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Determining Productivity of Mechanized Harvesting Machines

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Abstract: In order to select the most profitable forest harvesting system, productivity of mechanized harvesting machines should be carefully determined under various operating conditions. This study identifies the factors affecting productivity of specific harvesting machines including skidder, feller-buncher, harvester, loader and forwarder. The productivity formulations of the machines are presented to assist logging managers determining harvesting costs and evaluating alternative harvesting systems. The unit cost of logging for selected machine combinations are investigated based on the average stand characteristics of the sample plots selected from Başkonuş Research and Application Forest in a Mediterranean city of Kahramanmaraş, Turkey.

Key words: Production formulas, logging systems, machine combinations

INTRODUCTION

Harvesting systems chosen must be balanced for the characteristics of the forest, machine types and intensity of the harvest operation to reflect variable factors that affect equipment productivity[1]. In most regions of Turkey, the application of mechanized harvesting equipment is currently low due to low labor costs and high fuel costs. However, they have been increasingly used in the regions with intensively managed forests. Therefore, estimating production rates of the equipment is very important for logging managers to develop cost effective mechanized harvesting systems.

Previous studies provide useful data to analyze productivity under various harvesting conditions. Regression equations generated based on study data are commonly used to express equipment productivity[2]. These equations provide an effective guide for logging managers to estimate production costs of logging equipment and to develop a cost efficient logging plan. The purpose of this study is, essentially, to identify the factors influencing production rate of specific mechanized harvesting machines, to present their production rate formulations and to investigate the cost efficiency of selected mechanized harvesting systems.

MATERIALS AND METHODS

Machine categories studied include skidder, feller-buncher, harvester, loader and forwarder. In order to estimate production rate, the approach taken is to calculate cycle time from an equation as a dependent variable and then convert to production using log size, volume, or weight. The most economical machine combination of the specified harvesting machines is also investigated.

Skidder: The skidding operations are usually done with skidders and crawler tractors that transport logs by dragging them with a grapple or chokers. The capacity of the skidder is highly dependent on its drawbar horsepower, weight and traction obtainable under the ground conditions during operation. Skid distance is generally the most important variable since it affects cycle time more than any other variables. If the skid distance increases, travel time will increase accordingly. In some cases where skid trail is quite straight, the longer the distance, the faster the travel speed without load.

In the case where ground slope on the skid trail is steep, the vehicle travels with lower speed, which means that cycle time will be longer. Greater load weight also reduces the travel speed, particularly on steep uphill trails. The load size variables including weight, number of logs grappled, or number of trees hooked is also important in skidding. As number of bunches grappled per turn increases, the time spent on grappling increases, which will increase the cycle time.

The following regression equation can be used to predict productivity on the basis of indicator variables for number of logs per turn, volume per turn and total

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distance traveled by the skidder on average 35% of ground slope[2]. Turn time in minutes for rubber-tired cable skidders (110-150 brake-hp) is estimated as follows:

$$\text{Time} = -0.1971+1.1287N_{log}+0.0045Vlm+0.0063D \quad (1)$$

where,

N_{log} = Number of logs per turn
Vlm= Volume per turn (m^3)
D = Total skidding distance (m)

The equation for calculating rubber-tired grapple skidder was derived as a function of distance, horsepower, load and number of bunches[3]. Cycle time equations developed for skidding whole-tree (Equation 2) and tree-length (Equation 3) systems were:

$$\text{Time} = -0.5988+0.01489D_{one\text{-}way}+0.01119HP - 0.00005097D_{one\text{-}way}HP +0.001241D_{one\text{-}way}N_b+1.616N_b-0.005599N_bHP+0.1398N_bN_t \quad (2)$$

$$\text{Time} = -0.0158+0.017D_{one\text{-}way}-0.0004HP+1.65N_b+0.00000057W_lHP -0.000011D_{one\text{-}way}HP-0.01398N_bN_t-0.005599N_bHP \quad (3)$$

where,

$D_{one\text{-}way}$ = One-way distance traveled in meters
W_l = Load weight in kg
HP = Machine flywheel horsepower
N_b = Number of bunches grappled
N_t = Number of trees per load

Cycle time for a crawler tractor equipped with choker can be predicted by using following equation[2] where *g* is ground slope in %:

$$\text{Turn time} = 14 - 0.1446g + 0.0714D + 0.3360N_{log} \quad (4)$$

Feller-buncher and harvester: Feller-bunchers cut trees near ground level using felling heads and then stack the trees into piles to await skidding. Since the felling head attached on the feller-buncher can cut various sizes of trees in approximately the same amount of time, relatively large trees allow the machine to produce greater volumes of wood per machine hour. Trees per unit area also affect the time to process trees. The time spent on moving, cutting and accumulating trees decreases when trees per unit area increase (Table 1). Harvesters are divided into two groups: single-grip harvester and double-grip harvester. Single-grip harvester both fells and processes with a single boom-mounted unit[4]. The double-grip harvester severs the tree with a boom-mounted unit and places it in the carrier-mounted processing unit for delimbing and bucking[4,5].

Table 1: Cycle times for specific feller-bunchers (Average slope = 35%)

Machine make	Volume (m^3 log^{-1})	Number of trees per h	Cycle time (min $tree^{-1}$)
PRENTICE 720	0.68	65	1.10
PRENTICE 730	0.68	75	0.80
TJ 2618	0.68	50	1.20
TJ 2628	0.68	60	1.00
TIMBCO T225-B	0.68	60	1.00
TIMBCO T445-B	0.68	70	0.86

The harvester productivity generally is closely related to tree size. As tree volume increases, production rate will increase since processing time for big trees is same as the small size trees. Steep slopes cause difficulties to harvester that may increase the time per tree. However, according to the study conducted by Grammel[6] even with very steep conditions, the harvester can work on thinnings at comparable costs to gentle terrain.

In timber of less than 55 cm diameter, the single-grip harvester is extremely productive at felling, delimbing and bucking[7]. According to a study conducted by Kellogg *et al.*[5] single-grip harvesters have become more popular than double-grip harvesters. The equation for solving single-grip harvester time is a function of volume and slope class. Total cycle time for the harvester can be calculated on the basis of Grammel[6]. Single-grip harvester time in cmin m^{-3} by the slope ranges from 26-40%:

$$Y = 56.62 \ln(X) + 322.09 \quad (5)$$

where,

Y = Cycle time per tree (cmin/m^3)
X = Volume per tree (m^3)

Hydraulic tracker loader: Many different systems of loading have been used from manual loading to highly mechanized loading. In order to reduce loading time and labor, various kinds of loaders have been built. The most versatile loader is the hydraulic loader since it gives positive control of the products ranging from short length to full-length material[8]. The equation for calculating hydraulic loader time can be derived as a function of load capacity of a hauling truck, volume per tree and number of pieces per truck, N_{piece}. The number of pieces per truck can be obtained by dividing truck load capacity by average tree volume. Then, total load time per truck, will be calculated by the equation developed by Schneider [9]:

$$\text{Load time} = 505.75 + 35.1N_{piece} \quad (6)$$

Forwarder: Forwarders are articulated vehicles used for transporting short wood or cut-to-length logs clear of the ground[4]. They are commonly used in the cut-to-length system combined with a single-grip or double-grip harvester. The forwarder requires a higher quality skid road than the skidder. For longer traveling distances, larger payloads with a forwarder, compared to skidders and crawlers may produce wood at a lower cost.

Cycle time of a forwarder includes travel time, loading time and other time elements such as delay time, brushing time, repositioning time and sorting time. Travel time is computed as a function of distance, machine horsepower, load weight and vehicle speed. It is common that forwarder travels uphill without load and downhill with load. The forwarder operator can change the position of the seat in the cab and drive uphill unloaded. When the machine is loaded, the operator turns the seat back to its normal position and drives downhill loaded. That eliminates the time spending on changing travel direction of the forwarder after loading, which might be very dangerous in woods under steep slope conditions. Return trails may be used to overcome this problem, but it requires a longer transportation distance from woods to landing.

The vehicle force diagram for a forwarder traveling uphill without load is illustrated in Fig. 1. Tractive effort and resistance are two primary opposing forces determine the non-turning performance of the machine. Tractive effort is basically the force available at the roadway surface to perform work[10]. Two major sources of resistance considered during operation are rolling resistance and grade resistance. Acceleration is assumed to be zero. Aerodynamic resistance is ignored since it does not have significant impacts on forestry machines at low speed. In the Fig. 1, R_r is the total rolling resistance (Newtons), R_g is the grade resistance (Newtons), F is the tractive effort of axles (Newtons), W is the total vehicle weight (Kilograms) and ϑ is the slope angle (Degrees). Since the forwarder is the all-wheel drive vehicle, tractive effort and rolling resistance are of all tires. Summing the forces along the machine's longitudinal axis provides vehicle motion equation: $F \geq R_r + R_g$

The grade resistance is equal to $W\sin\vartheta$. The rolling resistance is represented by the coefficient of the rolling resistance ($f_{r\,(\text{Loose soil})}$ = 10 %, CAT, 1996) multiplied by $W\cos\vartheta$, the vehicle weight acting normal to the roadway surface. The maximum tractive effort that the roadway surface can support must be greater or equal to sum of vehicle resistance, R_r+R_g. To determine uphill unloaded vehicle speed (V_{up}) in meters per minute, the following equation limited by the net flywheel (HP) of the vehicle and estimated tire slip (s) can be used:

$$V_{up} = \frac{HP60000}{(1+s)R_g + R_r} \tag{7}$$

The vehicle force diagram for a forwarder traveling downhill is illustrated in Fig. 2. In order to determine downhill loaded vehicle speed (V_{down}) in meters per minute, vehicle speed must be computed based on the engine brake horsepower, BHP:

$$V_{down} = \frac{BHP60000}{R_g - R_r}(1+s) \tag{8}$$

where $R_g - R_r$ is the required braking force to maintain constant velocity. Therefore, unloaded and loaded travel times will be calculated by dividing the forwarding distance by V_{up} and V_{down}, respectively.

In order to determine loading time per cycle, grapple loading capacity (m^3 $cycle^{-1}$), grapple unloading capacity (m^3 $cycle^{-1}$), forwarder's load capacity (m^3) and average grapple cycle time must be known:

$$LT = \left(\frac{FLC}{0.7LC} + \frac{FLC}{0.9LC}\right) GT \tag{9}$$

where,

LT = Loading time (min/load)
FLC = Forwarder load capacity (m^3)
LC = Grapple loading capacity (m^3/cycle)
GT = Average grapple cycle time (min/cycle)
0.7 and 0.9 = The factors estimated for grapple loading and unloading capacities, respectively.

The grapple loading capacity can be computed based on grapple capacity and log size (FAO, 1977):

$$LC = AreaL_{log}\,f \tag{10}$$

where,

Area = Area in closed grapple (m^2)
L_{log} = Log length (m)
f = Loading factor (varies depending on log length)

Delay time may or may not be predictable. Predictable delays during forwarding include receiving work instructions, setting up equipment on the work site, changing parts and removing obstacles, which make movement difficult. Unpredictable delays may be accidental or unnecessary losses of time, such as forgetting tools, conversation between the workers and all delays outside the normal process. Brushing time, spent on removing brush and felling of non-merchantable trees, depends on terrain conditions and stand characteristics.

Forwarding becomes more difficult as the ground slope increases since the higher center of gravity of the load results in lower stability. Due to risk of sliding sideways, the time spent on maneuvering and repositioning the forwarder increases as ground slope increases. It is also difficult to pick the logs up from the ground and putting them onto the forwarder in steep slopes.

RESULTS

The data representing the average stand characteristics of 16 sample plots, selected from Başkonuş Research and Application Forest in Kahramanmaraş, Turkey, were collected. The data included topographic data, stand data and timber data (Table 2). Based on these data, four mechanized thinning systems were examined to determine the most economical machine combination, which minimizes the stump-to-truck harvesting cost. The systems were balanced with the configurations (Table 3).

Table 2: Average stand characteristics

Stand characteristics	Items
Species	Cedar, Pine,Fir
Average DBH	4cm
Tree Height	22m
Tree Volume	$0.68m^3$
Trees ha^{-1}	413
Ground Slope	31%

Table 3: Configurations for mechanized thinning systems

System A	System B	System C	System D
1 Feller-buncher	1 Harvester	4 Sawyers	3 Sawyers
1 Grapple skidder	1 Forwarder	1 Forwarder	1 Crawler (cable)
4 Sawyers	Set-out trailers	Set-out trailers	1 Loader
1 Loader	---	---	---

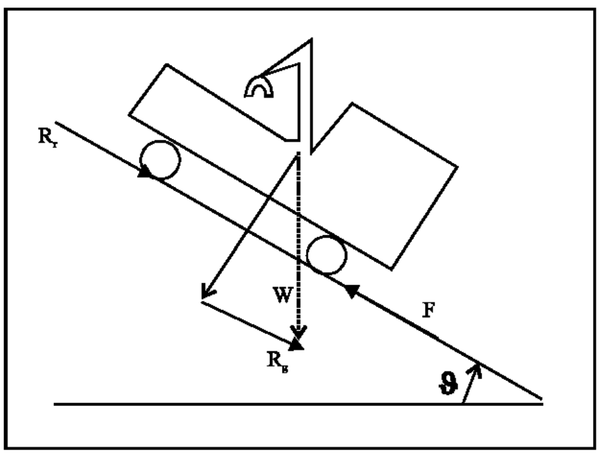

Fig. 1: Forces acting on a forwarder, traveling uphill without a load

The System-A requires a feller-buncher, one grapple skidder and four sawyers to balance the system. A Prentice 720 feller-buncher fells the trees, accumulates and places them in a selected location next to the skidding trail. Then, a CAT 525 grapple skidder transports them to the landing. The skidder worked approximately twice the time of the feller-buncher to balance the productivity of the system. At the landing, four sawyers remove limbs

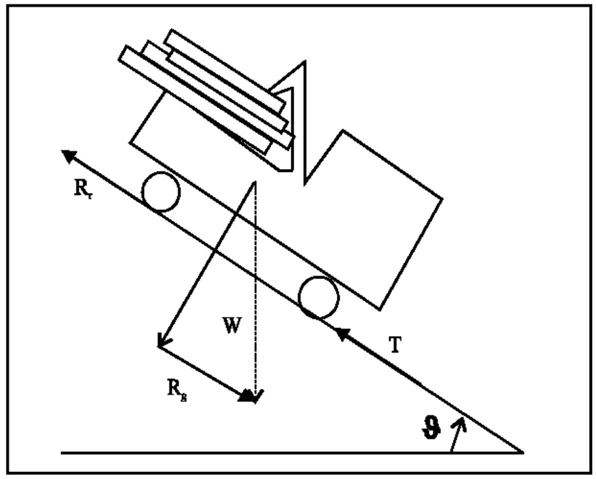

Fig. 2: Forces acting on a forwarder, traveling downhill with load

from trees and crosscut them. Loading is done by CAT 322-B loader at the landing. In System-B, a Timber Jack 1270-B single-grip harvester fells and processes (delimbs and cross cuts) the trees at the deck and then, a Timber Jack 1210-B forwarder transports them clear of the ground. Set-out trailers are placed at the landing for loading.

In System-C, one forwarder and four men for manual felling, bucking and delimbing are required. Timberjack 1210-B forwarder transports the logs processed by the sawyers in the woods. Set-out trailers are placed at the landing for loading. The System-D requires three men for felling and delimbing, three men for bucking and one cable skidder are involved the operation. The trees are felled and delimbed at the stump and transported by CAT D5HCS tracked-skidder with chokers to the landing. Bucking is done at the landing by three sawyers. CAT 322-B loader is operating at the landing for loading trees onto the trucks.

DISCUSSION

The variable factors influencing productivity of specific harvesting machines were identified and their production rate equations were presented. The most economical machine combination with minimum logging cost was determined based on the data representing the average stand characteristics of Başkonuş Research and Application Forest in the city of Kahramanmaraş. The unit cost of logging (US dollars) was estimated by dividing hourly equipment cost by hourly production. Analytical method was used to estimate hourly costs (US dollars) for selected harvesting machines based on the data representing economic conditions in Turkey[11]. The production rates of the machines

Table 4: Unit cost summary for specific harvesting machines

Machine make	Machine types	Machine rate ($ hr^{-1})	Cycle time (min)	Production (m^3 hr^{-1})	Unit cost ($ m^{-3})
CAT 525	Skidder	164	10.63 $trip^{-1}$	19.20[a]	15.35
CAT D5HCS	Crawler	170	17.50 $trip^{-1}$	9.30[a]	18.28
CAT 322B	Loader	234	0.90 $tree^{-1}$	45.33	5.16
TJ 1270-B	Harvester	324	2.50 $tree^{-1}$	16.32	19.85
TJ 1210-B	Forwarder	246	36.03 $trip^{-1}$	22.98[a]	10.71
Prentice 720	Feller-Buncher	300	1.10 $tree^{-1}$	37.09	8.09
STIHL 066M	Chain Saw (Felling)	3	15.50 $tree^{-1}$	2.63	1.14
STIHL 066M	Chain Saw (Bucking)	3	4.50 $tree^{-1}$	9.07	0.33
STIHL 066M	Chain Saw (Delimbing)	3	1.50 $tree^{-1}$	27.20	2.00

[a] Average distance per trip is 300 m and estimated numbers of trees per trip is 4.

Table 5: The logging cost summary for various harvesting systems

Harvst. system	Logging costs of the equipment ($ m^{-3})							
	Skidder	Crawler	Loader	Harvst.	Fell-Bunc.	Forwd.	Manual	Cost ($$m^{-3}$)
A	15.35	-	5.16	-	8.09	-	9.32	37.92
B	-	-	-	19.85	-	10.71	-	30.56
C	-	-	-	-	-	10.71	13.88	24.59
D	-	18.28	5.16	-	-	-	10.41	33.85

were computed using the production equations. Estimated cycle time, productivity and unit cost data for specific logging equipment and manual processing were indicated in Table 4. The logging cost summary for the harvesting systems was listed in Table 5. It should be noted that when these machine combinations were actually used in the selected plots, the initial cost of logging would be higher than the estimated costs until machine operators, maintenance staff and supervisors gain experience.

The results indicated that System-C using a forwarder and four sawyers produced wood at the lowest cost ($24.59 m^{-3}). In a similar study conducted by Greene *et al.*[12] the forwarder system produced wood at a lower cost than the cable skidder systems. They also found that the forwarder system using manual delimbing and bucking produced wood at a lower cost compared with the processor-forwarder system. Both forwarder systems were more efficient than cable skidder systems for thinning applications.

System-A balanced with a feller-buncher, a grapple skidder, a loader and four sawyers was the least cost efficient system ($37.92 m^{-3}). In a previous sstudy, Blinn *et al.*[13] developed a computer simulation to compare harvesting systems for northern hardwood. The results indicated that the mechanized system using a feller-buncher, a grapple skidder, four sawyers and a hydraulic slasher showed significantly lower capital efficiency as compared to the systems balanced with a forwarder and seven sawyers. However, this highly mechanized system produced wood at the highest labor efficiency.

The mechanized harvesting equipment analyzed in this study are not common in current logging operations in the most regions of Turkey since they are very expensive and highly correlated with the fuel price. They are also not favorable because of reduction in labor. However, mechanized harvesting systems would be more competitive if labor costs increase relative to fuel costs. Besides, they satisfy the public demand, which emphasizes the importance of multiple resources. It is anticipated that the production equations presented here will assist harvesting managers in Turkey to predict productivity and logging cost for the mechanized harvesting machines. The cost factors not included in this study such as forest road costs, worker safety and environmental costs should be considered in future studies to improve the prediction of equipment productivity.

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