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A detrimental soil disturbance prediction model for ground-based timber harvesting

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Abstract: Soil properties and forest productivity can be affected during ground-based harvest operations and site preparation. The degree of impact varies widely depending on topographic features and soil properties. Forest managers who understand site-specific limits to ground-based harvesting can alter harvest method or season to limit soil disturbance. To determine the potential areal extent of detrimental (potentially plant growth limiting) soil disturbance based on site characteristics and season of harvest, we developed a predictive model based on soil monitoring data collected from 167 ground-based harvest units. Data collected included dominant site parameters (e.g., slope, aspect, soil texture, and landtype), harvest season, harvest type (intermediate or regeneration), and the machine(s) used during ground-based harvest operations. Aspect ($p = 0.0217$), slope ($p = 0.0738$), landtype ($p = 0.0002$), and the interaction of harvest season × landtype ($p = 0.0002$) were the key variables controlling the areal extent and magnitude of detrimental soil disturbance. For example, harvesting during non-winter months on gently rolling topography resulted in greater soil disturbance than similar harvest operations on landscapes that are highly dissected. This is likely due to the ease with which equipment can move off designated trails. A geospatially explicit predictive model was developed using general linear model variables found to significantly influence the areal extent of detrimental soil disturbance on nine defined landtypes. This tool provides a framework that, with local calibration, can be used on other forest lands as a decision support tool to geospatially depict landtypes susceptible to detrimental soil disturbance during ground-based harvest operations.

Résumé : Les opérations de récolte et de préparation de terrain qui se déroulent sur le terrain peuvent avoir un impact sur les propriétés du sol et la productivité de la forêt. L'ampleur de l'impact varie énormément selon les caractéristiques topographiques et les propriétés du sol. Les aménagistes qui comprennent les limites inhérentes à chaque station pour la récolte sur le terrain peuvent modifier les méthodes de coupes ou la saison de récolte afin de minimiser la perturbation du sol. Pour déterminer l'étendue aréale potentielle des perturbations néfastes (qui peuvent limiter la croissance des plantes) du sol selon les caractéristiques de la station et la saison de récolte, nous avons élaboré un modèle de prédiction basé sur des données de suivi du sol collectées dans 167 unités de récolte sur le terrain. Les données qui ont été recueillies incluaient les principaux paramètres de la station (p. ex. pente, exposition, texture du sol et type de sol), la saison de récolte, le type de coupe (intermédiaire ou de régénération) et la machinerie utilisée lors des opérations de récolte sur le terrain. L'exposition ($p = 0{,}0217$), la pente ($p = 0{,}0738$), le type de sol ($p = 0{,}0002$) et l'interaction entre la saison de récolte et le type de sol ($p = 0{,}0002$) étaient les principales variables responsables de l'étendue et de l'ampleur des perturbations néfastes du sol. Par exemple, le fait de récolter à d'autres moments que pendant les mois d'hiver sur un relief vallonné perturbait davantage le sol que les mêmes opérations de récolte dans des paysages fortement disséqués. Cela est probablement dû à la facilité avec laquelle la machinerie peut s'écarter des sentiers désignés. Un modèle de prédiction géospatialement explicite a été développé à l'aide des variables du modèle linéaire général qui avaient une influence significative sur l'étendue aréale des perturbations néfastes du sol pour neuf types de sol caractéristiques. Cet outil procure un cadre qui, après une calibration locale, peut être utilisé sur d'autres territoires forestiers comme outil d'aide à la décision pour représenter géospatialement les types de sol sensibles aux perturbations néfastes du sol lors d'opérations de récolte qui se déroulent sur le terrain.

[Traduit par la Rédaction]

Introduction

Maintenance of site productivity on National Forests in the United States is federally mandated under the National Forest Management Act of 1976. In addition, the various sustainable forestry certification systems (e.g., Sustainable Forestry Initiative and Canada's National Standard for Sustainable Forest Management) also have criteria and indicators pertaining to maintaining soil productivity on industry or other publicly owned lands (Page-Dumroese et al. 2010*a*). Monitoring the effects of timber harvest on soils and site productivity is

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often required by these mandates and is a key component of adaptive management strategies (Curran et al. 2005*a*; Miller et al. 2010). In the United States, soil quality standards were developed within the US Department of Agriculture (USDA) Forest Service and defined thresholds for soil disturbance (USDA 1999). Thresholds for impaired soil productivity or hydrologic function (detrimental disturbance) were defined for rutting, compaction, displacement, severe burning, surface erosion, loss of surface organic matter, and soil mass movement. Soil disturbance cannot exceed these thresholds for soils to be considered in satisfactory condition. On most USDA Forest Service land, harvested units must have 85% of the area in satisfactory condition when harvest activities, including site preparation, are completed to fully meet policy directives. In addition, the Forest Service Manual 2500 (USDA 2010) directs that soil quality monitoring be used to validate the disturbance thresholds and refine management decisions.

Currently, there is no common soil monitoring protocol consistently applied in the United States to determine the level of soil disturbance resulting from management activities. Drawing conclusions about the effect of site variables (slope, aspect, soil texture, weather, etc.) on soil disturbance is difficult across large areas when disparate monitoring protocols are used to collect monitoring data (Reeves et al. 2011). Disparate soil disturbance monitoring techniques (Curran et al. 2005*b*; Craigg and Howes 2007) and differences in monitor training and experience (Miller et al. 2010) have been linked to results that are incomparable and unreliable.

Forest soils can be detrimentally impacted by timber harvest operations using rubber-tired and tracked vehicles (Curran et al. 2005*a*). Detrimental soil disturbance (DSD) associated with ground-based harvesting often includes rutting, lateral soil displacement, horizon mixing, and compaction (Clayton et al. 1987). However, soils do not respond uniformly to disturbance associated with ground-based harvest (Powers et al. 2005). Soil response to disturbance is inherently variable, changes over time depending on the level of impact, and may be cumulative within a watershed (Page-Dumroese et al. 2010*a*). Assuming that any soil disturbance causes a reduction in tree growth is unwarranted (Miller et al. 2004). Soil disturbance resulting from ground-based timber harvest may enhance (Gomez et al. 2002) or have no effect on subsequent tree growth (Miller et al. 2010). Conversely, soil disturbance can reduce juvenile (Geist et al. 2008) and midrotation tree growth and economic value (Murphy et al. 2004). However, Gomez et al. (2002) suggested that the correlation between soil disturbance and tree growth is dependent on soil texture and soil moisture regime. These differences underscore the importance of a site-specific approach to soil disturbance monitoring and the ability to correlate disturbance levels with long-term site productivity.

Soil changes linked to harvest activities depend primarily on soil moisture during harvest operations, soil organic matter content, and soil textural class. Other factors include the axle weight of the load applied, tire size, and the number of machine passes (Williamson and Neilsen 2000; Han et al. 2009). Site characteristics (inherent soil bulk density, forest type, soil parent material, and slope) also play a major role in how soils react to ground-based harvest activities (Curran et al. 2005*a*, 2005*b*; Agherkakli et al. 2010).

Soil disturbance monitoring can be labor intensive and cost prohibitive in an era of shrinking budgets. This necessitates that monitoring resources should be focused on high-risk sites and (or) inherently sensitive soils (Miller et al. 2010). Effectively predicting the susceptibility of specific soils to disturbance is a core component of an adaptive management process outlined by Curran et al. (2005*b*). Since current and future resource conditions drive management decisions (Peng 2000), the ability to predict soil disturbance levels due to ground-based timber harvest based on site characteristics and harvest season would provide land managers a valuable decision support tool. The decision support tool is fundamental to responsible use of forest lands and should be capable of identifying areas more susceptible to high disturbance levels resulting from ground-based timber harvest (Miller et al. 2010).

Previous attempts to correlate soil disturbance with site characteristics, equipment type, and harvest season by combining soil disturbance monitoring data have been relatively unsuccessful due to the use of disparate soil monitoring methods (Reeves et al. 2011). There are numerous classification systems for characterizing soil disturbance (e.g., Scott 2000; B.C. Ministry of Forests 2001; Heninger et al. 2002; Page-Dumroese et al. 2009). Regardless of the source of visual (qualitative) monitoring systems, they all include recognition that within a disturbance classification system, there are severity classes. Increasing severity levels become increasing concerns for knowledgeable users (e.g., deep ruts, excavated or displaced area, or berms). Changes in soil disturbance severity levels are dependent on the harvest system employed and the personnel conducting the field work or the monitoring protocol (Reeves et al. 2011). These findings suggest that the development of a harvest disturbance decision support tool be based on systematically collected soil monitoring data. To test this hypothesis, we accessed a soil disturbance monitoring database consisting of over 87 000 soil monitoring points systematically collected in western Montana on the Kootenai National Forest (KNF), USA. The objectives for developing this decision support framework were to (*i*) determine the factors affecting soil disturbance and (*ii*) create a geospatial model predicting the areal extent of DSD resulting from ground-based timber harvest soil as influenced by landscape characteristics and season of harvest.

Methods

Data collection

The KNF has monitored soil disturbance from harvest activities since 1988 using a consistent protocol based on soil quality standards developed for the Northern Region of the USDA Forest Service. We compiled post-harvest soil monitoring records from 167 ground-based timber harvest units that were provided by the KNF. Soil disturbance classifications were assigned and recorded for 87 744 monitoring points on these units. No soil monitoring data were used that were completed prior to the last revision of the Northern Region soil quality standards (USDA 1999). Data collected included dominant site parameters (e.g., slope, aspect, soil texture, and landtype), harvest season, harvest type (intermediate or regeneration), and the machine(s) used during ground-based harvest operations. Harvest season was de-

Table 1. Detrimental disturbance thresholds from the Northern Region Supplement No. 2500-99-1 (USDA 1999) and used by the Kootenai National Forest, USA, for soil monitoring determinations.

Disturbance type	Detrimental threshold value
Compaction	15% increase in natural bulk density
Rutting	Wheel (or track) ruts ≥2 in. (5 cm) deep in wet soils
Displacement	Removal of ≥1 in. (2.5 cm) of any surface horizon from a contiguous area greater than 100^2 ft. (9.3^2 m)
Severely burned soil	Physical and biological changes to the soil resulting from high-intensity burns of long duration as described in the Burned-Area Emergency Rehabilitation Handbook (FSH 2509.13)
Surface erosion	Rills, gullies, pedestals, and soil deposition
Soil mass movement	Any soil mass movement caused by management activity

Table 2. Selected physical characteristics and the number of units in each of the nine landtypes on the Kootenai National Forest, USA, used within this study.

					Number of harvest units	
Landtype	Slope (%)	Aspect	Elevation (m)	Area (ha)	Winter	Non-winter
302	30–60	Southerly	914–1280	17 912	0	3
321	10–40	Variable	762–1158	13 050	5	1
322	15–35	Variable	762–1524	32 225	1	5
323	15–35	Variable	762–1524	35 754	7	23
324	15–35	Variable	762–1219	37 306	3	19
328	15–35	Northerly	914–1646	20 877	3	7
329	15–35	Variable	914–1676	27 414	7	10
352	20–60	Northerly	671–1707	201 000	15	28
355	20–50	Northerly	914–1676	187 336	23	7

Note: Modified from Kuennen and Nielsen-Gerhardt (1995).

lineated by the month harvest operations were completed. Ground-based harvest units were those units where timber had been harvested by rubber-tired skidders, harvester/forwarder (cut-to-length), and tractors. Both hand-felled and machine-felled harvest units were included. Harvest units that were machine-felled and yarded by helicopter or skyline systems were not included because these harvest systems usually result in relatively low levels of DSD on the KNF and throughout the Northern Region (Reeves et al. 2011).

Field collection of soil disturbance monitoring data

Post-harvest soil disturbance monitoring data had been collected on the KNF using a three-class system (undisturbed, disturbance present but not detrimental, and disturbance present and detrimental) to determine the areal extent of DSD across the harvest unit. On this forest, DSD is defined as disturbance in excess of the soil quality standard thresholds for compaction, rutting, displacement, severe burning, erosion, and soil mass movement as defined in Table 1. Line transects were walked across each harvest unit from harvest boundary to harvest boundary perpendicular to the direction of ground disturbing activities such as skid trails and skyline corridors (Kuennen 2006). Transects perpendicular to the skid trail pattern were found to be the most efficient sampling method that represented disturbance due to harvest activities (Kuennen 2006). Soil disturbance classification was recorded at each step across the transect. A spade or knife was used to assess compaction change from an undisturbed level. Soil resistance to penetration by the spade or knife was calibrated against known bulk densities from similar soil types. Other ocular observations were used to determine both quantitative and qualitative disturbance values present.

Landtypes

There are 50 landtypes within the boundaries of the KNF as described by Kuennen and Nielsen-Gerhardt (1995). Of the 50 landtypes present on the KNF, nine were selected for this study based on the availability of post-harvest DSD data for each landtype. These nine landtypes cover over 1.4 million acres and represent ~47.5% of the landbase within the administrative boundaries of the KNF. These nine landtypes represent areas on which most harvest activities occur and therefore are the landtypes with the most complete soil disturbance monitoring records. Landtype boundaries were determined on the basis of physiography (Table 2), geology, and vegetation (Table 3) (Kuennen and Nielsen-Gerhardt 1995). As noted in Table 2, some landtypes are poorly represented due to the lack of harvest activities within those landtypes. Weighted means were utilized to better represent the variability within landtypes, and landtype was considered to be a fixed effect within the model.

Statistical analysis

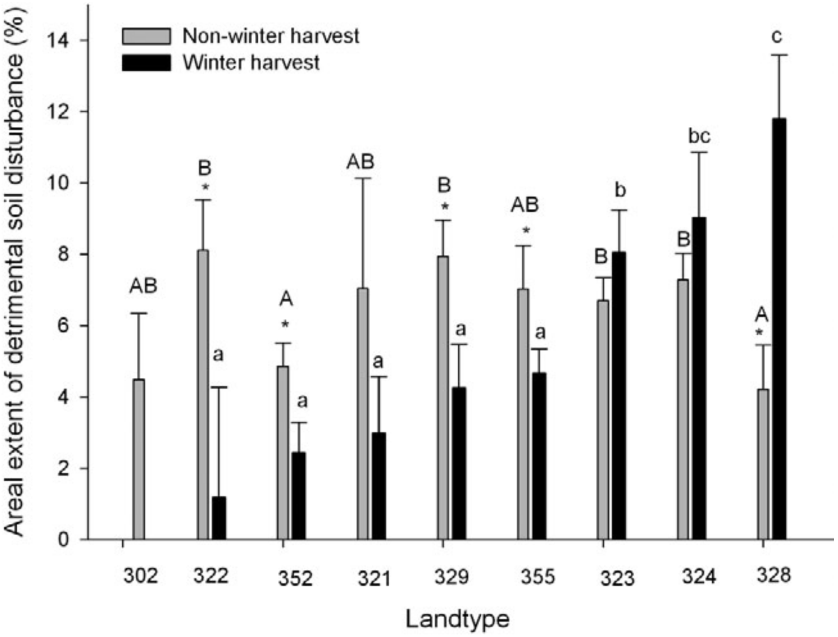
All analyses were done using SAS PROC GLM (SAS Institute Inc., Cary, North Carolina). A linear multiple regression analysis was used to test for significant effects (α = 0.10) of harvest season, aspect, slope, landtype, soil texture, ground-based equipment used, harvest type, unit acres, and coarse fragment content in the soil on the areal extent of DSD. Aspect, landtype, soil texture, ground-based equipment, and harvest type were treated as class variables. Pre-harvest DSD was subtracted from post-harvest DSD values where it was available for a harvest unit. When pre-harvest DSD was not available for a harvest unit, it was assumed to be zero. For the purposes of this study, harvest units listed as

Table 3. Selected geological characteristics for nine landtypes on the Kootenai National Forest, USA, used within this study.

Landtype	Soil parent material	Dominant landform
302	Compact glacial till	Glaciated mountain slopes
321	Calcareous glacial till	Drumlins/moraines
322	Loess and volcanic ash over compact glacial till	Moraines
323	Loess and volcanic ash over calcareous glacial till	Moraines
324	Calcareous glacial till	Moraines
328	Loess and volcanic ash over calcareous glacial till	Glaciated mountain slopes
329	Loess and volcanic ash over calcareous glacial till	Moraines
352	Loess and volcanic ash over compact glacial till	Glaciated linear mountain slopes
355	Loess and volcanic ash over compact glacial till	Glaciated rounded mountain slopes

Note: Modified from Kuennen and Nielsen-Gerhardt (1995).

Fig. 1. Mean areal extent of detrimental soil disturbance for each landtype and harvest season following ground-based timber harvest on the Kootenai National Forest, USA. Bars with the same letter are not significantly different ($\alpha = 0.10$). Uppercase letters are not comparable with lowercase letters. Bars with an asterisk above indicate significant differences ($\alpha = 0.10$) in detrimental soil disturbance between harvest seasons on the same landtype. No data were available for winter harvest on landtype 302.



winter were completed in December, January, or February. Harvest units completed during other months were treated as non-winter. Aspect was treated as a class variable consisting of the eight cardinal directions and harvest units that were flat (no definable aspect). Slope values were based on the maximum slope recorded for each harvest unit. Least-squared means were generated and used to test for significant differences between levels of predictor variables. Variables and interactions that did not have a significant effect on the areal extent of DSD were removed from the final model. However, insignificant variables that contributed to a significant interaction were retained in the final model statement. After each nonsignificant effect was removed, the model was examined again until only significant effects remained.

Table 4. Variables within the GLM used for predicting detrimental soil disturbance following ground-based timber harvest on the Kootenai National Forest, USA.

Variable	*p*
Aspect	0.0217
Slope	0.0738
Harvest season	0.1637
Landtype	0.0002
Harvest season × landtype	0.0002

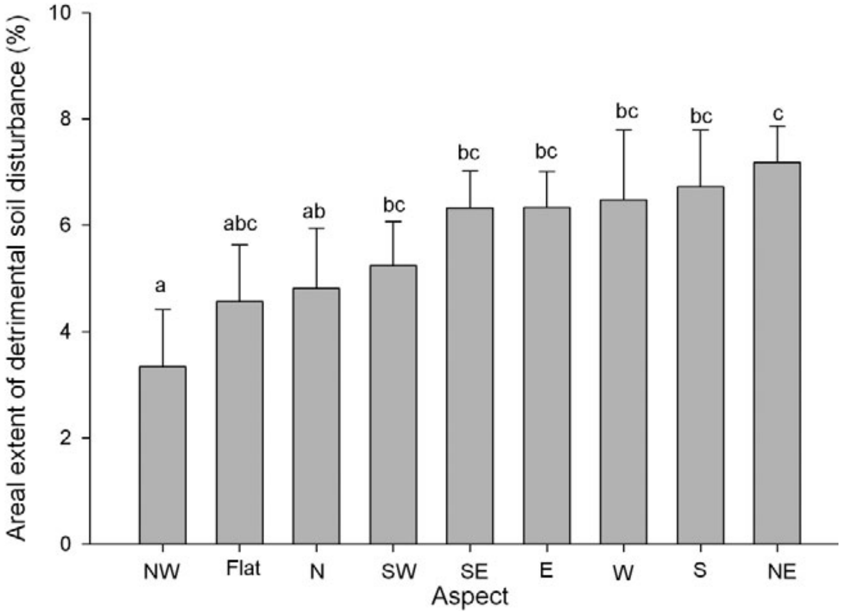
Geospatial modeling

Statistical parameters generated in the GLM analysis were used to geospatially represent the effect of aspect, slope, harvest season, landtype, and the interaction between harvest season and landtype on the areal extent of DSD following ground-based timber harvest utilizing a 30 m digital elevation model. The geospatial representation was produced using the following model equation:

$$\mathrm{DSD} = \mu + \alpha_i + \beta_j + \gamma_k + \delta_l + (\gamma\delta)_{kl}$$

where μ is the population DSD mean, α_i is the effect of as-

Fig. 2. Mean areal extent of detrimental soil disturbance following ground-based timber harvest as influenced by aspect on the Kootenai National Forest, USA. Bars with the same letter above are not significantly different ($\alpha = 0.10$).



pect ($i = 1, ..., p$ and p = nine aspect classes), β_j is the effect of maximum slope, γ_k is the effect of harvest season ($k = 1, ..., q$ and q = two harvest seasons), δ_l is the effect of landtype ($l = 1, ..., r$ and r = nine landtypes), and $(\gamma\delta)_{kl}$ is the effect of harvest season × landtype interaction ($kl = 1, ..., s$ and $s = 18$)

Equations developed through this process were programmed in Arc Macro Language in the Grid environment (Environmental Systems Research Institute 2007) enabling predictions of the areal extent of DSD resulting from ground-based timber harvest as influenced by harvest season and landtype.

Results

Factors controlling disturbance

DSD following ground-based timber harvesting was significantly affected by landtype and the interaction between harvest season and landtype (Fig. 1). Aspect, slope, landtype, and the interaction between harvest season and landtype were significant variables in the model (Table 4). DSD resulting from non-winter ground-based harvest was significantly higher ($p \leq 0.0356$) on landtypes 322 and 329 than non-winter harvest on landtypes 328 and 352, whereas DSD after winter ground-based harvest operations was significantly higher ($p \leq 0.0399$) on landtypes 323, 324, and 328. DSD resulting from non-winter harvest was higher ($p \leq 0.0433$) than DSD resulting from winter harvest on landtypes 322, 329, 352, and 355. Landtype 328 was unique amongst all landtypes, as DSD was significantly higher following winter ground-based timber harvest as opposed to non-winter harvesting ($p \leq 0.0007$). There were also differences in the areal extent of DSD resulting from ground-based timber harvest between aspects (Fig. 2). Based on post hoc results, harvest units with a northwest aspect had significantly lower amounts of DSD ($p \leq 0.0816$) than units with southwest, southeast, east, west, and northeast aspects but were similar to flat and north aspects (Fig. 2). DSD levels increased slightly (0.05% per 1% increase in slope) with an increase in the maximum slope value for the harvest unit (data not shown).

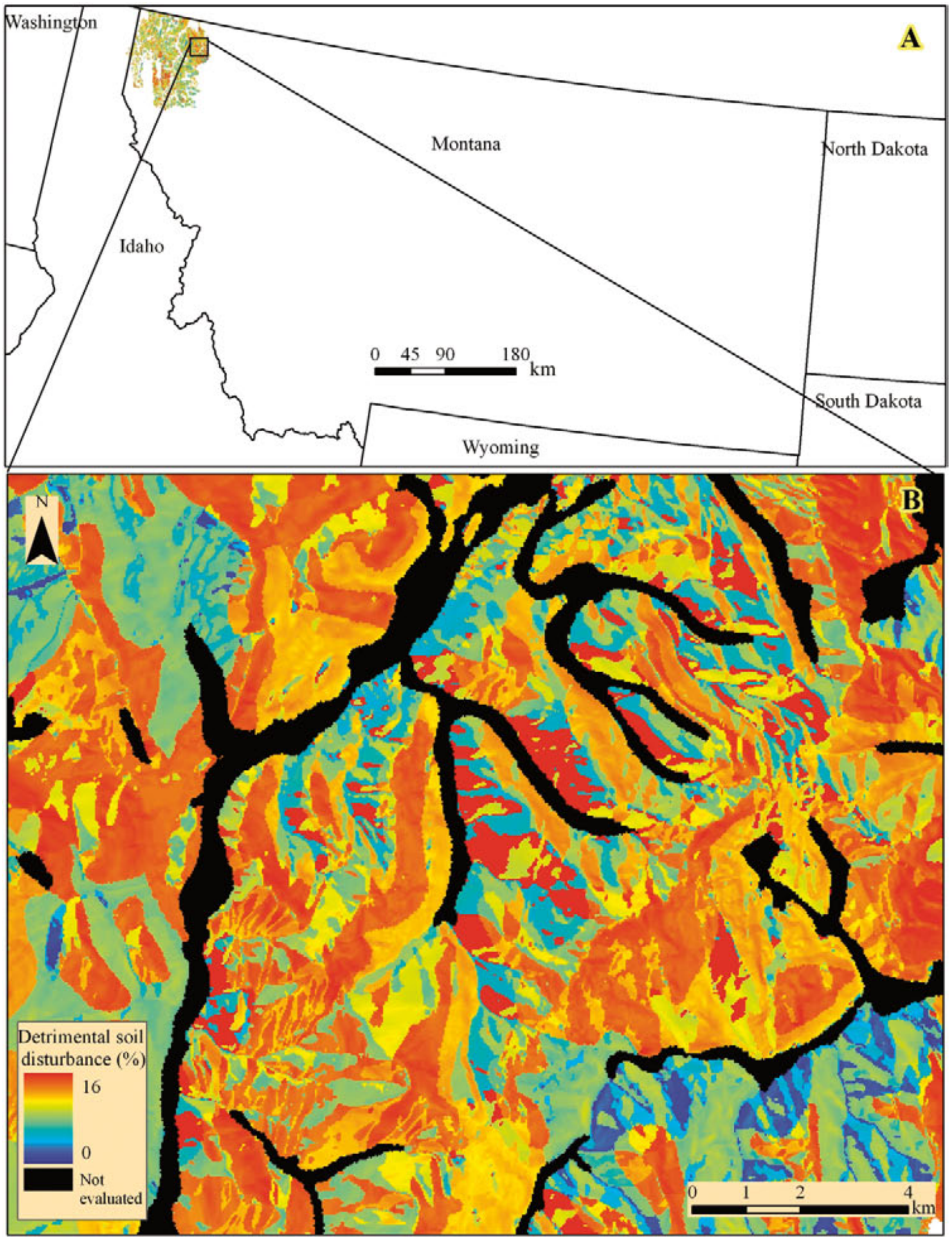
Geospatial representation of the statistical model

Geospatial representations of topographic and landtype influence on DSD following ground-based harvesting were created for each harvest season (Figs. 3 and 4) using parameter estimates generated from the GLM (Table 5). Modeled values for the areal extent of DSD resulting from winter ground-based harvest ranged from 0% to 14%; modeled non-winter DSD ranged from 0% to 16%. The overall areal extent of DSD between the two harvest seasons was similar; however, there was variation in the distribution of predicted DSD depending on the interaction between landtype and harvest season.

Discussion

One major emphasis of soil monitoring efforts, particularly in the USDA Forest Service, is the amount of DSD generated from ground-based harvesting and keeping that level below the threshold of 15% areal extent. After examining this relatively large data set, average DSD across all sites, landtypes, and season of harvest was usually well below the threshold, except for winter harvests on landtype 328. In general, the amount of DSD reported on harvest units depended primarily on the landtype and season of harvest. Harvest unit topography (slope and aspect) played a lesser, but still significant, role in the amount of DSD resulting from ground-based harvest. For example, sites with a northwest aspect likely had frozen soil later in the spring and earlier in the fall than soils with other aspects. Soil disturbance after non-winter harvests was significantly higher on moraines (landtypes 322 and 329) than on glaciated mountain slopes (landtypes 328 and 352). Aside from the dominant landforms delineating these land-

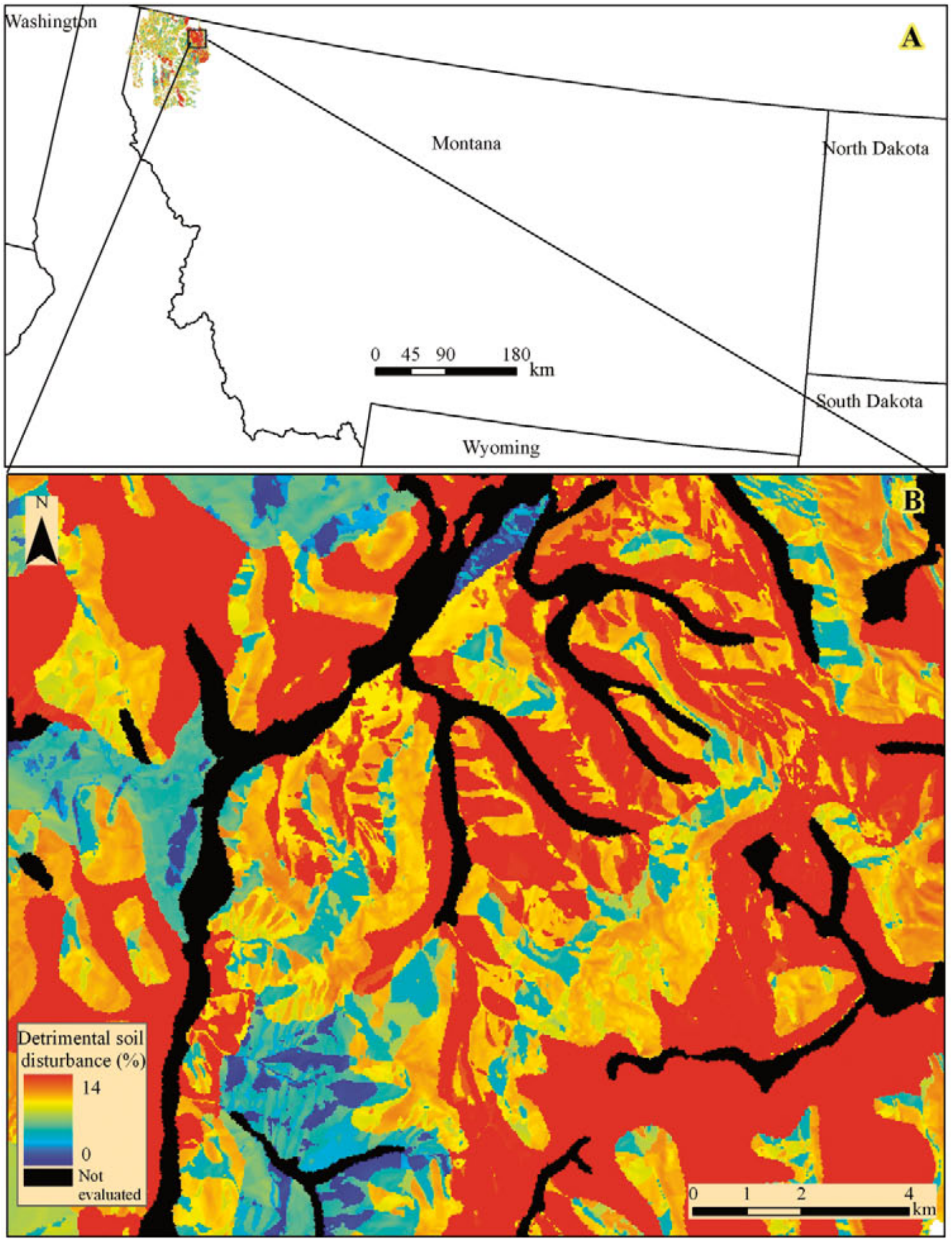
Fig. 3. Geospatial representation of the statistical model predicting areal extent of detrimental soil disturbance following winter ground-based timber harvest on the Kootenai National Forest, USA. (A) Landscape projection showing the regional setting of the study area. (B) Finer scale representation of detrimental soil disturbance within a segment of the study area. Areas in black depict landtypes where there were insufficient data.



types, other physical characteristics are similar. The rolling topography associated with moraines makes them conducive to ground-based harvest because of the relative ease with which harvest equipment can travel across the ground. Therefore, increased DSD on moraines may have been due to a lack of designated skid trails or the ability to turn freely across these sites. This disperses harvest activity across the harvest unit and does not confine DSD to designated areas, increasing the areal extent. On glaciated mountain slopes such as landtypes 328 and 352, machine travel was likely restricted to designated skid trails.

Winter harvest was relatively effective at decreasing DSD across most of the study area and is consistent with regionally published trends (Reeves et al. 2011). Winter harvest conducted during optimal conditions over frozen soil is effective at reducing DSD resulting from ground-based harvest (Miller et al. 2004; Johnson et al. 2007) and it is often prescribed as a best management practice because it has been shown to minimize soil damage (Johnson et al. 2007; Page-Dumroese et al. 2010*b*). However, on three landtypes (323, 324, and 328), winter DSD was greater than non-winter DSD and was significantly higher on landtype 328. This was particularly surprising on landtype 328 given the landtype's dominant northerly aspect (Table 2) and relatively low predicted disturbance levels for non-winter harvest (Fig. 1). KNF personnel believe that the predicted values are inconsis-

Fig. 4. Geospatial representation of the statistical model predicting areal extent of detrimental soil disturbance following non-winter ground-based timber harvest on the Kootenai National Forest, USA. (A) landscape projection showing the regional setting of the study area. (B) Finer scale representation of detrimental soil disturbance within a segment of the study area. Areas in black depict landtypes where there were insufficient data.



tent with actual post-harvest DSD levels resulting from winter harvest on landtype 328 (J. Gier, personal communication (5 October 2010)). There are a number of factors that may have influenced the high levels of DSD predicted by the model on landtype 328 for winter harvest. Kuennen (2007) noted that timber sale contract language on the KNF can state that harvest activities are restricted to ground that is frozen or covered by a minimum of 46–61 cm of snow; however, these parameters do not achieve the same objective. Ground that receives insulating snowpack prior to freeze-up will not freeze to the point necessary to produce optimal winter harvest conditions. On sites where skid trails are designated during winter harvest operations, snow should be removed from skid trails so they can “freeze up” before harvest activities commence to achieve ideal conditions (Kuennen 2007).

There were five harvest units on landtypes 323, 324, and 328 where winter harvest DSD levels ranged from 11% to 18%. These five harvest units represent 38.5% of the data for winter harvest on these landtypes. Harvest operations on these five units occurred during the winters of 1999–2000, 2000–2001, 2003–2004, and 2004–2005. During these time periods, temperature and precipitation data from the Libby 1 NE Ranger STN, MT weather station (High Plains Regional Climate Center 2010) indicate that temperatures at the weather station for December, January, and February were

Table 5. Parameter estimates used to geospatially predict areal extent of detrimental soil disturbance following ground-based timber harvest on the Kootenai National Forest, USA.

Variable	Class	Estimate	Variable	Class	Estimate
Mean		4.22	Non-winter × landtype	302	0.00
Slope (%)		0.06		321	1.69
				322	4.57
Aspect	E	0.24		323	–3.72
	N	–1.92		324	–4.11
	NE	0.51		328	–9.94
	NW	–3.67		329	1.32
	S	0.42		352	0.04
	SE	0.26		355	0.00
	SW	–1.02			
	W	0.00			
	Flat	–1.63			
Season of harvest	Winter	0.00			
	Non-winter	2.36	Winter × landtype	302	0.00
				321	0.00
Landtype	302	–2.54		322	0.00
	321	–1.68		323	0.00
	322	–3.49		324	0.00
	323	3.39		328	0.00
	324	4.36		329	0.00
	328	7.11		352	0.00
	329	–0.41		355	0.00
	352	–2.22			
	355	0.00			

above the 98 year average for each of the winters with high DSD levels on those landtypes. Additionally, precipitation levels over the same 3 month period were below the 98 year average for each of the winters with high DSD levels on those landtypes except for the winter of 1999–2000 (High Plains Regional Climate Center 2010). While site conditions at the time of harvest are unknown, these data suggest that winter harvest conditions on these five units may have been suboptimal due to higher than average temperatures and decreased snowpack leading to an increase in winter harvest DSD due to saturated soils during harvest activities.

Variation in DSD during winter harvest activities may be attributable to other factors. For example, categorizing December, January, and February as “winter” may have influenced our results. Weather station data indicate that these 3 months are the most likely to exhibit the necessary temperatures and snowpack to produce optimal winter harvest conditions. However, because forest records often lack specific start and stop dates, our categorization technique was based on the month in which management activity was complete. It is possible that DSD levels were high because of harvest operations that took place in late fall while soils were more susceptible to rutting and compaction after fall rains and before harvest operations were completed in the period that we designated as winter.

Operator and sale administrator skill and the harvest equipment may also play a role in the variation of DSD levels. Operator skill and experience have been documented to affect disturbance levels in similar harvest operations (Pinard et al. 2000; Stone 2002). Sale administrator knowledge of local conditions and operators on site can also have an impact on the amount of DSD resulting from timber harvest operations (Reeves et al. 2011). Although we found no significant DSD differences among ground-based harvest equipment, other research points out that different ground-based equipment can produce disparate results (Stone 2002; Page-Dumroese et al. 2006). Our findings may be due to a lack of precision in noting the type of harvest equipment used in each harvest unit. Ultimately, allocation of monitoring resources likely impacts our conclusions because post-harvest monitoring resources can be directed toward areas deemed more susceptible to high levels of disturbance. Consequently, monitoring activities for winter harvest in landtype 328 could have been restricted to harvest units that were known to be at risk due to suboptimal conditions. Similarly, it is possible that the values predicted by the statistical model are an anomaly due to a small sample size (Table 2).

Predictive models can be improved by increased sample points within a unit to assure that a greater proportion of variability is captured during the monitoring process. Predicted values for the areal extent of DSD were produced from 167 harvest units and extrapolated over millions of pixels encompassing many variations of physical composition. This is best illustrated by examining the predicted values for the areal extent of DSD for ground-based winter harvest. The model predicts post-harvest disturbance levels ranging from 0% to 15%. While modeled values appear to be reasonable over a broad range of conditions, values on the extreme ends of the spectrum may be influenced by extrapolations of poorly fitted or unfitted data.

During our analysis, we lacked sufficient data to withhold a portion of the data set to validate the model. Model validation is a key component in promoting user confidence and establishing the range of error associated with predicted values. However, we do provide a solid framework for testing, validating, and improving this model to predict site conditions that can cause DSD and give managers an opportunity to develop best management practices based on site-specific data. In addition, we also lacked pre-harvest soil disturbance data on some harvest units that might indicate a level of disturbance that we attributed to the current timber sale. We also did not have site-specific information on surface soil texture. Soil texture influences water infiltration and hydrologic function, but surface soil texture information is not specific to each timber sale area. Finally, weather conditions in the 10 day period before harvest operations begin could be a key factor in determining how much DSD will occur on a given site. Combining the framework presented here with other modeling efforts that evaluate soil hydraulic properties by using readily available data on soil properties (i.e., compaction, organic matter content, and soil texture) and local weather station data (Arp and Yin 1992; Balland et al. 2008) provides an opportunity to build a proactive system to determine soil disturbance potential. The limitations encountered in this study will help guide future data collection efforts, which in turn will help further develop and validate soil disturbance models.

Management implications

Developing an accurate predictive model and decision support tool to assess soil changes due to management activities can be accomplished for any region using current, consistently applied soil monitoring protocols, landtype (or soil) surveys, and geospatial data that are often readily available. Consistent application of soil monitoring protocols and database development are key components of this process and critical to an effective soil monitoring program. Delineating and accurately recording the specific piece of ground-based harvest equipment would improve the model that we have developed here. Incorporating specific ground-based harvesting equipment into the model could provide a key piece of information allowing managers to improve operational results by selective utilization of the most appropriate equipment that meets operational objectives. All harvest operations produce some type of soil disturbance and using a risk rating system as a portion of the overall risk analysis of proposed projects is an efficient, cost-effective step in identifying areas more susceptible to DSD-causing activities. Identifying areas more susceptible to high impact (i.e., ground-based) harvest techniques allows land managers to develop alternative strategies to meet management objectives and can help prioritize allocation of monitoring resources. Tools such as this one that incorporate a geospatial tool that predicts levels of disturbance can play a crucial role in project planning and are a key component of adaptive management strategies.

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References

Agherkakli, A., Najafi, A., and Sadeghi, S.H. 2010. Ground based operation effects on soil disturbance by steel tracked skidder in a steep slope of forest. For. Sci. **56**(6): 278–284.

Arp, P.A., and Yin, X. 1992. Predicting water fluxes through forests from mean monthly precipitation and mean monthly air temperature records. Can. J. For. Res. **22**(6): 864–877. doi:10.1139/x92-116.

Balland, V., Pollacco, J.A.P., and Arp, P.A. 2008. Modeling soil hydraulic properties for a wide range of soil conditions. Ecol. Model. **219**(3–4): 300–316. doi:10.1016/j.ecolmodel.2008.07.009.

B.C. Ministry of Forests. 2001. Soil conservation surveys guidebook. 2nd ed. Forest Practices Code of British Columbia. B.C. Ministry of Forests, Forest Practices Branch, Victoria, B.C.

Clayton, J.L., Kellogg, G., and Forrester, N. 1987. Soil disturbance – tree growth relations in central Idaho clearcuts. U.S. For. Serv. Res. Note. INT-372.

Craigg, T.L., and Howes, S.W. 2007. Assessing quality in volcanic ash soils. *In* Proceedings of the Conference on Volcanic-Ash-Derived Forest Soils of the Inland Northwest: Properties and Implications for Management and Restoration. *Edited by* D.S. Page-Dumroese, R. Miller, J. Mital, P. McDaniel, and D. Miller. RMRS-P-44. pp. 47–66.

Curran, M.P., Maynard, D.G., Heninger, R.L., Terry, T.A., Howes, S. W., Stone, D.M., Niemann, T., Miller, R.E., and Powers, R.F. 2005*a*. An adaptive management process for forest soil conservation. For. Chron. **81**: 717–722.

Curran, M.P., Miller, R.E., Howes, S.W., Maynard, D.G., Terry, T.A., Heninger, R.L., Niemann, T., van Rees, K., Powers, R.F., and Schoenholtz, S.H. 2005*b*. Progress towards more uniform assessment and reporting of soil disturbance for operations, research, and sustainability protocols. For. Ecol. Manage. **220**(1–3): 17–30. doi:10.1016/j.foreco.2005.08.002.

Curran, M.P., Maynard, D.G., Heninger, R.L., Terry, T.A., Howes, S. W., Stone, D., Niemann, T., and Miller, R.E. 2007. Elements and rationale for a common approach to assessment and reporting of soil disturbance. For. Chron. **83**: 852–866.

Environmental Systems Research Institute. 2007. ArcGIS 9.2. Environmental Systems Research Institute, Redlands, Calif. Available from http://www.esri.com/ [accessed 5 December 2010].

Geist, M.J., Hazard, J.W., and Seidel, K.W. 2008. Juvenile tree growth on some volcanic ash soils disturbed by prior forest harvest. U.S. For. Serv. Res. Pap. PNW-RP-573.

Gomez, A., Powers, R.F., Singer, M.J., and Horwath, W.R. 2002. Soil compaction effects on growth of young ponderosa pine following litter removal in California's Sierra Nevada. Soil Sci. Soc. Am. J. **66**(4): 1334–1343. doi:10.2136/sssaj2002.1334.

Han, S.-K., Han, H.-S., Page-Dumroese, D.S., and Johnson, L.R. 2009. Soil compaction associated with cut-to-length and whole-tree harvesting of a coniferous forest. Can. J. For. Res. **39**(5): 976–989. doi:10.1139/X09-027.

Heninger, R., Scott, W., Dobkowski, A., Miller, R., Anderson, H., and Duke, S. 2002. Soil disturbance and 10-year growth response of coast Douglas-fir on nontilled and tilled skid trails in the Oregon Cascades. Can. J. For. Res. **32**(2): 233–246. doi:10.1139/x01-195.

High Plains Regional Climate Center. 2010. Libby 1 NE Ranger STN, MT. Available from http://www.hprcc.unl.edu/cgi-bin/cli_-perl_lib/cliMAIN.pl?mt5015 [accessed 15 January 2011].

Johnson, L.R., Page-Dumroese, D.S., and Han, H.-S. 2007. Effects of machine traffic on the physical properties of ash-cap soils. *In* Proceedings of the Conference on Volcanic-Ash-Derived Forest Soils of the Inland Northwest: Properties and Implications for Management and Restoration. *Edited by* D.S Page-Dumroese, R. Miller, J. Mital, P. McDaniel, and D. Miller. RMRS-P-44. pp. 69–82.

Kuennen, L. 2006. Soil disturbance analysis and documentation methodology 1998–2005, Appendix A. Kootenai National Forest White Paper.

Kuennen, L. 2007. Thirty-five years of studying, learning about, and interpreting soil on the Kootenai National Forest. Young Dodge EIS. Kootenai National Forest.

Kuennen, L.J., and Nielsen-Gerhardt, M.L. 1995. Soil survey of Kootenai National Forest area, Montana and Idaho. USDA, Washington, D.C.

Miller, R.B., McIver, J.D., Howes, S.W., and Gaeuman, W.B. 2010. Assessment of soil disturbance in forests of the Interior Columbia River Basin: a critique. U.S. For. Serv. Gen. Tech. Rep. PNW-GTR-811.

Miller, R.E., Colbert, S.R., and Morris, L.A. 2004. Effects of heavy equipment on physical properties of soils and on long-term productivity: a review of literature and current research. NCASI Tech. Bull. 887. NCASI Research, Triangle Park, N.C.

Murphy, G., Firth, J.G., and Skinner, M.F. 2004. Long-term impacts of forest harvesting related soil disturbance on log product yields and economic potential in a New Zealand forest. Silva Fenn. **38**(3): 279–289.

Page-Dumroese, D.S., Jurgensen, M., Abbott, A., Rice, T., Tirocke, J., and DeHart, S. 2006. Monitoring changes in soil quality from post-fire logging in the inland northwest. *In* Proceedings of the Conference on Fuels Management — How to Measure Success. *Compiled by* P.L. Andrews and B.W. Butler. RMRS-P-41. pp. 605–614.

Page-Dumroese, D., Abbott, A.M., and Rice, T. 2009. Forest soil disturbance monitoring protocol. Vol. 1. Rapid assessment. U.S. For. Serv. Gen. Tech. Rep. WO-82a.

Page-Dumroese, D., Jurgensen, M.F., Curran, M.P., and DeHart, S.M. 2010*a*. Cumulative effects of fuel treatments on soil productivity. *In* Cumulative watershed effects of fuel management in the western United States. *Edited by* W.J. Elliot, I.S. Miller, and L. Audin. U.S. For. Serv. Gen. Tech. Rep. RMRS-GTR-231. pp. 164–174.

Page-Dumroese, D.S., Jurgensen, M., and Terry, T. 2010*b*. Maintaining soil productivity during forest or biomass-to-energy harvesting in the western United States. West. J. Appl. For. **25**: 5–12.

Peng, C. 2000. Understanding the role of forest simulation models in sustainable forest management. Environ. Impact Assess. Rev. **20** (4): 481–501. doi:10.1016/S0195-9255(99)00044-X.

Pinard, M.A., Barker, M.G., and Tay, J. 2000. Soil disturbance and post-logging forest recovery on bulldozer paths in Sabah, Malaysia. For. Ecol. Manage. **130**(1–3): 213–225. doi:10.1016/S0378-1127(99)00192-9.

Powers, R.F., Scott, D.A., Sanchez, F.G., Voldseth, R.A., Page-Dumroese, D., Elioff, J.D., and Stone, D.M. 2005. The North American long-term soil productivity experiment: findings from the first decade of research. For. Ecol. Manage. **220**(1–3): 31–50. doi:10.1016/j.foreco.2005.08.003.

Reeves, D., Page-Dumroese, D.S., and Coleman, M. 2011. Detrimental soil disturbance associated with timber harvest systems on national forests in the northern region. U.S. For. Serv. Res. Pap. RMRS-RP-89.

Scott, W. 2000. A soil disturbance classification system. Internal report. For. Res. Tech. Note. Pap. 00-1. Weyerhaeuser Co., Federal Way, Wash.

Stone, D.M. 2002. Logging options to minimize soil disturbance in the Northern Lake States. North. J. Appl. For. **19**: 115–121.

USDA. 1999. Region One Supplement No. 2500-99-1. USDA Forest Service, Washington, D.C.

USDA. 2010. Forest service manual 2500 watershed and air management. USDA Forest Service, Washington, D.C.

Williamson, J.R., and Neilsen, W.A. 2000. The influence of forest site on rate and extent of soil compaction and profile disturbance of skid trails during ground-based harvesting. Can. J. For. Res. **30**(8): 1196–1205. doi:10.1139/x00-041.