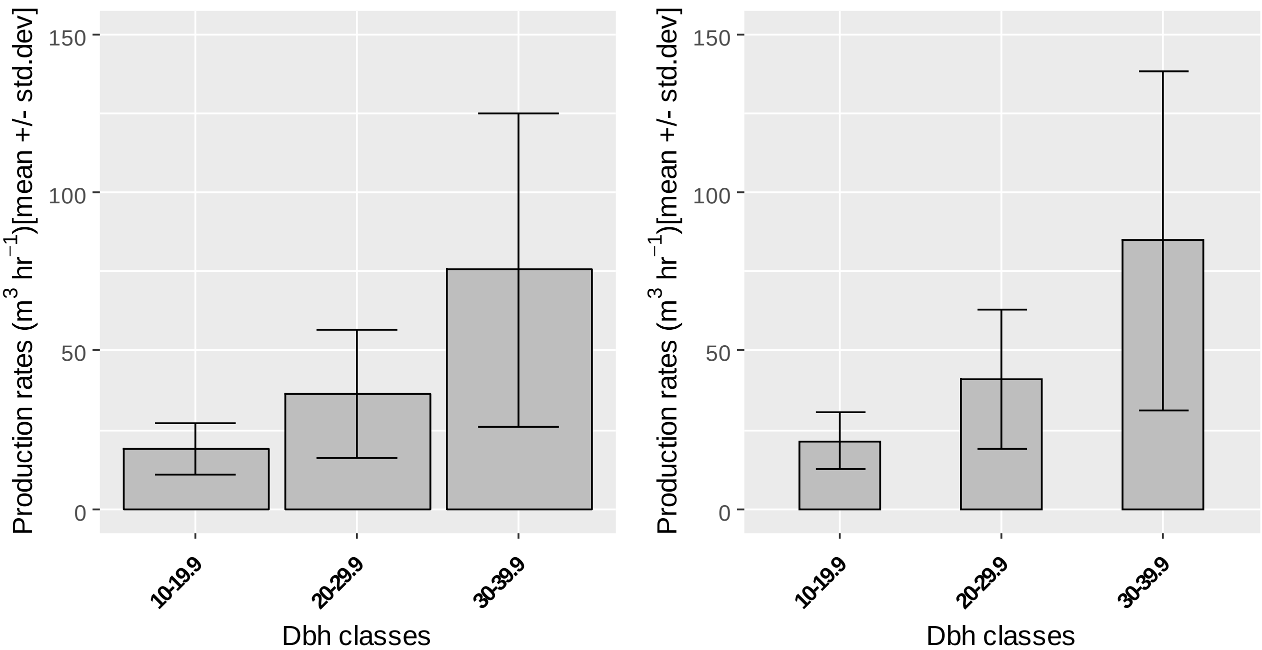

Figure 2. Error bars for, a) production rates with delays across different Dbh classes, b) production rates based PMH across different Dbh classes.

Regression Models

Regression models for predicting PMH and production rate were developed. The independent variables used for developing the models varied by types and number. For all the models, the number of variables varied between two and three. The parameter estimates of the models were significantly different from zero ($p < 0.05$) and the VIF values were <5 indicating acceptable level of multicollinearity.

Time consumption models

Apart from the models for predicting total PMH, models for predicting time consumption for individual productive work elements were also developed (Table 2). These included, moving to tree, cutting, moving to dump and bunching/dumping. The variability explained (i.e., adjusted R^2) by the time consumption models varied among the productive work elements. The adjusted R^2 ranged from 24% for the dumping work element to 43% for the dumping/bunching.

Improvement in adjusted R^2 was observed for the total PMH, where the adjusted -R^2 was about 50%. Performance of the total PMH model was also shown through the residual plot (Figure 3a), which did not indicate any sign of funnel pattern. Furthermore, the cross validation results indicated that the RMSEr value for PMH model was relatively smaller as compared to the individual work element models. However, the validation plots had shown a slightly pattern of over and under prediction for smaller and large values (Figure 3b).

Table 3. Time consumption models for individual work elements and entire work cycle

Work element	Time consumption model[a]	Adjusted R^2 (%)	RMSEr (%)
Moving to tree	$-0.0727 + 0.011DS_{tree} + 7.775Slope$	38	35.1
Cutting	$-0.019 + 0.472Slope + 0.002Dbh$	35	41.7
Moving to dump	$-0.0592 + 3.807Slope + 0.01DS_{dump}$	43	40.10
Dumping	$0.0018 + 0.0001DS_{dump} + 0.0014Dbh$	24	38.30
Total productive machinery hours	$\mathbf{-0.0916 + 0.0133DS_{tree} + 0.0078DS_{dump} + 12.0Slope}$	**50**	**28.69**

[a]DS_{tree}= Distance to tree, DS_{tree} = Distance to dump

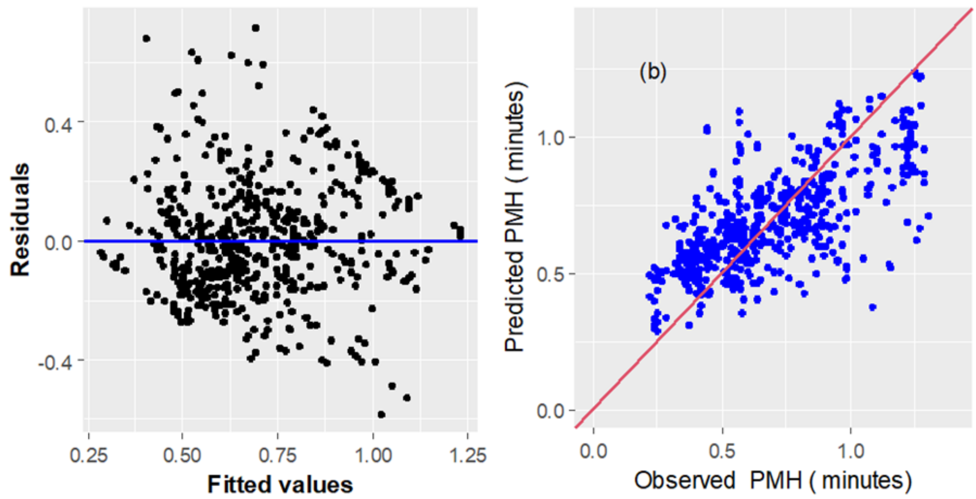

Figure 3. a) Residual plot of the PMH. (b) Relationship between observed and predicted PMH.

Production rate model

Dbh^2, distance to tree and slope appeared to the best predictors for production rates (P_{PMH}), based on the PMH when using feller buncher. The adjusted R^2 of the model (Equation 7) was 56% indicating a good fit. The residual plots showed slightly defined pattern, which was mostly caused by few observations with higher values (Figure 4a). The cross- validation results indicated that, RMSEr value for the production rate model was 45.37%. The RMSEr values were varying among the DBh classes indicating that tree size is a major criterion, which affect the production rates. The lowest RMSEr value was recorded in the class of 20.9-29.9 and the highest value in the class of 30.9-39.9 (Table 4).

$$P_{PMH} = 43.856 + 0.0698Dbh^2 - 1.215DS_{tree} - 589.437Slope \quad (7)$$

Table 4. Performance of the production rate model across tree Dbh classes

Dbh class	RMSE	RMSEr
10-19.9	8.65	40.54
20-29.9	16.09	39.16
30-39.9	49.21	58.05
All	14.83	45.37

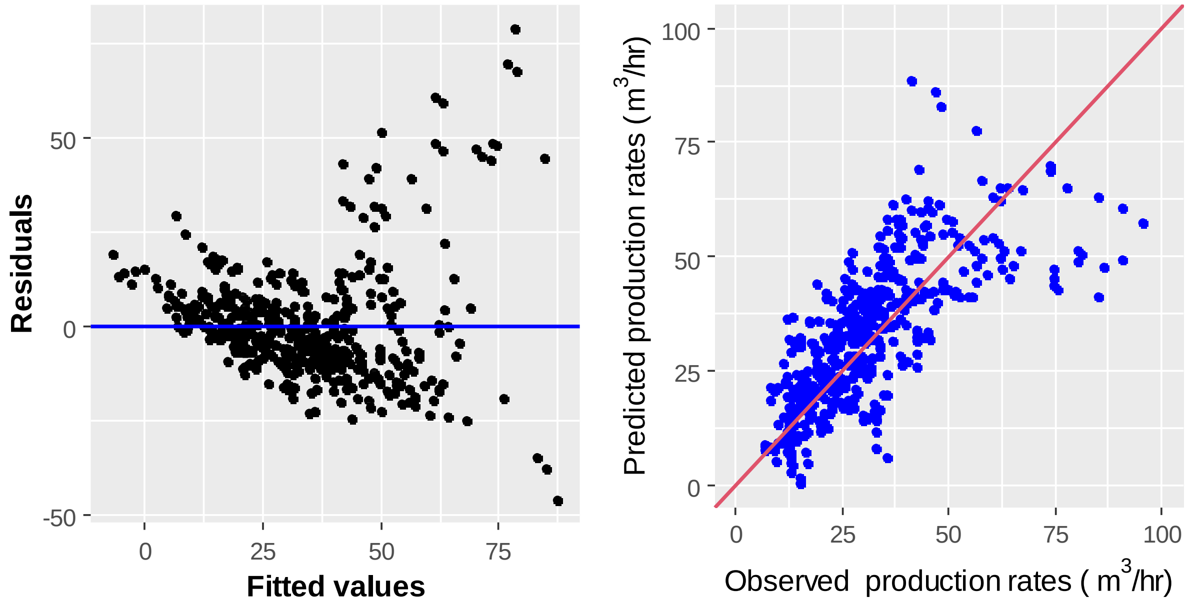

Figure 4. a) Residual plot for the production rate model. (b) Relationship between observed and predicted production rates.

DISCUSSION

The current study was conducted at SHFP in the southern highlands of Tanzania. The forest supplies substantial amount of harvested wood to forest industries in the southern highlands of Tanzania and nearby regions. Because of its potential, in supplying raw materials, a number of timber harvesting operations using different methods ranging from manual, semi-mechanized to mechanized have been tested and applied over decades. Since late 2000s, mechanized harvesting operations involving the use of heavy-duty machines such as feller buncher and grapple skidder have been applied for timber harvesting at SHFP (Mauya *et al*. 2011b). However, mechanized harvesting is a costly operation that should be well planned and managed efficiently (Melemez *et al*. 2014, Schweier *et al*. 2019). This requires detailed information on equipment productivity based on a time and motion studies which can assist logging managers to effectively plan their mechanized harvesting operations (Bilici *et al*. 2019, Miyajima *et al*. 2021). Thus, this study quantified time consumption and production rates of mechanized tree felling using feller buncher as well-developed predictive models for estimating time consumption and production rates of the feller buncher.

Analysis of the time consumption over the entire period of the study, indicated that average productive felling time for the feller buncher per tree was 0.7 minutes. This value is within the range of other studies conducted elsewhere. For example, Wang *et al*. (2004) reported an average felling time of 1.1min, while Long *et al*. (2002) reported an average total felling time of 1.41 min. The slightly difference in total felling time among studies may arise from a number of factors: which include stand conditions, working techniques, machinery type and operator experience. Also, the variations in methodological aspects like the work phases classification and variable definition of the measurement system may lead to variation in time consumption of the felling operation (Wang *et al*. 2004, Strandgard and Mitchell 2010, Mauya *et al*. 2011b, Bilici *et al*. 2019, Gülci *et al*. 2021, Miyajima *et al*. 2021). Furthermore, the statistical models for predicting total PMH resulted into better fits with adjusted R^2 of 50%. According to Dykstra (1976), typically values of R^2, a statistic which measures the fraction of response variable explained by the regression equation in most of the logging studies, is less than 0.5 and often less than 0.25. Thus, the adjusted-R^2 value obtained from this study, clearly indicate improvement in felling operations when using feller buncher.

Less time consumption in felling operations implies improvement in the production rates of the felling operations. The reported production rates under the approach that considered only PMH was relatively higher as compared to the approach that included delays. This implies that, effective elimination of delays in timber harvesting operations can have significant impact on the production rates. This is further justified by the results from the paired t- test which shown that, there signifance differences between the two approaches. The average production rate under the PMH approach was 32.69 m^3/h. This value is within the ranges of other studies reported elsewhere. For example, Long *et al*. (2002) conducted a time study to evaluate productivity and costs of feller buncher operating in central Appalachian hardwood forests. In their study, hourly productivity for feller-buncher ranged from 12.11 to 65. Gülci *et al*. (2021) reported average production rate of 74.96 m^3/h Turkey. The results from this study, further showed that tree size is a major factor which affect production rates of the feller buncher. In the lower Dbh classes the production rate was relatively smaller as compared to the middle and upper Dbh classes. For example, for the middle class the average production rates was 36.31 m^3/h and for the upper class was 75.48 m^3/h. Since 50% of the entire dataset comprised of the lower classes, production rate was relatively lower as compared to those reported by (Ghaffariyan *et al*. 2012, Simoes *et al*. 2014), Gülci *et al*. (2021). This implies that, in order to obtain higher production rates which are likely to offset costs for operating feller buncher consideration of the tree sizes to be harvested should be priority. Previous studies (e.g. Wang *et al*. 2004, Goychuk *et al*. 2011, Mauya *et al*. 2011b, Visser and Spinelli 2012, Bilici *et al*. 2019, Gülci *et al*. 2021, Miyajima *et al*. 2021), on feller buncher performance also reported that tree size is a main factor which affect the production rates of the feller buncher. The plausible reason for this could be that, as tree sizes increases in terms of Dbh, tree volume and production rate increase linearly. Apart from the tree sizes other factors which affect the production rates of the feller buncher include terrain (i.e., slope, ground strength and surface roughness), stand density and climatic conditions. For example, according to Conway (1986) if the ground slope exceeds 35% feller buncher loses efficiency to the point of making an operation infeasible. Steep topography also provides conditions, which tend to produce excessive tree breakage particularly when timber is felled downhill instead of along the contour. In this study, the ground slope was ranging from 0 to 4%, this created a favorable condition for improving the production rates of the models as well as estimates. The quality of the model fit as well as the prediction accuracy were within the range of other studies (e.g Long *et al*. 2002, Bilici *et al*. 2019, Gülci *et al*. 2021) reported elsewhere. However, the applicability of the models should take into accounts the ranges of predictor variables in which the models were developed to avoid uncertainty in the estimates of the production rates.

Based on the findings of this study, there is larger potential of improving the production rates of tree felling operations when using feller buncher as compared to conventional methods. Further studies particularly on cost aspects of feller buncher are highly encouraged in order to understand if the production rates offset the operational cost of the feller buncher. Furthermore, this study focused on small portion of clear-felling operations, it would be of interest if future study will focus on larger scales in order to have more observation as well as variations. Also, due to the technological and automation systems developed in harvesting machinery, possibility of incorporating the Internet of Things (IoT) for operational planning and logistics (Spinelli et al. 2020), according to the precision forestry approach, should be explored.

CONCLUSION

To conclude, this study had determined the time consumption and production rates of the feller buncher in tree felling operations. Two approaches for estimating production rates were compared, the findings concluded that the approach based on PMH was more efficient in the estimation of production rates. Additionally, the study developed models for predicting time consumption and production rates. The quality of the models as measured by the indicators of fits, were within the ranges of most of the reported studies. As such, the models can be used for predicting time consumption and production rates. Lastly, the study suggested that, future studies should look more on cost aspects of feller buncher in order to understand if the production rates offset the operational costs.

REFERENCES

Bilici, E., Akay, A. E. & Abbas, D. 2019. Assessing the effects of site factors on the productivity of a feller buncher: a time and motion analysis. Journal of forestry research 30:1471-1478.

Cambero, C., & Sowlati, T. 2014. Assessment and optimization of forest biomass supply chains from economic, social and environmental perspectives–A review of literature. Renewable and Sustainable Energy Reviews 36:62-73.

Conway, S. 1986. Logging Practice, Principle of Timber Harvesting System. MillerFreeman, USA, 416 pp.

Dykstra, D.P. 1976. Production rates and costs for yarding by cable, balloon, and helicopter compared for clearcuttings and partial cuttings.

Dykstra, D.P. 1983. World Forestry: Forestry in Tanzania. Journal of Forestry 81:742-746.

Ghaffariyan, M.R. 2021. Review of studies on motor-manual felling productivity in eucalypt stands. Silva Balcanica 22:77.

Ghaffariyan, M.R., Acuna, M. & Kellogg, L. 2012. Productivity of roadside processing system in Western Australia. Silva Balcanica 13:49-60.

Goychuk, D., Kilgore, M.A., Blinn, C.R., Coggins, J. & Kolka, R.K. 2011. The effect of timber harvesting guidelines on felling and skidding productivity in northern Minnesota. Forest Science 57:393-407.

Gülci, N., Yüksel, K., Gülci, S., Serin, H., Bilici, E. & Akay, A.E. 2021. Analysis of a feller-buncher productivity: a case study of whole-tree harvesting from Marmara region, Turkey. Annals of Forest Research 64:99-110.

Howard, A. 1992. Validating forest harvesting production equations. Transactions of the ASAE 35:1683-1687.

James, G., Witten, D., Hastie, T. & Tibshirani, R. 2013. An introduction to statistical learning. Springer.

Kärhä, K., Jouhiaho, A., Mutikainen, A. & Mattila, S. 2005. Mechanized energy wood harvesting from early thinnings. International Journal of Forest Engineering 16:15-25.

Li, Y., Wang, J., Miller, G. & McNeel, J. 2006. Production economics of harvesting small-diameter hardwood stands in central Appalachia. Forest Products Journal 56 (3): 81-86 56.

Long, C., Wang, J. McNeel, J. & Baumgras, J. 2002. Production and cost analysis of a feller-buncher in central Appalachian hardwood forest.in In: Proceedings, 25th annual meeting, forest engineering challenges a global perspective; 2002 June 16-20; Auburn, AL. Corvalis, OR: Council on forest engineering: 1-5.

Magagnotti, N., Kanzian, C., Schulmeyer, F. & Spinelli, R. 2013. A new guide for work studies in forestry. International Journal of Forest Engineering 24:249-253.

Malimbwi, R., Mugasha, W.A. & Mauya, E.W. 2016. Pinus Patula Yield Tables for Sao Hill Forest Plantations, Tanzania.

Mauya, E., Migunga, G.A., Kweka, A.E. & Silayo, D.A. 2011a. Productivity and cost analysis of grapple skidder at Sao Hill Forest Plantations, Tanzania. Tanzania Journal of Forestry and Nature Conservation 81:10-19.

Mauya, E., Migunga, G.A., Kweka, A.E. & Silayo, D.A. 2011b. Productivity and cost analysis of feller buncher at Sao Hill Forest Plantations, Tanzania. Tanzania Journal of Forestry and Nature Conservation 81:20-29.

Melemez, K., Tunay, M. & Emir, T. 2014. A comparison of productivity in five small-scale harvesting systems. Small-scale forestry 13:35-45.

Migunga, G., & Kabuka, S. 1996. Plantation timber harvesting management: A case study of Southern Paper Mill company woodlands Directorate. Management of Forest Plantations in Tanzania, Faculty of Forestry Record 63:215-218.

Miyajima, R.H., Fenner, P.T., Batistela, G.C. & Simões, D. 2021. Effect of Feller-Buncher Model, Slope Class and Cutting Area on the Productivity and Costs of Whole Tree Harvesting in Brazilian Eucalyptus Stands. Forests 12:1092.

Ngulube, E., Brink, M. & Chirwa, P.W. 2014. Productivity and cost analysis of semi-mechanised and mechanised systems on the Viphya forest plantations in Malawi. Southern Forests: A Journal of Forest Science 76:195-200.

Schweier, J., Magagnotti, N., Labelle, E. R. & Athanassiadis, D. 2019. Sustainability impact assessment of forest operations: A review. Current Forestry Reports 5:101-113.

Scott, A. 1973. Work study in forestry. Pages 26-39.

Sessions, J., Boston, K., Murphy, G., Wing, M., Kellogg, L., Pilkerton, S., Zweede J. & Heinrich, R. 2007. Harvesting operations in the Tropics. Springer.

Silayo, D.S.A., Kiparu, S.S., Mauya, E.W. & Shemwetta, D.T.K 2010. Working conditions and productivity under private and public logging companies in Tanzania. Croatian Journal of Forest Engineering: Journal for Theory and Application of Forestry Engineering 31:65-74.

Simoes, D., Fenner, P.T. & Tsutsui Esperancini. M. S. 2014. Productivity and costs of Beller-Buncher and forest processor in stands of eucalypts in first cut. Ciencia Florestal:621-630.

Soman, H., Kizha, A.R. & Roth, B.E. 2019. Impacts of silvicultural prescriptions and implementation of best management practices on timber harvesting costs. International Journal of Forest Engineering 30:14-25.

Spinelli, R., Magagnotti, N. & Lombardini, C. 2020. Low-investment fully mechanized harvesting of short-rotation poplar (populus spp.) plantations. Forests 11:502.

Strandgard, M., & Mitchell, R. 2010. Benchmarking feller-buncher productivity in Western Australian blue gum plantations. CRC for Forestry, Harvesting and Operations Bulletin 12, October 2010. University of the Sunshine Coast, Queensland.

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

Wang, J., Long, C. & McNeel, J. 2004. Production and cost analysis of a feller-buncher and grapple skidder in central Appalachian hardwood forests. Forest Products Journal 54:159.