Modelling Harvester-Forwarder System Performance in a Selection Harvest

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ABSTRACT

A harvester - forwarder system was studied in a selection harvest operation conducted in an interior forest stand composed of Douglas fir (*Pseudotsuga menziesii*), Ponderosa pine (*Pinus ponderosa*), and Grand fir (*Abies grandis*). A time-study analysis was used to develop models for predicting individual machine productivity over time for both the harvester and forwarder involved in the study. Analysis indicates that harvester productivity (13.85 m^3 per SMH) closely matched forwarder production (14.10 m^3 per SMH) during the study. Further analysis yielded models that can be used to predict system productivity across the range of stand values observed during the study. The results suggest that system productivity is balanced when operating in stands averaging 15 to 25 cm DBH. In stands of larger or smaller average diameter, productivity for the system becomes unbalanced and affects machine operation, particularly the forwarder. Further research is suggested to improve the developed predictor models and allow for prediction of system performance over a broad range of stand and site conditions.

Keywords: *harvest production, harvester, forwarder, selection harvest, cut-to-length harvesting system.*

INTRODUCTION

As forest managers focus on different ways to introduce diversity into the forest, concepts such as

uneven-aged management are being introduced to achieve these conditions. One approach, the selection method of regeneration, is being used in many areas of the western United States and Canada to develop and maintain uneven aged conditions within the stand and to rapidly create late successional conditions within treated stands.

Harvests based on the group selection method of regeneration remove a representative number of stems within specific diameter classes in a number of small areas within the stand. Harvests are made at time intervals ranging from 10 to 40 years to promote regeneration within the stand and to insure a diversity of growth within the stand.

Harvesting systems used for group selection harvests require more control over machine operations during the harvest to minimize residual stand damage and site impacts. However, the harvest system options available to forest managers are relatively limited. Manual felling and processing require excessive time and labour, while conventional mechanized systems which harvest tree-length material often produce more residual stand damage than is acceptable from a management standpoint.

One option that has received attention in western North America is the harvester-forwarder system. This system holds a number of advantages over conventional systems commonly used for thinning operations. The system incorporates only two machines throughout the harvest — a harvester designed to fell and process stems at the stump, and a forwarder designed to transport processed logs from the stump to the landing or roadside. Both machines are designed to minimize site and stand impacts when used under proper conditions. This is achieved primarily through compact and lightweight design features built into each machine [5].

The harvester strips the limbs from harvested stems and places this slash directly in the machine path to reduce soil compaction and rutting. The forwarder typically follows in the tracks produced by the harvester, reducing the chance of creating heavily compacted trails and minimizing the potential damage to the stand [2, 6, and 7]. In at least one study, this system was found to have minimal impact relative to soil disturbance, compaction, and residual stand damage [5].

The single-grip harvester works well in stands where a residual component is left standing, due to

the potential reduction in stand and site damage incurred during the harvest entry. Processing with this machine is limited to stems with a maximum groundline diameter of 65 cm or less. Stem capacity is limited by both the felling device—a hydraulically driven chainsaw—and the delimbing device—a set of delimbing knives combined with two feedrollers which draw the stem through the delimbing knives. The single-grip harvester fells, delimbs, bucks, and tops each stem using this boom-mounted head.

After harvesting operations are completed, the forwarder moves along the harvester trail and retrieves the piled logs with a small boom-mounted grapple, placing them in a bunk or storage bay located at the back of the forwarder.

Bunk capacity can range up to 24 t. Although intended for applications where the machine continually travels on the same trail, smaller capacity machines are used which have a payload capacity of 8 to 14 t [3].

The system is limited to sites where stem diameter, slope, and terrain conditions are appropriate. Even when these constraints are considered, the harvester-forwarder system is appropriate for harvesting many sites in the interior region of northwestern North America. The system can also be used on many coastal sites where the terrain is rolling or flat and slope is minimal.

This study focuses on the productivity of the individual machines and the development of models for estimating machine productivity in a selection harvest. Specifically, this study attempted to determine individual machine productivity of a harvester-forwarder system in a selection harvest, and determine the operable productivity range of the system and estimate system productivity for a range of stand conditions under the studied silvicultural prescription.

METHODS

The study was conducted in a mixed stand composed of interior Douglas fir (*Pseudotsuga menziesii*), Ponderosa pine (*Pinus ponderosa*), and Grand fir (*Abies grandis*), located on a relatively flat to rolling site with few obstacles to mechanized operations. The stand was fire-origin second growth approximately 75 to 80 years old.

Table 1. Summary statistics for study plots.

Plot	Mean	Std. Dev.	Range	Min	Max	N
Diameter at Breast Height (cm):						
1	28.4	13.6	48.5	8.0	56.5	49
2	28.8	12.9	46.5	10.0	56.5	56
3	23.7	11.9	48.0	7.0	55.0	80
Grouped[1]	26.5	12.9	49.5	7.0	56.5	185
Diameter at Groundline (cm):						
Grouped	28.9	11.4	44.5	9.0	53.5	106
Total Tree Height (m):						
Grouped	16.18	1.9	4.9	13.7	18.6	11

[1] ANOVA indicated no significant difference among the means at the 0.05 alpha level.

The silvicultural objectives of the harvest were to increase the growth potential of medium- and smaller-sized stems in the stand, and to recover pine infested with mountain pine beetle to minimize further infestation. In addition, an effort was made to modify species composition within the stand to favour Ponderosa pine and to reduce the percentage of mature Douglas fir. Trees were not marked for harvest prior to entry, and the harvester operator was responsible for selecting stems for removal.

Three plots of 800 m² (dimensions of 20 x 40 m) were selected within the stand. Each randomly selected plot was ribboned off, and all trees in the plot were measured and tagged for later referencing with time-study data. Summary statistics are provided in Table 1. Total stem height measurements were taken for a sub-sample of trees within these plots.

As suggested in Table 1, little variation existed between plots, although diameter ranged substantially within each plot. An ANOVA comparing mean diameter for the three plots indicated no significant difference at an alpha level of 0.05. Stand density within the plots ranged from 612 stems per ha for plot 1, to 1000 stems per ha for plot 3. The mean stand density for the site was estimated at 771 stems per hectare. Slope on these sites ranged from 0 to 10% across uniform or flat terrain.

Data collection was separated into two components—harvester and forwarder operations. Each machine was timed in a production environment for later development of regression equations to estimate individual machine productivity. In addition, independent variables associated with machine performance were collected. These variables included individual stem diameter at breast height and at the stump, slope, terrain class, and move distance for each machine. Timing and other data collection were conducted with a hand-held data recorder equipped with a timing program that allowed elemental times to be matched with corresponding independent variables. Recorded data were then down-loaded to a micro-computer for statistical analysis.

Cycle element times collected for the harvester operations included move, position head, cut tree, delimb, slash disposal, and delay. These production elements are common to most, if not all, single-grip harvesters, and define a complete machine cycle.

Forwarder operations were also subjected to time studies with elemental operations being timed using the hand-held data recorder. Cycle elements for the forwarder operations included travel empty, load logs, move-woods, sort-woods, travel loaded, unload, move-landing, sort-landing, and delay.

Data related to each element collected during the time study were subjected to regression analysis to develop regression models relating elemental time to some independent variable(s) associated with the stand or site. Estimates of total cycle time for each machine were then computed for a range of independent stand variables.

RESULTS

Of the 194 trees measured in the plots, over 58% (113 stems) were harvested, leaving 81 trees as residuals in the stand. Mean DBH for the harvested component was 22.5 cm with an estimated total height of 15.7 m, suggesting that the harvest focused on smaller-sized timber. No analysis of the residual component or site/stand impact was undertaken.

Harvester

Summary statistics detailing cycle element times for harvester operations are provided in Table 2. Figure 1 illustrates the proportion of time associated with an individual cycle for the harvester. The data suggest that each harvester cycle requires approximately 1.02 productive minutes, resulting in an average production of 58.73 stems per PMH. Machine utilization was estimated to average 87%, based only on the operational and mechanical delays observed during the study. The scheduled cycle time for harvester operations was estimated at 1.18 scheduled minutes per tree.
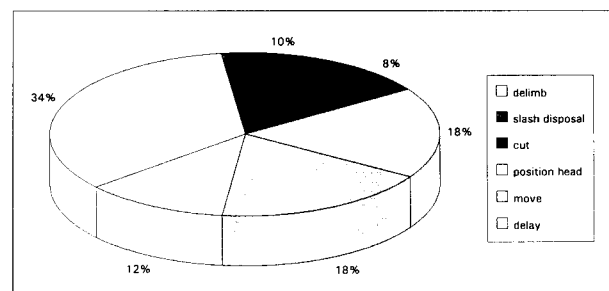

Figure 1. Elements of the harvester cycle.

Table 2. Summary statistics for harvester operations.

| Element | —(minutes per cycle)— | | |
	Mean	Std. Dev.	N
Delimb/Buck	0.3601	0.2634	106
Slash Disposal	0.1091	0.1686	140
Cut Tree	0.0802	0.0647	113
Position Head	0.1890	0.1057	104
Move	0.2833	0.1921	66
Total Productive Cycle	**1.0217**		
Delays			
Operational	0.0442	0.0077	5
Mechanical	0.1115	0.1679	3
Total Scheduled Cycle	**1.1774**		

Delimbing was the most time-consuming function, requiring approximately 34% of the cycle to complete. Moving the machine comprised 18% of a typical cycle, as did positioning the harvester head. The cut element required the least amount of time, comprising only 8% of a typical cycle.

Distance moved during the move function averaged 8.14 m, or about the operating radius of the boom. Maximum boom extension was estimated to be 10 m. Observed machine performance in the stand suggests that the operator typically moved a distance equal to the operating radius of the boom, and felled stems located within the half-circle area to the front and sides of the machine. In this case, for every 100 m^2 half-circle, approximately 1.7 stems were removed. The results also suggest that heavier stand densities would reduce the proportion of time spent moving the machine during operations and increase the number of stems harvested from each new point. The limited amount of data collected during the study, however, does not allow for verification of this hypothesis.

Regression analysis was conducted for several elements of the harvester cycle: fell tree, delimb, and move machine. The resulting regression models to predict these elemental times are presented below. Regression estimators were not developed for the other cycle elements, since no significant correlation was noted for these variables during the statistical analysis.

Fell Tree:

$$CUT = 0.0283 + 0.0019*DBH$$

Where:
    DBH = Diameter at breast height (cm)
    CUT = Time required to sever a single tree once sawhead is engaged (productive minutes).
    $r^2 = 0.276$
    $SE(y) = 0.0261$

Delimb:

$$DLIM = 0.3508*Ht - 5.1628$$

Where:
    Ht = Total tree height (m)
    DLIM = Time required to delimb, buck, and top stem (productive minutes)
    $r^2 = 0.463$
    $SE(y) = 0.194$

Move Machine:

$$MOV = 0.1944 + 0.0357*Dist$$

Where:
    Dist = Mean move distance (m)
    MOV = Time required to move machine between points in the stand (productive minutes)
    $r^2 = 0.873$
    $SE(y) = 0.118$

These elemental models were combined with observed mean values for the remaining cycle elements to generate a predictor equation for harvester total cycle time per tree based on mean stand DBH, mean total height, and estimated mean move distance. Within the overall model, each elemental predictor was adjusted to account for the productive time required to harvest a single tree. The developed model follows:

Harvester Total Cycle:
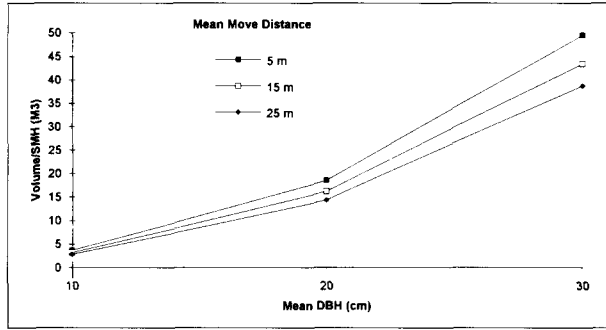
$$TC(H) = -4.6830 + 0.3508*Ht + 0.0208*Dist + 0.0019*DBH$$

Figure 2. Effect of diameter and mean move distance on harvester hourly production.

Where:

$TC(H)$ = Total cycle time per tree for single-grip harvester (productive minutes)

For the parameters observed in the harvested stands, the mean harvester cycle time is estimated at 1.04 minutes per tree on a productive basis—excluding delays—and 1.21 minutes per tree on a scheduled hour basis. Assuming a mean volume per stem of 0.24 m³, based on volume equations provided by the British Columbia Forest Service (1976) and observed means for the harvested component, the average hourly production of the harvester is estimated at 14.11 m³ on a productive hour basis, or 12.23 m³ on a scheduled hour basis.

Factors associated with the harvested stand component were varied to determine the effect of changes in diameter and mean move distance on machine productivity (Fig. 2). The graphed results indicate that mean move time plays a relatively minor role in defining productivity in stands with moderate to low stocking. As with most logging systems, however, average harvested tree diameter has a significant impact on machine productivity. In this analysis, hourly productivity increased by a factor of more than five when mean stand diameter increased from 10 to 20 cm.

Forwarder:

Cycle element times observed for the forwarder operations are summarized in Table 3, while a summary of the observations associated with the inde-

Table 3. Summary statistics for forwarder operations.

Element	—(minutes per cycle)— Mean	Std. Dev.	N
Move-Woods	4.3688	2.4843	95
Sort-Landing	2.1041	1.2582	59
Unload	5.3847	2.1158	193
Move-Landing	0.9584	0.3148	32
Travel Empty	2.6444	1.2735	9
Load Logs	9.4284	0.1502	267
Sort-Woods	2.0543	1.2459	86
Travel Loaded	1.7585	0.7493	8
Total Productive Cycle	**28.7016**		
Delays[1] Operational	1.4046	2.8457	7
Total Scheduled Cycle	**30.1062**		

[1] No mechanical or personnel delays were observed during the study.

Table 4. Summary of independent variables associated with forwarder operations.

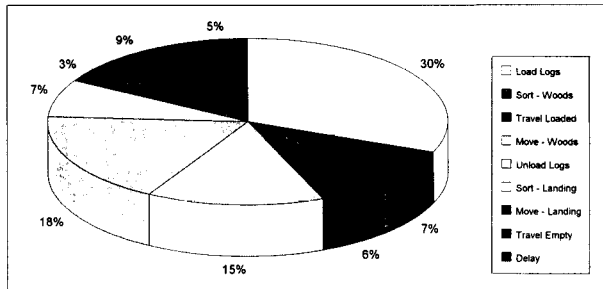| Element	Mean	Min	Max	Std. Dev.	N
Dist1 - Move-Woods (meters)	10.93	1.5	38.0	9.50	95
Dist2 - Move-Landing (meters)	10.34	1.5	32.0	7.59	32
Dist3 - Travel Loaded (meters)	121.50	71.0	241.0	57.87	8
Dist4 - Travel Empty (meters)	170.78	52.0	290.0	89.59	9
Number of Logs - Load Logs	2.03	1.0	7.0	0.96	267
Number of Logs - Unload Logs	3.14	1.0	8.0	1.74	193

Figure 3. Elements of the forwarder cycle.

pendent variables collected during forwarder-timing operations is provided in Table 4. Elements of the forwarder cycle and their proportional time requirements are illustrated in Figure 3.

Cycle times for the forwarder averaged 28.76 minutes per cycle on a productive basis, and 30.11 minutes per cycle on a scheduled basis. The load element comprised 30% of a typical cycle, while unload and move-woods comprised 18 and 15% of the cycle, respectively. Only minor operational delays were observed during timing, suggesting a machine utilization of 95%.

No mechanical delays were noted during the data collection. The high utilization rate associated with this machine may be misleading, due to the relatively short time spent observing its operation. Further studies, particularly long-term gross shift level studies, are suggested to quantify forwarder utilization rates more accurately.

Regression equations were derived for 4 elements—move-woods, move-landing, travel empty, and travel loaded. The regression equations are detailed below. No regression estimators were developed for the other elements, since no significant correlation was detected during the statistical analysis.

Move-Woods:

$$MW = 0.2084 + 0.0146^*Dist1$$

Where:
> Dist1 = Mean move distance between log piles in the woods (m).
> MW = Time required to move machine between points in the stand (productive minutes)
> $r^2 = 0.438$
> $SE(y) = 0.1576$

Move-Landing:

$$ML = 0.1763 + 0.0061^*Dist2$$

Where:
> Dist2 = Mean move distance between sorted products (m)
> ML = Time required to move machine between points at landing or roadside (productive minutes)
> $r^2 = 0.348$
> $SE(y) = 0.0646$

Travel Loaded:

$$TL = 0.2386 + 0.0125^*Dist3$$

Where:
> Dist3 = Mean distance from point of loading to landing or roadside (m)
> TL = Time required to move machine from woods to landing (productive minutes).
> $r^2 = 0.933$
> $SE(y) = 0.2089$

Travel Empty:

$$TE = 0.3418 + 0.0135^*Dist4$$

Where:
> Dist4 = Mean distance from landing or roadside to point of loading (m)
> TE = Time required to move machine from landing or roadside to woods (productive minutes)
> $r^2 = 0.900$
> $SE(y) = 0.4315$

Combining these regression models with the observed means for the remaining elements and delays, a model was developed to estimate the total cycle time per load for a forwarder operating in a similar range of stand conditions. All time estimates are provided in scheduled minutes with expected delays incorporated into the model. The prediction model follows:

Forwarder Total Cycle:

$$TC(F) = 20.3761 + 0.1734^*Dist1 + 0.0244^*Dist2 + 0.0125^*Dist3 + 0.0135^*Dist4$$

Where:

TC(F) = Total cycle time per load for forwarder (scheduled minutes)

For each machine cycle, the forwarder averaged 12 moves between log piles to acquire a load of logs. At each log pile, approximately three grapple loads of two logs were loaded into the bunk before the forwarder moved to the next pile. This suggests a mean pile size of 6 logs, although sort constraints or bunk capacity limits meant that some logs were left in the pile for later acquisition. These facts suggest that the loading and move-woods elements for the machine cycle are affected to a large extent by the size and grade of the logs in the pile, the mean number of logs in each pile, and the number of piles per ha.

In this study, an average of 78 logs was carried by the forwarder during each cycle, translating into an approximate payload of 7.48 m³ (approximately 7.5 t) per cycle. This payload is based on volume estimates derived from equations used by the British Columbia Forest Service [1]. This estimate falls substantially below the expected payload of the forwarder, rated at 10 t, and suggests that payload capacity falls for smaller sized logs, probably due the larger amount of wasted area between logs. Based on the observed mean cycle time of 30.11 scheduled minutes, however, estimated hourly production from this forwarder on comparable sites should average 14.91 m³ per SMH.

Comparison with estimated harvester production (13.84 m³ per SMH) suggests that system productivity is balanced when working in stands similar to those observed during the study. Further research should be considered to quantify the effect of log size on forwarder payload limits.

Mean harvested tree diameter and forwarding distance were varied in the production model to examine their impact on machine productivity. Results of this analysis suggest that changes in forwarding distance—at least those distances observed during data collection—have little effect on machine productivity. These results are similar to those derived by Makkonen [4] in a study of several small forwarders. However, the impact of diameter and log volume was found to be significant, with substantial increases in forwarder productivity occurring with increases in log volume.
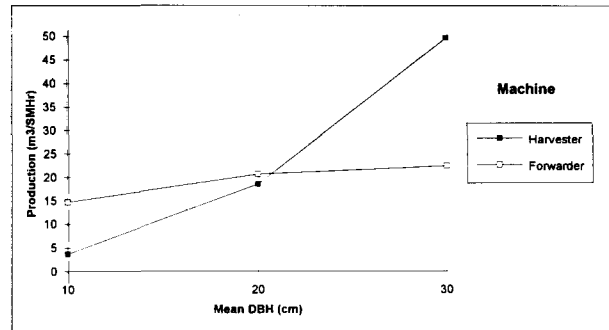

Figure 4. Comparison of harvester and forwarder productivity relative to changing mean stand diameter—all other factors held constant.

Using the production equations derived for both machines, an analysis was conducted of the total system performance. Plotting system performance over a range of harvested tree diameter values while holding all other variables constant revealed that harvester productivity lags behind forwarder productivity when harvesting small diameter stems, and exceeds forwarder productivity when harvesting larger diameter stems (Fig. 4). The results suggest that the optimal range of conditions for this system when conducting partial harvests is in stands with a mean harvested stem DBH of 15 to 25 cm. On either side of this range, the system becomes unbalanced and machine utilization rates are affected.

Generally, system productivity under the silvicultural prescription evaluated in this study is limited by forwarder performance. Forwarder productivity remains relatively constant while harvester productivity increases. Variables associated with both machines, such as mean travel distance for the forwarder and mean move distance between processing points for the harvester, would have significant impact on system balance. Generally, critical variables related to productivity could be modified during the harvest to improve system balance.

CONCLUSIONS

Production analysis of a harvester-forwarder system used to conduct a selection harvest in a mixed age Ponderosa pine stand indicates that the system was able to produce between 13 and 14 m³ per SMH. Development of machine cycle time equations allowed for further analysis of the system within the range of collected data.

The harvester-forwarder system evaluated in this study can be used effectively in selection harvests to produce moderate volumes of cut-to-length timber. In addition, the limited impact of this system minimizes the amount of residual damage that can occur in partial harvests. The results, however, suggest that, when harvesting both extremely large and small diameter stems, the system may become unbalanced and more attention must be placed on machine scheduling.

No attempt was made to estimate the unit cost of production. The very low rates of production noted when harvesting small diameter (10 to 15 cm DBH) stems suggest that little profit would be made when using a harvester-forwarder system.

The increasing need for raw wood products from the forests of the Pacific Northwest will probably create more opportunity for thinning, group selection harvests, and other types of partial harvest in the region. Harvester-forwarder systems can be used for this purpose in many stands in a productive, cost-effective manner.

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