# EFFECT OF TIMBER HARVESTING GUIDELINES ON FELLING AND SKIDDING PRODUCTIVITY IN NORTHERN MINNESOTA

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## ABSTRACT

We empirically evaluated how varying degrees of applying Minnesota's Timber Harvesting and Forest Management guidelines, along with operator and tract-specific variables, impact felling and skidding productivity of mixed aspen/hardwood/conifer stands in northern Minnesota. Felling and skidding productivity data from five mechanized logging businesses were collected on 52 clearcut harvest blocks from August 2006 to March 2007 using time-motion and geospatial sensors. Post-harvest data were collected using high resolution aerial photography and detailed on-site inventories. Regression analyses determined that felling productivity was influenced by guideline, tract and operator variables. Skidding productivity was influenced by both guideline and tract variables. Variables that were statistically significant in explaining felling productivity include the logger's use of a pre-harvest site map and/or pre-harvest meeting with the forester, harvesting in winter, merchantable timber volume per unit area, and the operator. Variables that were statistically significant in explaining skidding productivity were the area of landings and skid trails as a percent 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 implementing the guidelines we studied has minimal effect on felling productivity, though 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.

**Keywords:** Economics, timber harvesting productivity, GPS recorders, regression

## INTRODUCTION

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. Minnesota's voluntary site-level forest management guidelines (MFRC 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.

While society across the accrues many benefits from correctly applied timber harvesting and forest management guidelines (e.g., clean water, enhanced wildlife habitat, protected habitat of endangered and threatened species), their application has been reported to reduce landowner income through a reduction in stumpage prices, decreased harvestable timber volume, and increased time required to set up timber sales (Kilgore and Blinn 2003, Cubbage 2004, Blinn and Kilgore 2005). 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).

While past research provides considerable information on how site and stand variables (i.e., harvest volume per acre, tree specie composition and size) and a limited number of guideline variables impact felling and skidding productivity, no studies have examined how a more comprehensive suite of timber harvesting guidelines, along with tract and operator variables, impacts felling and skidding productivity. Therefore, we empirically evaluated how the application of Minnesota's Timber Harvesting and Forest Management guidelines (hereafter "guidelines"), operator and tract-specific variables impacted felling and skidding productivity of mixed aspen/hardwood/conifer stands in northern Minnesota.

## METHODS

The study's observational units were 52 spatially separated harvest blocks in northern MN, centered around Grand Rapids, MN, that were harvested from August 2006 to March 2007. The average harvest block area was 6.5 ha and ranged from 0.4 to 25.9 ha. 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. Clearcutting was the silvicultural prescription for all harvest blocks. 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.

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

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). YAMS data was 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 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 18-5Hz receiver and DGPS-XM4-ALT datalogger per skidder (Garmin 2009, Keskull 2009). The recorders were installed on all skidders to continuously record point locations (i.e., coordinates) for each machine at a four-second interval. GPS recorder data was downloaded on a weekly basis. Skidding productivity per harvest block was then estimated as a function of merchantable timber volume harvested and total skidding productive time per harvest block.

Non-stereo, natural color aerial photography at a 1:5,000 scale was taken for each harvest block during leaf-off condition shortly after the harvest operation was completed. The photography was rectified, converted to a TIFF file, imported into ArcGIS 9.2, and then used to identify the size, boundaries, and shape of harvest blocks, the location of tree clumps and individual scattered leave trees, infrastructure elements and water bodies, and to help direct the on-site, post-harvest data collection. GPS data was imported into ArcGIS to determine the location of productive and non-productive 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.

Harvest and residual timber volume per hectare and slash distribution were assessed via a post-harvest 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 meters wide were established at 30 meter 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 was available, the estimated harvest volume for each harvest block was compared to 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.

We fit two sets of models, one to describe the productivity of the felling operation (FELPROD) and the other to describe the productivity of the skidding operation (SKIDPROD). Dependent variables were felling productivity and skidding productivity, where each was measured in cubic meters harvested per productive hour of machine operation. For skidding, the total productivity for both skidders working in the harvest block was assessed. Table 1 contains a description of the independent variables by category, along with expected effects of each on felling and skidding productivity.

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

| Variable | Description | Data source(s) | Expected effect | |
|---|---|---|---|---|
| | | | Felling | Skidding |
| | | Guideline variables | | |
| ADMIN | Active administration by forester or landowner occurred during the timber sale (1 if active administration occurred, 0 otherwise) | Logger and forester | - | - |
| CLUMPS | Percentage of area within the block covered by clumps | [1, 2, 3] | - | - |
| SCATTREE | Number of scattered leave trees per hectare | [1, 2, 3] | - | - |
| STRLDENS | Percentage of area within the block covered by skid trails with at least 3 passes | [1, 2, 4] | NA | + |
| LANDDENS | Landings per hectare within a block | [1, 2, 3, 4] | NA | + |
| MAP | Harvest block map or pre-harvest on-site meeting | Logger and forester | + | + |
| PERIAREA | Ratio of harvest block perimeter to block area (M/ha) | [1, 2, 4] | - | - |
| WINTER | Block harvested during the winter (1 if a winter harvest occurred, 0 otherwise) | [4, 5] | + | + |
| SLASH | Slash was redistributed back across the harvest block (1 if redistribution occurred, 0 otherwise) | [3] | NA | - |
| | | Tract variables | | |
| VOLUME | $M^3$/ha of timber harvested | [3] | + | + |
| FLAT | Slope was relatively flat with 0 - 5% slope (1 if slope was relatively flat, 0 otherwise) | [3] | - | - |
| OWNER | Landowner was public (1 if public, 0 otherwise) | Logger and forester | - | - |
| | | Logger variables | | |
| SYSTEM1[6] | Logger 1 harvested the block (1 if Logger 1, 0 otherwise) | Logger | Unknown | Unknown |

[1]Post-harvest aerial photography
[2]ArcGIS
[3]Post-harvest, on-site inspection
[4]GPS data
[5]YAMS data
[6]Similar System$_i$ variables were created for logging businesses $i$ = 2, 3, 4, and 5

The general models estimated were of the following form:

$$y^F = f^F(G_i, T_i, O_i, \varepsilon_i^F), \tag{1}$$
$$y^S = f^S(G_i, T_i, O_i, \varepsilon_i^S) \tag{2}$$

where $y^k$ is productivity in cubic meters of timber per hour; $k = F, S$ refer to felling and skidding productivity respectively; $G_i$, $T_i$, and $O_i$, represent guideline, tract and operator variables, respectively, for harvest block $i$; and the $\varepsilon_i^k$ are random error terms. In a series of regression models based upon (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.

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. This is because the error terms $\varepsilon^F$ and $\varepsilon^S$ 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) equations. The SUR approach exploits variation in both models by estimating them simultaneously, using generalized least squares techniques. A Breusch-Pagan $\chi^2$ test (Breusch and Pagan 1979) can then be performed to determine whether the SUR estimates are preferred statistically to the independent OLS estimates.

## RESULTS AND DISCUSSION

Average felling and skidding productivity were 41 and 37 cubic meters per hour, respectively (Table 2). The other continuous variables show considerable variability. For example, the percent of area devoted to clumps ranged from 1 to 30 and the percent of area devoted to skid trails ranged from 4 to 35 percent. The volume of harvested material per hectare varied from 77 to 318 cubic meters.

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

| Variable | Units | Min | Mean | Max | St Dev |
|---|---|---|---|---|---|
| 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 |
| SCATTREE | Trees/ha | 1.480 | 27.970 | 67.950 | 17.136 |
| 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 |
| 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 |

We estimated the felling and skidding model pairs using Zellner's (1962) SUR methodology (Tables 3 and 4). Models 1-a (in Table 3) and 1-b (in Table 4) were estimated simultaneously as a pair of seemingly unrelated regressions (guideline only models), as were Models 2-a and 2-b (guideline and tract variable models), 3-a and 3-b (guideline, tract, and operator variable models), and 4-a and 4-b (preferred felling and skidding models). A Breusch-Pagan $\chi^2$ 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 3 and 4 contain the values of the Breusch-Pagan $\chi^2$ statistic and associated *p*-value for each test. Since the felling and skidding models were run simultaneously in the SUR analysis, the $\chi^2$ statistics and associated *p*-values are the same for each corresponding pair of models (e.g., Models 1-a and 1-b). In all cases, we reject the null hypothesis that the individual OLS specification is correct, in favor of the SUR alternative.

**Table 3**: Results for seemingly unrelated regression log-log felling models. Dependent variable is log(FELPROD); s.e. in parentheses. Significance codes: * $p < .1$; ** $p < .05$; and *** $p < .01$.[1]

| Explanatory variable | Model 1-a | Model 2-a | Model 3-a | Preferred Model 4-a |
|---|---|---|---|---|
| Intercept | 3.47671*** | 1.94341*** | 1.49135*** | 1.57916*** |
| | (0.3740) | (0.5419) | (0.5148) | (0.5108) |
| ADMIN | -0.02051 | -0.02437 | 0.09483 | 0.08104 |
| | (0.1000) | (0.0948) | (0.1003) | (0.0985) |
| log(CLUMPS) | -0.07185* | -0.03735 | -0.04729 | -0.05001 |
| | (0.0372) | (0.0304) | (0.0304) | (0.0300) |
| MAP | 0.20066*** | 0.19003*** | 0.18421*** | 0.18003*** |
| | (0.0641) | (0.0603) | (0.0558) | (0.0555) |
| log(PERIAREA) | -0.01867 | -0.04761 | -0.01567 | -0.02453 |
| | (0.0688) | (0.0561) | (0.0552) | (0.0546) |
| log (SCATTREE) | 0.01104 | 0.02454 | 0.03314 | 0.03123 |
| | (0.0479) | (0.0399) | (0.0371 ) | (0.0370) |
| WINTER | 0.23016*** | 0.06405 | 0.19475** | 0.17274** |
| | (0.0727) | (0.0758) | (0.0773) | (0.0762) |
| log(VOLUME) | | 0.24694*** | 0.31827*** | 0.30195*** |
| | | (0.0703) | (0.0710) | (0.0700) |
| FLAT | | 0.20292*** | 0.10464 | 0.11633 |
| | | (0.0660) | (0.0715) | (0.0703) |
| OWNER | | 0.06709 | 0.03790 | 0.03900 |
| | | (0.0664) | (0.0704) | (.06908) |
| SYSTEM1 | | | 0.11877 | 0.10240 |
| | | | (0.0893) | (0.0837) |
| SYSTEM2 | | | -0.03933 | -0.01428 |
| | | | (0.0884) | (0.0829) |
| SYSTEM3 | | | 0.29589** | 0.26677** |
| | | | (0.1245) | (0.1166) |
| SYSTEM4 | | | 0.05688 | 0.04188 |
| | | | (0.1434) | (0.1348) |
| Mult $R^2$ | 0.3672 | 0.6276 | 0.7345 | 0.7306 |
| Adj $R^2$ | 0.2828 | 0.5478 | 0.6437 | 0.6384 |
| Breusch-Pagan $\chi^2$ | 17.8147*** | 12.2894*** | 8.1404*** | 8.7200*** |
| p-value | 0.0000 | 0.0005 | 0.0043 | 0.0031 |

[1]Because the felling and skidding models were run simultaneously in the analysis, the $\chi^2$ statistics and associated *p*-values are the same in Tables 3 and 4 for each corresponding pair of models (e.g., Models 1-a and 1-b).

The last column of Tables 3 and 4 presents our preferred joint model. The felling productivity model (Model 4-a) includes all three sets of variables: guideline, tract, and operator. The skidding productivity model (Model 4-b) includes guideline and tract variables.

**Table 4**: Results for seemingly unrelated regression log-log skidding models. Dependent variable is log(SKPROD); s.e. in parentheses. Significance codes: * $p < .1$; ** $P < .05$; and *** $p < .01$.[1]

| Explanatory variable | Model 1-b | Model 2-b | Model 3-b | Preferred Model 4-b |
|---|---|---|---|---|
| Intercept | 2.92225*** | 2.25278*** | 2.01499*** | 2.22722*** |
| | (0.3343) | (0.4730) | (0.5003) | (0.4735) |
| ADMIN | 0.03317 | 0.09553 | 0.13797 | 0.09714 |
| | (0.0785) | (0.0841) | (0.1016) | (0.0844) |
| log(CLUMPS) | 0.01141 | 0.03117 | 0.03718 | 0.03059 |
| | (0.0278) | (0.0264) | (0.0294) | (0.0265) |
| log(STRLDENS) | 0.16753*** | 0.13875** | 0.12998* | 0.15215** |
| | (0.0497) | (0.0536) | (0.0581) | (0.0567) |
| log(LANDDENS) | 0.11068** | 0.10333** | 0.10317** | 0.11279** |
| | (0.0434) | (0.0455) | (0.0487) | (0.0481) |
| MAP | 0.02007 | -0.02128 | -0.00911 | -0.02465 |
| | (0.0501) | (0.0543) | (0.0562) | (0.0545) |
| log(PERIAREA) | -0.10145 | -0.10111 | -0.07635 | -0.10963* |
| | (0.0614) | (0.0614) | (0.0698) | (0.0627) |
| log(SCATTREE) | -0.00463 | 0.00157 | -0.00906 | 0.00222 |
| | (0.0356) | (0.0349) | (0.0362) | (0.0349) |
| WINTER | 0.11028* | 0.04402 | 0.11104 | 0.04009 |
| | (0.0567) | (0.0660) | (0.0777) | (0.0660) |
| SLASH | -0.08407 | -0.07076 | -0.07009 | -0.09206 |
| | (0.0588) | (0.0601) | (0.0702) | (0.0640) |
| log (VOLUME) | | 0.12332* | 0.17154** | 0.12239* |
| | | (0.0661) | (0.0734) | (0.0667) |
| FLAT | | 0.11588* | 0.07548 | 0.10879* |
| | | (0.0610) | (0.0750) | (0.0614) |
| OWNER | | -0.06206 | -0.06524 | -0.05541 |
| | | (0.0592) | (0.0697) | (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 |
| Adj $R^2$ | 0.4365 | 0.5223 | 0.5351 | 0.5267 |
| Breusch-Pagan $\chi^2$ | 17.8147*** | 12.2894*** | 8.1404*** | 8.7200*** |
| p-value | 0.0000 | 0.0005 | 0.0043 | 0.0031 |

[1]Because the felling and skidding models were run simultaneously in the SUR analysis, the $\chi^2$ 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).

Our analysis shows that felling productivity was significantly influenced by only two of the guideline-related variables: the use of a site map during harvest or pre-harvest 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 impact felling productivity (ADMIN, CLUMPS, PERIAREA, and SCATTREE) have no statistically significant effect as their degree of implementation changes. This 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 block. Consequently, its productivity is not likely to be slowed by the presence of clumps and leave trees. Similarly, this might explain why an oddly shaped stand does not inhibit felling productivity. 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. Felling productivity is not influenced by topography. This 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 conclude that this operator is more productive than the other four.

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 is as expected, as 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 turns. 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 (ADMIN) would inhibit skidding productivity as the operator might reroute skidding patterns to avoid problem spots (e.g., wet areas, leave tree clumps). This is not apparently the case within our harvest blocks. We conjecture that the operators 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 likely made, mitigated marginal reductions in travel speed and/or increases in distance that a skidder would otherwise 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 pre-harvest 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 pre-harvest meeting is largely borne by the feller operator.

We conjecture the finding that SCATTREE is not important in determining skidding productivity is related to the same reasons 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 may warrant 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. Skidding productivity does not appear to be significantly lower on publicly owned tracts.

## CONCLUSIONS

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 pre-harvest 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 layout of bunches for skidding.

While 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 three 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 adversely impact felling and skidding productivity.

Although not verifiable with our dataset, 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. Similarly, the results indicating that backhauling slash from the landing across the block did not significantly decrease skidding productivity seems counter-intuitive. 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.

In spite of the surprising lack of influence guidelines appear to have on felling productivity, our data suggests 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) all 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.

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