Effects of Forest Roads on Understory Plants in a Managed Hardwood Landscape

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Abstract: The effect of forest roads on species distribution and dispersal is an important conservation and management issue. We examined distributions of understory plants and their relationships to unpaved forest roads in a northern hardwood landscape in the Chequamegon National Forest, Wisconsin (U.S.A.). At six different sites, we recorded species cover, canopy cover, litter depth and cover, and bare ground at 11 distances (0, 5, 10, 15, 20, 30, 45, 60, 90, 120, and 150 m) from the road edge. At each of the 11 distances, we established a 60-m transect parallel to the road edge, within which we sampled 10 randomly placed 1 x 1 m plots (660 plots). We examined changes in species abundance (percent species cover per plot), richness, and Shannon-Wiener diversity ($H$) with distance from the roads in an effort to determine the degree and magnitude of road effects on plant distribution. The species richness and $H$ of native plants and the abundance of exotic species were clearly related to distance from the roads. Exotic species were most prevalent within 15 m of roads, occurring infrequently in the interior forest. The richness and $H$ of native species were lower on the roadsides but reached interior-forest levels within a short distance (5 m) from the roads. The roads appeared to be associated with a disturbance corridor that affected site variables up to 15 m into the hardwood stands. At our six sites we detected 117 species, 25% of which occurred more frequently near the road, with only 12% having a 90% or greater preference for the forest interior. Our results suggest that roads have associated effects that alter interior-forest conditions and thus plant species composition and abundance; however, these effects are limited in depth of penetration into managed forests.

Efecto de Caminos sobre las Plantas del Sotobosque en un Paisaje Forestal Bajo Manejo

Resumen: El efecto de caminos sobre la distribución y dispersión de especies forestales es un aspecto importante para su conservación y manejo. Examinamos la distribución de plantas de sotobosque y sus relaciones con caminos no pavimentados en un paisaje boscoso en el Parque Nacional Chequamegon, Wisconsin (E.U.A.). En seis sitios diferentes registramos la cobertura de las especies, la cobertura del dosel, la profundidad y cobertura de la hojarasca y el suelo desnudo a seis distancias (0, 5, 10, 15, 20, 30, 45, 60, 90, 120 y 150 m) del borde del camino. En cada una de las 11 distancias establecimos un transecto de 60 m paralelo al borde del camino, en cada uno muestreamos 10 parcelas de 1 x 1 m establecidas aleatoriamente (660 parcelas). Examinamos los cambios en la abundancia de especies (porcentaje de cobertura por parcela), la riqueza y la diversidad de Shannon-Wiener ($H$) con la distancia en un esfuerzo por determinar el grado y la magnitud de los efectos de caminos sobre la distribución de plantas. La riqueza de especies y $H$ de plantas nativas y la abundancia de especies exóticas estuvieron claramente correlacionados con la distancia del camino. Las especies exóticas fueron más prevalentes a 15 m del camino, y eran menos frecuentes en el interior del bosque. La riqueza y $H$ de especies nativas fueron menores en las orillas de caminos, pero alcanzaron los niveles de bosque interior a poca distancia (5 m) de los caminos. Los caminos parecen asociarse con un corredor de perturbación que afectó variables hasta 15 m al interior del bosque. En los seis sitios detectamos 117 espe-

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Paper submitted June 18, 2001; revised manuscript accepted September 18, 2002.
Introduction

Roads have become a prominent landscape feature (Forman & Alexander 1998) that we use daily and in almost every environment imaginable. Yet little attention has been paid to the associated edge effects of roads in the landscapes in which they are embedded. Historically, researchers have limited their interest in edges to borders between two different ecosystem types, such as forests and fields or clearcuts (Franklin & Forman 1987), but interest in edges associated with power-line corridors and roads is increasing (Pickett & White 1985; Luken et al. 1991; McIntyre & Lavorel 1994; Reed et al. 1996). Scientists know that edge effects can reduce the area of interior habitat by changing species composition, temperature, moisture, light availability, and wind speed (Gysel 1951; Chen et al. 1992, 1995; Euskirchen et al. 2001). Edges often have higher species richness and greater numbers of exotic species (Ranney et al. 1981; Brothers & Spin-garn 1992), potentially altering ecosystem processes and functions (e.g., productivity, Laurance et al. 1997) near the edge.

Road corridors constitute approximately 1% of the land area of the United States, with 10% of total U.S. road length (approximately 380,000 miles) within the national forest system (Forman & Alexander 1998). Roads have shaped the way modern humans interact with forests, providing people with more opportunities to venture into what were once remote wildlands. Designed as a corridor for human travel, however, roads can act as barriers to the movement of some species (Lovallo & Anderson 1996) while facilitating the movement of others (Schowalter 1988). Once edge effects on the surrounding landscapes are taken into account, the effects of roads are often considerably greater than their actual area implies. In a study in Wyoming, for example, the total area affected by roads and clearcuts together, including edge effects, was 2.5–3.5 times their actual area, with roads contributing more to fragmentation than clearcuts (Reed et al. 1996).

Roads typically create high-contrast edges between intact patches of forest habitat and corridors used for vehicle traffic (Trombulak & Frissell 2000). Unpaved road edges often have exposed mineral soil. When imposed on a landscape, roads comprise a disturbance corridor. Road construction and forest removal at the landscape level have been shown to constitute a significant risk to biodiversity in surrounding wetlands as well as aquatic ecosystems (Findlay & Houlahan 1997). In addition, roads are associated with both high and low plant diversity at different scales (Brosofske et al. 1999), indicating that further investigation of the associated effects of roads on vegetation is warranted.

We examined the effects of unpaved forest roads—the dominant road type in many managed forest landscapes—within a hardwood landscape in the Chequamegon National Forest in northern Wisconsin (U.S.A). Our objectives were to (1) examine the response of understory plant abundance and diversity to unpaved forest roads; (2) investigate the relationship between unpaved forest roads and the presence of exotic forest species; and (3) determine depth-of-edge-influence from roads on understory vascular plants. Chen et al. (1992) first introduced the concept of depth-of-edge influence for statistical delineation of the distance from the edge that is penetrated by significant edge influences. Such information is critical for forest managers in designing future road networks, developing reserves for native species, and working to control the spread of exotic plant species.

Methods

Study Sites

Our study area was located in the Washburn Ranger District of the Chequamegon National Forest. The Washburn Ranger District is managed for multiple uses, including timber, recreation, and biodiversity. Like many national forests, it is a mosaic of differing vegetation patches, harvest treatments, and transport and recreation corridors. Road density in the study area is 1.46 km/km² (Brosofske 1999)—relatively high for the Great Lakes region, where road densities range between 0.16 and 2.07 km/km² (Saunders et al. 2002). Most of these roads are unpaved forest roads experiencing light use, primarily for recreation, hunting, and logging. Many temporary-access roads, currently closed to traffic, also persist in the landscape, although most of these are not represented in the road-density figure. The topography of the landscape is flat, with dispersed rolling hills. The area is composed of coarse-textured outwash soils (i.e., loamy sand and sand) residing on Precambrian shield sandstone bedrock. The elevation of the study area ranges from 232 to 459 m, annual precipitation is 76–81 cm, and the growing season varies between 120 and 140 days (Albert 1995).

Our study was conducted along six different roads penetrating northern hardwood stands. The dominant over-
story species in these stands included red maple (Acer rubrum), sugar maple (Acer saccharum), quaking aspen (Populus tremuloides), bigtooth aspen (Populus grandidentata), red oak (Quercus rubra), and paper birch (Betula papyrifera). Selection was the primary means of timber harvesting and was performed every 10 to 20 years. The six roads were unpaved, composed of sand, gravel or a mix of the two. Road width varied from 6.3 to 8.4 m (defined by maintenance boundaries), with a mean width of 6.98 m. We detected minimal road traffic throughout the sampling period, with an estimated 0–15 vehicles passing per day. Vehicle traffic observed included activity associated with logging and with hunting and other recreational uses.

**Collection of Field Data**

In the summer of 1997, we conducted a pilot study to examine the relationship between roads and plant distribution. We measured plant species cover in 1 × 1 m plots at varying distances from unpaved forest roads of different widths (1) to determine the minimum number of plots needed to detect most of the plant species present and (2) to establish the minimum distance at which we would study the interior community. The pilot study contained no replication or randomization.

We constructed a series of species-distance relationships based on pilot data to determine the depth to which sampling should extend. The most rapid change in species richness occurred within 30 m of the road, with new species detected at up to 145 m. These preliminary results indicated that the edge effects from roads were most prevalent near road sides and diminished along a gradient from the road edge into the forest. Consequently, we sampled 150 m from roads to ensure that we reached interior conditions. By randomizing the occurrence of species in the pilot study, we constructed a species-area curve to determine the number of plots needed for adequate sample size. Nine 1 × 1 m plots appeared adequate to detect at least 95% of species present. We used 10 replicated plots at each sampling distance. Using a stratified, random sampling design (i.e., randomized plot location at each distance), we sampled percent cover of the understory plants by species adjacent to unpaved roads in hardwood forests. We used ArcInfo geographic information system to examine land-cover maps and performed field checks to choose six different road sites where an area of 150 × 60 m could be sampled. We selected sites where a 100-m continuous hardwood buffer existed on all sides to minimize the edge effects of other landscape features such as clearcuts, large canopy gaps, or other roads.

We conducted field sampling beginning in mid-June and continuing through mid-August 1998 to avoid most seasonal variation. We sampled 11 distances from the roadside into the forest: 0, 5, 10, 15, 20, 30, 45, 60, 90, 120, and 150 m. More than 50% of the sampling plots were within 30 m of the road, where we expected the most dramatic edge effects. At each of the 11 distances we randomly placed 10, 1 × 1 m plots, 5 within 30 m on each side of the central transect. At each plot we recorded the percent cover of each understory species and other site characteristics, including litter depth, slope, aspect, percent canopy cover, litter, bare ground, stumps, and coarse woody debris.

**Data Analysis**

Using mean species abundance across the six sites, we calculated squared Euclidean distance (SED) to compare dissimilarity in species composition between two adjacent distances (Jongman et al. 1995) and to examine the possibility of a community shift between road vegetation and forest-interior species. The SED was calculated as the sum of the squared differences in mean species abundance, \( X_i \), between two adjacent distances, A and B:

\[
\text{SED} = \sum_{i=1}^{s} (\bar{X}_{iA} - \bar{X}_{iB})^2,
\]

where \( i \) is individual species, \( s \) is the total number of species, and \( p \) is the number of sampling points (plots per distance, i.e., 10). Values that fell outside the range of the mean and two standard deviations were considered significantly dissimilar from adjacent distance values.

We performed detrended correspondence analysis (DCA; Hill & Gauch 1980) on plant species and used PC-ORD (McCune & Mefford 1997) to determine whether distinct understory plant communities existed. Correlations were calculated between the DCA scores and the site variables to identify potential relationships. We divided species into five functional groups: exotic species, graminoids, herbs, shrubs, and understory trees. We plotted the DCA scores as an ordination diagram and examined them using 95% confidence ellipses drawn around each group.

To examine the effects of roads on site variables, we calculated means and plotted them against distance. This allowed us to graphically examine road effects on stand characteristics and to investigate gradients into the interior forest associated with road effects. We analyzed exotic species (Gleason & Cronquist 1991) independently from other species to determine whether roads facilitated the invasion of exotic species. We calculated the frequency and abundance of exotic species to investigate the possibility that these species compete with native plant species. We calculated species richness and the Shannon-Wiener Diversity index (\( H' \)) both with and without exotic species. The effects of roads on species richness and \( H' \) were tested by analysis of variance (ANOVA). We used the Student-Newman-Keuls (SNK) multiple-range test to investigate the relationships between richness and \( H' \) with distance from roads (Proc GLM, Statistical Analy-

To determine species preferences for road edge or forest interior, we calculated frequency relative to the total for each species by distance. Those with a ≥90% preference for sites ≤5 m from the roads were considered road-favoring species, and those with a ≥90% preference for sites ≥15 m from the roads were considered forest interior-favoring species. The 5- and 15-m distances were determined based on the presence of exotic species, $H'$, and richness scores, and on the depth of road effects on site variables.

**Results**

We identified 117 species in 660 plots in the six sites (species list is available from: http://research.eescience.utoledo.edu/lees/pubs/CB_02/watkins.pdf). We found 15 exotic species, all of which were detected on the roadside. Of these, 10 were found only within 5 m of the road, 4 penetrated up to 45 m, and 3 penetrated up to 60 m into the forest. Only 1 species, white clover (*Trifolium repens*), penetrated 150 m into the forest.

The SED values indicated a high dissimilarity in composition between 0 and 5 m, with borderline statistical significance (Fig. 1) but likely strong ecological significance. This dissimilarity value was higher than all other values, indicating a shift in the vegetation community between 0 and 5 m that was not found between any other adjacent distances.

Few differences were found among the functional groups of species (exotics, graminoids, herbs, shrubs, and trees), as indicated in the DCA (Fig. 2a). The confidence ellipses overlapped greatly, suggesting that no distinctive compositional groups existed. However, axis 2 of the ordination was positively correlated with amount of bare ground ($R^2 = 0.43$), and 13 of the 15 exotic species were positively correlated with increasing amounts of bare ground (Fig. 2b). The variation along axes 1 and 3 was not correlated with any of our measured site variables.

Canopy cover, litter cover, and bare ground exhibited the most noticeable spatial trends in relation to roads (Fig. 3). Mean canopy cover on the roadside (0 m) was approximately 60% and increased to about 90% at 15 m, at which point it leveled off at interior-forest conditions. Most variation in canopy cover occurred at the roadsides (Fig. 3a). Litter cover was lowest at the roadside (mean cover of approximately 45%) but displayed the greatest variation. Forest-interior conditions were reached within 5 m of the edge, where litter cover reached a mean of approximately 97% (Fig. 3b). Litter depth was also lowest at the roadside (mean depth just below 4 cm at 0 m) and leveled off at approximately 5 cm deep for all other distances exception of 10 m, where there was a spike in litter depth and large variation (Fig. 3c). The spike in litter depth at 10 m and its associated variation reflected the sampling of several plots that fell in unusually deep pits of forest litter and were not representative of litter on the landscape.

Coarse, woody debris cover (Fig. 3d) was lowest at the roadside (0 m), with approximately 1% cover. There was a spike at 15 m, with 5% cover, and a leveling off at 20 m, with approximately 4% cover. Variation for woody-debris cover was relatively consistent at all distances. Stump cover displayed no distinct trends (Fig. 3e). The percentage of bare ground per plot was highest and varied most at the roadside (0 m). The variation in amount of bare ground showed the range of possibilities in exposed soil along the roadside that was not found at any other distance. Values within the range of the standard deviation included 15% to 85%, with a mean of approximately 50%. Even the lowest value of 15% was substantially greater than the average amount of bare ground found at other distances. Forest-interior conditions for the bare-ground variable were reached by 5 m, where average bare-ground cover was near 0% (Fig. 3f).

There was an obvious change in total species richness with distance when all 117 species were included. When we removed the exotic species from the analysis, distance significantly affected species richness ($p = 0.0001$). We detected a drop in native species richness near the roadside based on the SNK multiple-range test (Fig. 4d), with plots at 0 m containing lower richness ($p = 0.0001$) than those at all other distances. No other differences ($p = 0.05$) among distances were found.

The $H'$ varied significantly with distance ($p = 0.0019$) when all species were included (Fig. 4c). The SNK multiple-range test indicated that $H'$ values at 0, 5, and 20 m were lower ($p = 0.0019$) than at 120 m, but differences in $H'$ between all other distances were not significant.

![Figure 1](attachment:image.jpg) **Figure 1.** Changes in squared Euclidean distance (SED) with distance from unpaved roads into forests. Higher SED values and variation ($2 \times SD$) were found near roads, suggesting that a community shift occurred between 0 and 5 m from the roads.
(Fig. 4c). We removed the exotic species and conducted the analysis again, which again revealed significant variation in $H'$ with distance ($p = 0.0001$). The $H'$ at 0 m was lower ($p = 0.0001$) than at all other distances except 5 and 20 m, whereas the $H'$ at distances of 5 and 20 m was lower ($p = 0.0001$) than at 120 m but similar to that at all other distances. These results showed that the $H'$ of native species was lowest at the roadside. Forest-interior values were reached by 5 m, where the $H'$ of native species was statistically the same ($p = 0.0001$) as at all other distances, excluding 120 m (Fig. 4f).

Distance from the road was a significant factor ($p = 0.0001$) influencing exotic-species richness. Exotic-species richness at 0 m was higher than at all other distances ($p = 0.0001$), but there were no differences in richness among the remaining distances (Fig 4b). Twenty nine percent of all detected species were graminoids, and 22% of detected graminoids were exotic species. The richness of graminoid species was higher at the roadside (0 m) and at 5 m, and the richness at 0 m was higher than at all other distances, including 5 m ($p = 0.0001$, Fig. 4e). Thus, we concluded that graminoid species exhibited a road preference particularly noticeable within 5 m of the roads.

Changes in the richness, frequency, and abundance of exotic species also indicated that a zone dominated by

Figure 2. The detrended correspondence analysis (DCA). (a) Ordination with 95% confidence ellipses around five functional groups: exotic species, graminoids, herbs, shrubs, and understory trees. (b) Species ordination: exotic species occurred at higher values of axis 1 and along a range of values on axis 2, which was positively correlated ($R^2 = 0.43$) with increasing amount of bare ground. Exotic species are circled. See http://research.eeescience.utoledo.edu/lees/pubs/CB_02/watkins.pdf for abbreviations used.
exotic species occurred within 5 m of roads. The frequency and abundance of the exotic species showed a noticeable road preference. Exotic species were most frequent within 15 m of the roads and displayed similar patterns of abundance, with abundance highest within 5 m of roads.

We determined the preferences of all species for roads or forest interior by calculating frequencies at each distance relative to the total frequency at all distances. Those exhibiting a 90% or greater frequency within the area ≤5 m from roads were considered to have a preference for the road edge. Twenty-five percent of all species (i.e., 29 species) exhibited this road-edge preference. Twelve percent of all species (i.e., 14 species) exhibited a preference for forest interior, defined as a ≥90% preference for areas ≥15 m from roads.

**Discussion**

The roadside (up to 5 m) supported a vegetation community different from that of the forest interior. In particular, 25% of all species occurred more frequently within 5 m of the roadside, and exotic species were much more prominent near roads in terms of both frequency and abundance (percent cover and relative frequency data are available from http://research.ees.utoledo.edu/lees/pubs/CB_02/watkins.pdf). Other stud-
ies of edge effects have shown similar results in which edges caused shifts in community composition (Ranney et al. 1981; Luken et al. 1991; Baker & Dillon 2000). The roadside edge has lower canopy cover, allowing more light to reach understory plants, which often results in a species composition different from that of the forest interior. For example, exotic plants are more numerous along roads with higher light availability (Parendes & Jones 2000). Lower litter cover and higher amounts of bare ground would also favor those plants that can withstand disturbance. The presence of exotic species has been linked to areas of site disturbance (Hobbs & Huenneke 1992; Tyser & Worley 1992; McIntyre & Lavorel 1994; Brososke et al. 1999), which appeared to be the case along the roads in our study.

In addition to supporting a distinctive compositional community, roads through northern hardwood forests in our study also altered the richness and diversity of native and exotic species (Brosotske et al. 2001). Road proximity was associated with a decrease in native species richness and $H'$ and an increase in the richness of exotic species, with effects of the road diminishing around 10 or 15 m. Heightened degrees of disturbance decrease native-species richness and increase exotic-species richness (McIntyre & Lavorel 1994), likely as a result of competition. Our results support this conclusion because native species richness was the lowest and exotic species richness the highest where disturbance was most prevalent (i.e., the roadside).

A common finding of other edge studies is an increase in total species richness near the edge (Gysel 1951; Brothers & Spingarn 1992; Euskirchen et al. 2001), which is

Figure 4. Changes in (a) total species richness, (b) exotic species richness, (c) Shannon-Wiener diversity ($H'$), (d) native species richness, (e) species richness of graminoids, and (f) native species $H'$ with distance from unpaved forest roads into the forest.
contrary to our findings. Although exotic-species richness increased near roads and native-species richness declined, total species richness did not change near the road. The disturbance level of roads is often relatively extreme and ongoing compared with that of clearcuts and other types of nonroad edges, suggesting that our findings are consistent with expectations related to the intermediate-disturbance hypothesis. Therefore, roads appear to constitute a different type of edge that has singular influences on the plant community.

Roads can act as conduits for plant dispersal (Wace 1977; Tyser & Worley 1992), and exotic species increase their range by spreading along roadsides (Schowalter 1988; Wilcox & Murphy 1989; Tyser & Worley 1992). In our study, exotic species were most prevalent near roadsides, where light availability and soil disturbance was high. This suggests that before exotic species can move from the roads and colonize the forest interior, disturbances may be required. If interior disturbances occur, roadsides may act as a source of exotic species, facilitating their colonization of the forest interior. In the H.J. Andrews Experimental Forest, Oregon (U.S.A.), exotic species are widespread along roadsides and in recent clearcuts (areas of high disturbance) adjacent to roads (Parendes & Jones 2000). The decrease in the richness or $H'$ of native species and the presence of exotic species should be noted by land managers. Managers should not include the area 5 m from the roadside when inventorying high-quality forest-interior habitat in this landscape.

High road density and broad distribution of roads may have compounded effects at the landscape level (Reed et al. 1996; Saunders et al. 2002). Organisms adapted to forest-interior conditions may have difficulties inhabiting this zone because of strong competition and environmental limitations, significantly reducing overall forest-interior habitat at the landscape level (Saunders et al. 2002). The decline in site variables, such as canopy cover, litter cover, and duff depth, near roadsides has been associated with declining richness in certain native macroinvertebrate fauna near roads (Haskell 2000). In addition, increased road density and the alteration of vegetative communities near roads may have untold and detrimental effects on organisms such as herptiles and birds. For instance, Findlay and Houlanan (1997) developed predictive models suggesting that increasing hard-surface roads by 2 m/ha would decrease herptile richness by 19% and bird species richness by 14% in Ontario wetlands.

If the disturbance associated with roads provides the factors leading to increased abundance of exotic species, forest managers should be aware of this road effect and strive to minimize road-associated disturbance on the landscape if exotic species are a concern. Road closures are part of the approach to achieving this goal. There is a time lag between road construction and road effects (Findlay & Bourdages 2000), however, suggest-

ing that even a closed road may continue to influence species composition for many years.

Although direct vehicle transportation is an important vector for plant dispersal along roads (Wace 1977; Schmidt 1998), the corridor of open forest canopy, which allows increased wind movement and penetration through the forest, is also important, especially for closed roads. This corridor through otherwise closed-canopy stands can provide an inlet for exotic species to invade the forest interior. In our study, exotic species were not limited to the roadside area but were found deeper (150 m) in the interior forest (Fig 4b.), although in fewer numbers and lower abundance. Away from roads, propagules may be spread by wildlife, wind, water, or continued anthropogenic influences (e.g., off-road vehicles, logging equipment, hikers), but the dispersal avenues are usually less direct, continuous, and facilitating. Roads appeared to facilitate the dispersal of exotic species, but their successful establishment and growth seemed to depend on the disturbance associated with, and found near—with 15 m of—the immediate roadside. Ultimately, the best way to limit the spread of exotic species associated with roads and avoid the high costs of complete restoration (road obliteration, replanting, and herbicide application) may be to minimize road densities on the landscape and avoid building new roads in otherwise undisturbed forest habitat.

We determined two levels of road influence. The first was the zone of influence of exotic species, where occurrences of exotic species were highest. The depth-of-edge influence for this area appeared to be limited to 5 m from the road. The other road influence occurred in the form of disturbance and increased light availability. This road-disturbance zone was greatest within 5 m but extended to 15 m, where interior conditions were reached.

Acknowledgments

Funding for this project was provided by a competitive grant (97–35101–4315) from the U.S. Department of Agriculture’s National Research Initiative, the Research Excellence Funds of Michigan, and the U.S. Forest Service’s North Central Research Station (23–94–12). We thank R. Bi, S. Holmes, and J. Steele, who assisted with field data collection, and the staff at the Chequamegon National Forest, who provided logistical support and assistance with plant identification. We also thank D. Flaspholher, J. Glime, E. Euskirchen, S. Saunders, D. Zheng, M. Jaiteh, L. Gerdes, members of the Landscape Ecology and Ecosystem Science Lab, W. Baker, and two anonymous reviewers who provided many helpful suggestions on the manuscript.

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