Spatial impacts of soil disturbance and residual overstory on density and growth of regenerating aspen

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ABSTRACT

We examined spatial aspects of harvesting impacts on aspen regeneration at 25 sites in northern Minnesota. These sites had been clearcut or partially harvested 4–11 years ago. At each site, residual overstory, which was composed of trees other than aspen, soil disturbance, and tree regeneration were determined along transects leading away from skid trails into the neighboring stand. We characterized spatial extent of soil disturbance as soil strength using an Eijkelkamp soil cone penetrometer. Soil disturbance dropped off very quickly at the edge of skid trails, suggesting that the impact of harvesting traffic on areas adjacent to skid trails is minor. On skid trails, disturbance levels were higher on sites harvested in summer than on sites harvested in winter. Even after adjustment for differences in soil disturbance, stands harvested in winter had higher regeneration densities and greater aspen height growth than stands harvested in summer, suggesting that aspen regeneration was more sensitive to a given level of soil disturbance on summer-harvested sites versus on winter-harvested sites. Soil disturbance and residual overstory interactively reduced aspen regeneration densities and height growth, indicating that avoidance of soil disturbance is even more critical in partially harvested stands. Predictions based in the spatial patterns of impact found in this study indicated that harvesting conditions may have a great impact in future productivity of a site.

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1. Introduction

Forests in the Great Lakes region of the United States once contained vast expanses of forests dominated by white pine (*Pinus strobus* L.), red pine (*Pinus resinosa* Aiton.), jack pine (*Pinus banksiana* Lambert.), and northern hardwood species (Curtis, 1959; Ahlgren and Ahlgren, 1983). While these forests still constitute important components of the landscape, widespread logging and intense slash fires in this region during the mid-1800s to early 1900s resulted in an increase in aspen species (*Populus* spp.) in many areas previously dominated by these forest types (Graham et al., 1963; Schulte et al., 2007). Notably, aspen species were able to take advantage of and regenerate in disturbed areas created by natural disturbances and forest harvesting (Schier, 1976; Bates et al., 1989), despite management practices designed to encourage the establishment of other species, particularly conifers (Peterson and Peterson, 1992).

Forests dominated by trembling (*Populus tremuloides* Michx.) and bigtooth (*Populus grandidentata* Michx.) aspen now comprise roughly one-third of Minnesota's timberland, totaling almost 2.0 million hectares in 2006 with 46% of stands being older than 40 years (Domke et al., 2008). As the commercial importance of aspen has increased, forest managers have clearcut aspen stands, a strategy that takes advantage of the species' rapid reproduction from root suckers (Stoeckeler and Macon, 1956; Farmer, 1962; Steneker, 1974; Schier and Smith, 1979; Raile and Hahn, 1982; Bella, 1986). However, recent trends in forest management include leaving reserve trees, single or clumped, in clearcut areas (Kohm and Franklin, 1997, Puettmann and Ek, 1999). This strategy changes conditions for the regeneration niche of aspen, as a residual overstory left after a harvest has been shown to reduce aspen regeneration (Stoeckeler and Macon, 1956; Schier and Smith, 1979; Hove et al., 1990; Ffolliott and Gottfried, 1991; Palik et al., 2003).

Aspen regeneration by suckering is especially sensitive to soil disturbance (Stone and Elioff, 2000; Smidt and Blinn, 2002; Frey et al., 2003). Soil conditions after harvest are determined by site factors such as soil texture and moisture content, as well as logging

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equipment used, operator skills, and harvesting intensity (Dyrness, 1965; Froehlich, 1973). Harvesting traffic that decreases soil aeration and/or damages roots (Hatchell et al., 1970; Shetron et al., 1988) decreases the growth potential of roots and the ability of aspen to sucker (Youngberg, 1959; Hatchell et al., 1970; Stone and Elioff, 1998; Smidt and Blinn, 2002).

The impact of leaving residual trees after harvest varies by forest ecosystem and recent studies suggest that the presence of residuals may negatively influence regeneration in systems dominated by light demanding species such as aspen (Zenner et al., 1998; Palik et al., 2003). For proper evaluation, the tradeoffs associated with leaving residuals need to be quantified and put in perspective with other factors that influence tree regeneration. For example, harvesting impacts on soils are part of any ground-based harvesting operation, i.e., they occur in or near all areas in which residual overstory trees influence regeneration. Because aspen is a very light demanding species that regenerates through suckering (Perala, 1990) it may be especially sensitive to the combined effects of soil disturbance and the presence of a residual overstory. Specifically, aspen suckers simultaneously draw resources from the parent root system, which can be affected through harvesting traffic, and from photosynthesis, which can be affected by competition from residual overstory trees. To date, however, studies that investigated the impacts of soil disturbance on tree regeneration have not considered the impacts of residual overstory (e.g., Froehlich, 1979; Schier et al., 1985; Bates et al., 1990; Navratil, 1991; Shepperd, 1993; Smidt and Blinn, 2002; Zenner et al., 2007; Mundell et al., 2008). Similarly, studies quantifying the impacts of residual overstory on aspen regeneration have not incorporated the effects of soil disturbance (e.g., Stoeckeler and Macon, 1956; Perala, 1977; DeByle and Winokur, 1985; Huffman et al., 1999; Palik et al., 2003). By combining these two aspects, our study investigates a basic question about the drivers of ecosystem structure and places plant responses to competition, stress, and disturbances in a broader context. Moreover, it provides an investigation into the basic role of competition (Grace and Tilman, 1990; Grime, 2001), specifically whether and how the plant response to competition (from overstory trees) varies with different levels of stress and disturbances (through soil impacts, cf. Campbell and Grime, 1992; Turkington et al., 1993).

In many parts of the Lake States, harvesting is restricted in summer months as a result of access problems due to high water tables and about half of the harvesting operations in Minnesota occur during winter months (Puettmann and Ek, 1999). Thus, an additional consideration in assessing the influence of overstory residuals and soil disturbance on aspen regeneration is the effect of season of harvest on regeneration patterns. In particular, aspen suckering response has been shown to vary by season of harvest (Zehngraff, 1946, 1947; Stoeckeler, 1947; Stoeckeler and Macon, 1956; Smidt and Blinn, 2002; Frey et al., 2003) and this phenomenon has been attributed to a combination of lower aspen root carbohydrate stores in spring and early summer after leaf flushing (Schier and Zasada, 1973; Schier, 1981) and less site disturbance during winter harvests (Mace, 1971; Zasada et al., 1987; Berger et al., 2004; Mundell et al., 2008). As such, seasonal effects must be considered in an evaluation of aspen regeneration dynamics after harvesting.

In our study, we investigated the interactions of these three factors influencing post-harvest aspen regeneration. In particular, we were interested in characterizing the spatial aspects of the impacts of harvesting traffic and residual trees on aspen regeneration as influenced by gradients in traffic patterns and residual overstory tree densities. Correspondingly, the first set of objectives was to develop predictive equations that spatially quantified gradients in soil disturbance along a transect moving from skid trails to side areas (objective 1a) and whether or not summer harvests result in higher soil disturbance levels than winter harvests (objective 1b). We recognize that previous work has demonstrated that soil disturbance levels are often greater on skid trails and following summer harvests (e.g., Brais and Camiré, 1998; Berger et al., 2004); but the spatial extend of such impacts has not been documented. Also, the development of these predictive equations was necessary for addressing subsequent objectives exploring impacts of harvesting traffic on tree regeneration. In particular, the second set of objectives addressed whether and at what spatial scale harvesting traffic decreases tree regeneration density and growth through disturbance of the soil (objective 2a) and whether or not this relationship differs between sites harvested in winter and those harvested in summer (objective 2b). Objective 3 incorporated effects of residual overstory into the relationships established under objectives 1 and 2. It investigated whether the influence of harvesting traffic on regeneration density and height growth was also influenced by the presence of a residual overstory, and if so, at what spatial scale. To address objectives 2 and 3 we developed two-stage regression equations (Borders, 1989) that allowed for the prediction of spatial impacts of harvesting traffic on aspen regeneration without actually measuring soil disturbance on a site.

2. Methods

2.1. Study area and site selection

This study included 25 stands, located within 6 northeastern Minnesota counties (Fig. 1), that were dominated by trembling aspen (Populus tremuloides Michx.) and, to a lesser extent, bigtooth aspen (Populus grandidentata Michx.). All stands had been clearcut or partially harvested between 1988 and 1994 and were measured in the summers of 1997 and 1998, 4–11 (average 6) growing seasons after harvest. Sites were selected to assure a range of harvest regimes and fairly homogeneous within-site character-istics. Harvest regimes included summer and winter aspen clearcuts, aspen clearcuts with low hardwood residual basal area (<3 m^2/ha), and aspen cuts with heavy hardwood residual basal area (average 12 m^2/ha). None of the selected sites had incurred major disturbances or management activity following harvest. Table 1 provides more detailed site descriptions.

The overall mean annual temperature for the study region ranges from 3.8 to 5.6 °C, and the overall mean annual precipita-tion ranges from 66 to 76 cm (Anderson et al., 1996). All sites were fairly level, with an average slope of 8% and soil parent materials in these areas were mainly dominated by glacial tills (Anderson et al., 1996). Soil textural data collected from all field sites indicated they were located on similar classes of sandy loams and silt loams.

All sites were considered aspen harvests; that is, aspen was the main species cut. Based on harvesting records, the amount of aspen volume removed indicated that the pre-harvest densities of aspen were substantially higher than the densities considered minimum (20 trees/ha) for successful establishment of a fully stocked aspen stand (Perala, 1977). Northern hardwoods, including sugar and red maple (Acer saccharum Marsh. and Acer rubrum L.), basswood (Tilia americana L.), northern red oak (Quercus rubra L.), and paper birch (Betula papyrifera Marsh.), were the most common of the 22 tree species other than aspen in the residual stands. Thus, since harvesting focused on aspen, the other species collectively comprised 82% of the residual overstory basal area. Consequently, trembling and, to a lesser extent, bigtooth aspen were the most common species regenerating, comprising 97% of regenerating stems on all aspen sites. The most common of the 11 regenerating
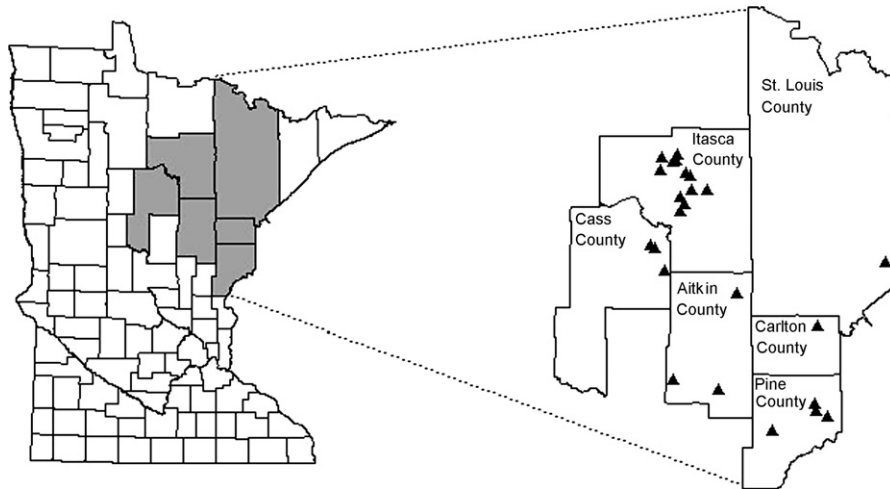
Fig. 1. Aspen-dominated study site locations in northern Minnesota.

tree species other than aspen—paper birch and red maple—together composed 2% of the total regeneration density.

2.2. Field collection and description of data

We screened target locations for potential field sites from timber sale maps obtained from the U.S. Forest Service, Minnesota Department of Natural Resources, and several counties in northern Minnesota and selected a total of 25 study sites (for breakdown of site into categories, see Table 1). On each study site, we established 20 "regeneration plots" (Fig. 2). Based on earlier work that suggested a negative exponential relationship between distance from skid trail and soil disturbances (Navratil's, 1991), we developed a refined sampling scheme that allowed us to evaluate the nature of this relationship by increasing the sampling intensity along transects that extended from landings or skid trails out into the adjacent areas. Five parallel rectangular (2 m × 5 m) plots were established along each of these transects. The first plot was located on the skid trail or landing, so its border followed the edge of the landing or skid trail. Importantly, while we did not know the specific amount of traffic on each skid trail location, their location was obvious as determined using a suite of factors, including harvest records and delineation of harvesting patterns (networks of landings and skid trails), soil conditions, and understory vegetation after careful site inspection (cf. Berger et al., 2004; Zenner et al., 2007). Despite these considerations, it is possible that misidentified skid trail locations may have been partially responsible for the high variability found within sites. The other plots on the transect were placed adjacent to the designated skid trail location with their centers located 1, 5, 9, and 15 m, respectively, from the edge of the landing or skid trail. We followed this approach as closely as possible, given specific site conditions. Transects were separated by a minimum distance of 25 m in an effort to ensure independence and minimize the influence of inter-clonal variation on aspen regeneration patterns. While minimum distances do not guarantee statistical independence, the high variability in conditions suggest that a reduction in variation due to lack of independence among transects is likely minor. Season of harvest for each stand was labeled as winter or summer, based on harvest documentation.

2.2.1. Tree regeneration and residual overstory

On each regeneration plot, we measured diameters (mm) at breast height (DBH) with a caliper or diameter tape for all trees >2.54 cm DBH. Because the tallest stem in each regeneration plot would likely constitute one of that stand's future dominant trees, we also measured its height with a height pole or clinometer. We measured overstory basal area from the center of regeneration plots using a 1-m factor prism and counted residual overstory as any individuals with a DBH of 18 cm or greater left standing after harvest.

After analyzing data from the first (1997) field season, we realized we needed to better characterize smaller size classes of regeneration trees in the aspen clearcuts (i.e., sites with residual basal area <1.0 m²/ha). Thus, for all aspen clearcut study sites investigated during the 1998 field season (11 sites), we established two 1 m × 1 m subplots on randomly selected corners of each regeneration plot. Within these subplots, we measured DBH (mm) and height (m) for all trees taller than 1 m regardless of DBH. Due to the lower regeneration densities on partial harvest sites, these additional regeneration plots were not necessary on these areas. Although aspen was the dominant regenerating species on all sites
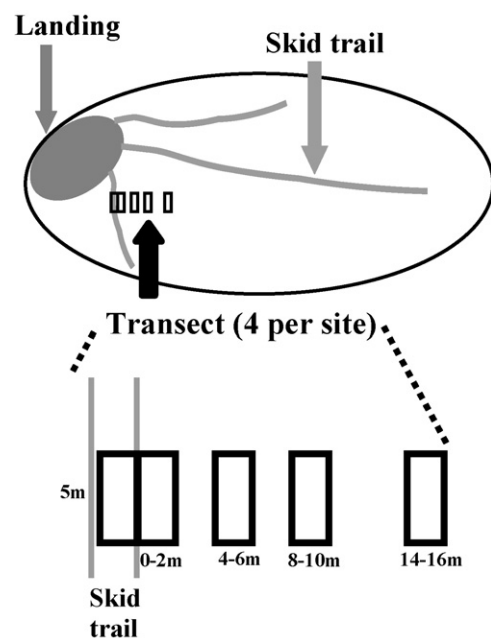

Fig. 2. Regeneration plot layout within aspen-dominated study sites. Five regeneration plots were placed along four transects per site, comprising 20 regeneration plots per site, to investigate patterns of aspen regeneration following harvest.

Table 1
Data for control conditions (plot #5 of transects) in aspen-dominated stands, by harvest type

Years since harvest	Season of harvest[a]	Site index[b]	Residual basal area (BA) (m²/ha)	Regen. density (trees/ha) of >2.54 cm DBH	Total regen. density (trees/ha)	Maximum regen. height (m)	Median soil strength (kPa)
Aspen clearcut—winter (residual BA < 1.0 m²/ha)							
4	W	23	2 (2.4)	5,500 (2,646)	30,500 (18,628)	5 (0.5)	3,224 (708.7)
8	W	24	1 (1.0)	9,750 (2,630)	16,000 (6,377)	7 (1.0)	5,344 (1,848.1)
5	W	23	0 (0)	9,500 (4,655)	28,250 (8,732)	6 (1.0)	2,924 (649.8)
6	W	23	0 (0.5)	2,000 (1,414)	9,500 (7,326)	5 (0.3)	4,499 (1,302.9)
6	W	23	0 (0)	5,500 (3,109)	35,500 (13,528)	6 (1.1)	6,423 (1,558.2)
11	W	23	0 (0)	8,750 (2,872)	25,000 (13,115)	8 (0.6)	4,849 (2,151.2)
11	W	15	0 (0)	5,000 (4,243)	23,750 (14,175)	5 (0.6)	2,374 (833.9)
Aspen clearcut—summer (residual BA < 1.0 m²/ha)							
6	S	24	1 (1.3)	4,250 (2,630)	–	6 (0.7)	1,675 (206.1)
7	S	24	0 (0)	8,250 (2,630)	29,500 (17,000.0)	9 (0.9)	3,712 (2,384.2)
6	S	24	0 (0.5)	7,500 (2,887)	22,500 (7,853)	7 (0.8)	925 (150.0)
5	S	26	1 (1.0)	3,000 (2,828)	31,750 (13,696)	5 (0.7)	3,861 (2,727.3)
7	S	23	0 (0)	7,000 (4,967)	–	7 (0.7)	1,250 (288.6)
4	S	20	0 (0.5)	4,000 (3,162)	64,000 (8,756)	5 (0.7)	3,424 (1,693.4)
Aspen cut with low residual overstory (residual BA = 3 ± 3.4 m²/ha)							
6	S	24	6 (2.4)	8,500 (4,796)	–	8 (0.6)	1,150 (147.2)
5	S	21	1 (0.8)	7,000 (3,742)	–	6 (0.3)	3,812 (753.0)
4	W	23	2 (1.6)	4,250 (2,217)	–	6 (0.8)	3,737 (1,387.3)
5	S	22	8 (4.8)	1,000 (817)	–	5 (0.3)	4,249 (932.5)
6	W	25	4 (3.4)	6,750 (2,363)	–	6 (0.4)	6,298 (787.2)
6	W	24	2 (1.6)	7,500 (4,435)	–	6 (1.3)	4,799 (803.9)
Aspen cut with heavy residual overstory (residual BA = 12 ± 8.1 m²/ha)							
5	S	21	5 (1.5)	2,250 (1,893)	–	5 (0.4)	2,381 (372.6)
6	W	20	18 (9.1)	250 (500)	–	6 (0)	550 (343.9)
6	S	21	18 (8.7)	1,250 (2,500)	–	6 (0)	1,968 (350.7)
7	W	22	18 (2.2)	0 (0)	–	–	1,125 (525.1)
6	W	15	4 (4.6)	6,750 (4,992)	–	8 (0.3)	2,066 (907.1)
6	S	17	15 (2.6)	3,000 (4,243)	–	7 (0.9)	1,112 (265.7)

Standard deviations are in parentheses.
[a] W = winter, S = summer.
[b] Site index values are for whole site.

(comprising at least 86% of the sites' stem densities) and was the tree species with maximum height on 99% of all plots, other tree species were also included in the density analysis.

2.2.2. Soil disturbance

To determine soil strength, we used an Eijkelkamp soil cone penetrometer (Bennie and Burger, 1988) to measure penetration resistance (kPa) of the soil matrix in each regeneration plot (ASAE, 1990). Assuming soil texture and moisture are similar across a site, soil strength can be used as an indicator of soil compaction (e.g., Godefroid and Koedam, 2004). Because this measure does not represent other impacts of harvesting traffic on soil, we interpreted soil strength data as a more generic, inclusive measure of soil disturbance (cf. Berger et al., 2004). In particular, these measurements provide a general approximation of the effects of harvesting traffic on the rooting environment of regenerating aspen. After clearing slash and the main duff layer, we pushed down on the penetrometer at a force that ensured a uniform penetration rate of approximately 30 mm/s (or slower); readings were taken when the cone reached 15 and 30 cm soil depth. We used a 1-cm^2 base area cone on all but three study sites, on which we used a 2-cm^2 base area cone. The penetrometer measurements for these three sites were converted by the following equation:

$$\text{Cone resistance} = \frac{\text{gauge reading}}{\text{base area of cone(cm}^2)}$$

We recorded a minimum of 10 randomly selected penetrometer readings per plot, ignoring readings when the penetrometer obviously had hit a buried rock or a root. To ensure that soil moisture conditions were relatively uniform by site, we took all measurements on a given site on a single day. Because of the higher incidences of hitting root and/or rocks when going down to 30 cm, the high correlations between the 15 cm and 30 cm measurements, and the dominant location of aspen roots in the upper soil surface, we used the 15 cm penetration readings in the analysis. Since the mean and median penetrometer values for each regeneration plot were correlated by an R^2 value of 0.99, we used the median value in the analysis to minimize the effects of outlying values.

2.2.3. Site conditions

To quantify several factors contributing to between-site variability, we determined stand age, site index, and soil texture for all sites, obtaining stand age and site index information from harvesting records. We determined soil texture from 10 samples collected from 5 points randomly located within each study site, but outside the regeneration plots. For each point, we took one sample from the 0 to 25-cm profile and another from the 26 to 50-cm profile. We conducted texture analysis in the lab in fall 1998/ winter 1999 using a modified hydrometer method (Grigal, 1973).

2.3. Data analysis

Because each site had a unique set of conditions and historical treatments, we did not set out to compare absolute regeneration densities and growth. Instead, we assumed within-site homogeneity and compared within-site trends that had been standardized to account for site differences. To standardize the data for each transect with 100% as the baseline, we considered the plot on each transect farthest away from the skid trail or landing (plot 5) to be the "control," in terms of harvesting impacts on soils. Measurement data from all other plots on the transect were divided by the respective values found in plot 5 to calculate "relative density," "relative total density," "relative maximum height," and "relative soil disturbance" or "predicted relative soil

disturbance." This standardization technique assumed that plot 5 always represented the control condition and thus contained lowest soil disturbance values, highest regeneration density, and highest maximum height, when adjusted for effects of residual overstory density. In actuality, however, this was not always the case, but for consistency we followed the same procedure on all sites. Residual overstory basal areas are absolute values.

We conducted statistical analyses using JMP 3.1.6.2 (SAS Institute Inc., 1996). Unless otherwise noted, relationships were considered significant when $p \leq 0.05$. We used simple and multiple regression analyses to determine the nature of relationships between soil properties, overstory conditions, harvesting conditions, plot location, and tree regeneration. Residual analysis was used to determine proper model forms.

The analyses were done iteratively using two-stage regression techniques (cf. Borders, 1989). Specifically, we developed models for predicting relative soil disturbance values and used these predicted values in subsequent regression models examining the regeneration response to soil disturbance and residual overstory (see details below). To avoid potential interacting effects of residual overstory, we used only aspen clearcuts in the analysis of soil disturbance trends and the effects of soil disturbance on tree regeneration on summer-harvested versus winter-harvested sites. As mentioned, aspen clearcut analyses included the smaller subplots to estimate aspen regeneration density (designated as "total regeneration density") and height response to soil disturbance. We chose to use two-stage regression to allow for the assignment of causality between soil disturbance and tree regeneration within these stands. We also ran an additional set of models using distance from skid trail as a predictor in place of predicted soil disturbance. The comparison between results of this additional set with those of the two-stage regression models was used to evaluate the robustness of our models.

To quantify the levels of soil disturbance on and off skid trails and landings (objective 1a), we regressed relative disturbance levels as a function of distance from the skid trail or landing. For analysis purposes, we added 0.1 to distance-from-skid-trail/ landing values and conducted a natural log transformation to reflect the nonlinear relationship. We used analysis of covariance to determine whether this relationship varied by season of harvest (objective 1b).

To test whether regeneration density and height were influenced by soil disturbance levels (objective 2a), we fit regression models predicting relative total density and relative maximum height as a function of predicted relative soil disturbance (as determined in objectives 1a and 1b). We used analysis of covariance to determine whether this relationship differed by season of harvest (objective 2b) as described for objectives 1a and 1b.

One transect that was already flagged as abnormal in the field because of its unique location on a side slope was determined to be an outlier (standardized Student-$t > 4$) and thus was omitted from the analyses. For height analysis, plots were omitted from analysis if there were no trees present. Density analyses thus contained 80 observations of summer aspen clearcuts and 135 observations of winter aspen clearcuts. Height analyses contained 104 observations of summer aspen clearcuts and 92 observations of winter aspen clearcuts.

We used two approaches to test the effects of residual overstory and soil disturbance and their interactions on tree regeneration (objective 3). The first approach consisted of fitting regression models to (1) predict relative density and relative maximum height as a function of predicted relative soil disturbance, residual basal area, and their interaction (predicted relative soil disturbance times residual basal area) and (2) test the parameters for

significance ($p > 0.10$). Analysis of covariance determined whether these relationships differed between sites harvested in summer and those harvested in winter, as described for objectives 1a and 1b. Three transects (i.e., 15 plots) were omitted from the density analysis because plot 5 (the control conditions) on these transects contained no trees, resulting in a total of 483 observations. In a similar manner, treeless plots were omitted from the height analysis, thereby reducing the number of observations to 322.

Our second approach to investigating the effects of residual overstory and soil disturbance on tree regeneration consisted of fitting regression models to predict absolute regeneration density and absolute maximum height as functions of predicted relative soil disturbance for each site. We then regressed the intercept and slope coefficients of each site against the respective residual basal area on the site. A significant slope of the intercept and slope models is an indicator that the effects of soil disturbance and residual basal area on regeneration are interactive.

3. Results

3.1. Soil disturbance values in aspen clearcuts

On aspen clearcut sites, median soil disturbance values varied across sites (Table 2). Individual penetrometer readings ranged from 300 to 8500 kPa across all sites, with readings on the control plots (plot 5) ranging from 300 to 7700 kPa (Table 1) and those on plots on the skid trails (plot 1) ranging from 750 to 8500 kPa. Relative soil disturbance decreased significantly with distance (DIST) from the skid trail (Fig. 3). We used Eqs. (1) and (2) to obtain predicted relative soil disturbance (PRED STR) for use in subsequent aspen clearcut analyses (standard errors in parentheses). Harvesting impacts on relative soil disturbance differed significantly by season of harvest. Sites harvested in the summer months showed significantly steeper ($p < 0.0001$) soil disturbance gradients (Eq. (1)) than areas harvested in winter (Eq. (2)).

$$\text{(Summer) PRED STR} = 162.75(6.6) - 21.41(3.28) \times [\ln(\text{DIST}(m) + 0.1)], \quad (1)$$
$$R^2\text{adj.} = 0.26, \quad p < 0.0001$$

$$\text{(Winter) PRED STR} = 116.33(4.2) - 5.76(2.08) \times [\ln(\text{DIST}(m) + 0.1)], \quad (2)$$
$$R^2\text{adj.} = 0.53, \quad p = 0.006$$

3.2. Disturbance levels and tree regeneration in aspen clearcuts

The regeneration density varied within harvesting treatments (Table 1), but across all treatments it ranged from 0 to 76,000 trees/ha. Density on control plots (plot 5) ranged from 0 to 15,000 trees/ha (Table 1); on plots on the skid trails (plot 1), it ranged from 0 to 5000 trees/ha. The range of maximum regeneration heights was
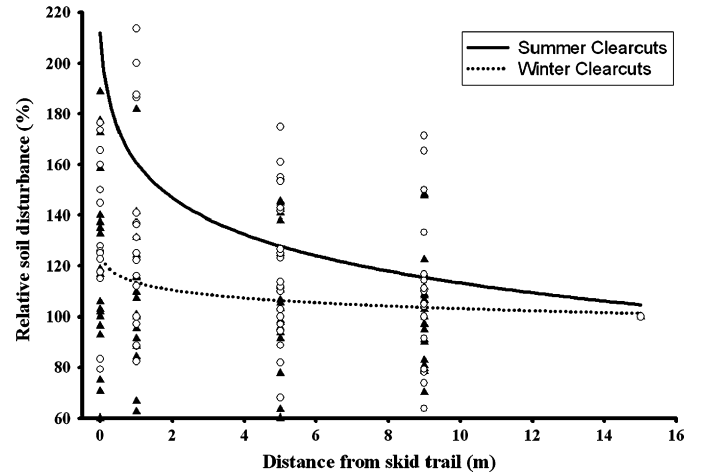

Fig. 3. Relative soil disturbance levels in aspen clearcuts in summer versus winter as a function of distance from skid trail. Circles represent summer harvests and triangles represent winter harvests.

3.3–9.3 m; maximum heights on control plots (plot 5) ranged from 4.1 to 9.3 m (Table 1), and on plots on the skid trails (plot 1), they ranged from 3.7 to 8.7 m.

The model fits and predictions from the equations using two-stage regression approaches (i.e., predicted soil disturbance) and those using distance from skid trail (DIST) to predict aspen regeneration densities and heights were alike (Table 3). For example, the R-squared values between predicted values for each approach ranged from 0.98 to 0.99. We focussed on results from the two-stage regressions due to the causality relationships implied in this approach, as interpretations of the equations and fits of models using distance from skid trail (Table 3) were basically identical.

In both summer- and winter-harvested aspen clearcuts, total regeneration density and maximum height were negatively associated with soil disturbance. Winter-harvested clearcuts had higher relative total regeneration densities than sites harvested in summer. The magnitude of this effect varied with predicted relative soil disturbance, as indicated by two robust models, Eqs. (3) and (4):

$$\text{Relative total density} = 247(20.4) - 1.4(0.16) \times \text{PRED STR} - 0.1(0.05) \times \text{PRED STR} \times \text{SEASON}, \quad (3)$$
$$R^2\text{adj.} = 0.27, \quad p < 0.0001$$

$$\text{Relative total density} = 238(20.6) - 1.4(0.16) \times \text{PRED STR} - 16.1(6.76) \times \text{SEASON}, \quad (4)$$
$$R^2\text{adj.} = 0.27, \quad p < 0.0001$$

where for SEASON, winter = 0 and summer = 1.

Table 2
Study site averages for aspen-dominated stands, by harvest type

Harvest type	Residual basal area (BA) (m²/ha)	Proportion of regeneration (%) that was aspen	Regeneration density (trees/ha) of >2.54 cm DBH	Total regeneration density (trees/ha)	Maximum regeneration height (m)	Median soil strength (kPa)
Aspen clearcut—winter	<0 (0.8)	97	3,808 (3,645)	21,963 (19,280)	6 (1.3)	3,120 (1,991.0)
Aspen clearcut—summer	<0 (1.1)	97	4,143 (3,923)	18,643 (16,843)	6 (1.4)	4,494 (2,030.5)
Aspen cut w/low residual overstory	3 (3.4)	99	3,758 (3,954)	–	6 (1.1)	4,152 (1,795.5)
Aspen cut with heavy residual overstory	12 (8.1)	95	1,842 (3,467)	–	6 (1.4)	1,904 (1,107.8)

Standard deviations are in parentheses.

Table 3
Regression equations for predicting the relative density and height of aspen regeneration based on distance from skid trail (DIST), season of harvest (SEASON), and residual basal area (BA)

Objective	Model	Adjusted-R^2
2	Relative density = 58.82 + 20.1 × ln(DIST + 0.1) + 7.20 × ln(DIST + 0.1) × SEASON	0.24
	Relative height = 89.87 + 4.08 × ln(DIST + 0.1) + 0.53 × ln(DIST + 0.1) × SEASON	0.15
3	Relative density = 15.84 + 43.95 × ln(DIST + 0.1) − 0.91 × BA − 2.04 × ln(DIST + 0.1) × BA	0.31
	Relative height = 82.83 + 7.61 × ln(DIST + 0.1) − 0.19 × ln(DIST + 0.1) × BA	0.16

See Section 2.3 for a detailed description of objectives.

On winter-harvested sites, the relative density in the control conditions (100% relative soil disturbance) was greater than 100% (Fig. 4a). This anomaly is an artifact of the standardization technique. Plot 5 (the control conditions) did not always have the lowest density in a given transect, which apparently led to inflated intercept and slope values for winter-harvested sites and could be partially responsible for the two robust models.

The slope (but not the intercept) of relative maximum height was significantly steeper ($p = 0.10$) for sites harvested in summer than for those harvested in winter (Eq. (5), Fig. 4b), indicating that the rate of change in height over changes in soil disturbance differs and aspen regeneration seemed to be more sensitive to changes in

Fig. 4. Predicted relative soil disturbance versus (a) relative total regeneration density by season of harvest (see Eq. (3)), and (b) relative maximum regeneration height by season of harvest (Eq. (5)) for aspen clearcuts. Intercepts are at 100% predicted disturbance, i.e., control conditions. Circles represent summer harvests and triangles represent winter harvests.

soil disturbance after summer harvests:

$$\text{Relative maximum height} = 139(7.2) - 0.35(0.06)$$
$$\times \text{PRED STR} - 0.03(0.017)$$
$$\times \text{PRED STR} \times \text{SEASON}, \quad (5)$$
$$R^2\text{adj.} = 0.16, \quad p < 0.0001$$

3.3. Interactive effects of residual basal area and soil disturbance on tree regeneration

Residual basal areas varied across sites (Table 1), ranging from 0 to 31 m^2/ha. In general, residual basal area negatively affected regeneration density and growth. The relative magnitude of this effect did not differ between summer- and winter-harvested sites, but varied with predicted relative soil disturbance, as indicated by Eq. (6):

$$\text{Relative density} = 379(30.1) - 2.3(0.24) \times \text{PRED STR}$$
$$- 17.5(4.1) \times \text{BA} + 0.1(0.03) \text{ PRED STR}$$
$$\times \text{BA}, \quad (6)$$
$$R^2\text{adj.} = 0.21, \quad p < 0.0001$$

Fig. 5a shows how this model can be used to predict density at three levels of residual overstory basal area. Recall that in winter aspen clearcuts, plot 5 (the control conditions) did not always have the lowest density in every transect, which could have inflated the intercepts and slopes of these models.

A full model that included PRED STR, BA, and PRED STR × BA as independent variables was not useful for predicting maximum regeneration height. Investigation of these variables individually or in pairs indicated that the relationships did not differ between summer- and winter-harvested sites. The model with the best fit and only significant parameters was:

$$\text{Relative maximum height} = 140(5.6) - 0.4(0.05) \times \text{PRED STR}$$
$$- 0.005(0.002) \times \text{PRED STR}$$
$$\times \text{BA}, \quad (7)$$
$$R^2\text{adj.} = 0.17, \quad p < 0.0001$$

A visual representation of this model is shown in Fig. 5b.

The second method of analyzing the effect of residual basal area and soil disturbance on regeneration density and height supported the findings just described. The intercept and slope coefficients of regeneration density on predicted soil disturbance decreased significantly ($p < 0.01$) as residual basal area increased. In a similar manner, the intercept and slope coefficients of maximum regeneration height on predicted soil disturbance decreased significantly ($p < 0.01$) as residual basal area increased.
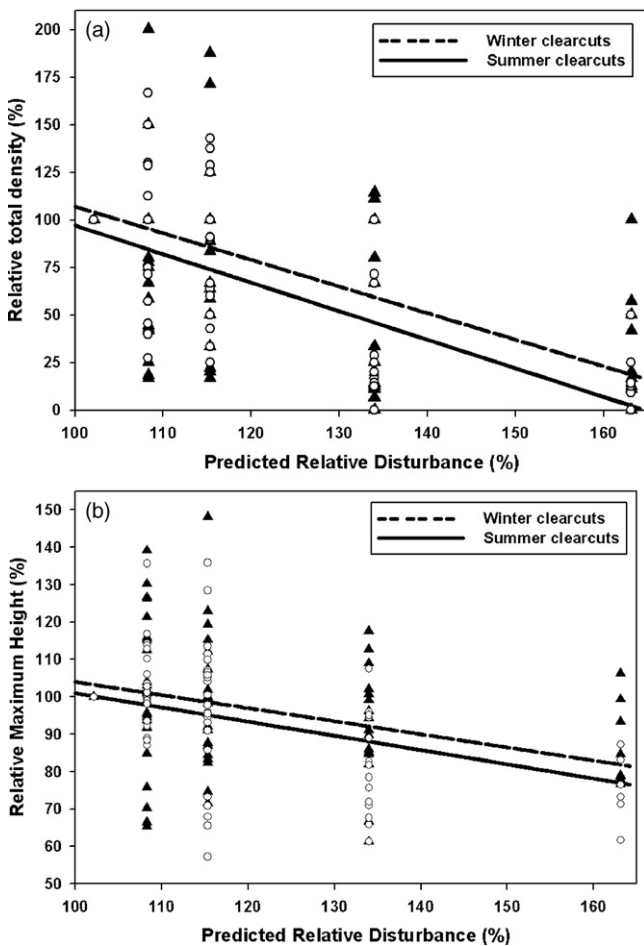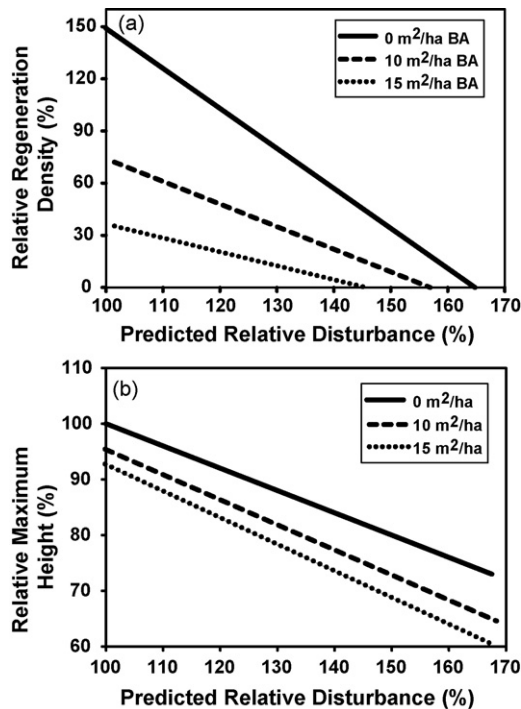
Fig. 5. Predicted relative soil disturbance versus (a) relative regeneration density and (b) relative maximum regeneration height, according to three levels of residual basal area (BA). Eqs. (6) and (7) were used to determine interactive effects of soil disturbance and residual basal area on aspen density (Eq. (6)) and height (Eq. (7)) response. Intercept is at 100% predicted disturbance, i.e., control conditions.

4. Discussion

Our findings indicate that the impact of harvesting traffic on these sites is quite evident, but fairly limited in extent, i.e., the major impact is on the skid trails and adjacent areas are relatively little impacted in terms of increased soil disturbance. Correspondingly, the "side" area as used, but not defined in terms of area, by Navratil (1991) is rather small. Thus, measuring the area in skid trails using a conservative assessment of outer edge (i.e., include areas with any signs of traffic in the skid trail) may provide a good estimate of the area in which aspen regeneration is influenced through soil disturbance. Also, the amount of variation found on "homogenous" sites indicates the need for a large sample, if detecting refined trends in soil and regeneration impacts is part of the objective. In particular, variation in clay content or erosion levels may require higher sampling intensities (Shaw and Carter, 2002). On the other hand, future studies with the objective to document soil disturbances due to harvesting traffic may not require the extensive transect sampling scheme used in this study. Instead because of the narrow "side" area (sensu Navratil, 1991), plots could simply be placed in areas on and off the skid trail. In hindsight, an experimental approach that relied on ANOVA would have been sufficient for this study as well, but changing the analysis method based on results appeared inappropriate.

The negative relationships we observed between soil disturbance and total regeneration density and maximum height are similar to those documented in other studies conducted in aspen systems within the Lake States (e.g., Bates et al., 1993; Smidt and Blinn, 2002; Fleming et al., 2006; Zenner et al., 2007) and Canada (Stone and Kabzems, 2002; Mundell et al., 2008). Similarly, many studies have found that aspen suckering occurs at a higher density and with greater height growth when harvest operations take place in the winter months (Weigle and Frothingham, 1911;

Zehngraff, 1946, 1947; Stoeckeler, 1947; Stoeckeler and Macon, 1956; Bates et al., 1993). In young stands, season of cutting had no impact on density, but late fall and winter cutting led to greater height growth, leaf area, and higher leaf area ratios (Landhäusser and Lieffers, 2002; Mulak et al., 2006). These studies point to the higher below-ground carbohydrate reserves in winter as being at least partially responsible for this phenomenon. Root starch concentrations are highest in early fall and remains at high levels throughout the dormant season; it is lowest in spring or early summer after leaf flush (Tew, 1970; Schier and Zasada, 1973; Landhäusser and Lieffers, 2003). Also, recovery of root starch concentrations after cutting was quicker after fall compared to spring operations (Landhäusser and Lieffers, 2006). Although we could not test this phenomenon directly, our results indicate that a combination of factors may be responsible for differences related to harvesting season. The steeper density and height reduction gradients on compacted plots on summer-harvested versus winter-harvested sites suggests that higher sensitivity of aspen regeneration to disturbance during summer months might also be responsible for less vigorous aspen regeneration following a summer harvest. In addition, the soil disturbance levels in summer-harvested sites were higher than those in winter-harvested sites, likely because the frozen soil was less susceptible to disturbance by harvesting equipment (Mace, 1971) or the soil was protected by a protective snow cover (Zasada et al., 1987).

Thus, our results suggest that winter harvests carry a three-fold benefit in terms of maximizing aspen regeneration: (1) roots have higher carbon storage at this time, (2) possibly related to this, suckers are less sensitive to disturbance created in winter months, and (3) soil disturbance levels are lower because of a protective snow layer and/or frozen soil conditions. The last advantage can be neutralized if low ground pressure harvesting equipment is used for summer harvests (Bates et al., 1993). A recent survey indicates that about half (54%) of all harvesting operations in Minnesota occur during winter months (Puettmann and Ek, 1999), but no such information exists for aspen harvests specifically.

As already mentioned, the control plots (plot 5) for some transects on the winter-harvested sites showed not only lower soil disturbance values than plots closer to the skid trails (plots 3 and 4), but also lower regeneration densities. This could be a result of random chance and/or measurement or mapping errors; e.g., some control plots might have been closer than 15 m to another, unrecognized skid trail. Other standardization techniques, such as combining the two plots farthest from the skid trail as controls, did not produce satisfactory results either. Thus, the analysis of regeneration density has to be viewed cautiously, because the intercepts and slopes of the relative densities on winter-harvested sites are artificially inflated. This does not invalidate our results; however, as, even inflated, the slopes for winter-harvested sites are still shallower than slopes for summer-harvested sites. Thus, the differences in slopes between summer- and winter-harvested sites would be even larger if "proper" standardization had been achieved. Consequently, even with this problem, the conclusions regarding the higher sensitivity of summer harvests to soil disturbances are valid.

Our findings corroborate those of other studies concluding that the practice of leaving residuals after a harvesting operation negatively affects aspen regeneration growth because of the competition from overstory trees (e.g., Stoeckeler and Macon, 1956; Schier and Smith, 1979; Hove et al., 1990; Ffolliott and Gottfried, 1991; Huffman et al., 1999; Mulak et al., 2006; Palik et al., 2003). However, our results also indicate that aspen regeneration patterns were affected by the interaction between the amount of residual overstory and the corresponding levels of soil disturbance. Again, the actual equations used to predict

density must be viewed with caution (see preceding discussion about standardization techniques). Consequently, avoidance of soil disturbance is even more critical in areas with heavy overstory residuals. Although the area affected by harvesting traffic in a single partial harvest is less than the area affected on clearcut sites [Stokes et al. (1997), for example, found that 13.7%, 13.2%, 12.5%, 9.6%, and 8.2% of the stand area were in skid trails after clearcutting, shelterwood, seed-tree, group selection, and single tree selection methods, respectively], this trend is reversed with multiple entries (Dwyer et al., 2004). Our findings suggest that a given level of soil disturbance is more detrimental to aspen regeneration under partial overstory canopy than in clearcut conditions. Thus, given the choice, partial harvest sites should be harvested in winter months and/or harvested with low impact harvesting machinery, if aspen regeneration is desired. On the other hand, the results of our study also show that harvesting disturbances and partial overstories can reduce aspen growth, thus potentially allowing other species that are more tolerant of competition to regenerate successfully. These aspects could be important in preventing the loss of other tree species in forests dominated by aspen.

While not an explicit objective of this study, our work also answers the question about whether soil disturbances persist or whether such harvesting impacts disappear quickly. Differences in soil disturbance levels between sites on skid trails and adjacent less trafficked areas remained significant, up to 11 years post-harvest. Earlier studies had suggested that soil compaction from harvesting operations was only a short-term problem, e.g., Holman et al. (1978) found that bulk density levels in areas apart from skid trails returned to precut levels within 1 year, whereas by the end of their 3-year study, skid trails in summer-harvested sites had not yet returned to their precut bulk density levels. More recent evidence, including our study, seems to lead to a different conclusion. Stone and Elioff (1998) found significantly greater bulk density and soil disturbance in compacted areas versus non-compacted areas 5 years after treatment. In some cases, it has taken over 40 years for soil compaction levels on skid trails to resemble precut conditions (Vora, 1988). All these studies support the notion that soil disturbance recovery on skid trails can be a very slow process, even in a climate with a freeze–thaw cycle, such as in northern Minnesota. Consequently, pre-harvest planning, including layout and discussions with skidder operations will help ensure that heavy logging traffic is minimized and confined to as few skid roads as possible (Dwyer et al., 2004), since the initial machinery passes create most of the disturbance (Hatchell et al., 1970; Murphy, 1982; Shetron et al., 1988; Shepperd, 1993; Williamson and Neilsen, 2000).

4.1. Long-term productivity implications

Although this study focused on the initial responses of aspen systems to post-harvest soil disturbance and differing levels of residual overstory retention, it is important to consider the impacts these initial responses may have on long-term productivity in these systems. Correspondingly, the following discussion uses our results to investigate what long-term impacts the observed "early" differences in density and height growth might have over the life of the stand and whether soil disturbance and residual overstory might reduce sustainable harvest levels. Navratil (1996) suggests that density and quality of regeneration play an important role in sustaining aspen productivity; however, Ek and Brodie (1975) found that when sites are fully captured by aspen, density differences seem to diminish over time. Furthermore, all density levels observed in this study are sufficient for aspen regeneration (Perala, 1977) and density differences at rotation age (50 years) are likely to be minimal due to natural self-thinning (Ek and Brodie, 1975). Thus, density reductions are not likely to be reflected in lower harvest volumes at rotation age.

On the other hand, height growth is commonly used as an indicator of site productivity (via site index) (Perala, 1977) and an estimate of the impact of soil disturbance and residual overstory on aspen yield at rotation age can be derived from the differences in early height growth. Correspondingly, we related the current height reduction due to soil disturbance and residual overstory differences to height difference at the end of a 50-year rotation. Since the current tallest suckers (which we used to calculate height reduction) are likely the dominant trees at rotation age, we assumed an equivalent reduction in top height (i.e., site index) and used Perala (1977) to quantify the yield for unimpacted stands and stands with reduced height growth (i.e., site index). Under the assumption that the soil and overstory impact lasts only 10-years and height growth would be unimpeded during the last 40 years of a rotation, we reduced the site index by the current height reduction (in absolute terms). Under the assumption that the impact lasted throughout a whole rotation and height growth would be impacted on the same relative basis throughout the rotation, we used the current height differences in relative terms and reduced the site index proportionally. Because this obviously is an extrapolation, we used these two assumptions to present best and worst-case scenarios. The best case scenario assumes that the impact of soil disturbance is only short term and under this assumption (for a full set of assumptions, see Table 4) leads to only minor losses in future growth. It is important to note, that in this scenario even leaving residuals for a decade after the regeneration harvest did not seem to lead to great reductions in future growth. The magnitude of this reduction probably is not detectable at rotation age.

The worst-case scenario assumes that the impacts of harvesting and residuals are influencing growth throughout the whole rotation (see Table 4). Under these assumptions, larger reductions, up to 9%, can be expected even in clearcuts. Harvest regimes that leave residual overstories will approximately double the expected loss in productivity, if these residual trees survive the whole aspen rotation. (*Note*: Eq. (7) does not distinguish between summer and winter harvests.)

Table 4
Estimated yield losses (% reduction in cords to 4 in. top) at rotation age 50-year for aspen stands with a site index of 24 m

Scenario	Season of harvest[a]	Area in skid trail (%)	Duration of impact (years)[b]	Yield reduction (%)	
				Clearcut	10 m^2/ha residuals
Best	Winter	10	10	1.5	2
Worst	Summer	20	50	9	19

Yield estimates were derived from Perala (1977).
  [a] For clearcut estimates only.
  [b] The impact of soil disturbance does not affect height growth after 10 or 50 years, and overstory residuals are harvested after 10 and 50 years for the best and worst case scenario, respectively.

Although they are vague estimates, these results support the notion that leaving residuals after harvest, despite having obvious ecological benefits, may negatively influence future harvestable timber volume. They also show that these impacts can be minimized through proper management. For aspen, this may mean leaving residuals on winter harvest sites, minimizing area in skid trail, and using low impact harvesting technology. Also, the question about longevity of these residuals or about their future removal from these stands is crucial in assessing their impact on future productivity.

Acknowledgements

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