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Modeling Productivity and Costs of Mechanized Tree Length Skidding Operations

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ABSTRACT

Skidding operation constitute the entire process of moving felled trees from the stump site to the roadside landing. This operation normally bears substantial amount of the mill delivery costs. Thus, detailed information on productivity and cost is important for planning of cost-effective skidding operation. This study was conducted at Sao hill Forest plantation to quantify productivity and costs of tree length skidding operations. Continuous time study technique using snap-back method was used for time recording. Costs data were obtained from Mufindi Paper Mill logging department. Productivity and costs modeling, were performed using Microsoft excel. The analysis, showed that; the average productivity of the grapple skidder using tree length (TL) ranges between 398.423 m^3/hr at a distance of 10 m and 49.862 m^3/hr at a distance of 80 m. On the costs analysis, the unit skidding costs tends to increase with an increase of skidding distance (m) from 512.197 TZS/m^3 at a distance of 10 m to 4,092.675 TZS/m^3 at a distance of 80 m. Based on these findings it is recommended that variables distance and volume are the core factors to consider during planning to enhance efficient and costs effective skidding operation.

Keywords: Skidding – mechanized logging – Productivity - Tree length – Sao Hill Forest Plantation.

INTRODUCTION

Timber harvesting or logging, comprises all technologies required to cut trees and transport logs from the stump area to a processing plant (Sessions *et al.* 2007). It is estimated that timber harvesting and transport costs constitute an estimated 50-70% of the mill-delivered costs (Laengin *et al.* 2010, Berg *et al.* 2014). Such high cost may reduce work efficiency and potentially lower profit. Effective planning of the operations can reduce costs and improve work efficiency but this requires detailed information on productivity and cost of different timber harvesting operation as part of the planning process (Williams and Ackerman 2016). Such information is also important for understanding the performance of harvesting machines and/or systems under varying stand and terrain conditions (Visser and Stampfer 1998, Visser and Spinelli 2012). In the forestry industry, there had been a long ongoing tradition of quantifying productivity and costs of harvesting operations under different environments as best way of improving operational planning (e.g. Lindroos *et al.* 2010, Eriksson and Lindroos 2014). However, a complete understanding of the productivity and costs of the timber harvesting operation requires a detailed understanding of its key operations, which make the entire system more improved (Silayo and Migunga 2013).

Wood harvesting is usually divided into three main interrelated phases (each with a number of sub-operations); cutting, terrain transport (short distance) and long-distance log transport. Since timber harvesting involves aggregates of components in order to accomplish an operation, it is therefore referred to as a system. Such system is often termed according to either the form in which the wood is transported or the method and equipment used or both (FAO 1976). When classifying based on the form of the tree in which the wood is harvested or the length of the log in which the wood is harvested, there are five main systems: cut to length (CL), tree length (TL), full-tree, whole-tree, and chipping system (Castro *et al.* 2014).

The TL skidding system including wood preparation such as felling and debranching (delimbing) is performed at the stump area while log cross cutting is normally done at the road side landing to make it ready for secondary transportation (FAO 1976, Adebayo *et al.* 2007). The CL has been the most widely practiced system given its advantage of requiring limited landing space as well as ease loading and transportation to the landing. Primary timber transportation from the stump area to the landing/road side under TL harvesting system is mainly conducted by animal and/or machine power i.e., by using tractors, skidders, cable yarding systems such as ground lead systems and skyline system.

In the recent decade there has been an increasing trend towards mechanization of the skidding operations given its advantage of higher productivity and cost effectiveness, as compared to labour intensive and semi mechanized methods (Mederski *et al.* 2010, Proto *et al.* 2018). A typical example of mechanized skidding operation is the use of grapple skidder. This skidder has globally been recommended in timber harvesting operations because of its ability to handle large loads, higher operating speeds, higher trafficability and higher productivity (Kluender *et al.* 1997, Mauya *et al.* 2011). To date there has been number of studies on productivity and cost of mechanized skidding operations using grapple skidders on a global scale (Mederski *et al.* 2010, Kulak *et al.* 2017) but far fewer studies have been conducted in the global south, though there is increasing adoption rates of the use of mechanized timber harvesting operational regional-wise. Furthermore, limited number of studies exists when considering mechanized log-length skidding operations at both global and regional scale. Given the difference in operating conditions caused by variations in stand, working conditions and terrain factors, it is important to quantify the productivity and cost of each form in order to select the best option which suit specific local condition while optimizing the profitability of the logging operation.

To our understanding, there is a considerable lack of data on the productivity and cost of mechanized skidding when using TL harvesting system in plantation forests of Tanzania. Moreover, in order to understand how stand and terrain parameters affect the productivity of mechanized tree length skidding operations, empirical models for predicting time consumption, productivity and costs are also required. This study investigated the following specific objectives; modeling grapple skidder productivity (m^3/hr), unit skidding costs (TZS/m^3) and assessing the factors affecting skidding time, productivity and costs.

MATERIALS AND METHODS

Study area description

The study was conducted at Sao Hill Forest plantation (SHFP) located at (80^0 18′ S to 80^0 33′ S and 350^0 06′ E to 350^0 20′ E) in Mufindi District, Iringa Region on the Southern highlands of Tanzania. The plantation is about 18km from Mafinga town. It is the largest government owned plantation in Tanzania with an estimated total area of about 135,903 ha. Currently the plantation is administratively divided into four blocks/divisions namely; Irundi, Ihefu, Ihalimba and Mgololo. Among the four divisions, the area under study was located at Ihefu which is division II. The block has a total planted area of about 12829 ha.

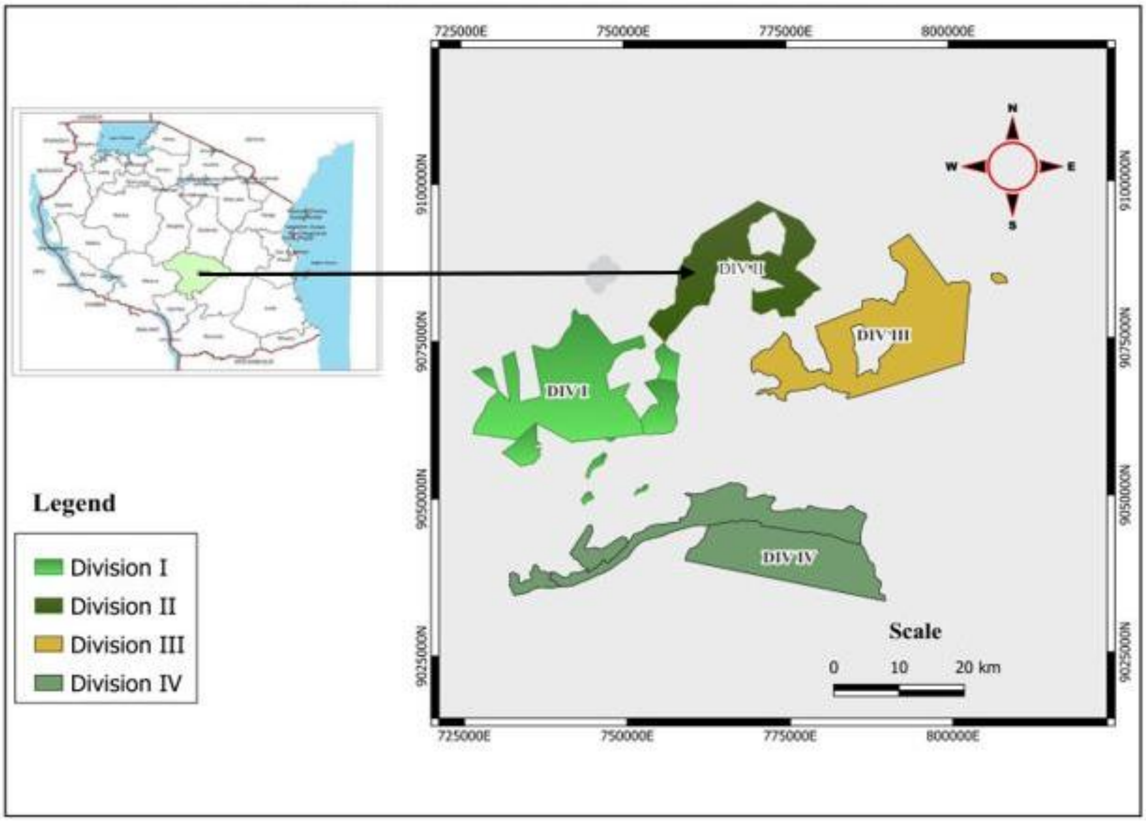

Figure 1. Map of Sao Hill Forest Plantation (SHFP) showing the study site (Divisions II).

Topography and climate

The topography of SHFP is rolling grassland with average altitude of 1,950 m above the sea level on the crests and falling down to 1,935 m in Ruaha flat-bottomed valleys. The highest area is Irundi Hill, which is about 2,000 m above sea level. The Climate of the area is generally cool distinguished by one dry season starting from July to November. The average annual rainfall at Sao Hill Forest plantation ranges between 750 mm to 1,050mm. There is one rainy season, which starts from November to April. Temperature ranges from 15^0 C to 26 ^{0}C in the year with an average of 20 ^{0}C.

Vegetation

Apart from plantation forest the area also has natural vegetation. The type of natural vegetation is normally determined by the amount of rainfall received in the area. The predominant natural vegetation is grassland with trees widely scattered. The main tree Species include; *Erythrina abyssinica, Parinari curatellifolia, Apodytes dimidiata and Albizia petersiana.*

Data collection

Data collection for this study was done in March 2018 in the Compartment 02, which was planted in 1987. Skidding operations was done by CAT, T.366 BLP grapple skidder. Time consumption, tree variables, topographical and cost data were collected.

Time consumption data

Time consumption data were collected using continuous time study techniques where a total 30 observations were studied. The entire work cycle for the grapple skidder was divided into four work elements which included; travel empty (TE), grappling (GP), travel loaded (Tl) and unloading (UNL). In addition to this, delays associated with each work element were recorded and categorized as either being necessary or unnecessary delay. Time recording for each element was done at the beginning of each work-element and the stop-watch was snapped back to zero at the end of each work element, elapsed time was read directly from the stopwatch and recorded on the field data form.

Single-tree variables data

For each individual tree/log, caliper was used to measure mid-diameter in cm where the Measuring tape was used for log length measurement in meters. The number of logs grappled per trip was also recorded. Volume for each tree was computed using Huber's formula as presented by (West and West 2009).

Terrain variable

Skidding distances for travel empty and travel loaded were measured using measuring tape, while the terrain of the area understudy was absolute flat and thus slope variation from the felling site to the landing was negligible.

Costs data

The machinery costs data were collected from logging department of Mufindi paper Mill and grouped into fixed and variable costs. Fixed costs do not vary with hours of operation. They are nether affected by the amount equipment/activity nor output and are incurred regardless of whether a piece of equipment is used or not. Fixed costs include depreciation, interest, insurance, and taxes. All the fixed cost components were computed based on the formulas described by Sessions *et al* (2007). Variable costs normally vary directly with the level of output produced by the firm.it tends to rise when the output increases and falls when the output produced decreases (Nwokoye and Ilechukwu 2018).

Data analysis

Data were analyzed through performing the descriptive statistical analysis, regression analysis and costs analyses. Regression models were developed to establish relationships between dependent and independent variables in skidding operation using Microsoft excel software. The independent variables for grapple skidder were; skidding distance (m), log/tree length (m), log mid diameter (cm) and log volume (m^3). While measured dependent variables were time for; travel empty (TE), grappling (GL), travel loaded (TL), Unloading (UNL) and total cycle time (CT) all recorded in terms of minutes with inclusion of delays time.

Production rate estimates

The log parameters which are logs lengths and middle diameters, were used for computation of individual log volume by using Huber's formula (Eqn1). Total volume and total observed time were used for calculating the production rate in skidding operation. Since Productivity is frequently measured in terms of output of goods or services in a given number of man-hour or machine-hours, (ILO 1979, Samset 1992, Silayo and Migunga 2014) the volume produced in a given skidding operation and the productive time obtained in the field were used for productivity (m^3/hr) computations (Eqn2).

$$\boldsymbol{Lvol} = \left(\frac{\pi d^2}{4}\right) \mathbf{L} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \textbf{(Eqn 1)}$$

Where:
Lvol –log volume (m^3),
d –middle diameter (cm), and
L –is the log length (m).

$$\boldsymbol{P} = \frac{\boldsymbol{Tvol}(\boldsymbol{m^3})\ (\boldsymbol{F})\mathbf{60}}{\boldsymbol{T}} \ldots\ldots\ldots\ldots\ldots (\boldsymbol{Eqn}\ \mathbf{2})$$

Where:
P= productivity in m^3/hr for a given skidding operation,
Tvol = total volume of all logs for a given skidding operation, m^3
60 = number of minutes in a workplace hour
T= total productive time (minutes) as measured in the field.
F =Fraction measuring the proportion of productive time (Eqn3).

$$\boldsymbol{F} = \frac{\mathbf{100}-\boldsymbol{D}}{\mathbf{100}} \ldots\ldots\ldots\ldots\ldots\ldots.\ldots\ldots\ldots \textbf{(Eqn 3)}$$

Where: ***D*** =Delay time expressed as percentage of workplace time in minutes.

Production costs estimates

Fixed and variable (operational) costs collected were analyzed by standard cost estimation method to develop unit costs for skidding by grapple skidder. The annual costs for the whole operation were converted to hourly costs (TZS/hr) basis (Eqn4). The unit costs of grapple skidder (TZS/m^3) were estimated based on the working hours spent in skidding operation as well as the volume of logs skidded in m^3/hr (Eqn 5).

$$\textbf{Hourly costs}(\boldsymbol{Tshs/hr}) = \frac{\textbf{Annual costs(Tsh/year)}}{\textbf{Working days per year} * \textbf{Working hours per day}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots \textbf{(Eqn 4)}$$

$$\textbf{Unit costs } (\boldsymbol{TZS/m^3}) = \frac{\textbf{Hourly costs } \left(\textbf{Tshs}/_{\textbf{hr}}\right)}{\textbf{Production rate } \left(\textbf{m}^3/_{\textbf{hr}}\right)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \textbf{(Eqn 5)}$$

RESULTS

The grapple skidder work cycles

Time elements of the grapple skidder using tree length (TL) system were categorized into travel empty (TE), grappling (GL), travel loaded (Tl), unloading (UNL) and delays (DE). where the minimum total skidding time was 2.0 minutes, maximum total skidding time was 4.033 minutes and the average skidding time per cycle was 2.828 minutes. The most time consumed work element was travel loaded (Tl) 1.097 minutes per turn equivalent to 38.794% of the total skidding time and the least time consumed work element was unloading (UNL) 0.141 minutes per turn equivalent to 4.970% of the total skidding time Figure 1 and Table 1.

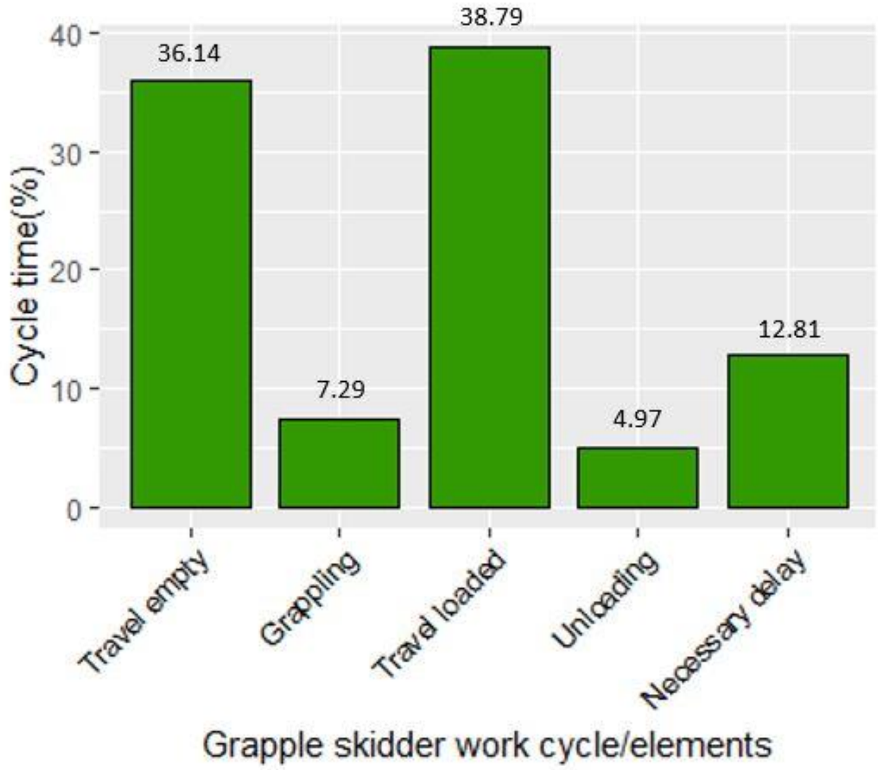

Figure 1. Work element/cycle distributions for the grapple skidder using TL harvesting system.

Table 1. Descriptive statistics of the grapple skidder Work elements/cycle using tree length (TL) harvesting system showing distribution of time spent by the grapple skidder.

Descriptions	TE	GL	Tl	UNL	Delay time(min)	Cycle time(min)	Total time(min)
Mean	1.022	0.206	1.097	0.141	0.362	2.466	2.828
Standard Error	0.045	0.019	0.060	0.007	0.026	0.093	0.102
Median	1.067	0.175	1.050	0.150	0.333	2.600	2.933
Mode	0.733	0.133	0.783	0.150	0.333	N/A	N/A
Standard Deviation	0.245	0.102	0.330	0.038	0.144	0.510	0.558
Sample Variance	0.060	0.010	0.109	0.001	0.021	0.261	0.312
Kurtosis	-0.415	1.192	-0.010	3.205	28.541	-0.861	-0.628
Skewness	0.303	1.053	0.654	1.003	5.290	-0.044	0.183
Range	0.950	0.467	1.300	0.183	0.817	1.900	2.033
Minimum	0.633	0.033	0.633	0.083	0.300	1.667	2.000
Maximum	1.583	0.500	1.933	0.267	1.117	3.567	4.033
Sum	30.667	6.183	32.917	4.217	10.867	73.983	84.850
Count	30	30	30	30	30	30	30
Confidence Level (95.0%)	0.091	0.038	0.123	0.014	0.054	0.191	0.208

Key: **TE** = Travel empty; **GL**= Grappling; **Tl** = Travel loaded; **UNL** = Unloading.

Production rate of the grapple skidder using tree length harvesting system

Based on the output summarized on Table 2, the average productivity of the grapple skidder using tree length (TL) system was observed to be 56.404 m^3/hr using observed time collected from the field and 55.944 m^3/hr while using the predicted time. Also, the productivity of the grapple skidder was observed to lie on a range of 398.423m^3/hr at a skidding distance of 10m to 49.862 m^3/h at a skidding distance of 80 m.

Table 2. Descriptive statistics of the grapple skidder cost and productivity results using tree length (TL) harvesting system.

Descriptions	Skidding distance (m)	Volume of logs trip (m^3)	Log diameter per trip	Unit costs (Tsh /m^3)-[actual time]	Unit costs (Tsh /m^3)-[predicted time]	Productivity [actual time] (m^3/h)	Productivity [predicted time] (m^3/h)
Mean	70.284	2.975	24.054	4,013.625	4033.156	56.404	55.944
Standard Error	2.069	0.170	1.137	242.014	234.221	3.416	3.298
Median	74.400	2.734	23.650	3,708.032	3904.137	55.040	52.402
Mode	79.900	N/A	N/A	N/A	N/A	N/A	N/A
Standard Deviation	11.333	0.933	6.230	1,325.567	1282.879	18.708	18.065
Sample Variance	128.434	0.870	38.811	1,757,126.698	1,645,778.275	349.999	326.361
Kurtosis	-1.286	1.330	-1.167	-0.253	-1.023	0.829	-1.034
Skewness	-0.547	1.072	0.018	0.648	0.341	0.792	0.431
Range	31.400	4.185	21.375	5,099.198	4,266.594	80.751	61.686
Minimum	51.600	1.587	13.975	1,853.472	2,187.103	29.351	31.621
Maximum	83.000	5.772	35.350	6,952.670	6,453.698	110.102	93.306
Sum	2,108.530	89.239	721.624	120,408.739	120,994.692	1,692.126	1,678.315
Count	30	30	30	30	30	30	30
Confidence Level (95.0%)	4.232	0.348	2.326	494.975	479.035	6.986	6.746

The costs of the grapple skidder in tree length harvesting system

Based on the costs analysis of the grapple skidder, the results showed that; the total hourly fixed costs per scheduled machine was estimated to be 37,676.872 TZS/hr while the total hourly variable costs per productive machine was estimated to be 166,394.055 TZS/hr. On the view of individual costs distribution for the grapple skidder, the most cost full fixed costs variable was depreciation which consume 18.101% of the total fixed costs followed by insurance and the last was the interest costs which consume 0% of the total fixed costs. For the case of variable costs, the most expensive item was fuel cost which consume 68.844% followed by maintenance, lubricants, tires and least expensive is labor cost which consume 0.245% of the total variable cost as presented in Figure 2

Factors influencing time consumptions, productivity and costs for the grapple skidder

A total of 19 different regression models were developed to predict skidding time consumptions, productivity and costs of the grapple skidder using TL harvesting system, where the validation was done by considering the coefficient of determination (R^2) as presented in Table 3.

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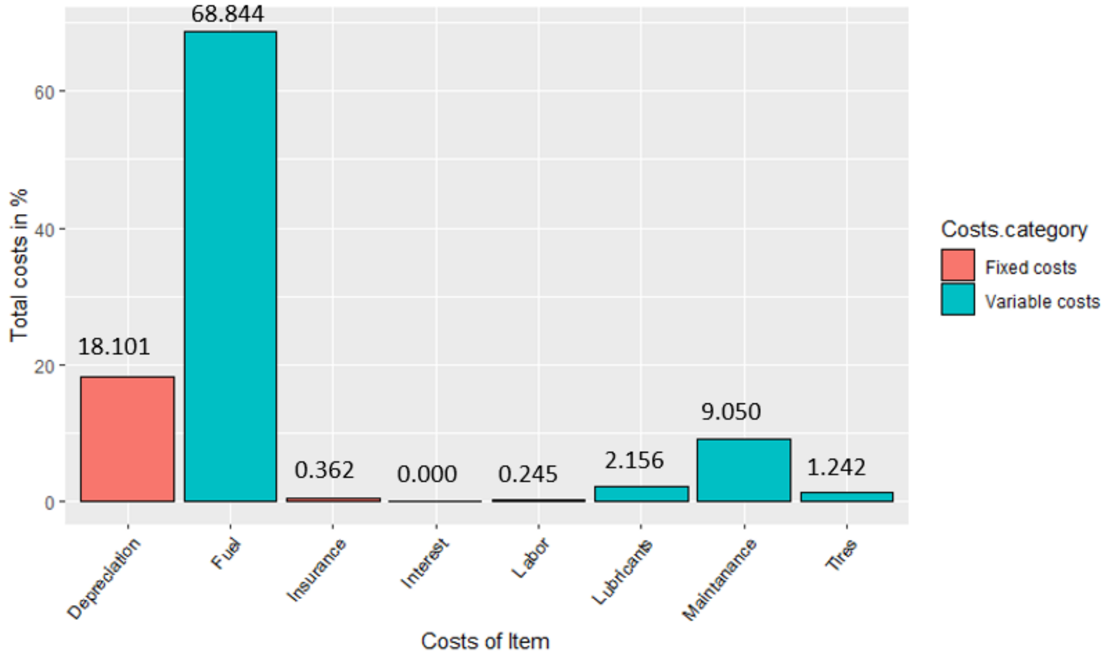

Figure 2. Costs distribution for the grapple skidder using tree length (TL) harvesting system.

Table 3: Time consumption, productivity and costs regression models for the grapple skidder at SHFP.

Eqn No	Grapple skidder regression hypothesis	Grapple skidder regression models	Coefficient of determination
1	Travel empty = f {skidding distance in m}	TE = -0.014 + 0.015skd	0.4333
2	Grappling time = f {Average volume (m3) & Average log diameter per turn}	GL = 0.201 +0.006 Log vol - 0.001 Log dm	0.0047
3	Grappling time = f {Average volume (m3) per turn}	GL = 0.186 +0.007 Log vol	0.0037
4	Grappling time = f {Average number of logs per turn}	GL = 0.175 + 0.008 N logs	0.0041
5	Travel loaded = f {skidding distance (m) & Average volume(m3) per turn}	Tl = -0.773 + 0.024 skd + 0.060 Log vol	0.6990

Eqn No	Grapple skidder regression hypothesis	Grapple skidder regression models	Coefficient of determination
6	Travel loaded = f {Average volume(m3) & number of logs per turn per turn}	Tl = 0.803 + 0.098 Log vol +0.001 N logs	0.0765
7	Travel loaded = f {skidding distance in m}	Tl = -0.643 + 0.024 skd	0.6708
8	Unloading time = f {Average volume (m3) & number of logs per turn}	UNL= 0.123 - 0.004Log vol+0.008 N logs	0.0385
9	Unloading time = f {Number of logs per turn}	UNL = 0.111+0.008 N logs	0.0272
10	Unloading time = f {Average volume (m3) per turn}	UNL = 0.152-0.004 Log vol	0.0096
11	Total productive time = f {skidding distance (m) & average volume per turn}	TPT= -0.033+0.039skd+0.034 Log vol	0.6062
12	Total productive time = f {skidding distance (m)}	TPT=0.0398+0.039skd	0.6031
13	Total productive time = f {Average volume per turn}	TPT= 2.544+0.096Log vol	0.0256
14	Productivity = f {skidding distance (m), average volume (m3) & number of logs}	P=63.721-0.736skd+18.104Log vol-2.342NLogs	0.8862
15	Skidding costs = f {productivity, skidding distance (m) & average volume}	Sc=7099.004-68.951Productivity(m3/h) +7.046skd+101.441Log vol	0.8744
16	Skidding costs = f {productivity (m3/h) per turn}	Sc=7733.716-65.954Productivity(m3/h)	0.8665
17	Skidding costs = f {Average volume(m3) per turn}	Sc=7130.868-1047.938Log vol	0.5436
18	Skidding costs = f {skidding distance (m) & average volume (m^3)}	Sc=3414.782+55.889skd-1137.402Log vol	0.7577
19	Skidding costs = f {skidding distance (m) per turn.}	Sc=950.960+42.984skd	0.1290

Productivity and costs modeling for the grapple skidder.

By applying the developed regression model for the total productive time (TPT) from Table 3 i.e. (Eqn. 11), the grapple skidder productivity (P) and unit skidding costs (Sc) models was obtained and presented as equation 20 and 21 respectively i.e.

$$\mathbf{P} = \frac{Tvol\ x\ F\ x\ 60}{0.039skd + 0.034Log\ vol - 0.033} \ldots\ldots\ldots\ldots(20)$$

$$\mathbf{Sc} = \frac{204070.9\ (0.039skd + 0.034Log\ vol - 0.033)}{Tvol\ x\ F\ x\ 60} \ldots(21)$$

Coefficients used in the generation of models are; average volume of logs per trip, average skidding distance (skd), average fraction of skidder productive time (F) and total skidding costs in TZS/workplace machine hour which are 2.975, 0.870, 70.284 and 20,4070.9 respectively. Based on the two models obtained i.e. (Eqn 20 and 21), productivity and costs for the grapple skidder were predicted as presented in Figure 3.

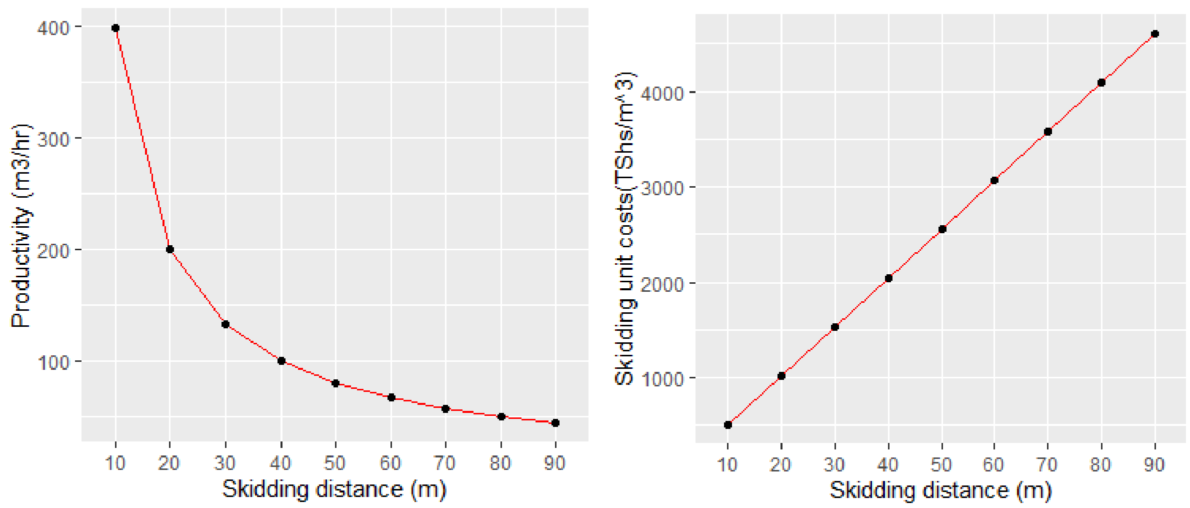

Figure 3. Predicted Productivity and costs for the grapple skidder in relation to skidding distance (m).

DISCUSSION

Work elements/cycles for the grapple skidder using TL harvesting system

Based on the time study technique used under this study, the work elements for the grapple skidder were categorized into six; Travel empty (TE), grappling/loading (GL), travel loaded (Tl), unloading (UNL) and delays specifically necessary delays (NED). The results show that; the most time-consuming work element for the entire cycle was travel loaded (TL) which consume about 38.794% of the total cycle time, followed by travel empty (TE), necessary delays (NED), grappling/loading (GL) and the last time-consuming work element was unloading/release (UNL) which consume 4.970% of the total cycle/productive time. Apart from that, the minimum skidding time was 2.0 minutes while the maximum grapple skidder productive time was 4.033 minutes and the average skidding time per turn is 2.828 minutes. The most influencing factors for the time consumption by the grapple skidder are skidding distance (m), volume of logs (m^3) per turn and number of logs per turn with exclusion of elevation/ terrain condition variable since the study was conducted in a gentle slope hence changing in elevation was significantly not considered. Other expected factors were the operating speed/experience of the operator and climate condition but these factors were not understudy.

Productivity and costs of the grapple skidder

From the analyzed findings, the average production rate of the grapple skidder was 56.404 m^3/hr with a range of 398.423 m^3/hr at a skidding distance of 10 m to a range of 49.862 m^3/hr at a skidding distance of 80 m. The results show that; the grapple skidder production rate tends to decrease as the skidding distance increase. Similarly, the study by Hiesl *et al.* (n.d) reported that efficiency of a skidder is greatly affected by skidding distance because it strongly affects the skidding time. When the skidding distance is long, the skidding time increases, and the overall productivity decreases. Hence the relationship between independent variable skidding distance and grapple skidder production rate is nonlinear i.e., it is curve linear. On the side of production costs; the unit skidding costs tends to increase with an increase of skidding distance (m) with a range of 512.197 TZS/m^3 at a skidding distance of 10 m to a range of 4,092.675 TZS/m^3 at skidding distance of 80 m. Other related studies Mauya *et al.* (2011) and Mousavi *et al.* (2012) reported that; if other variables for the grapple skidder such as slope, number of logs per turn and volume of logs per turn remain constant, still the machine i.e. (grapple skidder) has to travel from the stump area/felling unit to the roadside landing. Hence grapple skidder production rate decreases with the increase in skidding distance while it is vice versa to unit skidding costs which tends to increase with increase in skidding distance.

Factors affecting time consumptions, productivity and costs for the grapple skidder

Based on the independent variables used to predict time consumption for travel empty (TE),loading (L) and unloading (UNL) by the grapple skidder, the coefficients of determination (R^2) which obtained from the regression model reveal that the variables; log volume (m^3),log mid diameter and number of logs per turn were not good predictors since it has got poor coefficient of determination of less than 0.5 (Table 3).But for the case of cable skidder, the number of logs per turn and the log volume per turn are statistically significant factors affecting the time consumption since each log/tree are hooked or unhooked individually and it is manual process (Marčeta *et al.* 2014). On the other side the independent variables used to predict Tl, TPT, productivity and skidding costs are the good predictors of the machine time consumption since has got significantly coefficient of determination (R^2) of greater than 0.5. Based on the coefficient of determination obtained it indicate that; the most influencing factors for the grapple skidder time consumption, productivity and costs are skidding distance, number of logs and volume (m^3) per turn. Similarly according to Najafi *et al.* (2007) as cited in (Orlovský *et al.* 2020) conducted a time study focused on the skidder HSM-904, which found out that the skidding time consumption depends on the independent variables; skidding distance and the number of logs per turn. Therefore, these are statistically significant variables affecting the time consumption of the grapple skidder.

CONCLUSION AND RECOMMENDATIONS

The findings of this study are valuable for forest harvesting planning, forest managers and logging companies in order to ensure efficient utilization of the resources (machine, labour, energy, money and time) as well as to meet a timely market demand. The goal of this study was to find out the grapple skidder production rate and costs but also a suitable model for predicting skidding time, productivity and costs in TL timber extraction system in the pine plantation forest of Tanzania. Skidding distance was the main factor affecting the grapple skidder productivity, while number of logs and volume per turn were also important variables on prediction. The results of this study can provide a basis for computing the unit skidding productivity and costs in either forest plantation which bare similar characteristics so as to ensure an efficient and cost-effective planning so as to maximize productivity and minimize the operational costs.

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