Relationships between Soil Compaction and Harvest Season, Soil Texture, and Landscape Position for Aspen Forests

Randy Kolka, Aaron Steber, Ken Brooks, Charles H. Perry, and Matt Powers

ABSTRACT

Although a number of harvesting studies have assessed compaction, no study has considered the interacting relationships of harvest season, soil texture, and landscape position on soil bulk density and surface soil strength for harvests in the western Lake States. In 2005, we measured bulk density and surface soil strength in recent clearcuts of predominantly aspen stands (*Populus grandidentata* Michx. and *Populus tremuloides* Michx.) in the Chippewa National Forest in northern Minnesota. We stratified these clearcuts by the season harvested, soil texture, and topographic position. In nearly all cases, we observed higher bulk density and surface soil strength following harvesting compared with adjacent and similar but unharvested stands. Within harvested sites, fine-textured soils generally had higher surface soil strength (more compaction) than coarse-textured soils when harvested in the summer, and fine-textured sites harvested in the summer had higher surface soil strength than those harvested in the winter. Landscape position was an important factor only in fine-textured soils. Both summit and toeslope positions had higher surface soil strength following summer harvesting compared with winter harvesting. Overall, our results indicate that fine-textured soils located on both lower and upper slope positions and harvested during unfrozen soil conditions are most susceptible to compaction during logging.

Keywords: soil compaction, bulk density, soil strength, logging impacts, harvest season, topography

The use and size of ground-based harvesting machines began to increase rapidly about 50 years ago, followed by a concern that equipment was damaging soils and reducing productivity (McNabb 1993). Soil compaction resulting from timber harvesting can increase bulk density, soil strength, and surface erosion while decreasing air movement into and through the soil profile by decreasing pore space and continuity, therefore reducing infiltration capacity and tree root growth (Greacen and Sands 1980, Thompson et al. 1987, McNabb et al. 2001). The extent of compaction on bulk density, depth of impact, and subsequent soil recovery are all factors that determine the influence of timber harvesting on productivity (Page-Dumroese et al. 2006).

The texture of the soil can affect the site's susceptibility to compaction by harvesting equipment. The North American Long-Term Soil Productivity study found that fine-textured soils often had the lowest initial bulk density, but the same sites received the largest increase in bulk density following compaction from a single equipment pass (Page-Dumroese et al. 2006). On coarse-textured soils, compacted skid trails were sites of improved tree growth because of increases in soil available water capacity (Powers et al. 2005). Researchers in Tasmania examined soil compaction by harvesting equipment at six locations across a wide range of soils and found that soil texture, the number of machine passes, and soil depth (0–10 cm was more compacted than lower soil depths) all significantly affected the resulting change in bulk density (Williamson and Nielsen 2000).

Soil is most easily compacted when wet or moist, and the susceptibility of a soil to compaction decreases at lower soil water contents (McNabb 1993). One method to reduce the susceptibility of wet areas to damage from harvesting equipment is winter harvesting when soils are frozen. Winter harvesting is effective in limiting compaction when soils are frozen to a depth that is adequate to resist the pressure applied by harvesting equipment. Stone and Elioff (1998) found that winter harvesting of mature aspen (*Populus grandidentata* Michx. and *Populus tremuloides* Michx.) on frozen soils had little effect on soil physical properties.

Topography plays an important role in the redistribution of moisture, which can lead to some parts of the landscape being more susceptible to soil compaction or disturbance from harvesting activities (Block et al. 2002). This is especially true in depressional areas that have a high ratio of catchment area to dispersal area (Pennock et al. 1994). Soils in depressions may receive subsurface inflow and tend to remain wet for relatively long periods compared with the rest of the landscape; therefore, they are more susceptible to soil compaction (Block et al. 2002).

We are aware of only one other study that has examined the effects of landscape position, harvest season, and soil type when

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Randy Kolka (rkolka@fs.fed.us), US Forest Service Northern Research Station, 1831 Highway 169 East, Grand Rapids, MN 55744. Aaron Steber, JFNew Ecological Consulting, Verona, WI 53593. Ken Brooks, University of Minnesota, St. Paul, MN 55108. Charles H. Perry, US Forest Service Northern Research Station, St. Paul, NN 55108. Matt Powers, Michigan Technological University, Houghton, MI 49931. *Funding support was provided by the US Forest Service, Forest Health Monitoring, Evaluation Monitoring program. We also thank James Barott (Chippewa National Forest) and Coley Grostyan (University of Minnesota).*

This article uses metric units; the applicable conversion factors are: millimeter (mm): 1 mm = 0.039 in.; centimeters (cm): 1 cm = 0.39 in.; square centimeters (cm^2): 1 cm^2 = 0.155 $in.^2$; meters (m): 1 m = 3.3 ft; kilometers (km): 1 km = 0.6 mi; kilograms (kg): 1 kg = 2.2 lb; megagrams (Mg): 1 Mg = 2,204.6 lb.

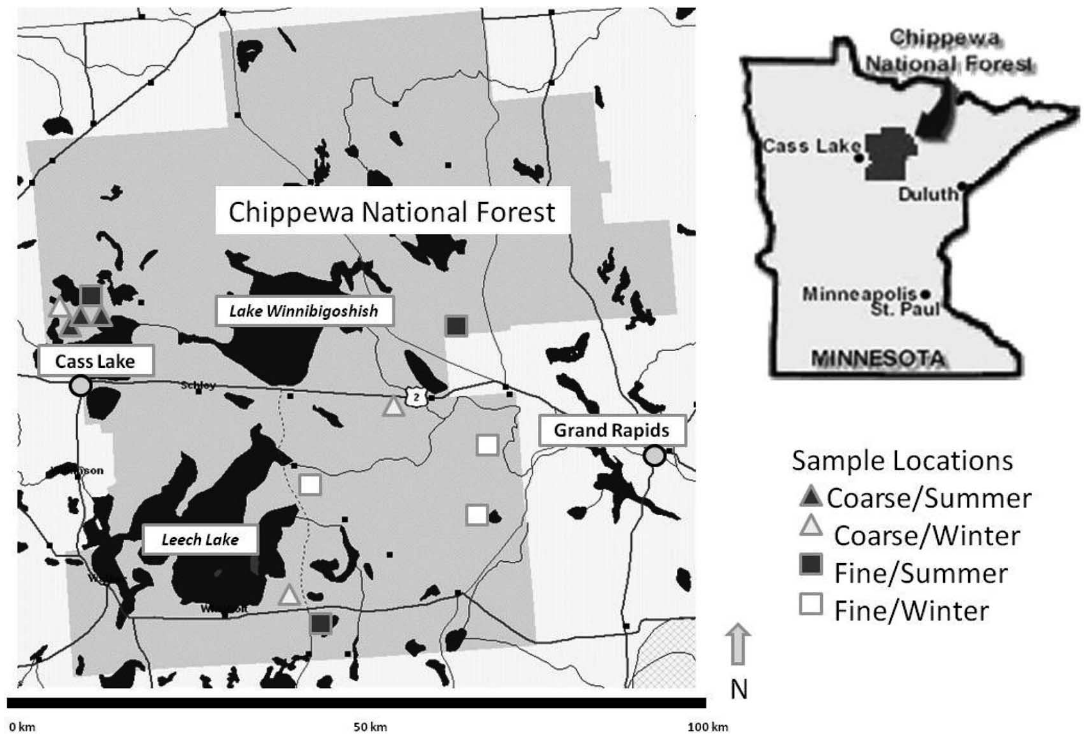

Figure 1. Approximate location of sampling sites in the Chippewa National Forest, Minnesota.

assessing bulk density following harvests (Block et al. 2002), and that study was conducted in the boreal region of Saskatchewan. In this study, we investigated the relationships between soil texture, harvest season, and landscape position, on the one hand, and soil bulk density and surface soil strength, on the other hand, following recent aspen harvests in the Western Great Lakes Laurentian Mixed Forest Province. With a better understanding of these relationships, our goal was to develop recommendations to minimize soil compaction during harvesting operations in this region.

Materials and Methods

Seventy-three predominantly aspen sites (stands) harvested between the winter of 2003–2004 and the winter of 2004–2005 were identified using GIS in the US Forest Service's Chippewa National Forest in northern Minnesota. Sampling and measurements took place in the summer of 2005. We stratified these clearcuts into four categories based on season harvested and potential for soil compaction based on soil texture (Page-Dumroese et al. 2006, Steber et al. 2007). We identified 73 harvest sites: 16 summer/coarse-textured, 8 summer/fine-textured, 7 winter/coarse-textured, and 42 winter/fine-textured. Three clearcuts, avoiding roads, landings, and skid trails, were randomly selected for sampling from each of the four season/soil texture groups (Figure 1). Adjacent aspen sites that were not recently harvested and had similar soils (same soil series) served as comparisons. Coarse-textured soils included sands, loamy sands, and sandy loams predominately from glacial outwash, and fine-textured soils included loams, silt loams, and clay loams predominately from glacial till. Soil texture was determined by soil maps and confirmed by field observation.

Because this was a retrospective study, we did not control for harvest system, the possibility of unfrozen soils during the winter harvests, soil moisture during summer harvests, and the number of equipment passes on our sampling plots, all of which could have affected our results. A postharvest survey of the logging plans indicated that conventional harvesting systems were similar among sites, with all loggers using either a tracked or wheeled feller-buncher and either one or two rubber tire grapple skidders. Tracked and wheeled feller-bunchers were used in both winter and summer harvests. Winter harvests included areas that were cut and yarded between November and March, and summer harvests were cut and yarded from June to September. Although we did not measure whether soils were frozen at the time of winter harvests, our air temperature and snow data (both amount and how much present on the ground) from 2003 to 2005 for Grand Rapids, Minnesota (<50 km from the sites), indicate that in both winters we had little snow cover in late fall/early winter and temperatures well below 0°C, conditions that would normally create frozen ground early in the winter harvest season. Also, we did not have any significant midwinter thaws and maintained a snow cover to the beginning of April. As a result, we are reasonably assured that the winter harvests occurred on frozen soils. Soil moisture undoubtedly varied during the summer harvests, but because no harvests occurred during April and May when soils are generally wettest following snowmelt, soil moisture levels were likely below saturation. Because measurement plots were randomly located, the number of equipment passes is part of the background variability among and within locations.

We installed sampling plots on the summit, backslope, and toeslope positions within each clearcut and paired unharvested comparison site. Slopes between the summit and toeslope had a mean of 18% ± 2% (standard error, range 14–22%) with no differences in slopes between harvested and unharvested sites or any of the soil texture and season of harvest combinations. Sampling plots were established by creating a circle with a 7.3-m radius, equal to the US Forest Service Forest Inventory and Analysis subplots (US Forest

Service 2005). Once the sampling plot was established, a grid of flags was placed over each plot consisting of 32 possible 2.4 × 2.4-m squares (Steber et al. 2007). We collected physical measurements of bulk density and surface soil strength at the center of three randomly selected squares within each plot.

We sampled for bulk density using soil cores. Samples were collected using an impact-driven soil corer from AMS Inc. with two 5-cm-diameter by 10-cm-long stainless steel core liners. Single samples were collected from 0–10 cm and 10–20 cm in each randomly selected square, for a total of three replicates at each depth (six samples per plot). Each sample was weighed, dried in an oven at 105°C for at least 24 hours, and weighed again to determine bulk density.

Surface soil strength was measured with a CL-700 pocket penetrometer from ELE International (Steber et al. 2007). The blunt tip of the penetrometer was vertically inserted into the mineral soil after removal of the forest floor to a groove located 6 mm from the tip. On the rare occasions that coarse fragments prevented penetration to a depth of 6 mm, no measurement was recorded, and another insertion was made in the same general area until a depth of 6 mm was reached. Soil moisture was at or near field capacity in the upper 6 mm during penetrometer measurements. The penetrometer was then read directly in kg cm^{-2} to obtain the measurement. On extremely soft soil, a CL-701 adapter foot was connected to the pocket penetrometer, increasing the effective area of the piston 16 times. Measurements read with the adapter foot were divided by 16 to get the surface soil strength of the soil. Each measurement was converted from kg cm^{-2} to kPa. In each plot, three measurements were collected per sampling square, for a total of nine measurements per plot.

We analyzed the penetrometer and bulk density data using linear mixed models with slope position (summit, backslope, or toeslope), soil texture (fine or coarse), harvest season (summer, winter, or no harvest), and all interactions among these three variables as fixed effects plus random effects to account for spatial autocorrelation within slope position transects and the pairing of no-harvest sites with harvested sites. We used Tukey tests for post hoc multiple comparisons of significant main effects and two-way interactions, and Bonferroni-adjusted *t*-tests for multiple comparisons of all means within a given soil texture class and for all fine-textured means to coarse-textured means comparisons for significant three-way interactions. Model assumptions were evaluated with residual plots, and all analyses were performed using SAS version 9.2 (SAS Institute) at an $\alpha = 0.05$ significance level.

Results and Discussion

Harvesting Relationships

In nearly all cases, harvesting led to greater surface soil strength and bulk density than in unharvested sites. Surface soil strength and bulk density of the 10–20-cm soil profile were always greater at harvested sites than at unharvested sites, regardless of slope position, soil texture, or season of harvest (Table 1). Bulk density of the 0–10-cm soil profile was also higher at harvested sites than unharvested sites, although there were several instances in which the bulk density of the 0–10-cm soil profile from harvested stands was similar to that of unharvested stands when considering all combinations of soil texture, harvest season, and landscape position (data not shown). Both summer- and winter-harvested sites had greater bulk densities for the 0–10-cm soil profile than unharvested sites when comparing summit locations, but only summer-harvested sites had

Table 1. Harvest season comparisons on surface soil strength and bulk density for both harvested and unharvested comparison sites and fine- and coarse-textured soils in the Chippewa National Forest, northern Minnesota.

	Harvested		
	Summer	Winter	Unharvested
Fine-textured soils			
Surface soil strength (kPa)	257.8[a]	208.4[b]	22.9[c]
Bulk density 0–10 cm (Mg m^{-3})	1.29[a]	1.19[b]	1.05[c]
Bulk density 10–20 cm (Mg m^{-3})	1.61[a]	1.52[b]	1.37[c]
Coarse-textured soils			
Surface soil strength (kPa)	197.8[b]	207.2[b]	20.8[c]
Bulk density 0–10 cm (Mg m^{-3})	1.26[a]	1.19[b]	1.07[c]
Bulk density 10–20 cm (Mg m^{-3})	1.55[a]	1.45[b]	1.42[c]

[a,b,c] Mean values with the same letter are not significantly different at $\alpha = 0.05$. Letters delineate statistically similar results within rows for surface soil strength and bulk density and compared between fine and coarse-textured soils for surface soil strength only.

greater bulk densities than unharvested sites for the 0–10-cm soil profile when comparing backslope locations (data not shown). There were no significant differences in bulk density of the 0–10-cm soil profile between harvested and unharvested sites when comparing toeslope locations, regardless of the season of harvest (data not shown). Within unharvested sites, there were never any significant differences in surface soil strength or bulk density among slope positions or soil textures (data not shown). Given the nearly universal trend of greater soil compaction and bulk density at harvested sites than at unharvested sites and the absence of slope position or soil texture effects within the unharvested treatment, we focused the following sections on presenting differences among slope positions, season of harvest, and soil textures within the harvested sites.

Soil Texture Relationships

Surface soil strength was higher on fine-textured soils than on coarse-textured soils at summit and toeslope locations of summer-harvested sites, but there were no differences in surface soil strength associated with soil texture at backslope locations of summer-harvested sites (Figure 2). There were no significant differences in surface soil strength associated with soil texture at winter-harvested sites, regardless of slope position. Soil texture did not have a significant relationship with bulk density for the 0–10-cm depth ($P = 0.855$) or the 10–20-cm depth ($P = 0.300$). The surface soil strength results are consistent with a companion study using similar texture groups in five Great Lakes National Forests, where surface soil strength of fine-textured soils in aspen clearcuts was greater than on clearcuts with coarse-textured soils (Steber et al. 2007). Somewhat contrary to our results, others have found that bulk density of fine-textured soils was higher across a range of sites following harvesting and compaction treatments and were the slowest to recover after site treatment compared with coarse-textured soils (Brais 2001, Page-Dumroese et al. 2006).

Harvest Season Relationships

Surface soil strength was higher at summer-harvested sites than at winter-harvested sites for summit and toeslope locations on fine-textured soils, but there were no differences between summer- and winter-harvested sites for backslope locations on fine-textured soils (Figure 2). There were no significant differences in surface soil strength associated with harvest season on coarse-textured soils at

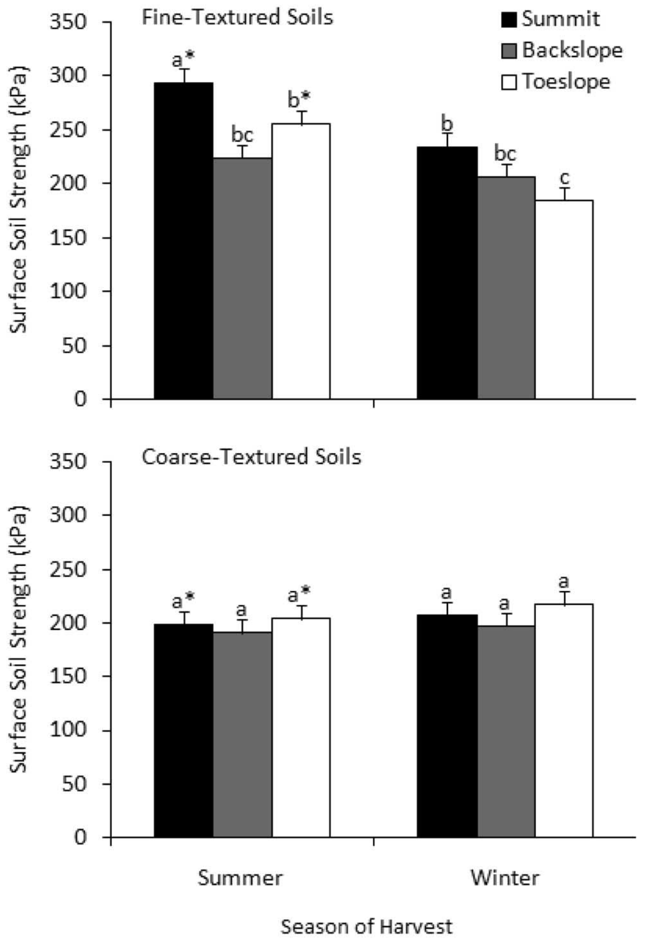

Figure 2. Surface soil strength from three slope positions in aspen stands with different soil characteristics that were harvested in different seasons. Different letters indicate significantly different means (α = 0.05) within a panel, and an asterisk indicates a significant difference between treatments across panels. Error bars represent 1 standard error.

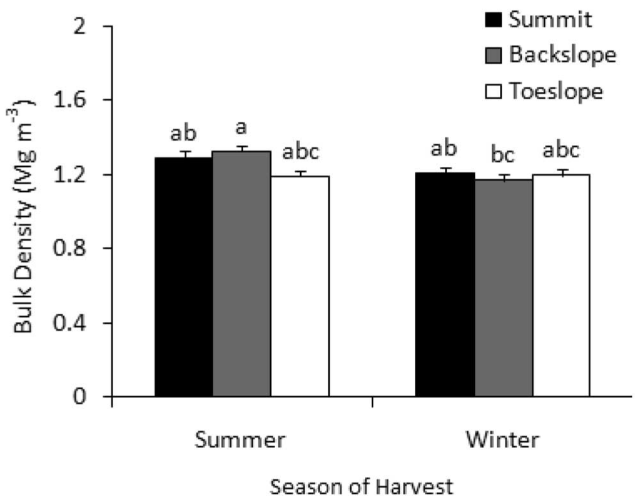

Figure 3. Bulk densities of soil samples from depths of 0–10 cm taken from three slope positions in aspen stands harvested in different seasons. Error bars represent 1 standard error. Mean values with the same letter are not significantly different at α = 0.05.

any slope position. Bulk densities were generally greater at summer-harvested sites than at winter-harvested sites for both the 0–10- and 10–20-cm soil depths ($P < 0.001$ for both, Table 1), but the relationship with harvest season varied depending on slope position for the 0–10-cm depth ($P = 0.022$ for the slope by season interaction). Bulk density of the 0–10-cm soil profile was greater at backslope locations of summer-harvested sites than at backslope locations of winter-harvested sites, but there were no significant differences in bulk density of the 0–10-cm soil profile between summer- and winter-harvested sites at summit or toeslope locations (Figure 3). Similar to our results for soil surface strength, Krzic et al. (2004) found that soil penetration resistance at depths below 21 cm was consistently higher in summer-harvested aspen stands than in those harvested in the winter. These effects were still evident 11 years after harvest. Arocena and Sanborn (1999) found high rates of soil compaction on medium- and fine-textured soils and suggested that harvesting and mechanical site preparation should occur under either dry summer or frozen winter conditions to prevent soil compaction. Our data reinforce the importance of restricting logging to times when soils are frozen. Fine-textured soils harvested during summer appear to be at the greatest risk from compaction, but even winter-harvested sites showed significant increases in surface soil surface strength and bulk density of the 0–10- and 10–20-cm soil profiles, regardless of soil texture ($P = 0.548$ and $P = 0.079$ for the texture by season bulk density interaction of 0–10-cm and 10–20-cm depths, respectively) (Table 1).

Landscape Position Relationships

Slope position had a significant relationship with surface soil strength, but the apparent effect of slope position varied depending on both soil texture and harvest season ($P = 0.001$ for the slope by texture by season interaction). On fine-textured soils, surface soil strength was greater at summit locations than at toeslope locations for both summer- and winter-harvested sites and greater at summit locations than at backslope locations for summer-harvested sites (Figure 2). There were no significant differences among slope positions at sites with coarse-textured soils. Slope position did not have a significant relationship with bulk density at either the 0–10-cm depth ($P = 0.446$) or the 10–20-cm depth ($P = 0.560$). In Saskatchewan, Block et al. (2002) also found no significant differences in bulk density among the shoulder, backslope, and footslope positions, although there were differences between pre- and postharvest conditions within landscape positions, as in our study.

At the toeslope position, where presumably soil moisture is highest among landscape positions, surface soil strength was significantly lower on fine-textured soils that were harvested in the winter than at the toeslope position where harvests occurred on soils that were not frozen (Figure 2). McNabb et al. (2001) also found that soil wetness, in conjunction with the level of trafficking, principally explained the compaction of soils when wide-tired skidders operate on soils with moisture content near or above field capacity. If the soil was wetter than field capacity, it was significantly compacted regardless of the type of machine used. McNabb et al. (2001) concluded that managing felling operations to maximize transpiration of trees to reduce soil wetness is an effective tactic to avoid significant soil compaction. In Block et al. (2002), areas classified as depressions showed a significant increase in bulk density at both the 10- and 20-cm depths following harvesting. Corns and Maynard (1998) found that operational clearcut logging in the fall, when soil moisture was low, had only short-term effects on soil properties, plant community development, and aspen suckering. Given that lower landscape positions, such as toeslopes, are the most susceptible to compaction because of higher soil moisture, our results and those of others indicate the best management approach is to harvest lower landscape positions when soils are frozen during winter, especially for fine-textured soils.

Conclusion

Minimizing the negative effects on soil physical properties during harvest operations is a primary objective of modern forest management because of compaction effects on soil productivity. Timber management practices that strive to limit soil compaction are essential, particularly in susceptible areas. It is clear from our study and others that soil compaction occurs during harvesting, independently of soil texture, harvest season, and landscape position. The US Forest Service has a monitoring guideline that >15% compaction is detrimental to forest sustainability (Powers et al. 1998). In this study, none of the winter harvests increased bulk density more than 15%; however, summer harvests increased fine-textured soil bulk density at 0–10 cm 23% and at 10–20 cm 17.5%. Summer harvests also increased coarse-textured soil bulk density at 0–10 cm 18%, but the 10–20-cm depth was well below the 15% limit.

In this research, we had hoped to parse out the important influences on compaction that occurs following aspen harvesting. Although we found few differences in bulk density within harvested comparisons, we found a number of differences in surface soil strength among soil texture/harvest season/landscape position combinations. The results of our research in northern Minnesota, as well as other studies, indicate that compaction is generally greatest on fine-textured soils harvested during unfrozen soil conditions. Our analysis of landscape position indicated that both upper (summit) and lower (toeslope) topographic positions were susceptible to compaction in fine-textured soils when comparing summer versus winter harvesting.

Minnesota harvesting guidelines recommend winter harvesting on susceptible soils, analogous to the fine-textured soils in this study. Our results would support this guideline. Managers should also consider limiting harvesting on coarse-textured soils to the winter months although compaction effects were not as severe as on fine-textured soils harvested in the summer. Landscape position only appears to be a factor on fine-textured soils. If harvesting on fine-textured soils during unfrozen conditions, care should be taken to minimize operations on both summit and toeslope positions.

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