Impacts of Skidding Traffic Intensity on Soil Disturbance, Soil Recovery, and Aspen Regeneration in North Central Minnesota

Eric K. Zenner, Jeremiah T. Fauskee, Alaina L. Berger, and Klaus J. Puettmann

ABSTRACT

ABSTRACT: We investigated the effects of different levels of ground-based skidding traffic intensity on soil disturbance, characterized by resistance to penetration (RP) within the top 15 cm of soil, as well as soil recovery, regeneration, and early growth of quaking aspen (*Populus tremuloides* Michx.) suckers 3 years after a clearcut with reserves summer harvest. Equipment traffic was confined to a network of skid trails, and a GPS was used to determine the number of skidder passes at each of 30 sampling points that were preestablished along an anticipated disturbance gradient ranging from landings to skid trails to areas off skid trails. Thirty-one percent of the harvest area was affected by skid traffic, and up to 603 passes were recorded for a plot. RP increased nonlinearly with the number of passes and reached highest levels at the soil surface. Three years after harvest, soils showed partial recovery in the upper 10-cm layer, with full recovery of the surface layer (0–5 cm depth) when affected by 4 or fewer passes. The deepest layer (10–15 cm), however, showed little recovery since harvest. Sucker density, height, and basal diameter of all suckers and height, basal diameter, and dbh of the tallest suckers were significantly reduced with increasing traffic intensity but were not related to increases in RP. Predicted reduction of sucker density was approximately one-third after 10 passes; reductions of height, basal diameter, and dbh were between 1.5 and 2.5% at 10 passes and 3.5 and 6.5% at 25 passes. Because skidding traffic affected only a limited portion of the stand, the productivity of the future aspen stand was not severely impaired, at least in the very short term.

Keywords: aspen, GPS, harvesting, soil compaction, skid trail

Preservation of soil health and prompt establishment of adequate tree regeneration are key elements for sustaining forest productivity. However, effects of trafficking by heavy ground-based harvesting equipment, such as increased soil compaction (Hatchell et al. 1970), are often of concern for long-term productivity. Soil compaction changes physical soil properties and affects site quality by reducing macropore space, soil infiltration capacity, and soil aeration and increasing soil resistance to root penetration (Reisinger et al. 1992, Grigal 2000). Harvesting disturbances of the soil also affect regeneration success by injuring roots, reducing the respiratory activity of roots, and restricting the effective rooting area and root growth (e.g., Hatchell et al. 1970, Martin 1988). It is well established that severity of soil damage increases nonlinearly with number of equipment passes and that most of the resulting compaction occurs during the first few passes (e.g., Hatchell et al. 1970, Williamson and Neilsen 2000, McNabb et al. 2001). Effects of soil disturbance may persist for several decades because of very slow recovery rates (Corns 1988, Shepperd 1993, Grigal 2000), although they ultimately depend on soil properties such as texture (Miller et al. 1996, Williamson and Neilsen 2000). Ultimately, the suite of factors associated with soil disturbances can lower tree stocking and reduce stand growth and forest productivity (Wert and Thomas 1981, Grigal 2000).

Potentially adverse effects of soil disturbances from skidding traffic on regeneration, growth responses, and soil recovery may be of particular concern for forest types that are managed on short rotations or managed with silvicultural systems that require repeated harvesting entries. Such is the case for fast-growing, early successional quaking aspen (*Populus tremuloides* Michx.) stands managed on rotations between 35 and 50 years for fiber production, where harvesting related soil disturbances have been identified as an important impediment to regeneration success and growth (Zasada and Tappeiner 1969, Bates et al. 1993, Alban et al. 1994, Stone 2002, Smidt and Blinn 2002).

Much of our understanding of traffic effects, however, is inferred from retrospective evaluations in which former skid trails are identified through visual indicators of soil disturbance levels (Reisinger et al. 1992, Smidt and Blinn 2002, Berger et al. 2004). Hereby, intensity and distribution of soil disturbances are used as indicators of traffic intensity, rather than deriving site damage from traffic intensity. Consequently, the exact spatial extent of skidding traffic and the actual number of equipment passes are rarely known, resulting in poor quantifications of "light" or "heavy" impact. Sampling has often focused on skid trails that have been subject to sufficiently high levels of disturbance such that changes to the soil and vegetation are still visible several years after harvest. Concentrating sampling on these areas may under-represent

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those with fewer passes that may have visibly recovered, which may underestimate the areal impact and overemphasize the severity of impact of skidding traffic on the stand or landscape scale. Aust et al. (1998) suggest that visual soil disturbance classes are not necessarily a good representation of ecological impacts and should not be used to develop soil damage categories. GPS technology can provide an alternative to directly quantify the relationship between skidding traffic intensity and estimates of change in soil physical conditions and their variability (McMahon 1997, Carter et al. 1999, McDonald et al. 2002).

In this study, we tracked skidder movement with GPS to determine the frequency of traffic at exact locations and the spatial distribution/extent (i.e., the area impacted by skidding) to directly link traffic intensity (i.e., the number of skidder passes) to changes in physical soil responses and productivity. Because both severity and extent of site disturbance determine stand-level productivity losses, we deliberately concentrated skidding traffic on as few designated skid trails as possible to minimize the areal extent of soil disturbance (e.g., Hatchell et al. 1970, Grigal 2000, Smidt and Blinn 2002). Such a traffic pattern creates a wide gradient of traffic intensity in a harvested area wherein soil disturbances are most severe on landings, truck roads, and skid trails where machinery traffic is concentrated (Martin 1988, Berger et al. 2004). To assess soil disturbance (soil compaction), we chose measuring resistance to penetration (RP) over bulk density in this study, because RP is an indirect measure of pore continuity and root growth, with reduced root penetration found to occur at approximately 2,500 kPa on a variety of soils (Taylor and Burnett 1964, Taylor et al. 1966). RP is a more sensitive measure of logging traffic intensity than bulk density, because particle rearrangement after soil disturbance can increase RP but not bulk density (Froehlich and McNabb 1984) and greater increases in RP than bulk density are commonly found for the same logging intensity (Alban et al. 1994, Brais 2001). Finally, increased RP is linked to decreases in site productivity (Brais 2001). Specific objectives of this study were (1) to relate the number of passes to the amount of soil disturbance (immediately after harvesting) and soil recovery (3 years after harvesting) by quantifying how much soils increased RP over control levels at different soil depths, and (2) to relate the number of passes and RP to regeneration density and early growth responses of quaking aspen suckers.

Methods

Study Area

The approximately 6.5 ha study site is located in northern Minnesota (47°12′N and 93°03′W) and is owned and managed by the University of Minnesota. The study site falls within the Northern Minnesota Drift and Lake Plains section and the St. Louis Moraines ecological subsection of the Minnesota Ecological Classification System (Minnesota Department of Natural Resources 2003). The climate is temperate, with mean monthly temperatures ranging from −15 to 19°C and a mean annual temperature of 3.4°C. Average annual precipitation is 682 mm, with 56% of the precipitation falling between May and August and a cumulative annual snow depth of 157 cm. Soils are well-drained with sandy loam, loam, and silt loam textures and fit within the Nashwauk soil series with inclusions of the somewhat poorly drained Keewatin soil series (Anderson et al. 1996). Major species on this northern hardwood site included aspen, paper birch (*Betula papyrifera* Marsh.), red maple (*Acer rubrum* L.), sugar maple (*Acer saccharum* Marsh.), red oak (*Quercus rubra* L.), balsam fir (*Abies balsamea* [L.] Mill.), and basswood (*Tilia americana* L.). Average preharvest stand basal area was 39.7 m^2 ha^{-1}, of which 15 m^2 ha^{-1} was aspen.

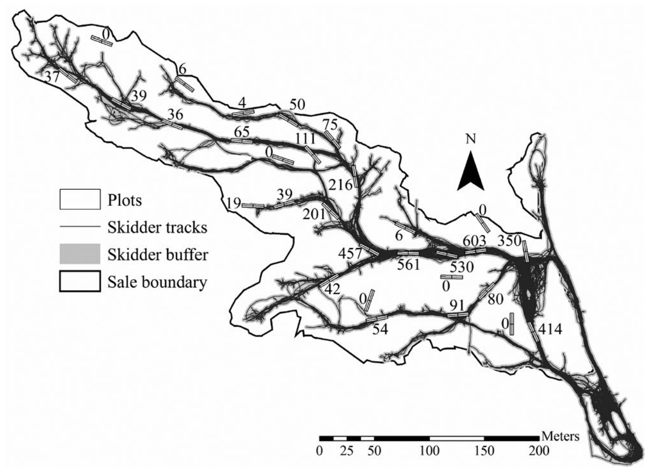

Figure 1. Sale boundary and skid tracks in a 6.5 ha timber sale in north central Minnesota. Permanent plots were established to record resistance to penetration, basal area, and aspen density prior to, immediately after, and 3 years after harvest. Numbers represent the number of passes over a given plot. Skidder buffer adds one-half times the track width (1.55 m) to the outermost skidder tracks.

Sampling Design and Harvesting

No roads or skid trails were present within the periphery of the site prior to installation of this study. A network of skid trails and landings was laid out prior to the harvest in consultation with forest managers to confine skidding to a small portion of the stand. Thirty permanent sampling plots (3 × 20 m) were established for soil compaction and aspen regeneration measurements (Fig. 1). Plots were aligned with the layout of the skid trails and designed to cover the gradient of expected disturbance conditions created through skidding traffic (1 plot in the landing, 22 in skid trails, and 7 off main skid trails).

During August 9–23, 2000, the site was clearcut with reserves (full-tree harvesting of approximately 2,250 m^3 of aspen, balsam fir, red maple, and paper birch roundwood), and an average postharvest basal area of 6.5 m^2 ha^{-1} (range, 0 to 23 m^2 ha^{-1}) of immature red oak, basswood, and sugar maple reserve trees was retained for another rotation. Harvesting was done with a Timberjack 608B feller buncher (track 4.06 m long and 61 cm wide) and a Timberjack 450C grapple skidder (tires 77.5 cm wide). Generally, soils were dry during the harvesting periods. Harvesting was suspended during a few light rain events to maintain harvesting efficiency and avoid undue rutting.

Data Collection

During harvest, a Trimble XRS GPS receiver was attached to the skidder while in operation. Waypoints with a positional dilution of precision of 10 or lower were collected every 2 seconds during operation and postprocess differentially corrected. The cleaned and corrected waypoints were transferred into Pathfinder Office and then converted into tracks in ArcView. Data gaps resulting from poor satellite coverage were filled in from field notes taken during harvest. Plot coordinates and skidder tracks were overlaid in ArcMap 9.0, and the number of skidder passes was calculated for each plot. The track width of the skidder (3.11 m) was applied as a buffer

Table 1. Average resistance to penetration (RP; in kPa) and relative resistance to penetration (in %, in parentheses) data by depth category and year for plots with 0 passes (controls; *n* = 6), 1–10 passes (*n* = 3), 11–100 passes (*n* = 12), and >100 passes (*n* = 8). RP values were relativized by the average RP values of the 0 pass control plots.

	Control (0 passes)	Low (1–10 passes)	Medium (11–100 passes)	High (>100 passes)
Depth 0–5 cm				
1999	440.8 (100)	444.8 (100.9)	477.0 (108.2)	404 (91.7)
2000	522.3 (100)	613.9 (117.5)	914.5 (206.0)	1,721.6 (329.6)
2001	250.1 (100)	255.3 (102.0)	1,076.1 (109.3)	416.6 (166.6)
Depth 5–10 cm				
1999	638.9 (100)	601.3 (94.1)	630.0 (98.6)	652.3 (102.1)
2000	838.6 (100)	974.6 (116.2)	1,700.5 (202.8)	2,182.3 (260.2)
2001	539.7 (100)	610.8 (113.2)	774.8 (143.6)	965.7 (178.9)
Depth 10–15 cm				
1999	758.0 (100)	669 (88.3)	700.3 (92.4)	788.2 (104.0)
2000	1,038.2 (100)	994.6 (95.8)	1,919.5 (184.9)	2,310.1 (222.5)
2001	638.7 (100)	727.5 (113.9)	1,015.0 (158.9)	1,304.6 (204.3)

to the skidder traffic paths (tracks) in ArcMap to determine the proportion of the area affected by skidder traffic.

RP was measured in the mineral soil matrix with a Rimik CP-20 soil penetrometer with a 30° cone and a 13 mm diameter base. After clearing slash and the main duff layer, RP readings [measured in kilopascals (kPa); American Society of Agricultural Engineers 2002] were recorded in increments of 1.5 cm to a depth of 15 cm for a total of 10 readings for each measurement point. Readings when the penetrometer had obviously hit a buried rock or log were ignored. To ensure that soil moisture conditions were relatively uniform within a site, we took all measurements on a single day. A total of 40 measurement points per plot were collected in 1999 (preharvest), 2000 (immediately postharvest), and 2003 (3 years postharvest). Measurement points were placed along two parallel transects in each plot. The landing plot was later removed from analysis because operators modified the skid-trail layout so its alignment was perpendicular to skidding traffic. RP data for six skid trail plots from 2000 were unavailable. Mean RP values were calculated for each plot and for each of three depth categories (0 to 5 cm, 5 to 10 cm, and 10 to 15 cm; Table 1).

Preharvest basal area and postharvest residual basal area (2003) were measured from the center of the permanent plots with a 2-m factor prism. In the summer of 2003, measurements of postharvest aspen regeneration density were taken on one 0.001-ha regeneration plot (2 × 5 m) in the center of each permanent plot (i.e., centerline of the skid trail) that included the track/tire area of the skidder. In addition, height, dbh, and basal diameters of all aspen suckers were recorded in the half of permanent plots that covered the extreme ends of the traffic intensity spectrum.

Data Treatment and Statistical Analysis

Owing to variability of soil moisture and other environmental factors, absolute measures of RP cannot be compared across years (Berger et al. 2004). To account for this inherent site variability, we standardized RP values for each year and soil depth category. Although areas off the skid trails are not a true control, these plots came closest to reflecting untrafficked, inherent site conditions. Thus, we divided RP values by the respective mean RP value of the 0 pass plots to obtain relativized RP values. This procedure is akin to a relativization by minimum (sensu McCune and Grace 2002) and assigns a value of 100% to RP values equivalent to the average in control plots.

A repeated measures mixed model analysis design with an unstructured covariance structure (Littell et al. 2006) was used to test for effects of skidding traffic intensity, soil depth category, and time since harvest on change of RP values. Multiple linear regression analysis was used to quantify the relationship of number of skidder passes (or RP values), preharvest aspen basal area, and residual basal area to aspen sucker density and growth (height, basal diameter, and dbh) 3 years after harvest. All statistical analyses were performed in SAS for Windows (Version 9.1; SAS Institute 2004).

Results and Discussion

Harvesting Traffic

Actual traffic intensities and pathways of areas affected by the skidder revealed an expected strong gradient in traffic intensity that went from the landing and primary skid trails, which were subjected to hundreds of equipment passes (maximum number of 603 passes recorded for one plot), out into the general harvest area, where equipment passes were fewer in number and more spatially dispersed (Fig. 1). In all, 31% of the harvest area was occupied by skid trails and the landing, of which 12.4% sustained 1 to 10 passes, 11.2% sustained 11 to 100 passes, and 7.4% sustained more than 100 passes.

The maximum number of 603 passes is substantially higher than expected or previously reported (e.g., Carter et al. 1999), and the estimate of areal extent (31%) in skid trails and landing is higher than the 15% that is feasible with predesignated skid trails that are 30 m apart and pull winch line to logs (Garland 1997) or the 22–23% observed following a clearcut and a shelterwood treatment (Stokes et al. 1997). However, the number of passes and the areal extent in skid trails are obviously site-specific and vary as a function of the size and shape of the harvesting unit, harvest volume, and harvesting equipment. For example, the layout of our harvest unit had only one haul road just outside the eastern perimeter of the unit, to which logs had to be skidded over a distance of up to 400 m. In addition, the reach of feller bunchers is limited, requiring more skid trails than skidders with pull winch lines. Not surprisingly, restricting skidding traffic to skid trails in this study resulted in approximately 2–4 times more area (18.6%) that sustained more than 10 passes than was determined with GPS technology for dispersed skidding [4.8% as determined by Carter et al. (1999), or 10.5% as determined by McDonald et al. (2002)]. Nonetheless, 12.4% of the area that sustained between 1 and 10 passes is substantially less than the 38.5–56.7% (Carter et al. 1999) and 61.7% (McDonald et al. 2002) reported with dispersed skidding. Furthermore, an untrafficked area of 69% in this study was substantially higher than the 37.6–55.7% (Carter et al. 1999) and 27.9% (McDonald et al.

2002) or the 7–43% observed after dispersed skidding (Zasada and Tappeiner 1969, Mace et al. 1971, Martin 1988).

Soil Disturbance and Recovery

The spatial pattern of variable traffic intensity was closely mirrored by the pattern of increases in RRP shortly after harvest. A steep, nonlinear increase in RRP with the first few passes (Fig. 2) is consistent with previously reported results (e.g., Hatchell et al. 1970, Shetron et al. 1988, Williamson and Neilson 2000, McNabb et al. 2001). Results from previous studies, most of which were based on a relatively small (<30) number of passes, indicate that after a few passes, additional traffic would contribute little to increased compaction (e.g., Hatchell et al. 1970, Carter et al. 1999, Williamson and Neilsen 2000). This was clearly not the case in this study, where RRP continued to increase with traffic intensity and was, after 35 passes, only about half that observed at the highest traffic intensity (Fig. 2). Increase in soil compaction is largely dependent on soil conditions, such as soil texture and soil moisture at harvest (McNabb et al. 2001, Bock and Van Rees 2002). The slower and continued increase of RPP with increasing traffic intensity in this study was likely due to the much broader range of traffic intensities examined and to dry weather conditions during harvest in this study (June 23 to August 23, 2000, received only 70% of the normal precipitation amount; Climatology Working Group 2007). Soils with higher moisture content have been shown to visually deteriorate following fewer machine passes than dry soils (Williamson and Neilsen 2000); conversely, drier soil conditions minimize soil compaction and rutting (Stone 2002) and may require more machine passes for the same amount of soil damage.

The variable increase in RPP with soil depth in this study has also been observed previously (e.g., Reisinger et al. 1992, Alban et al. 1994, Stone and Elioff 1998). More passes were necessary to double RRP in lower than in upper soil layers, and for a given number of passes, RRP increased more at the soil surface than in lower layers. For example, RRP doubled over untrafficked levels in soil depths of <5, 5–10, and 10–15 cm after 25, 33, and 61 equipment passes, respectively; in the plot with the highest number of passes (603), predicted RRP increased 227, 190, and 159% in the three soil depths, respectively (Fig. 2). More passes are required to increase RRP in deeper soil layers, because as compaction increases, soil porosity, and particularly the volume of macropores, declines (Incerti et al. 1987) and the proximity of soil particle aggregates increases (Greacen and Sands 1980). With the destruction of the majority of macropores, soils resist further compaction, transmitting an increasing proportion of the applied forces to lower depths and making further compaction more difficult (Williamson and Neilsen 2000).

Soil recovery rates in this study varied differentially with soil depth and amount of compaction (Fig. 2). Three years after harvest, the upper soil layer (0–5 cm soil depth) in this study exhibited the most dramatic recovery; recovery in the lower soil layers was slower. Full recovery of the surface layer to untrafficked levels is predicted in plots that were subjected to four or fewer equipment passes. At skidding intensities of 10 and 25 passes, reductions in RRP after 3 years are predicted to be 93, 56, and 25% and 87, 56, and 28% for soil depths of <5, 5–10, and 10–15 cm, respectively. RRP values after 603 passes were reduced by 81, 47, and 32% for the three soil depths, which is still 43, 82, and 107% above untrafficked levels, respectively. These findings match results from previous studies in which recovery in the upper 10 cm has been seen in less than a

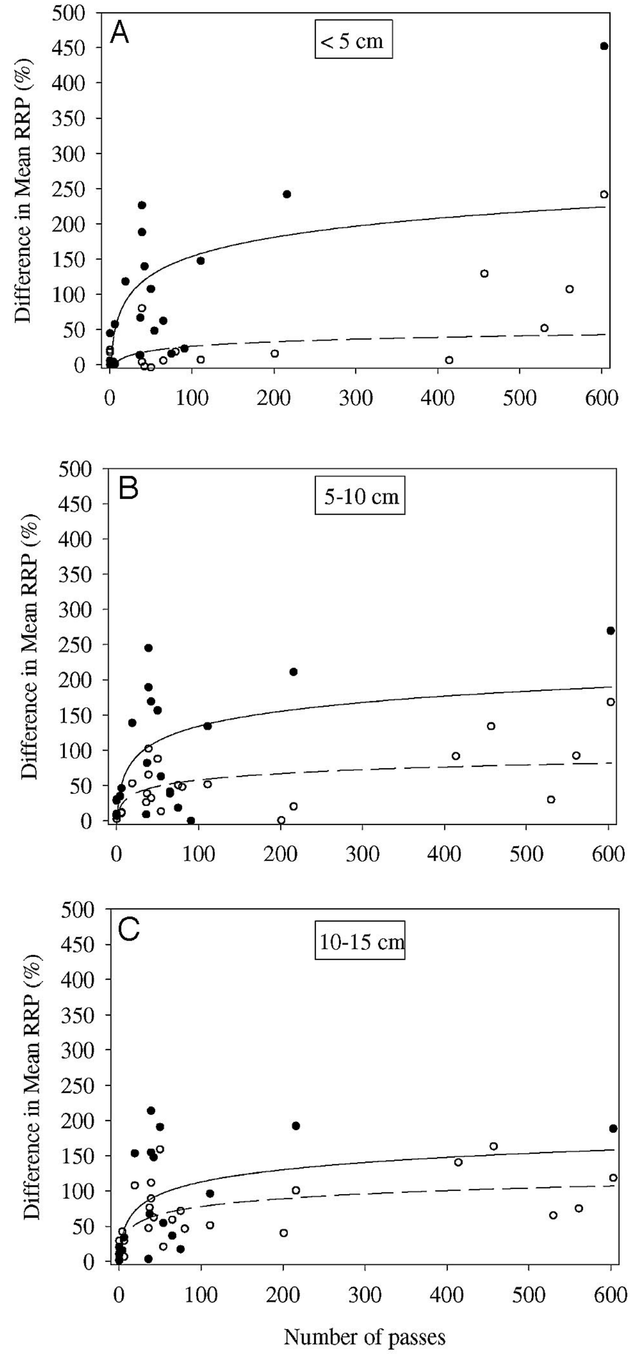

Figure 2. Change in relative resistance to penetration (RRP %) from pre- to postharvest (filled circles, solid line, Y_1) and from preharvest to 3 years postharvest (open circles, dashed line, Y_2) in the soil surface (upper 5 cm) [$Y_1 = -27.1 + 39.2 \times \ln(\text{no. passes})$; $Y_2 = -16.6 + 9.3 \times \ln(\text{no. passes})$] (A), the soil layer between 5 and 10 cm depth [$Y_1 = -8.7 + 31.0 \times \ln(\text{no. passes})$; $Y_2 = -2.9 + 13.2 \times \ln(\text{no. passes})$] (B), and the soil layer between 10 and 15 cm depth [$Y_1 = -6.4 + 25.5 \times \ln(\text{no. passes})$; $Y_2 = 2.6 + 16.3 \times \ln(\text{no. passes})$] (C) as a function of skidding traffic intensity. The three-way interaction of time by soil layer depth by number of passes was highly significant ($P = 0.002$) in the model.

decade on loamy soils and often within 4 years (Mace 1971, Thorud and Frissell 1976, Reisinger et al. 1992, Alban et al. 1994). Our results indicate that recovery of deeper layers may require substantially more time (in keeping with the >9 years in Thorud and Frissell 1976 and >32 years in Wert and Thomas 1981). However, the recovery of compacted soils and the restoration of macroporosity

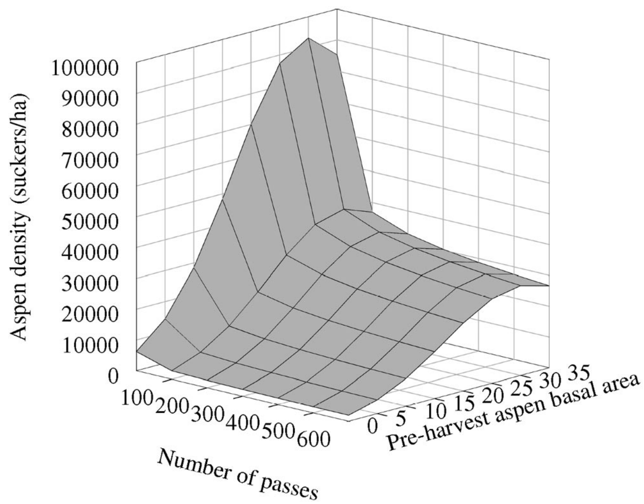

Figure 3. Density of aspen suckers per hectare (Y) 3 years postharvest as a function of preharvest aspen basal area (BA; $m^2\ ha^{-1}$) and skidding traffic intensity [$\ln(Y) = 8.735 + 0.183 \times$ Aspen BA $- 0.003 \times$ (Aspen BA)$^2 - 0.181 \times \ln$(no. passes); all P values < 0.005; $R^2 = 0.768$]. Residual basal area was not statistically significantly related to the density of aspen suckers ($P = 0.066$).

following compaction are extremely variable, and recovery rates are ultimately a function of level of soil compaction, soil type, soil texture, soil depth, the amount of organic material in the soil, freezing/thawing cycles, moisture and temperature changes, activities of soil biota, and plant root penetration and decay (Mace 1971, Thorud and Frissell 1976, Greacen and Sands 1980, Froehlich et al. 1985, Corns 1988, Reisinger et al. 1992).

Aspen Regeneration and Early Growth

Sucker density was negatively influenced by traffic intensity. Three growing seasons after harvest, sucker density ranged from 333 (414 passes) to 77,500 (untrafficked) stems ha^{-1}. On average, aspen density was 31,500 stems ha^{-1} (range, 10,300 to 77,500 stems ha^{-1}) in untrafficked areas and 28,100 stems ha^{-1} (range, 300 to 67,800 stems ha^{-1}) in skid trails. Accounting for the influence of preharvest aspen basal area on postharvest sucker density (Smidt and Blinn 2002), our model predicted a decline from 93,000 to 29,000 stems ha^{-1} at a preharvest aspen basal area of approximately 30 $m^2\ ha^{-1}$, which is predicted to produce the highest sucker density. Even with as few as 10 passes, predicted aspen sucker density is reduced by one-third; at 603 passes, the predicted reduction in sucker density is 69% (Fig. 3).

Because late summer aspen harvests produce heavier aspen sucker densities than spring or early summer harvests (Stone 2002), possibly due to increasing carbohydrate reserves in the parent roots as the summer progresses (Bates et al. 1993), absolute numbers of aspen suckers cannot be easily compared with studies with different harvesting timing. Nonetheless, lower stocking along skid trails subject to high traffic is not unexpected. In central Alberta, aspen sucker density in skid trails was reduced by 74–88% compared with the general harvest area (Navratil 1996), by 81% (48,700 stems ha^{-1} in untrafficked areas and 9,100 stems ha^{-1} in skid trails) in northeastern British Columbia (Kabzems 1996), and by an average of 90% (47,800 stems ha^{-1} in untrafficked areas and 4,900 stems ha^{-1} in skid trails) across six 1–12-year-old harvests in western Colorado (Shepperd 1993). In north central Minnesota, Stone and Elioff (1998) found a 51% reduction (40,400 stems ha^{-1} in control areas and 19,600 stems ha^{-1} in compared areas) after five growing seasons.

Density reductions in young stands do not necessarily result in understocked stands, however. A wide range of early densities has been considered acceptable for young aspen stands, partially due to converging density trends during the first 20 years (Navratil 1991). For example, Graham et al. (1963) considered a first-year sucker density of 15,000 ha^{-1} as minimal stocking and 30,000 ha^{-1} as optimal. Perala (1977) recommended that sucker density at age 2 should exceed 10,000 stems ha^{-1} to produce a productive aspen stand, whereas Steneker (1976) considered 6,000 stems ha^{-1} adequately stocked. In light of these recommendations, our model indicates that a preharvest stand with an aspen basal area of 7.5 $m^2\ ha^{-1}$ is adequate to ensure stocking of 6,000 suckers ha^{-1} at age 3 even on the most trafficked skid trails (Fig. 3). A 10 $m^2\ ha^{-1}$ preharvest aspen basal area with 0 passes would ensure a sucker density of nearly 30,000 ha^{-1} at age 3, and a stand with a preharvest aspen basal area of 20 $m^2\ ha^{-1}$ could withstand over 100 passes before the aspen regeneration density fell below 30,000 stems ha^{-1} on skid trails. Thus, despite substantial reductions in sucker density on limited areas of skid trails, the overall stand was fully stocked with aspen.

In addition to reduced sucker density, increasing traffic intensity significantly reduced sucker vigor as expressed by height and basal diameter of all suckers and height, basal diameter, and dbh of the tallest suckers in this study (Fig. 4). At 603 passes, predicted sucker height and basal diameter of all aspen and the tallest aspen were reduced by approximately 56 and 68%, respectively, and dbh of the tallest aspen was reduced by 78%. Predicted reductions of height, basal diameter, and dbh were between 1.5 and 2.5% at 10 passes and between 3.5 and 6.5% at 25 passes. However, because typical tree spacing in mature aspen stands allows neighboring trees to occupy the space above skid trails (Navratil 1991), the impacts may prove negligible in the long run.

Although traffic intensity had a negative effect on both aspen density and growth, neither postharvest RP nor RRP was statistically significantly associated with aspen density ($P = 0.300$); height ($P = 0.718$) or basal diameter ($P = 0.748$) of all aspen; or height ($P = 0.757$), basal diameter ($P = 0.464$), or diameter ($P = 0.260$) of the tallest aspen. This suggests that RP values after harvest (in 2000), which ranged from 522 to 1,038 kPa in plots with 0 passes and from 1,721 to 2,310 kPa in plots with over 100 passes, were below levels that restrict suckering and growth of aspen. Specific RP values at which root growth is restricted are thought to be between 2,500 and 3,000 kPa for many plant species, including conifers (Taylor et al. 1966, Greacen and Sands 1980), but are not known for aspens. Given that only 17% of RP measurements in 2000 (of 4,931) and 0.7% in 2003 (of 8,975) exceeded the critical value of 2,500 kPa, other properties altered by skidding traffic and implied by higher RRP values, such as rutting and the destruction of macropores and its effects on soil aeration and drainage, may be more important for restricting the growth potential of roots and the ability of aspen to sucker and grow (Zasada and Tappeiner 1969, Bates et al. 1993, Stone and Elioff 1998). Reductions in air permeability, soil porosity, and hydraulic conductivity change the availability of soil moisture and nutrients within the uppermost 20 cm of the soil profile (Froehlich et al. 1986), and limits on root extension, root branching, and root density can result in reduced seedling growth in compacted areas (Helms and Hipkin 1986, Pregitzer et al. 2002). Perhaps most importantly, reductions in sucker density and growth

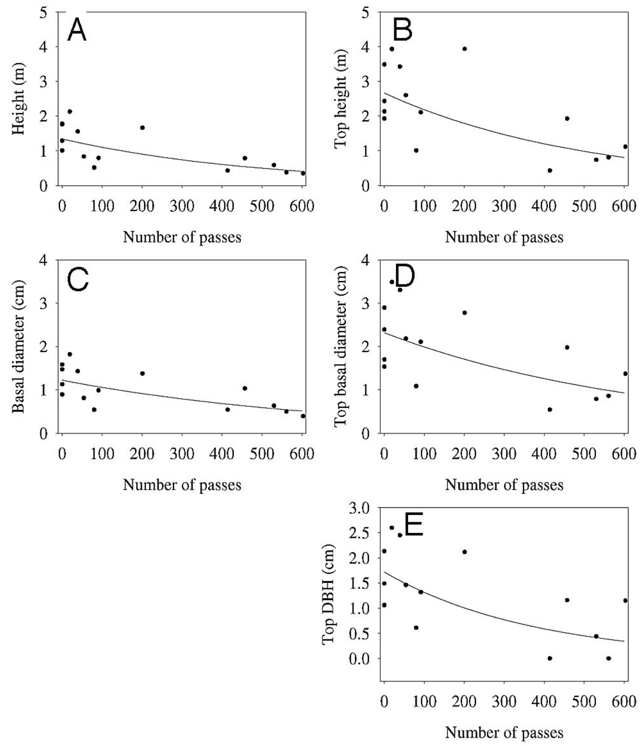

Figure 4. Effect of skidding traffic intensity on 3-year postharvest average aspen sucker height (m) [ln(*Y*) = 0.295 − 0.002 × no. passes; *P* (no. passes) < 0.001; R^2 = 0.588] (A), top height of the 10 tallest aspen [ln(*Y*) = 0.980 − 0.002 × no. passes; *P* (no. passes) = 0.004; R^2 = 0.481] (B), average aspen basal diameter (cm) [ln(*Y*) = 0.203 − 0.001 × no. passes; *P* (no. passes) = 0.003; R^2 = 0.508] (C), basal diameter of the 10 tallest aspen [ln(*Y*) = 0.841 − 0.002 × no. passes; *P* (no. passes) = 0.009; R^2 = 0.417] (D), and dbh of the 10 tallest aspen [ln(*Y*) = 0.541 − 0.003 × no. passes; *P* (no. passes) = 0.016; R^2 = 0.373] (E). Residual basal area was not statistically significantly related to any aspen growth measures (all *P* > 0.48).

arise because aspen roots are very vulnerable to physical damage and displacement (Navratil 1991, Bates et al. 1993). Most aspen suckers are produced from meristems on the parent roots that are near the soil surface (Sandberg and Schneider 1953). Thus, damage and injuries to the shallow parent root system can serve as entry ports for pathogens and as a sink for stored carbohydrates, causing severe reductions in vigor and growth of emerging suckers (Bates et al. 1993, Smidt and Blinn 2002).

Although a reduction between 1.5 and 2.5% at 10 passes appears to be rather moderate 3 years after harvest, it is likely that differences in growth increase with time. Effects of soil compaction have increased from 2 to 5 years after harvest in another study (Stone and Elioff 1998) and after 10–12 years when young trees start exploiting soils at depth of 20–30 cm (Corns 1988). Increasing impacts with time are likely linked to the ability of new root suckers to continue to access existing carbohydrates and nutrients in the parent root system. Unless parent roots are severely damaged, suckers rely heavily on these roots for survival and growth for many years. Zahner and De Byle (1965) found that new roots that develop at the base of the sucker contributed little to the growth of suckers up to 6 years old and still only contributed to approximately one-half of total growth in suckers 25 years of age. It is thus likely that aspen suckers in this study have not yet become dependent on their own root systems. This delay may give young aspen suckers a reprieve from the effects of soil compaction. Due to the slow recovery process in the deeper soil layers, however, this benefit may not last long enough to offset the adverse effects on sucker growth that have been documented in many studies, particularly in heavily trafficked areas (e.g., Smidt and Blinn 2002).

Conclusions

By detailed assessment of a harvesting operation, we were able to quantify the areal extent and link the intensity of skidding traffic to changes in physical soil responses and soil recovery dynamics. Restricting skidding traffic to trails in this study led to extremely high traffic intensities on a smaller portion of the harvest site than has been reported for dispersed skidding. Skidding traffic led to increased soil resistance to penetration; delayed soil recovery, particularly in the deeper soil layers; and decreased aspen sucker density and growth in skid trails compared with the general harvest area. At first, the maintenance of acceptable stocking levels of aspen on the majority of skid trails and the relatively small reductions in aspen height, basal diameter, and dbh growth (<6.5% in areas with up to 25 passes, which is typical for dispersed skidding) might indicate that limiting the impacts of harvest equipment traffic to skid trails may not have been necessary for this site. However, the lack of association of density and growth reductions with increases in resistance to penetration suggests that other effects of soil disturbance, such as reduction in macropores and injuries to aspen roots, may be more important than compaction per se. Given an apparent reliance of sucker growth on parent root stock and the potential for delayed growth reductions, the limitation of these impacts to a smaller percentage of the harvest area via restricting skidding traffic to a trail system likely minimizes future yield reductions.

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