A productivity model for first thinning of *Pinus patula* using a tractor and double-drum winch in South Africa

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Abstract

The productivity of skidding tractors in intermediate harvesting operations has not been determined in Mpumalanga. The objective of this study was to develop a productivity model using a farm tractor in first thinning operations in *Pinus patula* compartments. A work study design was used to assess the performance of skidding agricultural tractor. From 350 samples, important data variables collected were elemental times for each work cycle, extraction distance, slope and load volume. Stepwise and subsets regression analyses were conducted prior to multiple linear regression analysis. Analysis of variance was used to compare mean productivity estimates of the different models developed. Results showed that the best model was estimated by an interaction of distance x slope (ds), distance x load volume (dv) and slope x load volume (sv) as follows: $\ln(\hat{y}_2) = 1.33 - 0.00154ds + 0.00174dv + 0.161sv$. The mean estimate for this model was 5.036 $m^3 mhr^{-1}$. The developed models predicted similar results to estimation results of the observed model although there were statistically significant ($P<0.001$) differences among mean estimates (3.6-5.5 m^3 mhr^{-1}). All the three models yielded R^2 adj. = 38%; SE = 0.458% at $P<0.001$. It can be speculated that the remaining variation not explained by the models may be associated with long extraction distances, delays and effect of slope as a main variable in the model. While the developed models mirrored reasonably well with the observed estimates of skidding productivity, these models should not be stretched to conditions dissimilar to those of their generation. Future research focus should be made on (1) effects of weather conditions and vehicular characteristics on skidding productivity; (2) effect of winching lines on skidding productivity.

Keywords: Box-cox transformation, double-drum winch, intermediate harvesting, Nelshoogte plantation, New Holland 8030, skidding distance.

Introduction

Thinning is principally done in saw log production regimes to reduce competition on the growing stock before clear-felling (Evans & Turnbull, 2004; Vincent *et al*., 2009; Savelli *et al.,* 2010). Felled trees are commonly extracted by using ground-based timber skidding systems such as purposely built skidders and agricultural tractors fitted with safety skidding components (Krieg *et al.,* 2010; Savelli *et al*., 2010). The use of universal agricultural tractors has gained wide acceptance in forest thinning operations over the past century (LeDoux & Huyler, 1992; Zečić *et al*., 2005) due to the associated low capital costs (Gumus & Turk, 2010).

Productivity of these tractors working in thinning operations is largely affected by site based factors, timber characteristics and weather conditions (Özturk, 2010). Ground based factors include slope, ground roughness and ground condition, and skidding distance. The productivity of a tractor working in first thinning stands or trees of smaller sizes is affected by the skidding distance, slope and the piece size (Spinelli & Baldini, 1992). Piece size determines the physical capability of the machines to extract the timber. For instance, small piece sizes take long time to make a full payload as opposed to large diameter pieces (Gumus & Turk, 2010). Stand density influences ease and productivity of work in thinnings for extracting machines. Densely populated stands slow down production rates due to presence of narrow navigation passages for the machines (Nuutinen & Björheden, 2015). The distance covered by a tractor to extract timber influences the amount of cycle times and costs. Tu-ek and Pacola (1999) indicated that long skidding distances are directly proportional to cost increases in thinning operations. A study conducted by Spinelli *et al.* (2011) reported that long skidding distances yielded less number of cycles per hour and resulted in increased costs.

Notwithstanding this, Nelshoogte forest plantation uses blanket decisions to guide planning in relation to the productivity of skidding tractors in intermediate harvesting operations. Therefore, this study sought to develop a productivity model for the tractor with a double-drum winch to guide planning decisions in first thinning of pine saw timber stands in Mpumalanga.

Methodology

Study sites

The study was conducted in seven *Pinus patula* compartments (management units comprising even aged stands) in Nelshoogte forest plantation, in Mpumalanga, during the first thinning operation intended to reduce stand density from approximately 929 to 650 trees ha^{-1}. Information relevant to the study for each compartment on crop and terrain characteristics are presented in Table 1. Thinning operations were carried out when compartments were between 8 and 12 years old. The selection of compartments for study was intended to cover the range of situations existing in Nelshoogte forest plantation.

Table 1. Crop and terrain characteristics for seven *Pinus patula* compartments at time of first thinning used in this study

Compartment	Area (ha)	Month and year of planting	Month and year of thinning	Pre-thinning stems ha^{-1}	Mean dbh (cm)	Mean Height (m)	Slope (%)		Skidding distance (m)		Skidding direction
							Min	Max	Min	Max	
A13	8.51	June1999	Aug 2011	833	17.80	11.17	6.7	6.7	3	310	Flat
C17	6.73	Jan 2000	May 2011	784	17.21	14.80	19.2	26	6	65	Downhill
C45	7.32	Nov2002	Feb 2012	778	17.49	13.47	0	16	5	73	Uphill
C48b	6.31	Nov2000	Jun 2011	718	19.95	14.34	12.5	16.7	3	140	Uphill
C49b	7.74	Nov 2000	June 2011	912	17.71	12.42	10.9	15.7	3	220	Uphill
H17	41.05	Nov 2001	Aug 2011	878	18.09	12.67	6.8	12.3	5	173	Uphill
H21a	38.37	Jan 2003	Oct 2011	778	18.39	12.36	13.2	18	5	172	Uphill

Harvesting systems design

A 75kW New Holland 8030 double drum winch tractor was used in combination with a felling chainsaw at stump point and a cross-cutting chainsaw at the roadside in the harvesting area. Tree lengths were chain choked to 11 mm thick and 35 m long winches of a tractor to facilitate skidding to the roadside. Two chokermen and one de-chokerman were present to facilitate loading and off-loading of tree lengths at the two end points, respectively. A work study design was used in assessing work elemental times (International Labour Organisation, 1979) and timber volume skidded per cycle for a tractor. Work elements for the tractor were as follows: travel-empty at road side, travel-empty infield, choking, travel-loaded infield, travel-loaded at road side, de-choking and delay. A delay was defined as any non-productive time of a machine in excess of 15 minutes due to personal, operational or mechanical interruption (Ngulube *et al*., 2014).

Operator performance and sample size

The tractor and chainsaw operators, choker and de-chocker men were deemed to have average work performance skills as defined by the British Standard 3138-1969 (Niebel & Freivalds, 1999). These harvesting crew members were well experienced and performed satisfactorily. Determination of the minimum number of work cycles (sample size) was done in two-stages. An activity sampling was firstly conducted to determine critical (P = 0.05) work elements prior to calculation of sample size. Secondly, a statistical method (Kanawaty, 1997) was used to determine the minimum sample size of the study. Three hundred fifty-seven (357) work cycles were determined and used in the study.

Data collection

Elemental times for each work cycle of a tractor were measured in centiminutes by using a digital stopwatch. Average skidding distances were measured in metres using a linear tape for each cycle on every skidding trail. Average slopes on skidding routes were measured by using the Hypsometer Vertex III in percent in the direction of travel. The number of tree lengths extracted was recorded at the roadside. Butt, middle and top over-bark diameters of tree-lengths were measured in centimetres using a calliper. Top diameter was determined as the upper minimum utilisable stem diameter. Diameter under-bark was estimated as a function of log section diameter and length parameters (van Laar & Akça (2007). Length of utilisable stems was measured in metres using a linear tape. Newton's formula was used for determination of under-bark volume (Bredenkamp, 2012) of the utilisable tree-length as shown in equation (Eqn) 1.

$$V = \pi \left[\frac{D^2 + 4{d_m}^2 + d^2}{240000}\right] l \qquad \text{[Eqn 1]}$$

Where V = utilisable volume under-bark in m^3

D = butt diameter under-bark in cm

d_m = middle diameter under-bark in cm

d = top diameter under-bark in cm

l = length in m

Data analysis

Data were analysed using MINITAB Release 13.30 statistical software. A box-cox transformation was conducted to identify an appropriate transformation to satisfy a normality test. Stepwise and subset regression analyses was used to identify significant (at P = 0.05) independent variables of the model. The adjusted R^2 and Mallows' Cp criteria were used to guide choice of the best subset of model variables (Hudak *et al*., 2006). Data were randomised and partitioned into 60:40 ratios for training and test sets. A training data set was used to build a model using multiple linear regression analysis. Performance of the model was tested using reserve data from the same sample population. Furthermore, the models were statistically compared using One-way analysis of variance (unstacked) on the training datasets. Significantly different means were separated by using Tukey's honestly significance difference (HSD) post-hoc test at P = 0.05.

Results

Productivity factors

Skidding productivity candidate model parameters included: (1) load volume (*v*), (2) slope (*s*), (3) distance x slope (*ds*), (4) distance x load volume (*dv*), (5) slope x load volume (*sv*) (6) distance x slope x load volume (*dsv*) and (7) distance (*d*).

The results (Table 2) show factors of significance that affect skidding productivity in the study area. In model 2, only distance x slope, distance x load volume and slope x load volume posed highly significant (P<0.001) contribution to skidding productivity (R^2 adj. = 38.2 %; Cp = 1.95). Best factors (R^2 adj. = 38.02; Cp = 2.77) in model 3 are distance x slope, distance x load volume, slope and slope x volume. However, slope is not contributing significant (P>0.05) variation to the model. Model 4 is dependent on distance x slope, distance x load volume, slope and load volume (R^2 adj. = 38.01; Cp = 2.99). The interaction of distance x load volume is accounting for a highly significant (P<0.001) variation in the model.

Table 2. Model factors and the associated selection criteria

Model	Best factors	d	ds	dv	dsv	s	sv	v	R^2 adj. (%)	Mallows' Cp
2	3	ns	**	**	ns	ns	**	ns	38.20	1.95
3	4	ns	**	**	ns	ns	**	ns	38.08	2.77
4	4	ns	**	*	ns	**	ns	**	38.01	2.99

ns, * and ** denote not significant, significant and highly significant, respectively at P = 0.05)

Productivity models

Mean skidding productivity ($\hat{y}_{i=2,3,4}$) in m^3 mhr^{-1} of a New Holland 8030 tractor are estimated as shown in Eqn 2, Eqn 3 and Eqn 4.

$$\ln(\hat{y}_2) = b_0 + b_1 ds + b_2 dv + b_3 sv \quad \text{[Eqn 2]}$$

$$\ln(\hat{y}_3) = b_0 + b_1 ds + b_2 dv + b_3 s + b_4 sv \quad \text{[Eqn 3]}$$

$$\ln(\hat{y}_4) = b_0 + b_1 ds + b_2 dv + b_3 s + b_4 v \quad \text{[Eqn 4]}$$

Results of parameter estimators and goodness of fit for three productivity equations developed are presented in Table 3. The mean skidding productivity estimate for Eqn 2 was (fitted with *ds*, *dv* and *sv*) is 5.036 m^3 mhr^{-1} with an R^2 adj. of 38±0.458%. Eqn 3 used four variables (*ds*, *dv*, *s* and *sv*) to estimate 3.577 m^3 mhr^{-1} (R^2 adj. = 38.1±0.458%). The overall contribution of variables to variances were highly significant (P<0.001) in all the equations. Eqn 4 has a mean estimate of 5.034 m^3 mhr^{-1}.

Table 3. Productivity estimator and goodness of fit parameters for a New Holland 8030 tractor

Eqn	Parameter estimators					$\hat{y}_i$ (m^3mhr^{-1})	R^2 adj. (%) ±RMSE	PRESS	P
	b_0	b_1	b_2	b_3	b_4				
2	1.33	-0.00154	0.00174	0.161	-	5.036	38.0±0.458	45.6	<0.001
3	1.20	-0.00183	0.00231	0.093	0.1236	3.577	38.1±0.458	45.7	<0.001
4	0.86	-0.00171	0.00163	0.205	0.428	5.034	38.0±0.458	45.8	<0.001

Comparison of models

Mean skidding productivity estimates for the developed models (Observed, Eqn 2, Eqn 3 and Eqn 4) were compared (Table 4). Mean productivity estimates for the observed model are 5.544 m^3 mhr^{-1}; SD = 3.564. Eqn 3 estimates 3.577 m^3 mhr^{-1} with SD of 0.861. Analysis of variance results show that there are highly significant (P<0.001) differences among model estimates. However, means for the observed model and Eqn 2 are not statistically different. Similarly, means for Eqn 2 and Eqn 4 and statistically indifferent. Statistically different models are Observed, Eqn 3 and Eqn 4.

Table 4. Comparison of mean skidding productivity estimates of a New Holland 8030 tractor using the training datasets

Model	Number of observations	Mean productivity estimates (m^3mhr^{-1})	Standard deviation (SD)
Observed	214	5.544^a	3.564
Eqn 2	214	5.036^{ab}	2.139
Eqn 3	214	3.577^c	0.861
Eqn 4	214	5.034^b	2.017
		P	<0.001
		Pooled SD	2.350

Means with same letters in superscript denote statistically insignificance differences at P = 0.05 using Tukey's HSD

Discussion

Productivity factors and models

Candidate models for intermediate harvesting productivity are represented by Eqn 2, Eqn 3 and Eqn 4. These models have slight differences in their constructs. The differences arise from number and interaction of variables used in the constructs. Eqn 2 used three variables while Eqn 3 and 4 applied four variables to estimate mean productivity values. Eqn 2 can be considered be to a superior model because it is simple yet robust enough to equally predict productivity. This is also revealed through a comparatively low predicted residual error sum of squares value (PRESS = 45.6). Accordingly, a good model should be less complex in its variable constructs but effective enough. Interactions of distance x slope and distance x volume emphasise the importance of tractor performance in all the models under review. In other studies, (Ghaffarian *et al*., 2007; Sowa *et al*., 2007; Nikooy *et al*., 2013), it was reported that main variables of significance to productivity are distance, volume and slope. The interaction of these variables could be considered as more important due to the fact that the tractor interfaces with each one of them at the same time in the production process.

Inclusion of slope as a main factor in the model did not contribute significant variation (particularly to Eqn 3) unlike the interactions of distance x slope and slope x load volume (Table 2). This is because >70% of skidding was done uphill (Table 1). Upslope skidding dramatically reduces productivity because engine torque becomes limiting to maximum performance of a tractor (Ghaffariyan *et al*., 2008; Mousavi, 2012; McEwan *et al*., 2013). Conversely, excessive downhill slope may have portrayed similar results as machine operation is then constrained by vehicular and personal safety concerns.

Model validation

In general, all models displayed similar values of root mean square error (RMSE = 0.458) for the given sample size. This may be attributed to differential residual sums of squares that mainly existed on outlier observations that are associated with high variance inflation factors. However, outliers helped to explain the importance of mechanical, operational or personal delays in a skidding operation above the normal cycle times. Delays are a common occurrence particularly in thinning extraction operations. Tree hang-ups, poor butt presentation and inadequate skid trail planning mar extraction operations in intermediate harvests (Nikooy *et al*., 2013). It is important that outlier situations are managed in an operation in order to maximise productivity (Carson II, 1992). The goodness of fit for these models can be considered as acceptable for use.

Comparison of models

All the models accounted for almost the same amount of variation (R^2 adj. = 38%; RMSE = 0.458) as shown in Table 3. Eqn 3 was significantly different from other models using Tukey's HSD. The repeated incorporation of slope (as a main variable and interactive variable) might have induced collinearity in the model (Joly *et al*. 2012). The existence of such a phenomenon drastically reduces model performance. No wonder the model estimated the lowest mean productivity ($\hat{y}_3$ =3.577 m^3 mhr^{-1}) but it was also associated with the smallest standard deviation (SD<1). Low standard deviation is a good measure for model stability. Based on practical experience, mean values of 4.0 - 8.3 m^3 mhr^{-1} are considered to be normal for a 75kW New Holland 8030 double drum winch tractor. The results compare favourably with similar studies (Spinelli & Baldini, 1992; Savelli *et al*., 2010; Spinelli & Magagnotti, 2011a) involving tractors in thinning operations.

Sixty-two percent of the variation could not be explained by these models (Eqn 2, Eqn 3 and Eqn 4). It can be speculated that excessive skidding distance (310 m) travelled by the tractor had a negative effect on variance account (Özturk, 2010; Spinelli & Magagnotti, 2011b) in first thinnings. For an agricultural tractor in Turkey, Akay (2005), recommended skidding distance of between 50 and 70 m while Krieg *et al*. (2010) recommended 250 m as an optimum skidding distance for the 75kW New Holland 8030 double drum winch tractor in South Africa. Secondly, the models did not include ground roughness and ground conditions as part of terrain to estimate cycle time. These variables can have profound effects on travel speeds of the skidding machine in a compartment. Manoeuvrability of the tractor in thinning operations may limit travel speeds due to limited driving spaces and high load jam. Furthermore, tractor operators face problems in manoeuvring reverse-wise because tractor cabins are designed mainly for forward driving operations (Russell and Mortimer, 2005). Timber skidding in first thinnings requires a lot of manoeuvring with forward and reverse movements. This may be exacerbated by inadequate skid trail planning in the harvested compartments. Other possible factors in the unexplained variation may include poor felling direction, butt presentation, and wrongly chocking tree lengths leading to high drop-offs on the way (Zečić *et al*., 2005).

Piece size is yet another important logging chance factor affecting thinning operations. The skidding of smaller tree lengths thus increases the cycles and machine hours per shift. The smaller the size of the tree harvested, the lower the volume in m^3 per cycle (Längin *et al*., 2010) implying that tree size has a direct impact on the productivity of a tractor with a double-drum winch in thinning operations. Henceforth, optimal load size is thus significant, especially when extracting small-sized trees.

Conclusions and recommendations

It has been confirmed that skidding productivity is mainly influenced by interactive effects of distance, slope and load volume per cycle. However, there are highly significant differences in the results of various model constructs. Best models have fewer variables and yet robust enough. This notwithstanding, productivity may also be affected by skidding direction, piece size and operational efficiency of an operator. On average sites, a 75kW New Holland 8030 double drum winch tractor has the capacity to winch up to 8 m^3 mhr^{-1} in *P. patula* first thinning operations. This will, however, vary from site to site as factors affecting timber skidding productivity do not remain constant in a compartment.

As such, the developed models should be used within the confines of the observed conditions for effective results. Future studies should include more factors in the model such as different weather conditions and vehicle characteristics *visa viz*; engine speeds, wheel pressure and engine efficiency. It may be interesting to also compare the productivity of a tractor using tag lines and main line in thinning operations and the effect of directional felling on tractor productivity.

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