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Roads in northern hardwood forests affect adjacent plant communities and soil chemistry in proportion to the maintained roadside area

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HIGHLIGHTS

► Surface materials were transported distances in proportion to maintained roadside area.
► Pb, Cd, Cu, and Zn concentrations increased with greater traffic volume.
► Soils were more alkaline near the road and acidic in the adjacent native forest.
► Microtopography and direction of water flow defined plant communities.
► Native plants were more prevalent near gravel roads than highways.

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ABSTRACT

The spatial extent of the transported materials from three road types was studied in forest soil and vegetative communities in Vermont. Hypotheses were two-fold: 1) soil chemical concentrations above background environment would reflect traffic volume and road type (highway > 2-lane paved > gravel), and 2) plant communities close to the road and near roads with greater traffic will be disturbance-tolerant and adept at colonization. Soil samples were gathered from 12 randomly identified transects for each of three road types classified as “highway,” “two-lane paved,” and “gravel.” Using GIS mapping, transects were constructed perpendicular to the road, and samples were gathered at the shoulder, ditch, backslope, 10 m from the edge of the forest, and 50 m from road center. Sample locations were analyzed for a suite of soil elements and parameters, as well as percent area coverage by plant species. The main effects from roads depended on the construction modifications required for a roadway (i.e., vegetation clearing and topography modification). The cleared area defined the type of plant community and the distance that road pollutants travel. Secondarily, road presence affected soil chemistry. Metal concentrations (e.g., Pb, Cd, Cu, and Zn) correlated positively with road type. Proximity to all road types made the soils more alkaline (pH 7.7) relative to the acidic soil of the adjacent native forest (pH 5.6). Roadside microtopography had marked effects on the composition of plant communities based on the direction of water flow. Ditch areas supported wetland plant species, greater soil moisture and sulfur content, while plant communities closer to the road were characteristic of drier upland zones. The area beyond the edge of the forest did not appear to be affected chemically or physically by any of the road types, possibly due to the dense vegetation that typically develops outside of the managed right-of-way.

1. Introduction

Roads have varied ecological impacts on the adjacent plant and soil environment due to physical and chemical disturbances resulting from roadway construction, roadside maintenance, and vehicle emissions (Forman, 2000; Lee et al., 2012). The two main areas influenced by a road are the roadside right-of-way and vegetated region just beyond the right-of-way, which often consists of a semi-natural habitat with some native species (Trombulak and Frissell, 2000).

Roadway construction is a major disturbance that has direct and indirect impacts on plant communities and soil properties. The initial clearing for the road corridor during the construction phase typically establishes the base age of woody species (Spooner and Smallbone, 2008). Nearby vegetation has a large influence on the species richness of the vegetation that repopulates the cleared areas (Cilliers and Bredenkamp, 1999; Sullivan et al., 2009; Wardle et al., 2004). Site

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grading during the clearing process alters the hydrology of the roadside environment, resulting in channelization of streams, draining of wetlands, or development of new hydrologic zones which can create or destroy habitat for various plants (Forman and Deblinger, 2000; Gobel et al., 2006; Jodoin et al., 2008). Finally, as the road base is built up, large quantities of material are imported, creating a source of mineral material unique to the local environment that may contribute to subsequent chemical disturbances (Auerbach et al., 1997).

In addition to the initial physical disturbance from the construction of the road, vehicular traffic and regular maintenance of the road and right-of-way cause recurring physical disturbance that may benefit introduced species (Pickering and Hill, 2007). Regular annual mowing will select for plants that seed earlier in the season (prior to the mowing date) and plants with a lower growth habit (Grime, 1977). Vehicle-generated wind currents can act as dispersal agents for certain species of plants (Sahlodin et al., 2007; Sullivan et al., 2009), sometimes spreading invasive species (Jodoin et al., 2008; Venner, 2006). Mobilized dust in wind currents can travel for hundreds of meters, settle on plants, and interfere with photosynthesis and transpiration (Auerbach et al., 1997).

The roadside environment is also influenced by chemical disturbances. Though most reports investigated chemical disturbance from recurring processes such as dust deposition, road salt, and exhaust (Auerbach et al., 1997; Cape et al., 2004), roads also have initial chemical impacts due to leaching of new construction material. The first flush of chemicals from a new road may contribute to the current chemical levels if compounds are retained in the soil (Azizian et al., 2003). Acute chemical disturbances can also occur after a road is constructed through accidental spills of hazardous materials or passenger vehicle accidents that leak materials (Forman et al., 2003).

Road dust and seasonal salt applications are important contributors to recurring chemical disturbances that continuously impact plant communities and soil health. Road dust is composed of finely ground minerals of the road's parent material. If a road base is calcareous (particularly with gravel roads), the resulting dust can significantly change the pH next to the road and alter the availability of micronutrients (Auerbach et al., 1997). The road dust can contain ground particles of tires, brake lining, and asphalt. When distributed to the roadside environment, these materials can increase concentrations of metals, particularly zinc (Adachi and Tainosho, 2004). In areas with snow, highway departments apply road salt seasonally to reduce ice and allow faster and safer movement of vehicles. This salt is transported to roadside soil during winter when large particles are dispersed off the road by vehicles, or in spring thaws when salt goes into solution during transport with melted snow (Gobel et al., 2006). Salt in the roadside environment can cause water stress in plants, and, if washed from the soil by precipitation, it will travel great distances through surface aquatic systems and potentially to large bodies of water (Forman and Deblinger, 2000).

While there have been studies investigating different aspects of the roadside environment, there is a paucity of environmental impact data available for rural forest ecosystems in northern latitudes necessary for accurate transportation system models. This study describes impacts of roads on plant communities and soil chemical readings at various distances from three road types. Our hypotheses were two-fold: 1) soil chemical concentrations above background environment would reflect traffic volume and road type (highway > two-lane paved > gravel), and 2) plant communities close to a road and adjacent roads with greater traffic will be disturbance-tolerant and adept at colonization.

2. Materials and methods

The study was conducted in Chittenden County, Vermont, USA. The forests within the study areas are generally classified as Northern Hardwood Forests and White Pine Northern Hardwood Forests (Eyre, 1980; Thompson and Sorenson, 2005). Sample sites were located throughout Muddy Brook (8262 ha centered at 44°24′34″ N 73°08′00″ W) and Allen Brook (2900 ha centered at 44°25′28″ N 73°04′01″ W) watersheds in mostly rural residential areas (Fitzgerald and Parker, 2009).

2.1. Site selection

All potential sampling sites were identified using aerial photography in Google™ Earth version 6.03.2197 to locate sections of forest that covered an area at least 100 m perpendicular to the road, and extending at least 100 m in each direction parallel to the road. Large sections of forest were used as possible study locations so that samples would be unaffected by edge effects of fields, development, or other roads. A distance of 100 m from the road was selected because other studies have found that the maximum dust and pollution attenuation occurs within that distance (Tamm and Troedsson, 1955; Yin et al., 2011). Transects that encompassed a gradient of distance from the road were created to quantify the distribution of transported materials originating from the road. The forest boundary was defined by an abrupt change in canopy cover where tree trunks were greater than 8 cm diameter at breast height (DBH) adjacent to an open area such as a road, field, or development (Little, 1979). Data were recorded describing the road profile, composition of plant communities, and geographic coordinates using a Trimble GeoXH® (Sunnyvale, CA) global positioning system (GPS).

After general sampling areas were identified, a measuring wheel and GPS were used to record possible sample locations at the study sites. From the edge of the forest, 100 m lengths were measured parallel to the road. The distance was chosen to insure independence among transects by avoiding overlap or interference. At each 100 m length, a potential sampling site GPS position was recorded. Twelve actual sample locations per each of three road types were selected from the potential sample sites using a random sequence generator (Haahr, 2009) to minimize bias. These GPS points recorded by the ground survey were loaded into ESRI ArcMap software for analysis with other map layers.

The sampling strategy within the transect was adapted from a study of roadside vegetation in Terra Nova National Park which defined modified roadway zones as the shoulder, sideslope, ditch, backslope, and native vegetation (Karim and Mallik, 2008). The shoulder is located next to the driving surface of the road, and the sideslope is the adjacent area built up during road construction to support the main road surface. The ditch is a low point that carries away water from the road surface, and the backslope is the cleared area that maintains ditch functions. These features are common on the three road types in this study, classified broadly as 'highways,' 'two-lane paved,' and 'gravel' which correspond approximately with the Federal Highway Administration's classification of arterial, collector and local (USDOT, 2011).

2.2. Road attributes

Three different road types, delineated by road surface, had significantly different Average Annual Daily Trips (AADT) and roadside dimensions (Fig. 1). Highways had the greatest AADT value (mean ± 1 SD: 31,158 ± 3624 vehicles day^{-1}), almost by an order of magnitude over two-lane paved roads (3868 ± 3389 vehicles day^{-1}) which, in turn, had an AADT value an order of magnitude greater than gravel roads (287 ± 181 vehicles day^{-1}) (Sullivan, personal communication; VTrans, 2010). The three road types shared similar topographic features (i.e., shoulder, sideslope, ditch, and backslope), but features on highways were larger and cleared to a much greater extent than gravel roads. Two-lane paved roads had intermediate sizes of topographical features (Fig. 1). Gravel roads were oldest, at a mean of 152 years,

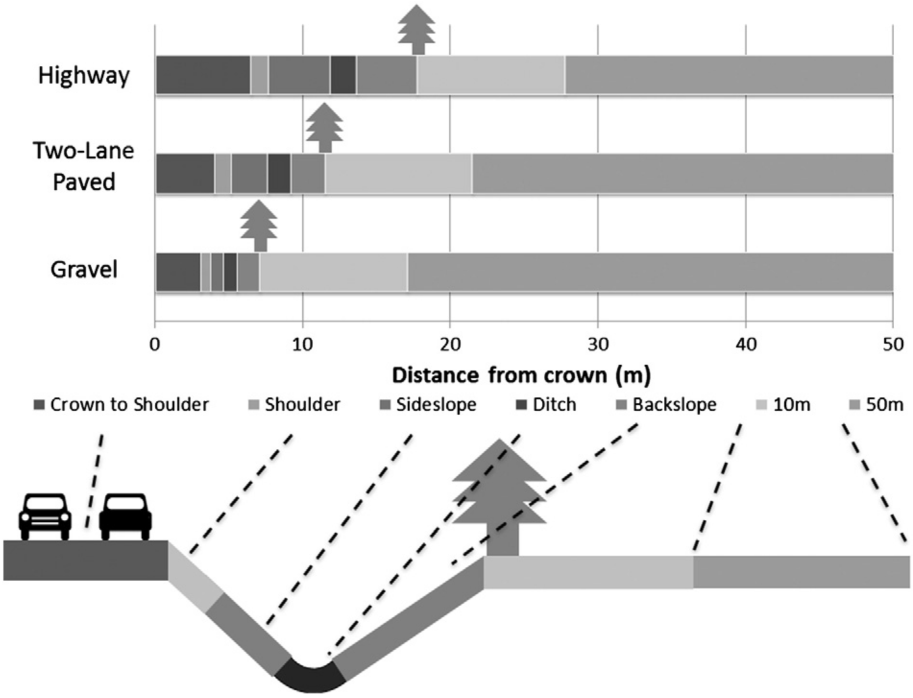

Fig. 1. Measured dimensions of roadside microtopography. Tree icon represents the edge of the forest defined as visually in line, and parallel the road, with the first tree > 8 cm diameter at breast height (DBH). The road crown (0 m) represents the effective 'center' of each road type.

followed by two-lane paved roads and highways, at 135 and 47 years old, respectively (Vermont Department of Motor Vehicles, 2010).

2.3. Data collection and road maintenance

Road attribute data were collected through database mining and interviews with public works officials (J. Cota, personal communication; USDOT, 2010; VTrans, 2010). Quantities of winter maintenance products applied to the road were determined by auditing the mean mass of product purchased for the past ten years to account for annual weather differences and carryover of product from year to year. The mean mass of product purchased was divided by the length of applicable roads in a maintenance jurisdiction to estimate kilograms per meter of chemical application. Sodium chloride (NaCl) and pickled sand (5% by mass NaCl to prevent caking) are products used by the Vermont Agency of Transportation, Vermont municipalities, and many other highway departments in the US to maintain safe winter driving conditions. It was assumed for calculation purposes that all roads receive pickled sand, only two-lane paved roads and highways receive NaCl, and only gravel roads receive calcium chloride ($CaCl_2$) dust suppressant, as this is the standard practice in the area. These products were not necessarily applied evenly across all road surfaces in the district; in practice they are applied as the conditions of the road warrant (J. Cota, personal communication). However, for analysis purposes, we assumed even product distribution.

Soil samples were collected from the twelve transects for three road types, at the center of the six microtopographic locations for a total of 216 samples from 11 May to 3 June 2009. At the predetermined location, leaf duff and plant debris were removed to expose the organic (O2) horizon, containing only well-decomposed organic matter and mineral soil.

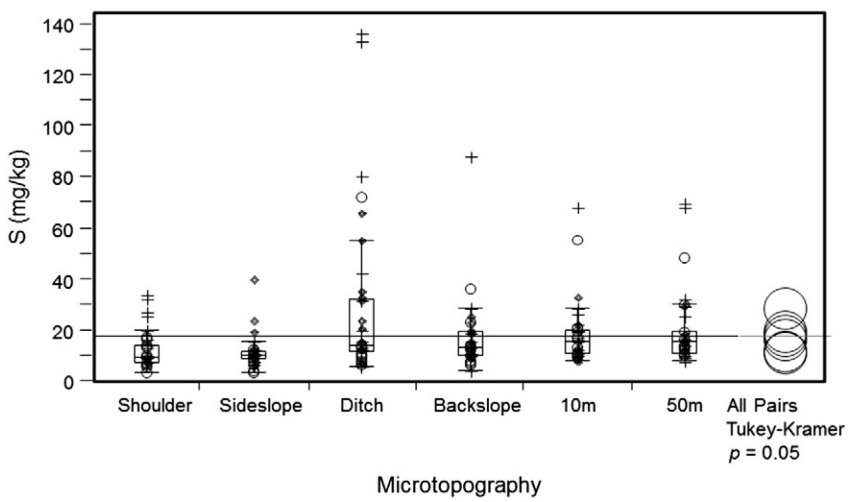

Fig. 2. Sulfur concentration as a function of microtopography category among three road types (○: Gravel, +: Two-Lane Paved, ◊: Interstate Highway). Box plots represent the 10%, 25%, median, 75%, and 90% quantiles. Circles represent significance of the Tukey–Kramer HSD test. Circles for means that are significantly different either do not intersect or intersect slightly so that the outside angle of intersection is less than 90°.

Two soil cores were collected using a bulk density probe (AMS Inc., 5.08 cm diameter, 7.62 cm length) at 1 m on either side of the predetermined location parallel to the road. Each of these soil cores was ejected into a plastic bag, labeled and stored at 4 °C until processed. Bulk density was also determined as grams per cubic centimeter. The soil samples were prepared for chemical analysis by air-drying and passing through a 2-mm sieve. Large aggregates that did not pass through the sieve were ground in a mortar and pestle and returned to the 2-mm sieve. The mass of gravel particles larger than 2-mm was recorded.

Soil nutrients were extracted for analysis using a Modified Morgan method (Lunt et al., 1950; Morgan, 1941), the regional standard for acidic spodosols. Roadside soils were analyzed from solution analysis by inductively coupled plasma mass spectrometry (ICP) for plant-available elements to explore the relationship between roadside micronutrient levels and plant distribution. Elements included phosphorus (P), potassium (K), magnesium (Mg), aluminum (Al), calcium (Ca), zinc (Zn), sulfur (S), manganese (Mn), boron (B), copper (Cu), iron (Fe), sodium (Na), lead (Pb), nickel (Ni), cadmium (Cd), and chromium (Cr). Cation exchange capacity (CEC) and cation ratios of calcium, potassium and magnesium (%Ca, %K, %Mg) were also analyzed (Martin and Kopp, 1994). The pH was determined using a Mehlich buffer method with water (Mehlich, 1976). The percent organic matter (%OM) was determined by loss on ignition and converted to a Walkley–Black equivalence (Walkley and Black, 1934). Quality control and quality assurance were achieved by including an internal standard reference material in each batch of 20 samples, replicating 10% of samples, and correcting output for calibration and reagent blanks (Hoskins, 2006).

The GPS was used to return to the same locations for sampling of herbaceous vegetation between 16 June and 25 August 2009. A flexible hoop encircling one square meter was placed on top of vegetation next to the GPS position where soil was gathered. The number of unique plant species was recorded, as well as the percentage of ground area covered by each of those species. Non-vegetative coverage was recorded as *leaf duff* or *bare soil*. Reference objects were held at arm's length to gauge percent coverage. Shrub data were only collected at the backslope, 10 m, and 50 m microtopographic areas because shrubs were not present at other locations, given the annual road maintenance. Shrubs that were within a 10 m^2 sweep were quantified and identified. A professional forester analyzed tree species along each transect at the 10 m and 50 m sites. A 10× prism plot was used at each location to determine the basal area of the tree by species. The sites were then categorized using a Society of American Foresters classification system (Eyre, 1980).

Two-way analysis of variance (ANOVA) was performed to determine the effects of road type and microtopography on a range of dependent variables: average annual daily trips (AADT), road age, NaCl application, average vehicular speed, soil chemical properties, and coverage by herbaceous wetland plants and native species. Tukey–Kramer Honestly Significant Difference (HSD) tests were performed as post-hoc tests to identify pairs where statistically significant differences occurred. Chemistry data were transformed as a normal standardized distribution within each microtopographic category for all road types prior to analysis. ANOVA and mean comparisons were computed using JMP version 8.0.2 software by SAS Institute Inc. (Cary, NC).

3. Results

3.1. Soil chemistry and road type

Values for pH and %Ca decreased with more heavily used roads (Table 1). Gravel roads had the greatest pH values and %Ca and highways had the smallest pH values and %Ca. Two-lane paved roads were at intermediate levels compared to the other two. The metals Zn, Cu, Pb, and Cd all increased with road use intensity (Table 1).

3.2. Soil chemistry and distance from road

Soil pH, bulk density, Ca, Zn, %Ca, and mass of gravel (soil particles >2 mm) all exhibited a similar trend with the greatest values close to

Table 1
Mean (±1 SE) values of soil components from all three road types and five microtopography positions within those road types. Road types or microtopography with contrasting symbols of uppercase and lowercase, respectively, were statistically different ($p<0.05$).

	Road type (all microtopography)			Microtopography (all road types)					
Sample size	N=72	N=72	N=72	N=36	N=36	N=36	N=36	N=36	N=36
Component	Highway	2-Lane paved	Gravel	Shoulder	Sideslope	Ditch	Backslope	10 m*	50 m**
>2 mm (g/cm^3)	0.19 ± 0.02^A	0.30 ± 0.03^B	0.38 ± 0.04^B	0.58 ± 0.05^a	0.45 ± 0.04^b	0.32 ± 0.03^c	0.22 ± 0.03^c	0.09 ± 0.01^d	0.08 ± 0.01^d
Moisture (%)	46.6 ± 3.6^A	53.7 ± 9.9^A	34.8 ± 3.9^A	10.4 ± 0.9^a	20.8 ± 1.6^{ab}	53.5 ± 9.0^{bc}	59.6 ± 11.5^c	60.1 ± 10.0^c	65.2 ± 10.1^c
Bulk density (g/cm^3)	0.94 ± 0.03^A	0.94 ± 0.04^A	1.01 ± 0.05^A	1.37 ± 0.03^a	1.18 ± 0.03^b	0.99 ± 0.05^c	0.84 ± 0.05^{cd}	0.70 ± 0.03^d	$0.70\pm.04^d$
pH	6.7 ± 0.1^A	6.9 ± 0.1^{AB}	7.2 ± 0.1^B	7.8 ± 0.1^a	7.7 ± 0.0^{ab}	7.2 ± 0.1^{bc}	7.0 ± 0.1^c	5.9 ± 0.2^d	5.9 ± 0.2^d
Organic matter (%)	6.4 ± 0.4^A	8.7 ± 1.6^A	6.3 ± 0.9^A	2.4 ± 0.3^a	3.1 ± 0.3^{ab}	5.7 ± 1.0^{ab}	8.1 ± 1.1^{bc}	12.1 ± 1.9^c	11.9 ± 2.7^c
Available P (mg/kg)	4.6 ± 2.2^A	4.1 ± 0.7^A	3.1 ± 0.5^A	2.8 ± 0.3^a	3.0 ± 0.3^a	3.1 ± 0.8^a	3.2 ± 0.4^a	7.0 ± 3.9^a	4.1 ± 1.5^a
K (mg/kg)	54.1 ± 3.1^A	68.8 ± 8.9^A	62.85 ± 4.9^A	24.7 ± 1.4^a	38.5 ± 3.1^{ab}	56.1 ± 6.9^{bc}	80.8 ± 8.4^{cd}	84.2 ± 8.4^{cd}	87.4 ± 14.5^d
Mg (mg/kg)	189 ± 12.2^A	177 ± 16.0^A	206 ± 17.2^A	135 ± 10.8^a	148 ± 13.6^a	194 ± 15.7^{ab}	234 ± 27.6^b	203 ± 17.0^{ab}	240 ± 38.7^{ab}
Al (mg/kg)	22.2 ± 2.8^A	28.5 ± 6.7^A	22.2 ± 4.0^A	7.8 ± 1.1^a	6.03 ± 0.7^a	14.3 ± 2.9^a	17.5 ± 3.5^a	60.8 ± 10.8^b	41.0 ± 7.4^b
Ca (100 mg/kg)	22 ± 1.3^A	50 ± 7.6^A	146 ± 18.0^B	141 ± 26.5^a	102 ± 23.0^{ab}	89 ± 19.3^{abc}	57 ± 13.8^{bcd}	28 ± 5.1^{cd}	24 ± 3.5^d
Zn (mg/kg)	5.7 ± 0.7^A	4.8 ± 0.7^A	1.4 ± 0.1^B	8.9 ± 1.5^a	4.3 ± 0.6^b	3.5 ± 0.8^b	2.2 ± 0.3^b	2.5 ± 0.4^b	2.2 ± 0.7^b
S (mg/kg)	16.6 ± 1.4^A	22.8 ± 3.3^B	12.9 ± 1.3^A	12.3 ± 1.4^a	10.9 ± 1.0^a	28.7 ± 5.4^b	16.6 ± 2.5^a	18.1 ± 2.0^{ab}	15.8 ± 2.5^{ab}
Mn (mg/kg)	26.9 ± 2.9^A	27.0 ± 3.5^A	35.9 ± 2.3^B	25.0 ± 3.1^a	24.7 ± 2.8^a	37.3 ± 4.6^a	32.7 ± 6.2^a	29.3 ± 3.0^a	30.8 ± 3.1^a
B (mg/kg)	0.24 ± 0.02^A	0.38 ± 0.04^B	0.30 ± 0.03^{AB}	0.26 ± 0.02^a	0.38 ± 0.03^a	0.31 ± 0.03^a	0.36 ± 0.04^a	0.26 ± 0.06^a	0.28 ± 0.06^a
Cu (mg/kg)	0.50 ± 0.07^A	0.48 ± 0.12^{AB}	0.26 ± 0.02^B	1.21 ± 0.23^a	0.46 ± 0.06^b	0.36 ± 0.054^b	0.16 ± 0.01^b	$0.17\pm.022^b$	0.15 ± 0.04^b
Fe (mg/kg)	9.5 ± 1.69^A	11.7 ± 3.14^A	9.7 ± 1.4^A	11.0 ± 1.9^{ab}	5.5 ± 1.1^a	11.0 ± 2.8^{ab}	4.8 ± 0.9^a	18.8 ± 5.2^{ab}	10.4 ± 3.2^b
Na (mg/kg)	84 ± 12.1^A	260 ± 61.4^B	53 ± 10.8^A	90 ± 23.9^a	161 ± 18.5^a	212 ± 91.3^a	198 ± 63.6^a	56 ± 21.8^a	26 ± 4.4^a
Pb (mg/kg)	6.0 ± 1.0^A	8.2 ± 4.1A	0.8 ± 0.1^A	5.2 ± 1.9^a	5.4 ± 1.6^a	2.7 ± 0.6^a	1.7 ± 0.3^a	5.7 ± 3.8^a	10.3 ± 9.2^a
Ni (mg/kg)	0.25 ± 0.02^A	0.15 ± 0.01^B	0.13 ± 0.01^B	0.20 ± 0.02^{ab}	0.17 ± 0.02^a	0.26 ± 0.04^b	0.13 ± 0.01^a	0.17 ± 0.02^{ab}	0.13 ± 0.01^a
Cd (mg/kg)	0.11 ± 0.01^A	0.06 ± 0.01^B	0.04 ± 0.00^C	0.04 ± 0.01^a	0.07 ± 0.01^a	0.06 ± 0.01^a	0.06 ± 0.01^a	0.08 ± 0.01^a	0.08 ± 0.01^a
Cr (mg/kg)	0.08 ± 0.00^A	0.07 ± 0.00^A	0.08 ± 0.00^A	0.09 ± 0.00^a	0.08 ± 0.01^a	0.09 ± 0.00^a	0.08 ± 0.01^a	0.07 ± 0.00^a	0.08 ± 0.01^a
CEC [cmol(±)/kg]	18.5 ± 1.8^A	29.6 ± 3.7^A	76.9 ± 8.9^B	71.6 ± 13.3^a	52.4 ± 11.5^{ab}	48.1 ± 9.5^{ab}	30.8 ± 7.0^b	26.6 ± 3.2^b	24.1 ± 3.1^b
%Ca	72.7 ± 3.6^A	77.1 ± 4.0^A	86.1 ± 2.8^A	95.8 ± 0.6^a	93.3 ± 0.7^{ab}	84.6 ± 3.7^{ab}	85.3 ± 1.5^b	53.3 ± 6.4^c	56.7 ± 7.4^c
%K	2.2 ± 0.4^A	1.6 ± 0.3^{AB}	1.0 ± 0.2^B	0.3 ± 0.1^a	0.6 ± 0.1^{ab}	1.0 ± 0.3^b	1.2 ± 0.1^c	3.3 ± 0.6^c	3.3 ± 0.7^c
%Mg	11.5 ± 0.5^A	7.2 ± 0.5^B	5.5 ± 0.6^B	3.9 ± 0.6^a	6.1 ± 0.7^{ab}	7.5 ± 0.9^{bc}	9.9 ± 0.8^c	10.5 ± 0.8^c	12.2 ± 0.8^c

* 10 m from edge of forest.
** 50 m from road center.

the road, and decreasing with distance from the road (Table 1). Other soil components (soil moisture, %OM, K, Mg, Al, %K, and %Mg) showed the opposite trend, with smaller values close to the road and values increasing with distance from the road (Table 1). Sulfur was one unique topography-dependent element exhibiting no gradient with the road, but a greater concentration and greater variability in the ditch (Fig. 2). Mean S levels in the ditch were greater than the shoulder, sideslope and backslope (Table 1). There was a positive relationship between the application of winter maintenance materials (sand and salt) and an increase in P, Al, and B at the shoulder and sideslope.

Two-lane paved roads received more direct NaCl de-icing product, compared to highways ($p<0.0001$). Gravel roads did not receive direct applications of NaCl. Highways and two-lane paved roads received similar levels of pickled sand (8.5 kg m^{-1} yr^{-1} and 8.8 kg m^{-1} yr^{-1}, respectively) ($p=0.4607$), but both were greater than the gravel roads (6.6 kg m^{-1} yr^{-1}) ($p<0.0001$). Including all sources of NaCl (direct applications of NaCl and pickled sand), two-lane paved roads received the most (19.0 kg m^{-1} yr^{-1}) ($p<0.0001$), highways the second most (14.1 kg m^{-1} yr^{-1}) ($p<0.0001$), and gravel roads received the least (1.0 kg m^{-1} yr^{-1}) NaCl ($p<0.0001$). The majority of the NaCl contribution was from NaCl de-icing salt. In addition to NaCl, gravel roads received liquid 35% solution calcium chloride ($CaCl_2$) to suppress dust and bind small particles during the summer months (2.0 L m^{-1} yr^{-1}), but no other road types received this treatment.

3.3. Vegetation and road type

The effects of road type on vegetation were related through the scale of the microtopographic features, which then defined vegetation habitat and annual maintenance procedures. The low mean coverage of noxious weeds (<4%) demonstrated no apparent relationship between the presence of noxious weeds and road use intensity, despite other studies indicating that roadsides should be a pathway for invasive plants (Lelong et al., 2007; Maheu-Giroux and de Blois, 2007). However, the frequency of *Phalaris arundinacea* L. (reed canarygrass), a moisture-loving grass species on the Vermont invasive watch list (but not a Class B noxious weed), differed among road types ($p=0.0101$; USDA, NRCS, 2012). This grass was most frequent on two-lane paved roads and was found most commonly in the sideslope and ditch. More herbaceous species were classified as obligate upland plants at the highway, compared to the gravel roads ($p=0.0023$).

3.4. Vegetation and distance from road

Microtopography played a large role in predicting the presence of native or introduced species, as well as plants with an affinity for moisture-rich soil. Generally, more introduced species were established at the shoulder and gradually diminished with greater distance from the road. Native species showed the reverse trend, with fewer natives at the shoulder and gradually increasing toward the 50 m sites (Fig. 3). This effect was significant for the two-lane paved roads and highways ($p\leq0.0001$), but not for the gravel roads ($p=0.0533$). More obligate wetland plants and facultative wetland plants were established in ditches, and close to ditches (Fig. 4). Upland plants and facultative upland plants were most prevalent near the shoulder. Richness, diversity, and number of individual native or introduced herb or shrub species were similar among road types ($p>0.15$).

4. Discussion

In comparison to our hypothesis that distance of chemical disturbance would vary depending on road type, we found that roads alter the roadside plant composition and soil chemistry, primarily due to the proximity from the road and microtopography of the right-of-way. The magnitude of these effects is determined by road type confounded with traffic volume and area cleared for the road corridor. Based on our study of herbaceous plants and soil chemistry, effects from roads were not apparent beyond the forest edge, suggesting that buffer zones of vegetation mitigate airborne chemicals and other road effects. However, it is possible that a future study of lichen or nematode communities would illuminate subtle roadside effects of traffic beyond the forest edge (Walker and Everett, 1987; McCune, 1988; Neher, 2001; Wardle et al., 2004).

Transition zones, particularly the edge of the backslope and the edge of the forest, are important determinants of plant composition and other road effects. Qualitative field observations suggested that the forest edge creates a "wall" of shrubby vegetation utilizing high light availability and low disturbance from mowing. A greater richness and diversity of shrub species at the backslope location compared to 10 m and 50 m sites support the hypothesis that these shrubs are responding to greater resource availability as well. These shrubs physically separate the roadside environment from forest

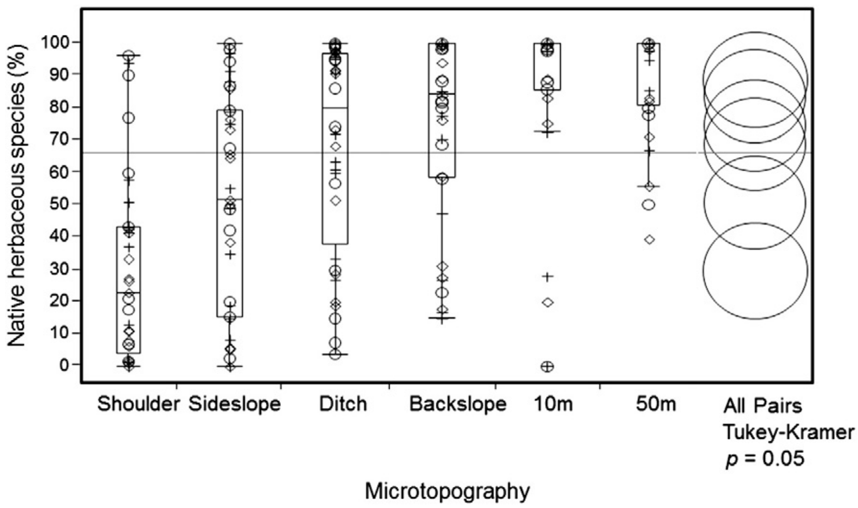

Fig. 3. Native herbaceous species as a function of microtopography category among three road types (○: Gravel, +: Two-Lane Paved, ◊: Interstate Highway). Circles represent significance of the Tukey–Kramer HSD test. Circles for means that are significantly different either do not intersect or intersect slightly so that the outside angle of intersection is less than 90°.

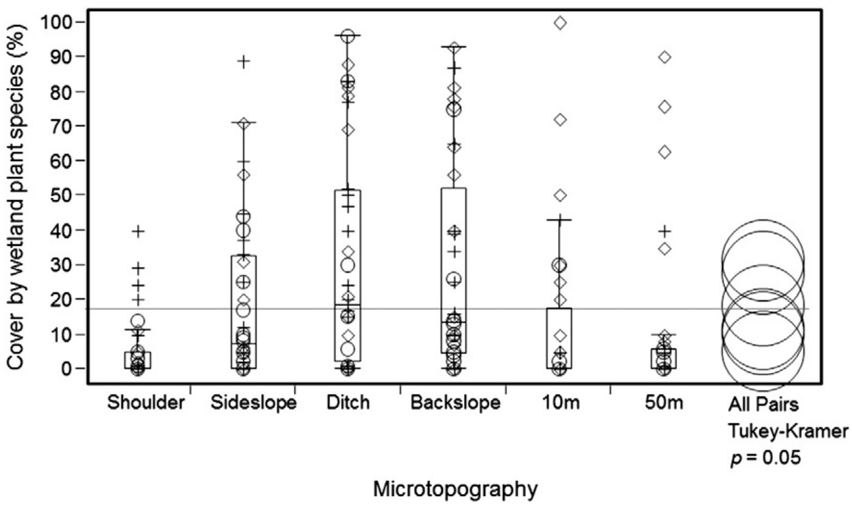

Fig. 4. Land coverage by facultative/obligate wetland plant species as a function of microtopography category among three road types (○: Gravel, +: Two-Lane Paved, ◊: Interstate Highway). Circles represent significance of the Tukey–Kramer HSD test. Circles for means that are significantly different either do not intersect or intersect slightly so that the outside angle of intersection is less than 90°.

environment and likely isolate the interior forest from roadside light and dust.

4.1. Soil chemistry and road type

The positive relationship of metals (i.e., Zn, Cu, Pb, and Cd) to road type is likely due to traffic volume causing greater brake pad and tire material degrading on vehicles during regular operation (Kummer et al, 2009; Lagerwerff and Specht, 1970). These metals are found in brake lining, oil, tires, fuel, and other vehicle parts, which deteriorate and release metal to the roadside environment that can then be detected in roadside soil (Davis et al., 2001). Though Pb was used as a gasoline additive in Vermont from 1920 to 1986, Pb levels next to the road do not appear to be related to the age of the road. Rather, Pb levels are related to AADT, suggesting that the Pb may have originated from fuel impurities, degrading vehicle parts, and from older, resuspended road dust (Kummer et al., 2009; Mielke et al., 2011).

4.2. Soil chemistry and distance from road

Soil pH became more alkaline with closer proximity to roads. Levels of Ca relate to breakdown of road surface and distribution of road particles through dust. Therefore, it seems logical that Ca concentrations were greatest near the road edge extending to the backslope of gravel roads, and to a lesser extent paved road types (which often have a gravel shoulder). Similarly, pH and road distance were related in another study conducted in a wetland environment, where pH differences were attributed to water flow through a calcareous road base (Campbell, 1993). While the road base likely contributed to changes in pH, our results suggested that dry deposition of road dust was also a factor in changes to soil pH. Some road dust originates from winter sand applications, but also from soil particles tracked from gravel roads to paved roads on tires (Forman et al., 2003). This is similar to other studies that found some increased pH values at the roadside (Lee et al., 2012). The presence or absence of a forest has a stronger effect on pH and most other soil chemistry, albeit auto-correlated with the distance from the road.

The transition from forest soil conditions to roadside soil conditions occurs at the backslope, and we see that the closer a sample site was to the forest, the more it was similar to forest conditions. Sites within the forest and some backslope sites had greater organic matter content, likely due to contribution of leaf litter, which covers the majority of forest sample areas and is not subject to disturbance. The organic matter content, as well as shade from forests, contributes to relatively high soil moisture measured in the forest, yet the soil does not remain saturated. Ditch areas, by contrast, remain saturated and, thus, support wetland species.

4.3. Vegetation and road type

Our data support our hypothesis that more native plants are observed near gravel roads than two-lane paved or highways. One-time physical clearing for a roadway, and annual maintenance required for particular road type, both contribute to the magnitude of impact on vegetation structure. The right-of-way zone influences exposure to sunlight because these areas are cleared during construction and managed with mowing to maintain visibility by preventing the encroachment of the forest. The large expanse of consistently cleared highway roadside appears to select for introduced species, which are more tolerant of mowing disturbance and, possibly, chemical disturbance (Grime, 1977; Western and Juvik, 1983). There are likely more occurrences of *Sonchus*, *Bromus*, *Equisetum*, *Vicia*, *Galium*, *Festuca*, *Elocharis*, and *Onoclea* species at highway sites due to the high availability of light and the yearly mowing maintenance (Magee and Ahles, 2007; Tilman, 1984; USDA, NRCS, 2012). These plants utilize greater micronutrient levels available at the roadside driven by neutral pH values. The introduced species are likely adapted to conditions of high resource availability compared with native plants (Grime, 1977; Lee et al., 2012).

Not only are the highway roadsides more suitable habitat for particular introduced species and grasses, but a wider cleared right-of-way for the highway also results in a larger total area covered by these species (McKinney and Lockwood, 1999; Christen and Matlack, 2006). The right-of-way for gravel roads is narrower, rarely mowed, and closer in proximity to the native forest, providing less total area with selective pressures that favor introduced species and grasses (Grime, 1998).

4.4. Vegetation and distance from road

Road type also impacts the plant communities, with a greater proportion of native plants associated to gravel roads compared with the highway. The reason for this difference relates back to the scale of microtopographic areas. All microtopographic sample points along gravel roads were within two or 3 m of each other because the features were much smaller and spatially closer to the forest ecosystem than paved roads. Thus, the forest ecosystem has more influence on gravel roadside environments compared with highway roadside environments based on proximity. Highway microtopography covers a larger area, and is more influenced by the open roadside areas rather than the adjacent forest.

Other studies have shown significant differences in road effects with the presence of a vegetation buffer (Kirchner et al., 2005). Similarly, the backslope and forest edge are important transition zones. Increased shade and greater organic matter from leaf duff at the backslope are likely contributing to a larger percentage of native plants and species which are more similar to the forest community (Supplementary data, Table S1). The 10 m and 50 m sites are similar in plant composition, indicating that at some point beyond the edge-effect zone of the forest (between the backslope and 10 m from the forest edge), the plant community stabilizes and represents native communities. Greater representation of native plants at farther distances from a road was consistent with other studies (Gelbard and Harrison, 2003). Forest sites appear to be influenced greatly by high shade, leaf duff, moisture, and low disturbance afforded by an established forest.

An interesting observation was that topography of the roadside areas determined the incidence of upland and wetland plant species. The topography of a roadside creates wet soils in the ditch because water is collected from road surfaces as well as sources away from the road, and subsurface flow is impeded by compaction (Lee et al., 2012). High incidence of obligate wetland and facultative wetland plant species in the ditch, as well as high soil S content, a product of anaerobic reduction–oxidation reactions in saturated soil, follow from frequent saturation of the ditch. Upland plants are well represented across all road types at the shoulder and sideslope because the design of a road requires that these features be elevated and drain well. Highways had the greatest coverage of upland plants, which reflects the open, dry, well-drained nature of these sample areas.

According to our study, there were no secondary effects of roads because understory herbaceous plants were unaffected by soil chemistry. Rather, the presence or the absence of forest and proximity to a road seemed to have the largest effect. It is likely that organic matter differences at the road edge are due to both a decrease in contribution of forest leaf litter, and an increase in disturbance (Haskell, 2000). Soils in forest sites have the opposite conditions and a higher percent organic matter. Analysis of the relationship between nematode communities and plant communities might provide more insight into the interrelationship between plant coverage and soil conditions (Neher, 2001; Wardle et al., 2004).

5. Conclusions

This research supported findings that within an established forest environment, the use-intensity effects of roads on soil and vegetation were contained within the corresponding right-of-way (Lee et al., 2012). Increased traffic contributed to higher levels of metals in roadside soil, but these effects did not extend past the forest edge. However, more traffic was correlated positively with wider maintained roadside areas, so the forest edge was effectively farther back compared to lesser-used roads.

Maintained roadside area width was the most significant factor responsible for the roadside environment's deviation from native plant and soil composition. Large maintained areas close to the road were more similar to grassland communities than they were to native forest communities. Plants at the edge of the forest grow in response to increased resource availability and buffer the interior forest from roadside effects.

To reduce impacts of roads, the width of cleared area should be reduced and traffic consolidated to fewer individual vehicles on the road. The forest edge should be cultivated to maximize the insulating effect and maintain low-resource-adapted native plant communities within the forest. By reducing the transportation system's physical footprint and cultivating native vegetation borders, it may be possible to maintain natural plant communities and stem the introduction of chemicals into the environment.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.scitotenv.2013.01.062.

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