The Effect of Timber Harvesting Guidelines on Felling and Skidding Productivity in Northern Minnesota

Denys Goychuk, Michael A. Kilgore, Charles R. Blinn, Jay Coggins, and Randall K. Kolka

Abstract: Substantial investment has been made in the development and application of scientifically based best management practices (i.e., guidelines) intended to protect and enhance the ecological, environmental, and aesthetic attributes of forest resources. When correctly applied, guidelines can increase environmental benefits on site and to adjacent resources, as well as improve forest health and productivity. We empirically evaluated how varying degrees of application of Minnesota's Timber Harvesting and Forest Management guidelines, along with operator and tract-specific variables, affect felling and skidding productivity of mixed aspen/hardwood/conifer stands in northern Minnesota. To do so, felling and skidding productivity data from five mechanized logging businesses were collected on 52 clearcut harvest blocks in northern Minnesota from August 2006 to May 2007 using time-motion and geospatial sensors. Additional postharvest data were collected for each block using high-resolution aerial photography and detailed on-site inventories. With use of these data, separate regression models were developed to estimate the impact that timber harvesting guidelines and tract and operator variables have on felling and skidding productivity. Results of regression analyses and diagnostic tests showed that felling productivity is influenced not only by guideline variables but also by tract and operator variables. Skidding productivity is influenced by both guideline and tract variables. The error terms of the separate felling and skidding models are statistically correlated, calling for their simultaneous estimation using a method known as seemingly unrelated regression. Specific explanatory variables that are statistically significant in explaining felling productivity include the logger's use of a preharvest site map and/or preharvest meeting with the forester, harvesting in winter, merchantable timber volume per unit area, and the operator. Variables that are statistically significant in explaining skidding productivity are the area of landings and skid trails as a percentage of the harvest area, ratio of the harvest block perimeter to the block area, slope, and merchantable timber volume per unit area. The findings suggest that implementing the guidelines we studied has minimal effect on felling productivity, although several adversely affect skidding productivity. By considering how to lay out the harvest block to facilitate skidding efficiency, a feller operator may be able to reduce the impact of some guidelines on skidding productivity. FOR. SCI. 57(5):393–407.

Keywords: economics, timber harvesting productivity, global positioning system (GPS) recorders, regression

SUBSTANTIAL INVESTMENT HAS BEEN MADE in the development and application of scientifically based best management practices (i.e., guidelines) that are intended to protect and enhance the ecological, environmental, and aesthetic attributes of forest resources (Kilgore and Blinn 2004). These guidelines have been developed in response to growing public concern about the need to mitigate the perceived and actual negative environmental impacts associated with various timber harvesting and other forest management activities. When correctly applied, their benefits can increase environmental protection to the site and adjacent resources and improve forest health and productivity (Arthur et al. 1998).

In the United States, initial efforts to develop forest management guidelines were often in response to federal legislation that required states to develop plans for controlling nonpoint source water pollution (Blinn and Kilgore 2001, Ellefson et al. 2001). As a result, water-related aspects of forest systems are the most common components of state guidelines or regulatory programs (Archey 2004, Kilgore and Blinn 2004). Practices that address visual, cultural, and soil- and wildlife-related aspects of forest resources are becoming more frequent parts of guidebooks or regulations (Kilgore and Blinn 2004). For example, Minnesota's voluntary site-level forest management guidelines (Minnesota Forest Resource Council 2005) were designed to mitigate the perceived and actual negative environmental impacts on clean water, cultural resources, riparian areas, soil productivity, wetlands, wildlife habitat, and visual quality.

Whereas society across the United States accrues many benefits from correctly applied timber harvesting and forest management guidelines (e.g., clean water, enhanced wildlife habitat, and protected habitat of endangered and threatened species), their application has been reported to reduce landowner income through a reduction in stumpage prices,

Denys Goychuk, Department of Forest Resources, University of Minnesota—goyc000l@umn.edu. Michael A. Kilgore, Department of Forest Resources, University of Minnesota, 301K Green Hall, 1530 Cleveland Avenue North, St. Paul, MN 55108-6112—Phone: (612) 624-6298; Fax: (612) 625-5212; mkilgore@umn.edu. Charles R. Blinn, Department of Forest Resources, University of Minnesota—cblinn@umn.edu. Jay Coggins, Department of Applied Economics, University of Minnesota—jcoggins@umn.edu. Randall K. Kolka, USDA-Forest Service, Northern Research Station—rkolka@fs.fed.us.

Acknowledgments: This research was funded by the US Forest Service, University of Minnesota's Department of Forest Resources and Department of Applied Economics, University of Minnesota Extension, and the Minnesota Forest Resources Council. The authors express their gratitude to Mike Phillips for assistance with obtaining study equipment, to Ray Higgins for helping establish contact with study participants, to Donna Olson and Levi Meld for assisting with field data collection, and to the participating logging businesses.

Manuscript received May 6, 2010, accepted February 28, 2011

decreased harvestable timber volume, and increased time required to set up timber sales (Ellefson and Miles 1985, Kilgore and Blinn 2003, Cubbage 2004, Blinn and Kilgore 2005). Much of that research has focused on assessing economic factors related to the application for water quality practices. Certain guidelines also have the potential to adversely affect the felling and skidding productivity of a logging business, thereby increasing variable operating costs (Ellefson and Chang 1994). For example, leaving standing, live trees on the harvest block may require modifying felling and skidding patterns, thereby increasing the total distance equipment travels. Redistributing slash back across the harvest block after full-tree skidding to the landing is an extra step that might increase skidding costs. Reducing infrastructure (i.e., skid trails and landings) within the harvest block to reduce soil compaction may require a longer skidding distance to the landing. The degree to which these modified harvesting practices impose additional financial cost to the logging business depends on site and stand characteristics, harvesting equipment, and operator proficiency (Kilgore and Blinn 2003).

Numerous studies have described how different non-guideline factors influence felling and skidding productivity. For felling operations, the most important variables found to influence productivity include the harvest volume removed per hectare, average tree volume, residual stand density, type of felling equipment used, and topography of the harvest block (Brock et al. 1986, Howard 1988, Shaffer et al. 1993, Kellogg et al. 1996, Eliasson et al. 1999, Andersson and Eliasson 2004, Adebayo et al. 2007). The most important factors influencing skidding productivity have been found to be skidding distance, skidding load volume, the type of skidding equipment used, and silvicultural prescriptions for the harvest block (Brock et al. 1986, Howard 1987, Kellogg et al. 1996, Kluender et al. 1997, Egan and Baumgras 2003, Wang et al. 2004, Dodson et al. 2006, Behjou et al. 2008).

Several studies have assessed the impact of a limited number of forest management guidelines on felling and skidding productivity. They include the effects of residual clumps and buffer strips (Lickwar et al. 1992, Blinn et al. 2001), scattered residual trees (Keegan et al. 1995, Egan and Baumgras 2003, Wang and LeDoux 2003), preharvest planning and mapping (Shaffer and Meade 1997), and skid trail design (Kluender et al. 1997, Shaffer et al. 1998).

Whereas past research provides considerable information on how site and stand variables (i.e., harvest volume per acre, tree species composition and size) and a limited number of guideline variables affect felling and skidding productivity, no studies have examined how a more comprehensive suite of timber harvesting guidelines, along with tract and operator variables, affect felling and skidding productivity. To address this information gap, we empirically evaluated how the application of Minnesota's Timber Harvesting and Forest Management guidelines (hereafter "guidelines"), along with operator and tract-specific variables, affected felling and skidding productivity of mixed aspen/hardwood/conifer stands in northern Minnesota. To our knowledge, this is the first study of its kind to examine such a wide suite of variables thought to influence harvesting and skidding productivity.

Methods

Study Areas

The study's observational units were 52 spatially separated harvest blocks in northern Minnesota that were harvested from August 2006 to May 2007 (Figure 1). Twenty of the harvest blocks, representing 46.2% of the harvested area, were privately owned, roughly mirroring the mix of public versus private timberland in this part of the state (Miles et al. 2004). All harvest operations were conducted within the boundaries of the Laurentian Mixed Forest Province (Minnesota Department of Natural Resources 2008), distributed over a five-county area generally centered near Grand Rapids, MN. Sixty-three percent of the harvest blocks had flat terrain, defined as having a slope of 5% or less. The average harvest block area was 6.5 ha and ranged from 0.4 to 25.9 ha. The total area of the 52 harvest blocks was 336 ha.

Quaking aspen (*Populus tremuloides* Michx.) and balsam poplar (*Populus balsamifera* L.) represented more than 60% of the growing timber by volume in the 52 harvest blocks. Other key species harvested included paper birch (*Betula papyrifera* Marsh.), white pine (*Pinus strobus* L.), red pine (*Pinus resinosa* Ait.), balsam fir (*Abies balsamea* [L.] Mill.), white oak (*Quercus alba* L.), red oak (*Quercus rubra* L.), maple (*Acer* spp.), and American basswood (*Tilia americana* L.). For comparison, the aspen cover type represents approximately 41% of Minnesota's total forestland and accounts for more than half of the annual harvested timber by volume (Miles et al. 2004). Clearcutting was the silvicultural prescription for the harvest blocks, although there was considerable variability in the amount and configuration of live trees left within the harvest area, depending on regeneration prescription and/or site features. For example, clumps of merchantable trees may be left unharvested to protect unique wildlife habitat or historic/cultural features. In addition, riparian zones may contain substantial merchantable timber for water quality, visual, or wildlife purposes. Total harvest volume per block varied from 72.3 to 4,001.4 m^3 with a mean harvest volume of 1,216.5 m^3. Harvest volume varied from 77.0 to 318.9 m^3/ha among harvest blocks.

Logging Businesses

Harvesting of the 52 study blocks was accomplished by five independent logging businesses who volunteered to participate in the study. Although selection of these logging businesses was not random, selection criteria for all firms included in the study were the following: they had at least 10 years of logging experience, used similar felling (on tracks with a self-leveling cab) and skidding (rubber-tire grapple skidder) equipment, full-tree skidded trees to a landing for delimbing, harvested only stumpage sales purchased on the open market, operated one feller-buncher (hereafter feller) and two grapple skidders per harvest block, and conducted no manual felling. Using one feller and two

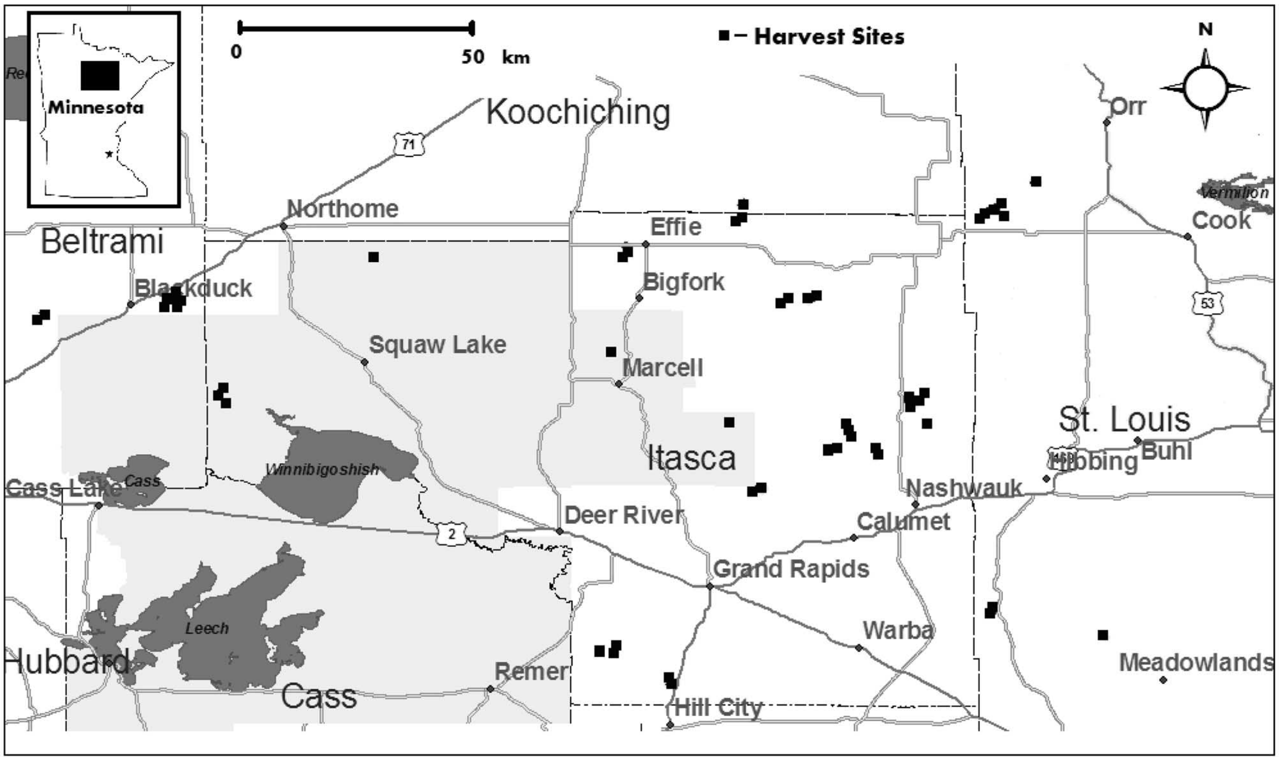

Figure 1. Location of the 52 harvest blocks in northern Minnesota.

grapple skidders on the harvest block is a typical equipment configuration in Minnesota, common to nearly 90% of the logging businesses in the northern part of the state (Powers 2004).

In Minnesota, the forester, landowner, and/or logger determine which guidelines are appropriate for a site before harvesting commences. Whereas a forester makes that decision on public lands, all three entities may be involved in determining the use of guidelines on private lands. Because Minnesota's guidelines are site-level, the decisionmaker(s) will consider a number of factors before defining the specific guidelines relevant for a timber sale. Those factors include site characteristics (e.g., soils, topography, and the presence of waterbodies or cultural resources), landowner objectives (e.g., create specific wildlife habitat or regenerate a covertype), resource needs (e.g., presence of insects or disease), and the setting of the site within a landscape context if wildlife enhancement is important. Once identified for a site, the relevant guidelines are defined in a sale prospectus on public lands and private lands when a forester is involved. Those unique, site-specific guidelines also become part of the timber sales contract between the buyer and the seller. When no forester is involved in setting up the timber sale, a prospectus generally is not created, and the guidelines may or may not be part of any contract between the landowner and the buyer. By including the guidelines in a contract, the administrative authority on each timber sale (forester or landowner) is then able to assert control over their application during the harvesting operation.

In our study, we collected data from timber sales for the five logging businesses obtained before their involvement in this study. Although we did evaluate guidelines that were applied in each harvest block, none of the researchers had any involvement determining which guidelines would be applied nor in controlling their application on-the-ground. Our assessment was not constructed to determine compliance with the guidelines (i.e., did the application of the guidelines meet the standards in the guidebook?), nor was it to determine which guidelines were or should have been applied in a harvest block. Instead, we identified which guidelines were applied and collected associated metrics (e.g., number of wildlife leave trees, skid trail density, and landing density).

Aspen was the primary stumpage species purchased by each business, although other merchantable species were present on all harvest blocks. All feller and skidder operators had at least 3 years of experience and typically operated the same machine from block to block to reduce operator-to-operator production variability. Monitoring of all harvest operations by the study team occurred throughout the 10-month study period on all harvest blocks for each business to diminish the "Hawthorne effect" (Parsons 1974), in which study participants have been reported to alter their behavior when they knew they were being observed.

Data Collection

Timber harvest production data, postharvest aerial photography, and postharvest on-site monitoring were collected for each harvest block used in the study. Each of these data sources is described below.

Harvest Production Data

Each feller was equipped with a Yellow Activity Monitoring System (YAMS) electronic vibration recorder (Kinetic Electronic Designs CC 2009). YAMS recorders, which store machine vibrations electronically and are capable of recording up to 114 hours of machine activity between data downloads, have been used in other studies to evaluate harvesting equipment productivity (e.g., Thompson 2001). The YAMS recorder provides a more accurate depiction of productive machine operating time than an engine hour meter. Unlike an engine hour meter that records engine running time regardless of whether the equipment is operating or idle, the YAMS records the intensity and frequency of vibrations and allow the user to filter out "noise" during the analysis (e.g., remaining motionless with the engine idling, undergoing lubrication and maintenance, or being transported over the road to another harvest block). Hence, use of a YAMS recorder made it possible to distinguish between productive and nonproductive felling operating time. YAMS data were downloaded on a weekly basis during the operator's scheduled break periods to avoid interfering with the normal operations of the study participants. Felling productivity per harvest block was then estimated as a function of merchantable timber volume harvested and total felling productive time per harvest block.

Skidding productivity and infrastructure design were assessed using global positioning system (GPS) recorders, consisting of one Garmin GPS 18 5-Hz receiver and DGPS-XM4-ALT datalogger per skidder (Garmin 2009, Keskull 2009). Similar equipment has been used in other studies (McDonald 1999, McDonald et al. 2000, McDonald and Fulton 2005). The recorders were installed on all skidders to continuously record point locations (i.e., coordinates) for each machine at a 4-second interval. We used a 4-second interval because it was a reasonable tradeoff between data resolution and computational complexity. A skidder was considered to be productive when it was moving within the boundaries of a harvest block for at least 2 continuous minutes. Davis and Kellogg (2005) reported that average delay and grapple time for an average skid cycle is less than 2 minutes (1:11 and 0:28, correspondingly). Klepac and Rummer (2000) reported that total positioning and grappling time was 0.73 and 0.84 minute for two different skidders. A 2-minute interval was selected because it facilitated accounting for stops to load/short delay/position, while sorting out any delays that were too large for a typical documented skidding cycle. GPS receivers have been found to work well with limited overhead forest canopy (Firth and Brownlie 1998, Bolstad et al. 2005). With all 52 harvest blocks subject to clearcut silvicultural treatments, we found that our GPS receivers were able to receive a consistently strong satellite signal.

GPS recorder data were downloaded on a weekly basis. Data collected included information on the skidder's location (latitude and longitude), time and date of operations, and travel speed. Skidding productivity per harvest block was then estimated as a function of merchantable timber volume harvested and total skidding productive time per harvest block. The condition of the soil and ground vegetation at the time of harvest was documented when the study team was on site to download the GPS recorder data.

As a part of our weekly on-site visits to download YAMS and GPS data, skid trails were walked to assess harvest progress within the block (where feasible). In addition, while on site we reviewed the participating logging businesses' harvest documents (e.g., harvest block maps and timber appraisal reports) and recorded the season of harvest.

Postharvest Aerial Photography

Nonstereo, natural color aerial photography at a 1:5,000 scale was used for each harvest block during leaf-off condition shortly after the harvest operation was completed. The photography was rectified, converted to a TIFF file, and then imported into ArcGIS 9.2. Once in a geographic information system (GIS) environment, the photography was used to identify the size, boundaries, and shape of harvest blocks and the location of tree clumps and individual scattered leave trees, infrastructure elements, and waterbodies and to help direct the on-site, postharvest data collection. The skidder GPS data for each harvest block were imported into ArcGIS to determine the location of productive and nonproductive skidder operations across the harvest block, skidding distances, the location, number, and size of landings, and the location, length, density, and use intensity of skid trails.

Postharvest On-Site Monitoring

Harvest and residual timber volume per hectare and slash distribution were assessed via a postharvest field survey during spring and summer 2007 using a 5% systematic random transect sampling approach following the technique described by Sparks et al. (2002). Parallel transects (1.5-m wide) were established at 30-m intervals across each harvest block. Within each transect the species of all standing residual trees and stumps were identified, with tree diameters at breast height estimated to the nearest centimeter from stump dimensions using regression coefficients developed by Raile (1978). Merchantable timber volumes were subsequently estimated using net volume equations for the aspen-birch cover type for northeastern Minnesota (Raile 1980). On the eight harvest blocks for which mill-scaled timber volume data were available, the estimated harvest volume for each harvest block was compared with the total merchantable volume actually removed from the harvest block using consumer scaling tickets. A paired, two-sample *t* test for differences in the means of the field-based and scaled harvest volume estimates [$P(t_7 > 2.3646) = 0.0604$] indicates a mildly significant difference.

Model Specification

We fit two sets of models, one to describe the productivity of the felling operation and the other to describe the productivity of the skidding operation. Dependent variables were FELPROD (felling productivity) and SKPROD (skidding productivity), where each was measured in cubic meters harvested per productive hour of machine operation. For skidding, SKPROD represents the total productivity for both skidders working in the harvest block.

A primary focus of our study was to assess the effect of the guidelines on felling and skidding productivity. It might be the case, though, that other explanatory variables play an important role in determining productivity. Two categories of variables that could be influential and that are included in some versions of the estimated models are nonguideline variables related to the harvested blocks and a set of discrete operator variables. For harvest block i, these categories of variables are denoted as G_i (guideline variables), T_i (tract variables), and O_i (operator variables). Table 1 contains a description of the independent variables by category, along with expected effects of each on felling and skidding productivity.

The general models estimated were of the form

$$y^{\mathrm{F}} = f^{\mathrm{F}}(G_i, T_i, O_i, \varepsilon_{\mathrm{i}}^{F}), \tag{1}$$

$$y^{\mathrm{S}} = f^{\mathrm{S}}(G_i, T_i, O_i, \varepsilon_{\mathrm{i}}^{S}), \tag{2}$$

where y^k is productivity in cubic meters of timber per hour, k = F, S refer to felling and skidding productivity respectively, and the ε_i^k are random error terms. In a series of regression models based on 1 and 2, we investigated the effect of guideline-related activities on felling and skidding productivity (our primary research question) as well as the potential for other variables to affect the relationship of interest.

Specification of the regression models required three important decisions. One was the functional form for the two equations (linear or log-linear, for example). Another was the set of variables to include (guideline-only variables G_i in the equations, for example, or all three sets of variables). A third was whether to treat the felling and skidding equations independently or estimate them simultaneously in some fashion.

Regarding the choice of a functional form, there is little theoretical information on which to base a particular choice. One approach that allows the data to guide the selection of a functional form is recommended by Box and Cox (1964). The Box-Cox transformation takes the form

$$Y^{(\lambda)} = \frac{Y^{\lambda} - \alpha}{\lambda} = \ln Y \qquad \text{if} \quad \lambda = 0, \tag{3}$$

If $\lambda = 1$ in 3, the variable remains linear. If $\lambda = 0$, the variable is transformed by the natural log. In a series of tests, reported below, we determined that a log–log specification was preferred.

Because the effect of guidelines on productivity was our primary interest, we report the results of estimating the two models (i.e., felling and skidding productivity) using only those explanatory variables related to the guidelines. Realizing that other variables can influence productivity, we performed additional estimations in which tract variables and then also binary operator variables were included. Further tests, in the form of F tests restricting certain parameter values to zero, were performed to explore which sets of variables should be retained in the models.

It is possible to estimate models 1 and 2 as separate ordinary least-squares (OLS) models. Given that all of the variables, dependent and explanatory alike, come from the same harvest blocks, it is likely that OLS methods will produce inefficient estimates because the error terms ε^{F} and ε^{S} are likely to be correlated. Any unmeasured or unmeasurable variation in harvest blocks might exert its influence in both models. One method of addressing this possibility that is commonly used in econometrics is an approach that Zellner (1962) called seemingly unrelated regression (SUR)

Table 1. Independent variables tested for effect on felling (FELPROD) and/or skidding (SKPROD) productivity.

Variable	Variable description	Expected effect on FELPROD	Expected effect on SKPROD
Guideline			
ADMIN	Active administration occurred during the timber sale (1 if active administration occurred, 0 otherwise)	—	—
CLUMPS	Percentage of area within the block covered by clumps	—	—
STRLDENS	Percentage of area within the block covered by skid trails with at least 3 passes	None	+
LANDDENS	Landings per ha within a block	None	+
MAP	Availability of a harvest block map or preharvest meeting to help guide ongoing harvest activities (1 if a site map was available or meeting occurred, 0 otherwise)	+	+
PERIAREA	Ratio of harvest block perimeter to block area (m/ha)	—	—-
SCATTREE	No. scattered leave trees per ha	—	—
WINTER	Block harvested during the winter (1 if a winter harvest occurred, 0 otherwise)	+	+
SLASH	Slash was redistributed back across the harvest block (1 if redistribution occurred, 0 otherwise)	None	—
Tract			
VOLUME	m^3/ha of timber harvested	+	+
FLAT	Slope was relatively flat with 0–5% slope (1 if slope was relatively flat, 0 otherwise)	+	+
OWNER	Landowner was public (1 if public, 0 otherwise)	—	—
Logger			
SYSTEM1	Logger 1 harvested the block (1 if logger 1, 0 otherwise)	Unknown	Unknown
SYSTEM2	Logger 2 harvested the block (1 if logger 2, 0 otherwise)	Unknown	Unknown
SYSTEM3	Logger 3 harvested the block (1 if logger 3, 0 otherwise)	Unknown	Unknown
SYSTEM4	Logger 4 harvested the block (1 if logger 4, 0 otherwise)	Unknown	Unknown
SYSTEM5	Logger 5 harvested the block (1 if logger 5, 0 otherwise)	Unknown	Unknown

equations. This method is used widely in many fields, including forestry. Earlier applications of SUR in forestry settings include Murphy and Farrar (1988) and Borders (1989). More recent applications include those by Rose and Lynch (2001) and Naesset et al. (2005). The SUR approach exploits variation in both models by estimating them simultaneously, using generalized least-squares techniques. A Breusch-Pagan χ^2 test (Breusch and Pagan 1979) can then be performed to determine whether the SUR estimates are preferred statistically to the independent OLS estimates.

Model Variables

The list of explanatory variables and their hypothesized effect on felling and skidding productivity are summarized in Table 1. We assessed the following categories of variables: guideline, tract, and operator variables.

Guideline Variables

Active Administration

A binary variable (ADMIN) was created to indicate whether active, independent administration of the harvesting occurred while the operation was ongoing. For example, the administration might require the operator to fix a problem caused during the harvesting (e.g., neglected to fell designated trees) or to modify operations (e.g., reroute a skid trail to stay out of a low spot or lay additional slash down on a low area crossing). On a public agency harvest block, administration was done by an agency forester. On a private sale, administration was done by an industrial or consulting forester or the landowner. We hypothesized that active administrative oversight of the harvest operation to ensure all harvest requirements were followed would negatively affect felling and skidding productivity.

Wildlife Leave Trees

Minnesota's guidelines provide two general options for retaining leave (live) trees on otherwise clearcut harvest blocks: retain the leave trees in clumps or retain scattered individual leave trees across the harvest block (Minnesota Forest Resource Council 2005). Harvesting can occur with leave tree clumps, as long as the wildlife or aesthetic function of the clump is maintained by retaining sufficient basal area and tree size. The percentage of the harvest block area in clumps (CLUMPS) and number of residual trees per hectare (SCATTREE) were hypothesized to negatively affect felling and skidding productivity, as both create additional operational complexity for equipment operators in terms of positioning and moving their equipment across the harvest block. The negative relationship between logging productivity or stumpage bids and residual trees scattered across the harvest block (Mandzak et al. 1983, Kellogg et al. 1991, Kluender and Stokes 1994, Kluender et al. 1997, Eliasson et al. 1999) or trees retained in clumps (Kilgore and Blinn 2003) has been reported. Potential leave tree clumps were delineated using postharvest aerial photography and ArcGIS and then verified as actual leave tree clumps during the postharvest, on-site inspection. Within a harvest block, the area of all clumps 0.1 ha or larger (i.e., the minimum size recognized within Minnesota's guidelines) was combined and divided by total harvest area. SCATTREE was estimated using postharvest aerial photography.

Skid Trail Density

With the objective of minimizing soil compaction, Minnesota's guidelines recommend that equipment traffic be concentrated on skid trails using skid trail routes rather than the shortest practical distance between the felling operation and landing (Minnesota Forest Resource Council 2005). Further, the guidelines recommend that no more than 15% of the timber harvest area be occupied by skid trails subject to three or more machine passes (a pass is an individual trip with a machine, loaded or unloaded, over a defined area) and that all other machine trafficking (1–2 passes) occupy no more than an additional 30% of the harvest area. As an index of the infrastructure associated with skid trails, the percentage of area containing skid trails with three or more passes within the total harvest block area (STRLDENS) was included as an explanatory variable. Increasing the proportion of area covered with skid trails was hypothesized to positively influence skidding productivity (Bradshaw 1979). The GPS skidder point location data were overlaid with a grid layer with a 1-m^2 cell size and the number of skid track points per pixel (m^2) was calculated in ArcGIS. This raster format map was then linked to postharvest aerial photography for each site to delineate areas with different skidding intensities.

Landing Density

The guidelines recommend that the number and size of landings are kept to a minimum to reduce soil erosion and the extent of soil compaction and potential loss of soil productivity (Minnesota Forest Resource Council 2005). The number of landings per hectare of harvest area (LANDDENS) was introduced as an explanatory variable that could positively affect skidding productivity. We hypothesized that a positive relationship exists between landing density and skidding productivity, as fewer landings typically correspond to longer skidding distances (Brock et al. 1986, Kluender et al. 1997, Egan and Baumgras 2003, Wang et al. 2004, Dodson et al. 2006, Behjou et al. 2008). The landings and harvest areas were estimated in ArcGIS from the geospatial data collected by the GPS units and postharvest aerial photography and subsequently verified during the postharvest, on-site monitoring. When two adjacent harvest blocks shared a landing, the denominator was the total area for the combined blocks.

Harvest Block Map

A harvest block map or preharvest on-site meeting can serve as a means to communicate information to operators about the location of any special concern areas (e.g., block boundaries, waterbodies, and leave tree clumps) or infrastructure. The binary variable MAP was included in the model to indicate whether operators possessed a harvest map during the logging operation or had an on-site meeting with the supervising forester or landowner before beginning any harvest operations. Our hypothesis was that adequate communications about special concern areas and infrastructure before commencing harvest operations, as communicated through a harvest block map or preharvest on-site meeting, would improve felling and skidding productivity. Han and Renzie (2005) reported that skid trail planning and layout are important to minimize skidding distance within the harvest block. Likewise, Shaffer and Meade (1997) reported that more than 70% of the participants in their harvest planning program reported examples where harvest planning had a positive impact on their operation.

Harvest Block Shape

An increase in harvest block boundary length relative to the block area (PERIAREA) was assumed to have a negative effect on felling and skidding productivity. Both ratio components were calculated from aerial photography and GPS tracks using spatial analysis functions in ArcGIS.

Harvest Season

A binary variable (WINTER) was created to indicate the condition of the soil and ground vegetation at the time of harvest. The guidelines recommend winter harvesting as a means to protect soil, vegetation, and cultural resources (Minnesota Forest Resource Council 2005). Compared with logging operations in other seasons, winter harvests have been shown to considerably lower risks to soil compaction and vegetation loss on sensitive sites (Butt and Rollerson 1988, McNabb et al. 2001, Stone 2002). We were not able to find any previous research that examined the impact of winter harvesting on logging productivity. Our hypothesis was that harvesting on frozen ground increases felling and skidding productivity because of firmer ground conditions and better sight visibility.

Redistribute Slash

A binary variable was created to represent the method of slash management that was applied on the harvest block (SLASH). Minnesota's timber harvesting guidelines recommend that slash brought to a landing should be redistributed across the harvest block to minimize soil compaction, retain nutrients across the entire block, and address aesthetic concerns (Minnesota Forest Resource Council 2005). For each harvest block, slash distribution was assessed during postharvest field monitoring. We restricted the SLASH variable to one of two broad categories: slash is piled in close proximity to the landing, or slash is redistributed across the harvest block. Our hypothesis was that harvest blocks where slash was redistributed would have lower skidding productivity, because operators would be spending extra time picking up the slash at the landing and redistributing it within the harvest block. Kilgore and Blinn (2003) found that requiring back hauling of slash across the harvest block to avoid piling it at the landing had a moderate negative effect on a logger's willingness to pay for stumpage.

Tract Variables

The following second set of variables contains information about each harvest block that is not related to the guidelines. Although data on several tract variables were collected, the variables we selected were those that we thought would have an influence on felling or skidding productivity based on the literature and our judgment.

Harvest Volume/Area

The continuous variable (VOLUME) was created to indicate the volume of merchantable timber that was removed from the block per unit area and estimated from the postharvest field data. The volume of timber harvested per hectare was hypothesized to have a positive impact on both felling and skidding productivity. Various studies have reported that logging productivity decreases as harvest volume per hectare decreases (McDonald et al. 1969, Mellgren 1990, Keegan et al. 2002).

Topography

A binary variable (FLAT) was created to indicate whether the average slope across the harvest block was less than 5%. Each harvest block's slope was measured with a clinometer during the postharvest on-site visits. At least one clinometer reading was taken for each transect walked during the postharvest field data collection, with the block's slope calculated as the average of the clinometer readings taken for each harvest block. Topographic relief has been reported to have a negative impact on felling and skidding productivity, as both lower speed and alternative travel routes are often needed to maintain safe operating conditions in steeper terrain conditions (Olsen and Gibbons 1983, Mellgren 1990).

Landowner Type

Characteristics of a harvest block (e.g., block size, timber quality, landowner experience with timber harvesting, and extent of preharvest planning) can vary, depending on whether the harvest block is publicly or privately owned. A binary variable (OWNER) was created to specify whether the owner of the harvest block was a public entity (county, state, or federal). We expected felling and skidding productivity to be lower on public harvest blocks, because these ownerships often require substantial additional considerations and restrictions not always found on private forestland harvest blocks. In addition, public forests can contain physical features (e.g., block size and timber quality) that are less desirable to loggers than those of their private sector counterparts.

Operator Variables

Finally, a set of dummy variables (SYSTEM1–SYSTEM5) was included to capture variation across the five logging companies that were included in the study. Differences across the logging companies in the proficiency and skill of individual employees in applying the guidelines or operating equipment, equipment age, or other factors might not be reflected in any of the other measured variables. Although it has been reported that there are differences in productivity between logging operators (Hassler et al. 2000, Egan and Baumgras 2003), we had no basis to predict which operators would achieve the highest felling and skidding productivity.

Results

Average felling and skidding productivity were 41 and 37 m^3/h, respectively (Table 2). The other continuous variables show considerable variability. For example, the percentage of area devoted to clumps ranged from 1 to 30% and the percentage of area devoted to skid trails ranged from 4 to 35%. The number of scattered trees ranged from 1.5 to 68/ha, and the volume of harvested material per hectare varied from 77 to 318 m^3/ha.

The means of the binary variables likewise contain interesting information. Almost 90% of the harvest blocks were subject to active administration, whereas only 36% had a map for the harvest block or included a preharvest meeting conducted with the forester or landowner. Harvest was restricted to winter conditions on 73% of the harvest blocks, 63% of the harvest blocks were relatively flat, slash was distributed back across the block 86% of the time, and 61% of the harvest blocks were publicly owned. Operators 1 and 2 accounted for 64% of the harvest blocks, with the remaining blocks distributed fairly evenly among operators 3, 4, and 5.

Box-Cox Tests of Functional Form

The basic guideline-only linear models represented by equations 1 and 2 are

$$\begin{aligned}\text{FELPROD} = {} & \beta_0^F + \beta_1^F\,\text{ADMIN} + \beta_2^F\,\text{CLUMPS} + \beta_3^F\,\text{MAP} \\ & + \beta_4^F\,\text{PERIAREA} + \beta_5^F\,\text{SCATTREE} \\ & + \beta_6^F\,\text{WINTER} + \varepsilon^F,\end{aligned}$$

$$\begin{aligned}\text{SKPROD} = {} & \beta_0^S + \beta_1^S\,\text{ADMIN} + \beta_2^S\,\text{CLUMPS} \\ & + \beta_3^S\,\text{STRLDENS} + \beta_4^S\,\text{LANDDENS} \\ & + \beta_5^S\,\text{MAP} + \beta_6^S\,\text{PERIAREA} \\ & + \beta_7^S\,\text{SCATTREE} + \beta_8^S\,\text{WINTER} \\ & + \beta_9^S\,\text{SLASH} + \varepsilon^S,\end{aligned}$$

Two sets of corresponding expressions, which are not presented here, contain additional explanatory variables. One set contains also the tract variables (VOLUME, FLAT, and OWNER). Another set contains the tract variables as well as the operator variables (SYSTEM1–SYSTEM4, where SYSTEM5 is the deleted case). The first phase of the analysis, then, includes six models: three for felling productivity and three for skidding productivity.

We first set out to determine whether the dependent variables and/or the explanatory variables in each model should be transformed logarithmically or in some other fashion. For each model, two tests were performed. First, with the explanatory variables in their linear form, for each model we estimated the optimal Box-Cox transformation on the dependent variable. Then this exercise was repeated for each model with all nonbinary explanatory variables transformed by the natural logarithm [1]. For all versions of both the felling and skidding models, we were unable to reject a null hypothesis of $\lambda = 0$. That is, a transformation of the dependent and independent variables by the natural logarithm is appropriate. We thus chose to adopt logarithmic transformations of all nonbinary variables.

OLS Results and **F** *Tests for Inclusion*

Tables 3 and 4 show the results of our initial OLS log–log models. Models 1 (Table 3) and 4 (Table 4), our base models, contain only guideline-related variables. The skidding models include three guideline variables

Table 2. Descriptive statistics for study variables across the 52 harvest blocks.

Variable	Units	Minimum	Mean	Maximum	SD
FELPROD	m^3/hr	23.200	40.990	59.080	9.951
SKPROD	m^3/hr	24.650	37.440	51.110	7.974
ADMIN	"Yes" = 1	0.000	0.885	1.000	0.323
CLUMPS	% of area	1.000	7.249	30.130	5.807
STRLDENS	% of area	4.000	14.220	35.200	5.941
LANDDENS	Landings/ha	0.060	0.260	0.800	0.185
MAP	"Yes" = 1	0.000	0.365	1.000	0.486
PERIAREA	m/m^2	0.010	0.029	0.070	0.013
SCATTREE	Trees/ha	1.480	27.970	67.950	17.136
WINTER	"Yes" = 1	0.000	0.731	1.000	0.448
SLASH	"Yes" = 1	0.000	0.865	1.000	0.345
VOLUME	m^3/ha	77.030	195.470	318.850	67.043
FLAT	"Yes" = 1	0.000	0.635	1.000	0.486
OWNER	"Yes" = 1	0.000	0.615	1.000	0.491
SYSTEM1	"Yes" = 1	0.000	0.327	1.000	0.474
SYSTEM2	"Yes" = 1	0.000	0.308	1.000	0.466
SYSTEM3	"Yes" = 1	0.000	0.115	1.000	0.;323
SYSTEM4	"Yes" = 1	0.000	0.135	1.000	0.345
SYSTEM5	"Yes" = 1	0.000	0.115	1.000	0.323

Table 3. Results for OLS log-log felling models.

Explanatory variable	Model 1	Model 2	Model 3
Intercept	3.47671‡ (0.3740)	1.94341‡ (0.5419)	1.49135‡ (0.5148)
ADMIN	−0.02051 (0.1001)	−0.02437 (0.0948)	0.09483 (0.1003)
log(CLUMPS)	−0.07185* (0.0372)	−0.03735 (0.0304)	−0.04729 (0.0304)
MAP	0.20066‡ (0.0641)	0.19003‡ (0.0603)	0.18421‡ (0.0558)
log(PERIAREA)	−0.01867 (0.0688)	−0.04761 (0.0561)	−0.01567 (0.0552)
log(SCATTREE)	0.01104 (0.0479)	0.02454 (0.0399)	0.03314 (0.0371)
WINTER	0.23016† (0.0727)	0.06405 (0.0758)	0.19475† (0.0773)
log(VOLUME)		0.24694‡ (0.0703)	0.31827‡ (0.0710)
FLAT		0.20292‡ (0.0660)	0.10464 (0.0715)
OWNER		0.06709 (0.0664)	0.03790 (0.0704)
SYSTEM1			0.11877 (0.0893)
SYSTEM2			−0.03933 (0.0884)
SYSTEM3			0.29589† (0.1245)
SYSTEM4			0.05688 (0.1434)
Mult R^2	0.3672	0.6276	0.7345
Adjusted R^2	0.2828	0.5478	0.6437
Breusch-Pagan χ^2	11.415*	12.119	15.503

Dependent variable is log(FELPROD); SE in parentheses.
*$P < 0.1$.
†$P < 0.05$.
‡$P < 0.01$.

Table 4. Results for OLS log-log skidding models.

Explanatory variable	Model 4	Model 5	Model 6
Intercept	2.73536‡ (0.3437)	2.21954‡ (0.4742)	2.03039‡ (0.5008)
ADMIN	0.03136 (0.0802)	0.08960 (0.0847)	0.12357 (0.1024)
log(CLUMPS)	0.01656 (0.0279)	0.03059 (0.0265)	0.03663 (0.0295)
log(STRLDENS)	0.21173‡ (0.0582)	0.14068† (0.0604)	0.11286* (0.0629)
log(LANDDENS)	0.15883‡ (0.0508)	0.13179† (0.0513)	0.12349† (0.0527)
MAP	−0.00566 (0.0512)	−0.02752 (0.0548)	−0.01088 (0.0566)
log(PERIAREA)	−0.14878† (0.0650)	−0.12324* (0.0645)	−0.09306 (0.0723)
log(SCATTREE)	−0.00914 (0.0357)	0.00205 (0.0350)	−0.01001 (0.0362)
WINTER	0.08512 (0.0578)	0.03901 (0.0661)	0.10856 (0.0782)
SLASH	−0.07309 (0.0689)	−0.09413 (0.0677)	−0.06891 (0.0760)
log (VOLUME)		0.12880* (0.0674)	0.17635† (0.0742)
FLAT		0.10078 (0.0620)	0.06376 (0.0760)
OWNER		−0.05642 (0.0597)	−0.06278 (0.0700)
SYSTEM1			0.03040 (0.0903)
SYSTEM2			−0.08502 (0.0894)
SYSTEM3			0.07959 (0.1243)
SYSTEM4			0.00748 (0.1485)
Mult R^2	0.5547	0.6395	0.6827
Adjusted R^2	0.4593	0.5286	0.5376
Breusch-Pagan χ^2	10.406	8.665	15.877

Dependent variable is log(SKPROD); SE in parentheses.
*$P < 0.1$.
†$P < 0.05$.
‡$P < 0.01$.

(STRLDENS, LANDDENS, and SLASH) that do not appear in the felling models for reasons described above. Models 2 and 5 augment the base models with tract variables, and models 3 and 6 include both tract and operator variables in addition to guideline variables. For all six models, the variables have the expected signs and the R^2 statistics, both adjusted and unadjusted, are quite high for a cross-sectional data set such as ours.

We performed a series of nested hypothesis tests to determine which sets of variables to include in the felling and skidding models (Table 5). The F test reported in the first entry of the felling portion of the table refers to a null hypothesis that the coefficients on all three tract variables in model 2 are zero. This is against an alternative hypothesis that any one or more coefficients are nonzero. In each case, we reject the null hypotheses for the felling models at conventional levels of significance. These tests indicate that the tract variables should not be excised from model 2, and neither the tract nor the operator variables should be removed from model 3. Evidence for including non-guideline variables in the skidding models is less strong. Although we can reject the null hypothesis that the tract variables are all zero in model 5, we cannot reject the null hypothesis that the operator variables are all zero in model 6.

These analyses lead us to conclude that the preferred OLS models are model 3 (guideline, tract, and operator variables) for the felling data and model 5 (guideline and tract variables) for the skidding data. Hereafter much of the focus will be on these models and their extensions.

Table 5. Variable-selection *F* tests.

	Felling models		Skidding models	
	Unrestricted	Unrestricted	Unrestricted	Unrestricted
Restriction	Model 2	Model 3	Model 5	Model 6
Tract coefficients = 0	$F_{3, 42} = 9.7917$ $P = 0.0000$	$F_{3, 38} = 8.4739$ $P = 0.0002$	$F_{3, 39} = 3.0597$ $P = 0.0394$	$F_{3, 35} = 2.3503$ $P = 0.0892$
Owner coefficients = 0		$F_{4, 38} = 3.8260$ $P = 0.0104$		$F_{4, 35} = 1.1904$ $P = 0.3321$
Tract and owner coefficients = 0		$F_{7, 38} = 7.5122$ $P = 0.0000$		$F_{7, 351} = 2.0172$ $P = 0.0806$

Collinearity, Heteroscedasticity, and Case Diagnostics

Cross-sectional data often exhibit certain violations of the assumptions required for OLS to be an appropriate model. Two fundamental violations that warrant careful attention are heteroscedasticity and multicollinearity. For each of the six OLS models, the Breusch-Pagan χ^2 test was performed to test the null hypothesis of constant variance of the error term across observations (Tables 3 and 4). Except in the case of model 1, whose *P* value of 0.076 indicates weak evidence of heteroscedasticity, we fail to reject the null hypothesis of homoscedastic errors at all conventional significance levels. Our preferred models 3 and 5 display no evidence of heteroscedasticity.

Multicollinearity of the explanatory variables can lead to instability of the parameter estimates. It also inflates the standard errors and can cause faulty inference on individual coefficient estimates. Many indicators, more or less formal, have been developed to guide the determination of multicollinear regressors (Belsley et al. 1980). We applied the technique of variance inflation factors (VIFs) to all six models (Kutner et al. 2004). A VIF greater than 5 is considered to be indicative of multicollinearity that might give cause for concern. Our results showed that multicollinearity is not a serious problem in any of the models. The SYSTEM variables, in particular SYSTEM4 in models 3 and 6, edge above the cutoff level of 5, but only slightly. For our preferred models, the maximum VIF in model 3 is 5.47 for SYSTEM4 (next highest VIF value is 3.81) and in model 5 is 2.52 for log(LANDDENS).

Two sets of analyses helped shed light on possible influential observations or outliers. First, Cook's distance measures the degree to which a single observation influences the estimated model. For our preferred models the largest Cook's distances are 0.33 (model 3) and 0.12 (model 5). These numbers are quite low and provide reassurance that the data contain no troublesome outliers. Second, the RESET test (Ramsey 1969) was applied to determine whether the linear specification used is appropriate. The test procedure adds powers of the fitted dependent variable as regressors and tests whether the fit of the model improves. For our preferred models, the resulting *F* statistics are insignificant, exhibiting *P* values of 0.706 (model 3) and 0.607 (model 5), which suggests that our models are correctly specified.

SUR

Finally, we estimated the felling and skidding model pairs using Zellner's (1962) SUR methodology (Tables 6 and 7). Models 7-a (in Table 6) and 7-b (in Table 7) were estimated simultaneously as a pair of SURs (guideline-only models), as were models 8-a and 8-b (guideline and tract variable models), 9-a and 9-b (guideline, tract, and operator variable models), and 10-a and 10-b (preferred felling and skidding models). Another Breusch-Pagan χ^2 test was performed to determine whether the SUR specification was preferred statistically to the corresponding two independent OLS equations. The last two rows of Tables 6 and 7 contain the values of the Breusch-Pagan χ^2 statistic and associated *P* value for each test. Because the felling and skidding models were run simultaneously in the SUR analysis, the χ^2 statistics and associated *P* values are the same for each corresponding pair of models (e.g., models 7-a and 7-b). In all cases, we reject the null hypothesis that the individual OLS specification is correct in favor of the SUR alternative.

The last column of Tables 6 and 7 presents our preferred joint model. The felling productivity model (model 10-a) includes all three sets of variables: guideline, tract, and operator. The skidding productivity model (model 10-b) includes guideline and tract variables. A comparison of felling models 3 (OLS) and 10-a (SUR) shows that, although model 10-a provides significant statistical improvement, the SUR specification does not lead to important changes in coefficient estimates relative to the OLS version. The same is true for a comparison of skidding models 5 (OLS) and 10-b (SUR).

Interpretation of Results

Our analysis shows that felling productivity was significantly influenced by only two of the guideline-related variables: the use of a site map during a harvest or preharvest meeting with the forester or landowner and winter harvesting. The use of both guidelines increased felling productivity. It is surprising the four guideline variables hypothesized to negatively affect felling productivity (ADMIN, CLUMPS, PERIAREA, and SCATTREE) have no statistically significant effect as their degree of implementation changes. This result is contrary to our expectation, but one can argue that, especially for the last three of these variables, the result seems reasonable. A feller covers virtually all operable areas of the harvest

Table 6. Results for SUR log–log felling models.

Explanatory variable	Model 7-a	Model 8-a	Model 9-a	Preferred Model 10-a
Intercept	3.47671‡ (0.3740)	1.94341‡ (0.5419)	1.49135‡ (0.5148)	1.57916‡ (0.5108)
ADMIN	−0.02051 (0.1000)	−0.02437 (0.0948)	0.09483 (0.1003)	0.08104 (0.0985)
log(CLUMPS)	−0.07185* (0.0372)	−0.03735 (0.0304)	−0.04729 (0.0304)	−0.05001 (0.0300)
MAP	0.20066‡ (0.0641)	0.19003‡ (0.0603)	0.18421‡ (0.0558)	0.18003‡ (0.0555)
log(PERIAREA)	−0.01867 (0.0688)	−0.04761 (0.0561)	−0.01567 (0.0552)	−0.02453 (0.0546)
log (SCATTREE)	0.01104 (0.0479)	0.02454 (0.0399)	0.03314 (0.0371)	0.03123 (0.0370)
WINTER	0.23016‡ (0.0727)	0.06405 (0.0758)	0.19475† (0.0773)	0.17274† (0.0762)
log(VOLUME)		0.24694‡ (0.0703)	0.31827‡ (0.0710)	0.30195‡ (0.0700)
FLAT		0.20292‡ (0.0660)	0.10464 (0.0715)	0.11633 (0.0703)
OWNER		0.06709 (0.0664)	0.03790 (0.0704)	0.03900 (0.06908)
SYSTEM1			0.11877 (0.0893)	0.10240 (0.0837)
SYSTEM2			−0.03933 (0.0884)	−0.01428 (0.0829)
SYSTEM3			0.29589† (0.1245)	0.26677† (0.1166)
SYSTEM4			0.05688 (0.1434)	0.04188 (0.1348)
Mult R^2	0.3672	0.6276	0.7345	0.7306
Adjusted R^2	0.2828	0.5478	0.6437	0.6384
Breusch-Pagan χ^2	17.8147‡	12.2894‡	8.1404‡	8.7200‡
P-value	0.0000	0.0005	0.0043	0.0031

Dependent variable is log(FELPROD); SE in parentheses. Because the felling and skidding models were run simultaneously in the SUR analysis, the χ^2 statistics and associated P values are the same in Tables 6 and 7 for each corresponding pair of models (e.g., models 7-a and 7-b).
*$P < 0.1$.
†$P < 0.05$.
‡$P < 0.01$.

Table 7. Results for seemingly unrelated regression (SUR) log-log skidding models.

Explanatory variable	Model 7-b	Model 8-b	Model 9-b	Preferred Model 10-b
Intercept	2.92225‡ (0.3343)	2.25278‡ (0.4730)	2.01499‡ (0.5003)	2.22722‡ (0.4735)
ADMIN	0.03317 (0.0785)	0.09553 (0.0841)	0.13797 (0.1016)	0.09714 (0.0844)
log(CLUMPS)	0.01141 (0.0278)	0.03117 (0.0264)	0.03718 (0.0294)	0.03059 (0.0265)
log(STRLDENS)	0.16753‡ (0.0497)	0.13875† (0.0536)	0.12998* (0.0581)	0.15215† (0.0567)
log(LANDDENS)	0.11068† (0.0434)	0.10333† (0.0455)	0.10317† (0.0487)	0.11279† (0.0481)
MAP	0.02007 (0.0501)	−0.02128 (0.0543)	−0.00911 (0.0562)	−0.02465 (0.0545)
log(PERIAREA)	−0.10145 (0.0614)	−0.10111 (0.0614)	−0.07635 (0.0698)	−0.10963* (0.0627)
log(SCATTREE)	−0.00463 (0.0356)	0.00157 (0.0349)	−0.00906 (0.0362)	0.00222 (0.0349)
WINTER	0.11028* (0.0567)	0.04402 (0.0660)	0.11104 (0.0777)	0.04009 (0.0660)
SLASH	−0.08407 (0.0588)	−0.07076 (0.0601)	−0.07009 (0.0702)	−0.09206 (0.0640)
log (VOLUME)		0.12332* (0.0661)	0.17154† (0.0734)	0.12239* (0.0667)
FLAT		0.11588* (0.0610)	0.07548 (0.0750)	0.10879* (0.0614)
OWNER		−0.06206 (0.0592)	−0.06524 (0.0697)	−0.05541 (0.0595)
SYSTEM1			0.03713 (0.0897)	
SYSTEM2			−0.07786 (0.0885)	
SYSTEM3			0.08977 (0.1237)	
SYSTEM4			0.02643 (0.1471)	
Mult R^2	0.5360	0.6347	0.6809	0.6380
Adjusted R^2	0.4365	0.5223	0.5351	0.5267
Breusch-Pagan χ^2	17.8147‡	12.2894‡	8.1404‡	8.7200‡
P value	0.0000	0.0005	0.0043	0.0031

Dependent variable is log(SKPROD); SE in parentheses. Because the felling and skidding models were run simultaneously in the SUR analysis, the χ^2 statistics and associated P values are the same in Tables 6 and 7 for each corresponding pair of models (e.g., models 7-a and 7-b).
*$P < 0.1$.
†$P < 0.05$.
‡$P < 0.01$.

block. Consequently, its productivity is not likely to be slowed by the presence of clumps and leave trees. Likewise, this reasoning might explain why an oddly shaped stand does not inhibit the performance of the feller. The fact that the ADMIN variable is insignificant suggests that any problems identified during sale administration required little additional felling productive time. With a focus on sustaining Minnesota's forest resources, the guidelines are generally thought to increase the cost of timber harvesting. At least with respect to these four guideline variables, this does not appear to be the case using productivity as a proxy measure of cost.

Felling productivity increased as the volume per hectare harvested increased, as expected. The log–log specification permits the estimated coefficient on this continuous variable to be interpreted as an elasticity. That is, as volume of merchantable timber per hectare increases by 1%, productivity of the felling operation increases by 0.30%. Felling productivity is not influenced by topography. This result is not as we expected, but the slopes were generally flat enough that it took little time to level the cab whenever slope changed, minimizing the impact on travel and felling speed. The result that the OWNER variable is insignificant is unexpected.

There is little variation in felling productivity among the five logging companies, even though all of our statistical tests indicate that these variables belong in the model. Only the SYSTEM3 coefficient is significantly different from zero. We can conclude that this operator is more productive than the other four, between which no significant statistical distinction can be drawn.

Skidding productivity is significantly influenced by three of the guideline-related variables: STRLDENS, LANDDENS, and PERIAREA. Skidding productivity responded positively to increases in the density of infrastructure associated with skid trails and landings. This result is as expected, because more infrastructure enhances skidder speed and/or shortens the roundtrip travel distance to acquire and bring timber to the landing As the PERIAREA variable increases, meaning that the tract is more irregularly shaped, all else equal, skidding productivity declines. This is also as expected, for it means that the skidder must make longer runs from a landing to felled timber. In these three cases, our results show that guideline implementation inhibited skidding productivity within a harvest block.

Six of the guideline-related variables included in the skidding model do not appear to influence skidding productivity. We expected that active administration of the harvest by a supervising forester or landowner (ADMIN) would inhibit skidding productivity as the operator might feel compelled or be required to reroute skidding patterns to avoid problem spots (e.g., wet areas or leave tree clumps). This is not apparently the case with the harvest blocks we studied. The operators studied, we conjecture, were able to harvest the stand efficiently, given the operating restrictions on the timber sale imposed by the supervising forester and/or landowner. The feller operator may have also been creating bunches for skidding such that productivity impacts from the variables we measured are minimized. The presence of leave tree clumps (CLUMPS) is also insignificant in determining skidding productivity. Again, we conjecture that the size and location of clumps throughout a harvest block, decisions that the feller operator probably made, mitigated marginal reductions in travel speed and/or increases in distance that a skidder would otherwise have had to travel on each round trip through the harvest block.

Somewhat surprising is the lack of influence of the MAP variable on skidding productivity. Skidding patterns, and hence productivity, are substantially influenced by the decisions made by the feller operator. It could be that regardless of whether a site map was used or preharvest meeting occurred, the feller operator's harvest patterns would be similar for a given stand—it just takes more time for the operator to figure out what these patterns should be. Thus, loss in productivity due to not having a site map or preharvest meeting is largely borne by the feller operator.

We conjecture that the finding that SCATTREE is not important in determining skidding productivity is related to the same reason that CLUMPS is also not an important factor. A skilled feller operator can leave trees in a pattern that does not inhibit the skidder's efficient travel through the tract. We were surprised that the WINTER and SLASH variables do not appear to influence skidding productivity. This is a finding that perhaps warrants further investigation.

Skidding productivity is weakly influenced by the VOLUME and FLAT variables (*P* values of 0.074 and 0.084, respectively). In the former case, the skidder can deliver a given quantity of timber to a landing more quickly if the volume of merchantable timber per hectare is greater. In the latter case we note that, unlike the feller which covers less ground, the skidder can also travel more quickly over flat terrain than steep. Unexpectedly, skidding productivity does not appear to be significantly lower on publicly owned tracts.

Conclusions

This research is one of the first attempts to assess empirically the tradeoffs between the degree of forest guideline implementation and logging productivity. Its strength is that data were based on direct field observations conducted over a 10-month period rather than on surveys, which can include subjective bias. Our study demonstrated that felling and skidding productivity are influenced by both common and unique factors. One factor influencing both felling and skidding productivity is the volume harvested per unit area. None of the guideline variables we evaluated were found to be significant in both operations. Influential factors unique to felling productivity include the season of operation, use of a planning map, or conducting a preharvest meeting with the forester or landowner and the operator. Those factors uniquely influencing skidding productivity are skid trail and landing density, the shape of the harvest block, and terrain. A feller operator can reduce the impact of guidelines on skidding through the placement of tree bunches for skidding.

Although some of the guideline variables we thought would influence felling and skidding productivity were significant, many were not. The harvest operations we evaluated were carried out 8–9 years after the guidelines were published, and all operators had at least 3 years of harvesting experience. These factors combined lead us to believe that logging companies have figured out how to apply the guidelines in a manner that minimizes their adverse effects on logging productivity. Had we monitored harvest blocks shortly after the guidelines were first published, we suspect additional guidelines would have been found to have an adverse impact on felling and skidding productivity.

Although not verifiable with our data set, it may be that applying the guidelines can actually increase the overall productivity of logging firms. For example, the guideline recommending that the logging crew develop a harvest block map or meet with the supervising forester or landowner before beginning the harvest operation can avoid costly mistakes that decrease productivity. Likewise, the results indicating that backhauling slash from the landing across the block did not significantly decrease skidding productivity seems counterintuitive. Yet, one could reasonably argue that logging operations have been more carefully planned as a result of the guidelines so that slash distribution does not impose marginally significant additional skidding travel time or distance. If the guidelines do increase logging efficiency, this would be consistent with Michael Porter's hypothesis that environmental regulations can prompt innovation that improves firm competitiveness (Porter 1991). Given the surprising lack of influence many of the guideline variables had on harvesting productivity, there is some evidence that this innovation is indeed occurring. Further investigation along these lines is warranted.

Despite the surprising lack of influence guidelines appear to have on felling productivity, our data suggest that applying some of the guidelines decreased skidding productivity. In particular, following the recommendations to minimize the density of infrastructure and allow harvest blocks to follow natural stand boundaries (instead of being rectangular) decreased skidding productivity for the logging firms we studied. It appears that, despite the loggers' best efforts to diminish the impact of these guidelines on productivity, their ability to mitigate those impacts has limitations.

Endnote

[1] All statistical analyses were carried out in the R environment for statistical computing and graphics R Development Core Team 2009.

Literature Cited

ADEBAYO, A., H. HAN, AND L. JOHNSON. 2007. Productivity and cost of cut-to-length and whole-tree harvesting in a mixed-conifer stand. *For. Prod. J.* 57(6):59–69.

ANDERSSON, J., AND L. ELIASSON. 2004. Effects of three harvesting work methods on harwarder productivity in final felling. *Silva Fenn.* 38(2):195–202.

ARCHEY, W.E. 2004. *The National Association of State Foresters: 2004 progress report—State water resources programs for silviculture.* The National Association of State Foresters, Washington, DC. 35 p. Available online at www.stateforesters.org/node/811; last accessed Sept. 27, 2010.

ARTHUR, M.A., G.B. COLTHARP, AND D.L. BROWN. 1998. Effects of best management practices on forest streamwater quality in Eastern Kentucky. *J. Am. Water Resour. Assoc.* 34:481–495.

BEHJOU, F.K., B. MAJNOUNIAN, M. NAMIRANIAN, AND J. DVORAK. 2008. Time study and skidding capacity of the wheeled skidder Timberjack 450C in Caspian forests. *J. For. Sci.* 54:183–188.

BELSLEY, D.A., E. KUH, AND R.E. WELSCH. 1980. *Regression diagnostics: identifying influential data and sources of collinearity.* John Wiley & Sons, New York.

BLINN, C.R., A.M. ALDEN, AND P.V. ELLEFSON. 2001. Timber harvester perceptions of costs and benefits from applying water quality BMPs in north-central USA. *Int. J. For. Eng.* 12(1):39–51.

BLINN, C.R., AND M.A. KILGORE. 2001. Riparian management practices: A summary of state guidelines. *J. For.* 99(8):11–17.

BLINN, C.R., AND M.A. KILGORE. 2005. The impact of Minnesota's forest management guidelines on the time required to set up public agency timber sales. *North. J. Appl. For.* 22(3):175–186.

BOLSTAD, P., A. JENKS, J. BERKIN, K. HORNE, AND W.H. READING. 2005. A comparison of autonomous, WAAS, real-time, and post-processed global positioning systems (GPS) accuracies in northern forests. *North. J. Appl. For.* 22(1):5–11.

BORDERS, B.E. 1989. Systems of equations in forest stand modeling. *For. Sci.* 35(2):548–556.

BOX, G.E., AND D.R. COX. 1964. An analysis of transformations. *J. R. Statist. Soc.* 26:211–246.

BRADSHAW, G. 1979. *Preplanned skid trails and winching versus conventional harvesting on a partial cut.* Research Note 62. Forest Research Laboratory, Oregon State University, Corvallis, OR. 4 p.

BREUSCH, T.S., AND A.R. PAGAN. 1979. Simple test for heteroscedasticity and random coefficient variation. *Econometrica* 47:1287–1294.

BROCK, S.M., K.D. JONES, AND G.W. MILLER. 1986. Felling and skidding costs associated with thinning a commercial Appalachian hardwood stand in northern West Virginia. *North. J. Appl. For.* 3(4):159–163.

BUTT, G., AND T. ROLLERSON. 1988. Prediction of forest soil compaction. P. 153–166 in *Degradation of forest soils: "Forest soils at risk," Proc. of the 10th BC soil science workshop*, Lousier, J.D., and G.W. Still (eds.). British Columbia Ministry of Forests Land Management Rep. No. 56. 331 p.

CUBBAGE, F.W. 2004. Costs of forestry best management practices in the South: A review. *Water Air Soil Pollut. Focus* 4(1):131–142.

DAVIS, C.T., AND L.D. KELLOGG. 2005. Measuring machine productivity with the MultiDat Datalogger: A demonstration on three forest machines, in *Proc. Council on forest engineering conference on soil, water, and timber management: Forest engineering solutions in response to forest regulation, July 11–14, 2005, Fortuna, CA,* Matzka, PJ (ed.). US For. Serv. Gen. Tech. Rep. PSW-GTR-194.

DODSON, E.M., T. DEBOODT, AND G. HUDSPETH. 2006. Production, cost, and soil compaction estimates for two western juniper extraction systems. *West. J. Appl. For.* 21(4):185–194.

EGAN, A.F., AND J.E. BAUMGRAS. 2003. A statewide study of ground skidding and harvested stand attributes in Appalachian hardwood stands. *For. Prod. J.* 53(9):59–63.

ELIASSON, L., J. BENGTSSON, J. CEDERGREN, AND H. LAGESON. 1999. Comparison of single-grip harvester productivity in clear- and shelterwood cutting. *J. For. Eng.* 10(1):43–48.

ELLEFSON, P.V., AND A.S. CHANG. 1994. State forest practice programs: Regulation of private forestry comes of age. *J. For.* 92(5):34–37.

ELLEFSON, P.V., M.A. KILGORE, AND M.J. PHILLIPS. 2001. Monitoring compliance with BMPs: The experience of state forestry agencies. *J. For.* 99(1):11–17.

ELLEFSON, P.V., AND P.D. MILES. 1985. Protecting water quality in the Midwest: Impact on timber harvesting costs. *North. J. Appl. For.* 2(2):57–61.

FIRTH, J., AND R. BROWNLIE. 1998. An efficiency evaluation of the global positioning system under forest canopies. *N.Z. J. For.* 43(1):19–25.

GARMIN. 2009. *GPS 18 technical specifications.* Available online at www.garmin.com/manuals/425_TechnicalSpecification.pdf; last accessed Aug. 8, 2009.

HAN, H.S., AND C. RENZIE. 2005. Productivity and cost of partial harvesting method to control mountain pine beetle infestations in British Columbia. *West. J. Appl. For.* 20(2):128–133.

HASSLER, C.C., S.T. GRUSHECKY, AND C.B. LEDOUX. 2000. The effects of group selection harvest size on logging productivity. *North. J. Appl. For.* 17(2):51–56.

HOWARD, A.F. 1987. Modeling the cost and profitability of timber harvesting with cable skidders. *North. J. Appl. For.* 4(2):87–92.

HOWARD, A.F. 1988. Harvesting profitability as affected by classification of costs and assignment of the components of scheduled time. *Can. J. For. Res.* 18(11):1369–1375.

KEEGAN, C.E., C.E. FIEDLER, AND F.J. STEWARD. 1995. Cost of timber harvest under traditional and "new forestry" silvicultural prescriptions. *West. J. Appl. For.* 10(1):36–42.

KEEGAN, C.E., M.J. NICCOLUCCI, C.E. FIEDLER, J.G. JONES, AND R.W. REGEL. 2002. Harvest cost collection approaches and associated equations for restoration treatments on national forests. *For. Prod. J.* 52(7/8):96–99.

KELLOGG, L.D., P. BETTINGER, AND R.M. EDWARDS. 1996. A comparison of logging planning, felling, and skyline yarding costs between clearcutting and five group-selection harvesting methods. *West. J. Appl. For.* 11(3):90–96.

KELLOGG, L.D., S.J. PILKERTON, AND R.M. EDWARDS. 1991. Logging requirements to meet new forestry prescriptions. P. 43–49 in *Forest operations in the 1990s: Challenges and solutions. Proc. of the 14th annual meeting of the Council on Forest Engineering, July 22–25. 1991, Nanaimo, BC,* McNeel, J., and B. Andersson (eds.).

KESKULL, R.I. 2009. DGPS-XM4-ALT GPS data logger. Available online at homepages.tig.com.au/~robk/logger-gps-dgps-xm4-alt.html; last accessed June 6, 2009.

KILGORE, M.A., AND C.R. BLINN. 2003. The financial cost to forest landowners who implement forest management guidelines: an empirical assessment. *J. For.* 101(8):37–41.

KILGORE, M.A., AND C.R. BLINN. 2004. Policy tools to encourage the application of timber harvesting guidelines in the United States and Canada. *For. Policy Econ.* 6(2):111–127.

KILGORE, M.A., AND C.R. BLINN. 2005. The impact of timber harvesting guidelines and timber sale attributes on stumpage bidding behavior. *North. J. Appl. For.* 22(4):275–280.

KINETIC ELECTRONIC DESIGNS CC 2009. *Yellow activity monitoring system.* Available online at www.ked.co.za/files/yamsprod.pdf; last accessed Aug. 8, 2009.

KLEPAC, J., AND R. RUMMER. 2000. *Productivity and cost comparison of two different-sized skidders.* 2000 ASAE Annual International Meeting, Paper No. 00-5015.

KLUENDER, R., D. LORTZ, W. MCCOY, B. STOKES, AND J. KLEPAC. 1997. Productivity of rubber-tired skidders in Southern pine forests. *For. Prod. J.* 47 (11/12):53–58.

KLUENDER, R.A., AND B.J. STOKES. 1994. Productivity and costs of three harvesting methods. *South. J. Appl. For.* 18(4):168–174.

KUTNER, M.H., C.J. NACHTSHEIM, AND J. NETER. 2004. *Applied linear regression models*, 4th ed., McGraw-Hill/Irwin, New York.

LICKWAR, P.M., C. HICKMAN, AND F.W. CUBBAGE. 1992. Costs of protecting water quality during harvesting on private forest lands in the Southeast. *South. J. Appl. For.* 16:13–20.

MANDZAK, J.M., K.S. MILNER, AND J. HOST. 1983. *Production and product recovery for complete tree utilization in the northern Rockies.* US For. Serv. Res. Paper INT-RP-306. Ogden, UT. 17 p.

MCDONALD, P.M., W.A. ATKINSON, AND D.O. HALL. 1969. Logging costs and cutting methods in young-growth Ponderosa pine in California. *J. For.* 67(2):109–113.

MCDONALD, T.P. 1999. Time study of harvesting equipment using GPS-derived positional data, in *Forestry engineering for tomorrow. Proc. of the International conference on forestry engineering*. Edinburgh University, Edinburgh, Scotland. Institution of Agricultural Engineers, Bedford, UK. 8 p.

MCDONALD, T.P. AND J.P. FULTON. 2005. Automated time study of skidders using global positioning system data. *Comput. Electron. Agric.* 48(1):19–37.

MCDONALD, T.P., S.E. TAYLOR, AND R.B. RUMMER. 2000. *Deriving forest harvesting machine productivity from GPS positional data.* ASAE Technical Paper No. 00-5011. American Society of Agricultural and Engineers, St. Joseph, MI.

MCNABB, D.H., A.D. STARTSEV, AND H. NGUYEN. 2001. Soil wetness and traffic effects on bulk density and air-filled porosity of compacted boreal forest soils. *Soil Sci. Soc. Am. J.* 65:1238–1247.

MELLGREN, P.G. 1990. *Predicting the performance of harvesting systems in different operating conditions.* Forest Engineering Research Institute of Canada Special Report SR-67. 22 p.

MILES, P.D., G.J. BRAND, AND M.E. MIELKE. 2004. *Minnesota's forest resources in 2003.* US For. Serv. Res. Bull. NC-246. North Cent. Res. Stn., St. Paul, MN. 36 p.

MINNESOTA DEPARTMENT OF NATURAL RESOURCES. 2008. *Ecological classification system.* Minnesota Department of Natural Resources. Available online at http://www.dnr.state.mn.us/ecs/index.html; last accessed Aug. 10, 2009.

MINNESOTA FOREST RESOURCE COUNCIL. 2005. *Sustaining Minnesota forest resources: Voluntary site-level forest management guidelines for landowners, loggers and resource managers.* Minnesota Forest Research Council, St. Paul, MN. Available online at www.frc.state.mn.us/documents/council/site-level/MFRC_FMG&Biomass_2007-12-17.pdf; last accessed May 4, 2011.

MURPHY, P.A., AND R.M. FARRAR JR. 1988. A framework for stand structure projection of uneven-aged loblolly–shortleaf pine stands. *For. Sci.* 34(2):321–332.

NAESSET, E., O.M. BOLLANDSÅS, AND T GOBAKKEN. 2005. Comparing regression methods in estimation of biophysical properties of forest stands from two different inventories using laser scanner data. *Remote. Sens. Environ.* 94:541–553.

OLSEN, E.D., AND D.J. GIBBONS. 1983. *Predicting skidder productivity: A mobility model.* Res. Bull 43. Forest Research Laboratory, Oregon State University, Corvallis, OR. 19 p.

PARSONS, H.M. 1974. What happened at Hawthorne? *Science* 183(4128):922–932.

PORTER, M.E. 1991. America's Green strategy. *Sci. Am.* 264(4):168.

POWERS, J.W. 2004. *Survey of Minnesota logging operators in 2004.* A Vital Forests/Vital Communities Report to the Blandin Foundation. Grand Rapids, MN: Blandin Foundation. 26 p.

R DEVELOPMENT CORE TEAM. 2009. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. Available online at www.R-project.org; last accessed Feb. 2, 2011.

RAILE, G. 1978. Estimating d.b.h. from stump dimensions. P. 30–33 in *Proc. 1977 Midwest Forest Mensurationists Meeting.* US For. Serv. Gen. Tech. Rep. NC-46. North Cent. Res. Stn., St. Paul, MN. 34 p.

RAILE, G.K. 1980. *A net volume equation for northeastern Minnesota.* US For. Serv. Gen. Tech. Rep. NC-66. North Cent. Res. Stn., St. Paul, MN. 11 p.

RAMSEY, J.B. 1969. Tests for specification error in classical linear least squares regression analysis. *J. R. Statist. Soc.* 31:350–371.

ROSE, C.E. JR., AND T.B. LYNCH. 2001. Estimating parameters for tree basal area growth with a system of equations and seemingly unrelated regressions. *For. Ecol. Manag.* 148:51–61.

SHAFFER, R.M., H.L. HANEY, E.G. WORRELL, AND W.M. AUST. 1998. Forestry BMP implementation costs for Virginia. *For. Prod. J.* 48(9):27–29.

SHAFFER, R.M., AND G.S. MEADE. 1997. Evaluation of harvest planning training. *For. Prod. J.* 47(7/8):69–71.

SHAFFER, R.M., K.R. BRUMMEL, T.W. REISINGER, AND B.J. STOKES. 1993. Impact of group selection silviculture on timber harvesting productivity and cost in Appalachian hardwood timber stands. *North. J. Appl. For.* 10(4):170–174.

SPARKS, J.C., R.E. MASTERS, AND M.E. PAYTON. 2002. Comparative evaluation of accuracy and efficiency of six forest sampling methods. *Proc. Okla. Acad. Sci.* 82:49–56.

STONE, D.M. 2002. Logging options to minimize soil disturbance in the northern Lake States. *North. J. Appl. For.* 19(3): 115–121.

THOMPSON, J.D. 2001. Calculating utilization rates for rubber tired grapple skidders in the southern United States. P. 29–31 in *Proc. of the 24th Annual Council on Forest Engineering meeting: Appalachian hardwoods; managing change; July 15–19, 2001; Snowshoe, WV,* Wang, J., M. Wolford, and J. McNeel (eds.). Council on Forest Engineering, Corvallis, OR.

WANG, J.X., AND C.B. LEDOUX. 2003. Estimating and validating ground-based timber harvesting production through computer simulation. *For. Sci.* 49(1):64–76.

WANG, J.X., C. LONG, J. MCNEEL, AND J. BAUMGRAS. 2004. Productivity and cost of manual felling and cable skidding in central Appalachian hardwood forests. *For. Prod. J.* 54(12): 45–51.

ZELLNER, A. 1962. An efficient method of estimating seemingly unrelated regression equations and tests for aggregation bias. *J. Am. Statist. Assoc.* 57:348–368.