Estimating Processing Times of Harvesters in Thinning Operations in Maine

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Abstract

Although harvester use in recent years has increased in Maine, in the past 25 years no productivity or cycle time information was made available for harvesters operating in Maine's softwood stands. In order to update regional production and cost models it was necessary to develop cycle time equations for harvesters. Time and motion studies of harvesters in thinning operations were conducted during the summer of 2012 at four harvest sites under a variety of stand and site conditions common to central Maine. Results show cycle time differences for harvesters based on stem size as well as hardwood and softwood species groupings. A linear mixed-effects model was developed to explain the influence of stem size and species on processing time. The combination of operator, machine, and site conditions was used as a random effect in this model, which explained 5 percent of data variance. The adjusted R^2 for this model was 0.20, and the model was validated using two independent harvester time studies conducted in 2013. Validation results show that the developed model predicts total harvest time within 5 to 25 percent of the observed time. This model will allow for updated logging cost predictions by land managers and logging contractors, but it also clearly shows the effect of stem size on time consumption and subsequently on productivity.

Owing in part to regenerating clear-cuts from the spruce budworm era in the 1970s and 1980s, forest operations managers in Maine must manage an increasing percentage of small diameter timber stands (diameter at breast height [DBH] < 27 cm). According to McCaskill et al. (2011), Maine has approximately 11 million acres of forest land dominated by small and medium diameter stems (DBH < 27 cm), so it is important to know machine productivity for harvest systems operating in these conditions. Cut-to-length harvesting is the second-most dominant harvesting method[1] in Maine in terms of weekly production (Leon and Benjamin 2013). Effective management of any forest operation requires accurate estimates of harvest costs and productivity, although monitoring these variables can be difficult (Wang et al. 2004, Holzleitner et al. 2011).

The forest industry has access to existing software to calculate harvest costs and productivity (Fight et al. 2003, 2006), but none of these models use machine productivity data from Maine. A literature review conducted by Hiesl and Benjamin (2013) found no forestry equipment productivity studies from Maine in the last 25 years. Harvester data from eastern Canada are mostly from the 1990s (Richardson 1989, Gingras 1994, Richardson and Makkonen 1994, Légère and Gingras 1998), while the more recent publications are from the western United States (Han et al. 2004, Adebayo et al. 2007, Bolding et al. 2009) and Europe (Jiroušek et al. 2007, Spinelli et al. 2010, Spinelli and Magagnotti 2010). Existing productivity and cycle time data for harvesters need to be used carefully due to regional differences in site conditions, species composition, and stem size.

The most common silvicultural treatments in Maine include partial harvests and shelterwood cuts (Maine Forest Service 2013). Clear-cuts represent only 5.5 percent of the total area harvested. Commercial thinning is one form of partial harvest and is of most interest, since small diameter

[1] In forest operations the term ''harvesting method'' is used to describe how wood is delivered to the roadside (e.g., whole-tree, cut-to-length, tree length). Harvesting system describes the combination of equipment used for a particular harvesting method. For more information on harvesting systems see Eckhardt (2007).

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softwood stands in Maine are in need of such treatment to improve stand growth and yield.

With increasing harvest of small diameter stems in this region it was necessary to conduct a time and motion study in order to update regional harvester cycle time, productivity, and cost models. Small diameter softwood stands were the main focus and are encountered not only in Maine and this region but also in other states and countries. The need to develop cycle time equations for harvesters in Maine is strengthened by the fact that previous cycle time and productivity studies show major differences in harvesting equipment as well as stand and site conditions (Hiesl and Benjamin 2013). The objective of this study was to develop a cycle time equation for dangle-head harvesters operating in commercial thinnings using data from four different harvesters, operators, and site and stand conditions to capture a broad range of processing speeds. It is expected that this information can be used as a baseline for regional harvesting operations.

Materials and Methods

Data were collected from four different commercial thinning sites throughout Maine from May until July 2012. Site conditions included stand densities from 1,326 to more than 4,800 trees per ha, basal area of 27 to 47 m^2/ha, and slopes of 1 to 5 percent (Table 1). All sites were thinned, with light to heavy removal intensities (25% to 90% basal area removal), and trail spacing on each site was 18 m. Three sites were softwood dominated (greater than 95% of *Abies balsamea* (L.) P. Mill., *Picea rubens* Sarg., *Tsuga Canadensis* (L.) Carr., and *Thuja occidentalis* L.) and up to 5 percent hardwood (*Fagus grandifolia* Ehrh., *Acer rubrum* L., *Betula alleghaniensis* Britt., *Betula papyrifera* Marsh., and *Populus tremuloides* Michx.). Site 1 was a mixed-wood stand with 50 percent softwood and 50 percent hardwood of the same species mix. The high removal intensity of Site 1 is attributable to the removal of hardwoods that dominated the diameter range of 17.5 to 58.0 cm and to the fact that the sampling point was located in an area that consisted of a heavy removal of hardwoods with few residual softwoods. The prescription for this site was a thinning with a 60 percent removal of basal area, which has been accomplished in the remaining stand. The postharvest stand density of this site is comparable to Site 3 at around 1,000 trees per ha. This site also provided cycle time data for the majority of hardwood trees in the data set.

Logging contractors and land managers gave permission to observe and measure productivity of active harvesting operations. The sites selected represent harvesting conditions common to this region in regard to species composition, ground conditions, and silvicultural prescription. The equipment used ranged in age from 1 to 7 years, and operators in the study had experience with harvesters ranging from less than 1 to 15 years (Table 2).

Harvest sites were selected based on the willingness of the logging contractor to be studied and the prerequisites of being a commercial thinning in a small diameter softwood stand. We also asked land managers to recommend logging contractors and crews that they deemed representative of the logging industry. A study area from each site was flagged for harvest to ensure a minimum sample of 250 trees per site, which resulted in a range of block size from 0.2 to 0.9 ha. All trees in each study area were painted in four different colors (blue, green, orange, yellow) based on 2.5-cm DBH classes (Glöde 1999, Eggers et al. 2010, Hiesl and Benjamin 2012). Trees larger than 29 cm had the DBH painted as a number on the bole. All four colors were used two times, in the same order, as shown in Table 3. Horizontal line samples were established to determine initial tree density and basal area (Strand 1958, Beers and Miller 1976, Husch et al. 1982).

Data collected for the harvester within each sample area included total cycle time to cut and process an individual tree, as well as travel to the next tree, although times for specific work elements of cut, fell, delimb, and cross-cut were not recorded separately. Cycle time was measured as productive machine minutes including delays less than 15 minutes. Diameter class and species were also recorded. A work cycle began and ended with an empty harvester head and included the time to cut, fell, delimb, cross-cut, and move to the next tree. Machine operators and researchers communicated via a two-way radio with headsets during active operations. Data were entered into a Palm Tungsten E2 with the time study software UMT Plus (Laubrass, Inc., Montreal, Quebec). The cutting and processing of a total of 1,096 (95%) softwood and 58 (5%) hardwood stems were observed and analyzed.

Data were analyzed using R (R Core Team 2012) and the car (Fox and Weisberg 2011) and nlme (Pinheiro et al. 2012) packages. A linear mixed-effects model with a random intercept was developed to predict the cycle time of harvesters. A ''dummy'' variable of species group was created to differentiate between softwood and hardwood species in the harvester analysis. The data set was truncated at a DBH of 27.5 cm due to a very small number of harvested trees with greater diameters.

To validate the developed model we used harvester data collected in 2013 from two harvest sites in central Maine. Stand and site conditions at both harvest sites were similar to conditions encountered during the time and motion studies in 2012. Site A was harvested by a Ponsse Ergo harvester ($n = 442$), while Site B was harvested using a

Table 1.—Stand and site information for four harvest sites.[a]

Site	Stand density (trees/ha)		Mean (SD) DBH (cm)	Basal area (m^2/ha)	Slope (%)	Basal area removed (%)	DBH removed (cm)	Softwood (%)	Hardwood (%)
	Preharvest	Postharvest							
1	1,326	269	20 (7.1)	36.1	3	90[b]	10–58	50	50
2	2,596	1,709	15 (5.1)	47.9	1	25	10–38	96	4
3	1,630	1,119	15 (4.6)	27.4	2	45	10–30	100	0
4	4,812	3,041	13 (3.6)	41.3	2–5	45	10–33	95	5

[a] DBH = diameter at breast height.

[b] The prescription for this site was a 60 percent removal of basal area. The sampling point for this site, however, was located in an area with high removal intensity of hardwoods and only few residual softwoods. The overall harvest site was comparable in postharvest stand density to Site 3.

Table 2.—Harvester equipment and operator information for four harvest sites.

Site	Make/model	Engine power (hp)	Machine hours	Operator experience (y)[a]	Productivity (m^3/PMH)[b]
1	Ponsse Ergo	275	7,500	15	18.6
2	Timberjack 1270D	215	14,650	12	15.2
3	Valmet 911.4	228	5,000	<1	12.6
4	Ponsse Fox	197	1,200	<1	10.1

[a] Operator experience with harvester.
[b] Productive machine hours (PMH) including delays less than 15 minutes.

Komatsu 911.4 harvester ($n = 89$). Both operators had more than 2 years of experience working with their particular machine. Balsam fir and red spruce were the dominant tree species harvested.

Results

Various visual investigation tools, such as Q–Q and residual plots, showed that the linear regression model assumption of normally distributed residuals was not met with an untransformed model. To satisfy model assumptions, the dependent variable of cycle time was log-transformed. DBH and species group (SPGRP) were significant variables ($P < 0.01$) for the logarithmic cycle time model (CT, in PMmin_{15}; Eq. 1; Table 4). Stand density, basal area, and removal intensity were not significant variables ($P > 0.05$) in predicting cycle time. Data were weighted to account for the variability of cycle time within each DBH class and between different harvest sites. Therefore different weighting was applied for each DBH class j at each harvest Site i (Eq. 2). The dummy variable SPGRP consists of two values: 0 for hardwoods and 1 for softwoods.

$$\log(\text{CT})_{ij} = -1.129 + 0.041 \times \text{DBH}_{ij} - 0.246 \times \text{SPGRP}_{ij} + \alpha_i + \varepsilon_{ij} \quad (1)$$

where α represents the combination of operator, machine, and site conditions and

$$\varepsilon_{ij} \sim N(0, \sigma^2 \times |\text{DBH class}_{ij}|^{2\delta_i}) \quad (2)$$

The unobserved random error (ε_{ij}) is assumed to be independent and from a normal distribution (N) with a mean of zero and the variance of the residuals (σ^2) multiplied with the power of the absolute value of the variance covariate DBH class. The parameter δ_i was estimated for each site. The adjusted R^2 of the fixed and random effects was 0.20; however, the adjusted R^2 for the fixed effects only was 0.17. Five percent of the random variation in the data can be explained by the combination of operator, machine, and stand conditions (α), while the remaining 95 percent are a combination of truly random variation and the influence of variables not studied (Table 5). The predicted cycle time for processing softwood (Fig. 1a) was consistently lower than the predicted cycle time for processing hardwood (Fig. 1b).The difference in cycle time between softwood and hardwood stems increased with increasing DBH.

A visual comparison of the observed processing time with the predicted processing time shows a good fit for Site A for both softwood and hardwood (Fig. 2). The total observed harvesting time was 241 minutes, while the total predicted harvesting time was 252.5 minutes. Thus the model overpredicted total harvest time by 5 percent. Comparing the observed processing times from Site B with the predicted processing times shows that the model predicts processing times in the upper third of observed values (Fig. 3). The total observed harvesting time was 43 minutes, with a predicted harvesting time of 53.7 minutes. In this case the processing time is overpredicted by 25 percent.

Table 3.—Diameter at breast height (DBH) class and color codes used during the time and motion study.

DBH class (cm)	DBH range, cm (in.)	Color
10.1	8.9–11.0 (3.5–4.4)	Blue
12.7	11.1–13.7 (4.5–5.4)	Green
15.2	13.8–16.3 (5.5–6.4)	Orange
17.8	16.4–18.8 (6.5–7.4)	Yellow
20.3	18.9–21.3 (7.5–8.4)	Blue
22.9	21.4–23.9 (8.5–9.4)	Green
25.4	24.0–26.4 (9.5–10.4)	Orange
27.9	26.5–29.0 (10.5–11.4)	Yellow
>29.1	DBH painted on bole	

Discussion

The effect of tree diameter on harvester productivity is well documented (Richardson 1989, Gingras 1994, Richardson and Makkonen 1994, Lanford and Stokes 1996, Holtzscher and Lanford 1997, Ovaskainen et al. 2004, Li et al. 2006, Adebayo et al. 2007, Jiroušek et al. 2007, Nakagawa et al. 2007, Spinelli et al. 2010), so it is not surprising to find this effect in the current study. As discussed further in Hiesl and Benjamin (2013), only Richardson (1989) and Spinelli et al. (2010) investigated the effects of stem size on the full range of tree diameters that are common to Maine's forests. Other studies that investigated a smaller range of tree diameters were Lanford and Stokes (1996), Holtzscher and Lanford (1997), and Nakagawa et al. (2007). Another influential factor associated with tree size that increases harvester cycle time and negatively impacts productivity is branch thickness (Richardson 1989, Richardson and Makkonen 1994, Glöde 1999). Owing to the small diameter of the trees harvested,

Table 4.—Regression coefficients for the logarithmic cycle time prediction function for harvester ($n = 1{,}154$).

Coefficient[a]	Estimate (SE)	Degrees of freedom	t	P
Intercept	−1.129 (0.109)	1,148	−10.327	<0.001
DBH	0.041 (0.003)	1,148	13.708	<0.001
SPGRP	−0.246 (0.077)	1,148	−3.197	0.001

[a] DBH = diameter at breast height; SPGRP = species group. The dummy variable SPGRP consists of two values: 0 for hardwoods and 1 for softwoods.

Table 5.—Random effects and their contribution to explaining the variation in the data for logarithmic cycle time prediction for harvester.

	SD	Variance	Variation explained (%)
Combo(α)[a]	0.11164	0.01246	5
Residual	0.49026	0.24035	95
Sum	NA[b]	0.25281	100

[a] The combined effects of operator, machine, and site conditions.
[b] NA = not applicable.

we assume that branch size was not a significant factor in our study; however, we did not measure any branches. The harvester analysis further showed that there was a significant difference in cycle time and productivity prediction, respectively, between softwood and hardwood harvesting, even though 95 percent of the trees sampled were softwood. Such results have also been reported by Spinelli et al. (2010) for a variety of species including spruce (*Picea* ssp.), white pine (*Pinus strobus* L.), Austrian pine (*Pinus nigra* J.F. Arnold), ash (*Fraxinus* ssp.), and alder (*Alnus* ssp.). Huyler and Ledoux (1999) reported that species might be an influential factor on harvester productivity, but they did not analyze this effect. Spinelli et al. (2010) used a total of over 15,000 trees with a much larger hardwood content to develop their productivity standards for harvesters in Italy. They were able to isolate the effect of poplar on harvester productivity as well as the effect of other hardwood species combined. With the small sample of hardwood trees ($n = 58$) in the current study it was not possible to isolate any particular species effects, so only a species grouping was used instead.

Adebayo et al. (2007) reported cycle time equations that use the number of logs produced from each stem. We didn't use this variable since the majority of stems processed resulted in only one log. Spinelli and Magagnotti (2010) used DBH by the power of 1.23, while our model uses a log-transformed dependent variable of cycle time and an unchanged DBH. Légère and Gingras (1998) reported that the removal intensity, based on the prescription, influenced the productivity of harvesting equipment, including harvesters. During the data analysis we found that among the four sites the removal intensity as well as the basal area and stand density did not significantly influence the cycle time of a harvester. The effect of different equipment on harvester productivity is also well documented (Richardson 1989, Gingras 1994, Richardson and Makkonen 1994, Légère and Gingras 1998, Han et al. 2004, Adebayo et al. 2007, Spinelli et al. 2010). We acknowledge that there is a great variability in cycle time among the individual harvest sites. Data were pooled since the objective of this study was to develop a general cycle time function that represents baseline time consumptions over a variety of site and stand conditions encountered in this region. Owing to this, the individual sites were chosen because of their differences in harvesting equipment, operator experience, and site and stand conditions to capture a broad range of typical harvesting conditions. This pooling of data allowed us to develop equations on a population level, an approach that has been applied before in a larger style by Spinelli et al. (2010) and has been suggested by Lindroos (2010).

Many existing studies have documented the influence of the operator on harvester productivity, some as high as 40 percent (Richardson 1989, Richardson and Makkonen 1994, Kärhä et al. 2004, Ovaskainen et al. 2004, Nurminen et al.

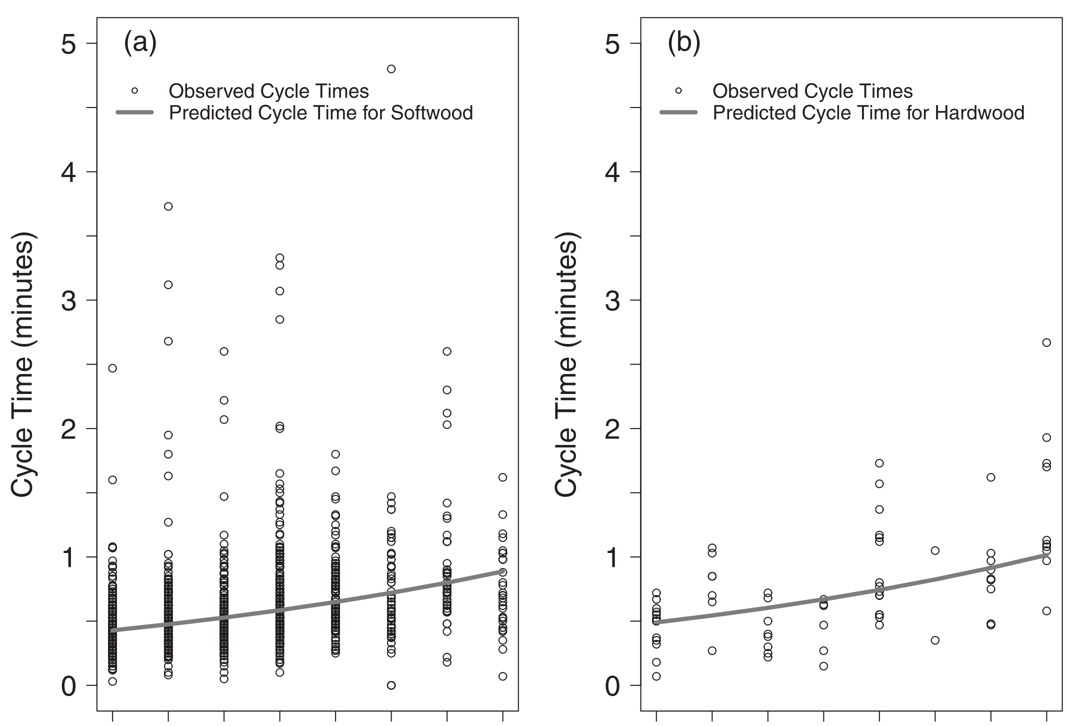

Figure 1.—Fitted and observed cycle time for harvester cutting and processing (a) softwood ($n = 1{,}096$) and (b) hardwood ($n = 58$).

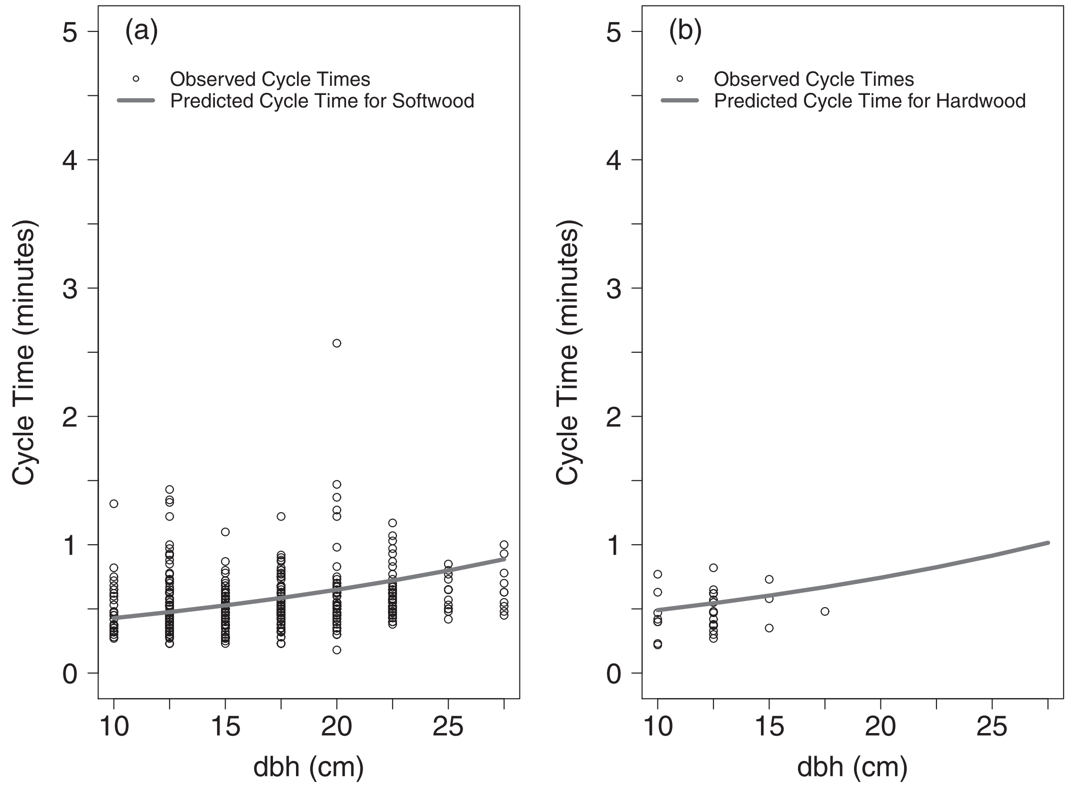

Figure 2.—Observed processing time compared with predicted processing time for harvest Site A: (a) softwood processing ($n = 414$*) and (b) hardwood processing (*$n = 28$*).*

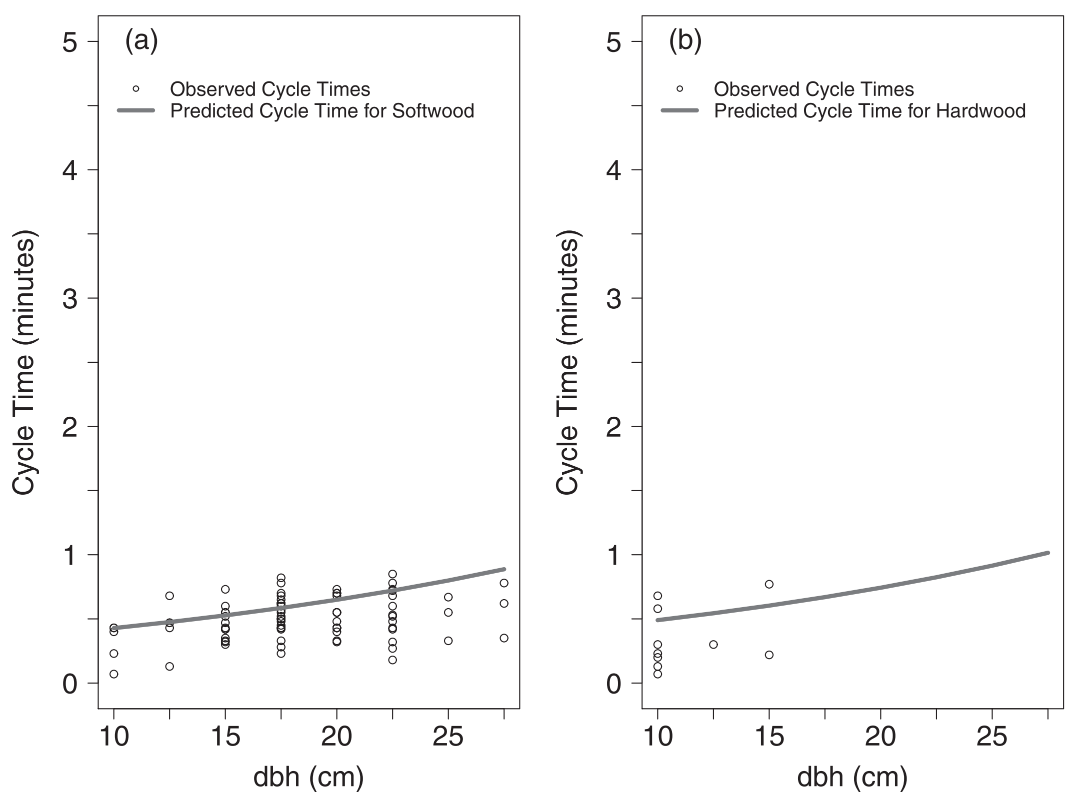

Figure 3.—Observed processing time compared with predicted processing time for harvest Site B: (a) softwood processing ($n = 79$*) and (b) hardwood processing (*$n = 10$*).*

2006, Lindroos 2010, Spinelli et al. 2010, Purfürst and Erler 2011, Purfürst and Lindroos 2011). The influence of the combination of operator, machine, and site conditions (''combo'' effect) in the present study explains 5 percent of the variation in the data for cycle time prediction (Table 5). Operator experience with harvesters ranged from less than 1 to 15 years, so we expected a larger effect on cycle time from the combination of operator, machine, and site conditions. The small effect observed (5%) may have resulted from simplified thinning prescriptions in stands dominated by only two species (red spruce and balsam fir); however, Kärhä et al. (2004) reported an operator effect of 40 percent in first thinnings of Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* L. Karst.) stands. Further, the uniform nature of harvested stems (less than 38 cm DBH) might also have been a factor in fewer harvesting decisions by the operators. To investigate the influence of the operator and machine on harvester performance, more data need to be collected, including a larger range of tree diameters and a larger number of operators.

Validation of the model with two independent data sets showed that the total harvest time estimated was within a range of 5 to 25 percent of the actual harvest time. Such a range was to be expected, because the cycle time function was developed using pooled data from four different harvesting operations, which all employed different harvesters and worked in a variety of site and stand conditions, and also represented multiple levels of operator experience. The validation clearly shows that the model fits very well with the time consumption of harvest Site A. For harvest Site B the model was more conservative and estimated a longer cycle time for individual trees than was observed. Several factors can influence processing speed of a harvester, which may be the reason for a faster than predicted processing of trees in this stand. Branch diameter is one influential factor on harvester processing speed and productivity (Richardson 1989, Richardson and Makkonen 1994, Glöde 1999). Harvest Site B was well spaced with few branches on the bole bellow the life crown. Trees from Sites 1 to 4, however, were in more dense stands, which were characterized by a large number of small branches on the bole from the ground up. This likely slowed the cutting and delimbing process. Over time more harvester data need to be included in this harvest cycle time model to refine the predictive power.

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Literature Cited

Adebayo, A. B., H.-S. Han, and L. Johnson. 2007. Productivity and cost of cut-to-length and whole-tree harvesting in a mixed-conifer stand. *Forest Prod. J.* 57(6):59–69.

Beers, T. W. and C. I. Miller. 1976. Line sampling for forest inventory. Research Bulletin No. 934. Department of Forestry and Natural Resources, Purdue University Agricultural Experiment Station, West Lafayette, Indiana.

Bolding, M. C., L. D. Kellogg, and C. T. Davis. 2009. Productivity and costs of an integrated mechanical forest fuel reduction operation in southwest Oregon. *Forest Prod. J.* 59(3):35–46.

Eckhardt, R. E. 2007. Renewable Biomass from the Forests of Massachusetts: Forest Harvesting Systems for Biomass Production. Innovative Natural Resource Solutions, LLC, Portland, Maine.

Eggers, J., A. McEwan, and B. Conradie. 2010. Pinus saw timber tree optimization in South Africa: A comparison of mechanised tree optimisation (harvester/processor) versus current manual methods. *South. Forests* 72(1):23–30.

Fight, R. D., B. R. Hartsough, and P. Noordijk. 2006. User's Guide for FRCS: Fuel reduction cost simulator software. General Technical Report PNW-GTR-668. USDA Forest Service, Pacific Northwest Research Station, Portland, Oregon.

Fight, R. D., X. Zhang, and B. R. Hartsough. 2003. User's Guide for STHARVEST: Software to estimate the cost of harvesting small timber. General Technical Report PNW-GTR-582. USDA Forest Service, Pacific Northwest Research Station, Portland, Oregon.

Fox, J. and S. Weisberg. 2011. An {R} Companion to Applied Regression. 2nd ed. Sage Publications, Inc., Thousand Oaks, California.

Gingras, J.-F. 1994. A comparison of full-tree versus cut-to-length systems in the Manitoba model forest. Special Report SR-92. Forest Engineering Research Institute of Canada (FERIC), Pointe Claire, Quebec.

Glöde, D. 1999. Single- and double-grip harvesters—Productive measurements in final cutting of shelterwood. *Int. J. Forest Eng.* 10(2):63–74.

Han, H.-S., H. W. Lee, and L. R. Johnson. 2004. Economic feasibility of an integrated harvesting system for small-diameter trees in southwest Idaho. *Forest Prod. J.* 54(2):21–27.

Hiesl, P. and J. G. Benjamin. 2012. Cycle time analysis of harvesting equipment from an early commercial thinning treatment in Maine. *In:* Proceedings of the 35th Council on Forest Engineering: Engineering New Solutions for Energy Supply and Demand. J. Roise and A. Hassan (Eds.). Council on Forest Engineering, New Bern, North Carolina.

Hiesl, P. and J. G. Benjamin. 2013. Applicability of international harvesting equipment productivity studies in Maine, USA: A literature review. *Forests* 4(4):898–921.

Holtzscher, M. A. and B. L. Lanford. 1997. Tree diameter effects on cost and productivity of cut-to-length systems. *Forest Prod. J.* 47(3):25–30.

Holzleitner, F., K. Stampfer, and R. Visser. 2011. Utilization rates and cost factors in timber harvesting based on long-term machine data. *Croat. J. Forest Eng.* 32(2):501–508.

Husch, B., C. I. Miller, and T. W. Beers. 1982. Inventory using sampling with varying probabilities. *In:* Forest Mensuration. 3rd ed. Krieger Publishing Company, Malabar, Florida. pp. 213–275.

Huyler, N. K. and C. B. Ledoux. 1999. Performance of a cut-to-length harvester in a single-tree and group-selection cut. Research Paper NE-711. USDA Forest Service, Northeastern Research Station, Radnor, Pennsylvania.

Jiroušek, R., R. Klvač, and A. Skoupý. 2007. Productivity and costs of the mechanized cut-to-length wood harvesting system in clear-felling operations. *J. Forest Sci.* 53(10):476–482.

Kärhä, K., E. Rökkö, and S.-I. Gumse. 2004. Productivity and cutting costs of thinning harvesters. *Int. J. Forest Eng.* 15(2):43–56.

Lanford, B. L. and B. J. Stokes. 1996. Comparison of two thinning systems. Part 2. Productivity and costs. *Forest Prod. J*. 46(11/12):47–53.

Légère, G. and J.-F. Gingras. 1998. Evaluation of methods of harvesting with protection of small merchantable stems. Technical Report-124. Forest Engineering Research Institute of Canada (FERIC), Pointe Claire, Quebec.

Leon, B. and J. G. Benjamin. 2013. A Survey of Business Attributes, Harvest Capacity and Equipment Infrastructure of Logging Businesses in the Northern Forest. The Northern Forest Logging Industry Assessment. University of Maine, Orono.

Li, Y., J. Wang, G. Miller, and J. McNeel. 2006. Production economics of harvesting small diameter hardwood stands in central Appalachia. *Forest Prod. J*. 56(3):81–86.

Lindroos, O. 2010. Scrutinizing the theory of comparative time studies with operator as a block effect. *Int. J. Forest Eng*. 21(1):20–30.

Maine Forest Service. 2013. Silvicultural Activities Report. 2011 Silvicultural Activities Report. Department of Agriculture, Conservation and Forestry—Maine Forest Service—Forest Policy and Management Division, Augusta, Maine.

McCaskill, G. L., W. H. McWilliams, C. J. Barnett, B. J. Butler, M. A. Hatfield, C. M. Kurtz, R. S. Morin, W. K. Moser, C. H. Perry, and C. W. Woodall. 2011. Maine's forests 2008. Resource Bulletin NRS-48. USDA Forest Service, Northern Research Station, Newtown Square, Pennsylvania.

Nakagawa, M., J. Hamatsu, T. Saitou, and H. Ishida. 2007. Effect of tree size on productivity and time required for work elements in selective thinning by a harvester. *Int. J. Forest Eng*. 18(2):24–28.

Nurminen, T., H. Korpunen, and J. Uusitalo. 2006. Time consumption analysis of the mechanized cut-to-length harvesting system. *Silva Fennica* 40(2):335–363.

Ovaskainen, H., J. Uusitalo, and K. Väätäinen. 2004. Characteristics and significance of a harvester operators' working technique in thinnings. *Int. J. Forest Eng*. 15(2):67–77.

Pinheiro, J., D. Bates, S. DebRoy, D. Sarkar, and R Development Core Team. 2012. nlme: Linear and Nonlinear Mixed Effects Models. R package version 3.1-104. http://CRAN.R-project.org/package=nlme. Accessed June 25, 2014.

Purfürst, F. T. and J. Erler. 2011. The human influence on productivity in harvester operations. *Int. J. Forest Eng*. 22(2):15–22.

Purfürst, F. T. and O. Lindroos. 2011. The correlation between long-term productivity and short-term performance ratings of harvester operators. *Croat. J. Forest Eng*. 32(2):509–519.

R Core Team 2012. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna.

Richardson, R. 1989. Evaluation of five processors and harvesters. Technical Report TR-94. Forest Engineering Research Institute of Canada (FERIC), Pointe Claire, Quebec.

Richardson, R. and I. Makkonen. 1994. The performance of cut-to-length systems in eastern Canada. Technical Report TR-109. Forest Engineering Research Institute of Canada (FERIC), Pointe Claire, Quebec.

Spinelli, R., B. R. Hartsough, and N. Magagnotti. 2010. Productivity standards for harvesters and processors in Italy. *Forest Prod. J*. 60(3):226–235.

Spinelli, R. and N. Magagnotti. 2010. Comparison of two harvesting systems for the production of forest biomass from thinning of Picea abies plantations. *Scand. J. Forest Res*. 25:69–77.

Strand, L. 1958. Sampling for volume along a line. *Meddelelser fra Det Norske Skogforsksvesen (Rep. Norwegian Forest Res. Inst.)* 15(3):326–331.

Wang, J., C. Long, and J. McNeel. 2004. Production and cost analysis of a feller-buncher and grapple skidder in central Appalachian hardwood forests. *Forest Prod. J*. 54(12):159–167.