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Spatial Extent of the Impact of Transported Road Materials on the Ecological Function of Forested Landscapes

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A Report from the University of Vermont Transportation Research Center

Spatial Extent of the Impact of Transported Road Materials on the Ecological Function of Forested Landscapes

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Spatial Extent of the Impact of Transported Road Materials on the Ecological Function of Forested Landscapes

UVM Transportation Research Center

August 17, 2012

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Disclaimer

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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 deposition. 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 [1].

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 [2]. Nearby vegetation has a large influence on the species richness of the vegetation that repopulates the cleared areas [3,4,5] Site 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 [6,7,8]. 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 later chemical disturbances [9].

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 causes recurring physical disturbance. 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 [10]. Vehicle-generated wind currents can act as dispersal agents for certain species of plants [5,11], sometimes spreading invasive species [8,12]. Mobilized dust in wind currents can travel for hundreds of meters, settle on plants, and interfere with photosynthesis and transpiration [9], which could select for species more tolerant or adapted to this roadside situation.

The roadside environment is also influenced by chemical disturbances, which primarily impact the soil, and indirectly impact vegetation. Though most reports investigate chemical disturbance from recurring processes such as dust deposition, road salt, and exhaust [9,13], 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 levels of chemicals in roadside soils if the particular compound is retained in the soil [14]. Acute chemical disturbance can also occur after a road is constructed through accidental spills of hazardous materials or passenger vehicle accidents may leak materials [15].

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 that, in turn, alters the availability of micronutrients [9]. On asphalt roads, the dust can contain ground particles of tires, brake lining, and asphalt. When distributed to the roadside environment, these materials can contribute to higher levels of heavy metals, particularly zinc [16]. 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 knocked off the road by vehicles, or in spring thaws when salt goes into solution during transport with melted snow [7]. 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 [6].

While there have been studies investigating different aspects of the roadside environment, there is a need for research in forest ecosystems and for development of methods to predict roadside environmental conditions with distance and road use intensity. This study determines how roads within a northern hardwood forest change the native plant and soil conditions at various distances from the road. It also provides a method to predict plant and soil conditions based on traffic volume. The study makes an important contribution to our understanding of plant-soil interactions, as influenced by roadside conditions. Specifically, the objective of this study was to determine the spatial extent of the effects of the road and these transported materials on forest plant communities, soil chemistry, and soil nematode communities immediately surrounding roadways broadly classified as 'highways,' 'two-lane paved,' and 'gravel' which correspond roughly with the Federal Highway Administration's classification of arterial, collector and local [17]. We propose to use nematodes as bioindicators because of their ubiquity, known response to chemical and physical perturbations to soil and water, and current consideration in regional and national monitoring programs. They integrate chemical and physical properties and the microbial community at lower positions in the food chain [18].

2. Research Methodology

The study was conducted in Chittenden County, Vermont, in the Northeastern U.S., where deicing salts are spread regularly on roads during winter months. Land cover in the state of Vermont is dominated by forest (approximately 75%), and many of the forested areas are directly connected with the roadways. The forests within study areas are generally classified as Northern Hardwood Forests and White Pine Northern Hardwood Forests [19, 20]. Sample sites were located throughout Muddy Brook (8,262 ha) and Allen Brook (2,900 ha) watersheds (Fig. 2-1) in mostly rural residential areas [21].

These locations were chosen to co-locate our study with a concurrent study by a team of aquatic ecologists investigating water quality, stream integrity and water pollutant load in relation to road type and road traffic density. The long-term goal was to link the watershed results with roadside results.

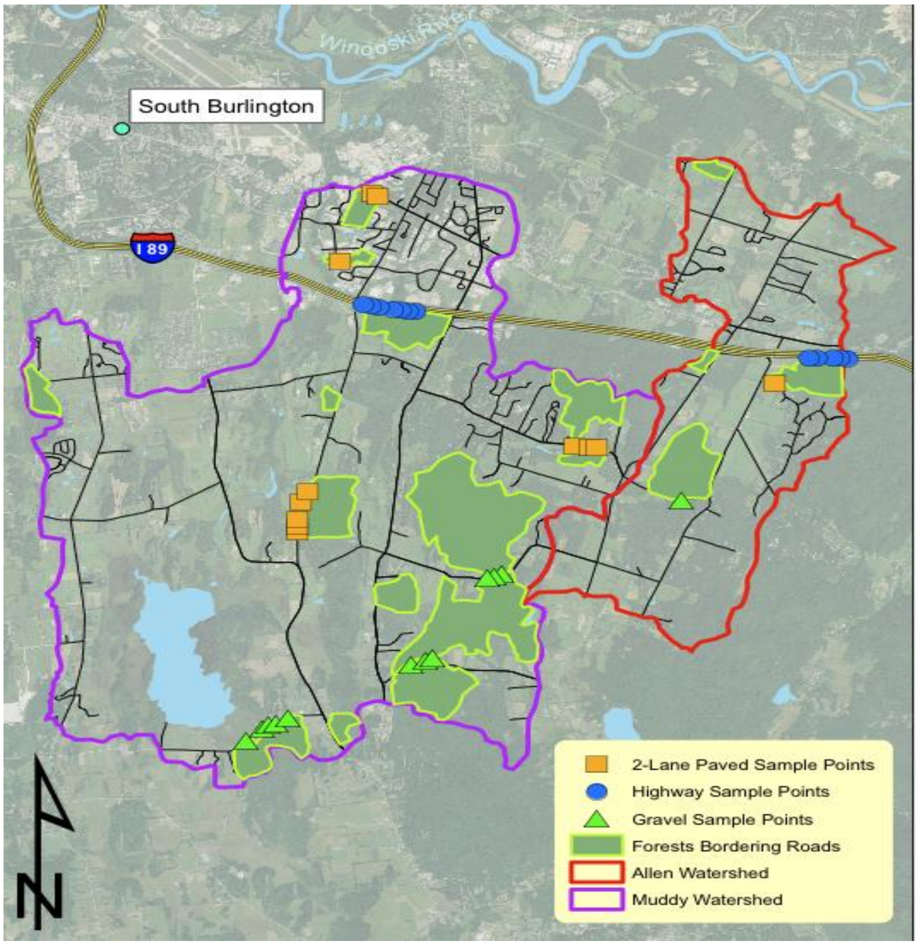


Figure 2-1. Map of watersheds and sampling locations for this study. Photo Credit D. Asmussen.

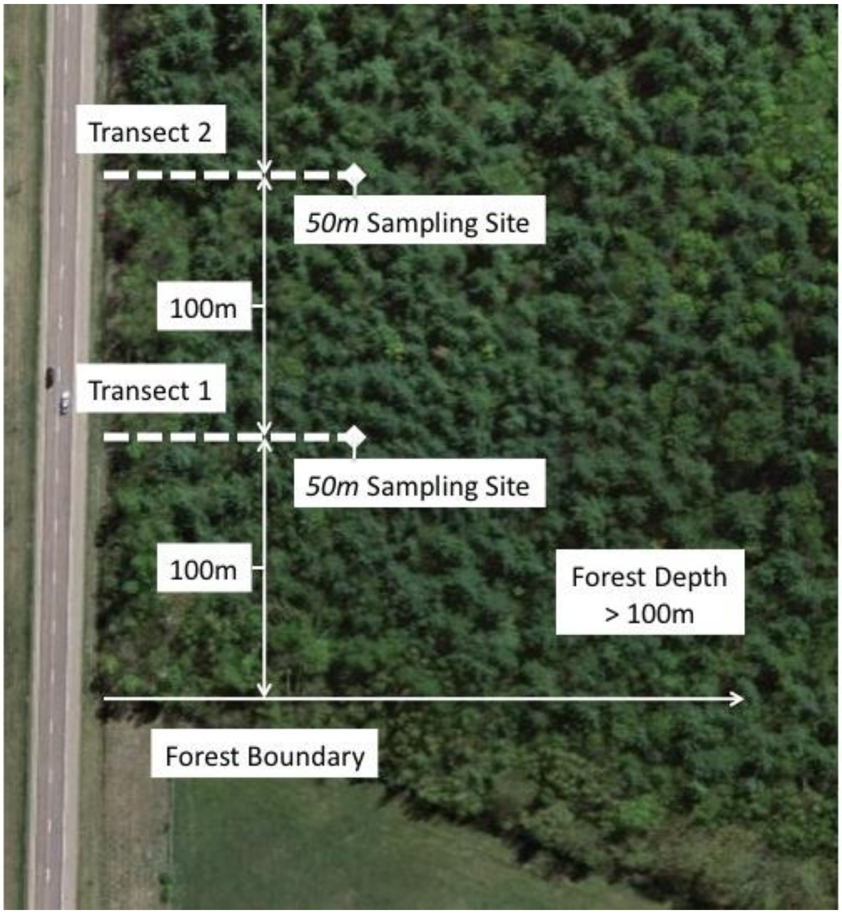


Figure 2-2. Transect layout.

2.1 Site Selection

Potential sampling sites were determined 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 200 m parallel to the road (Fig. 2-2). The distance was chosen to insure independence among transects by avoid overlap or interference. Ten locations were chosen for each road type from the potential sample sites using a random sequence generator [22] to minimize bias. These GPS points recorded by the ground survey were loaded into ESRI ArcMap program for analysis with other map layers.

The sampling strategy within a transect was adapted from a study of roadside vegetation in Terra Nova National Park that defined modified roadway zones as the shoulder, sideslope, ditch, backslope, and native vegetation [23]. 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.

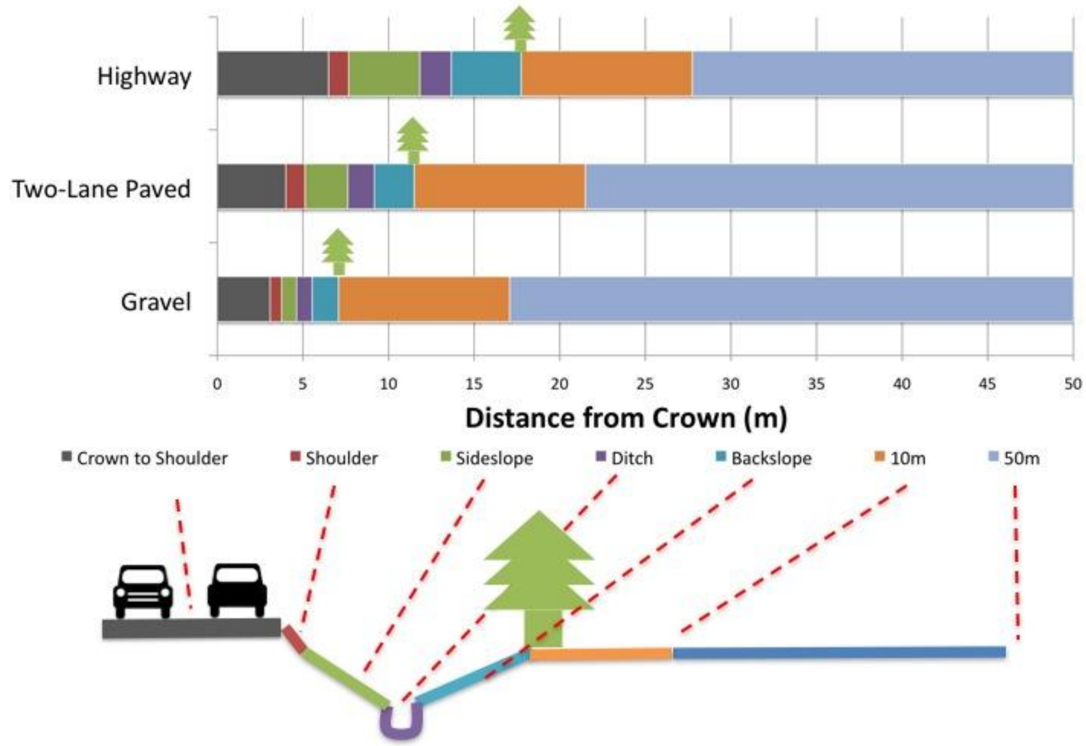


Figure 2-3. Measured Dimensions of Roadside Microtopography. Tree icon represents the edge of the forest which was defined as visually in line, and parallel the road, with he first tree > 8 cm diameter at breast height (DBH). The road crown (0m) is effectively the center of each road type.

2.2 Data Collection

Soil samples were collected from the three road types, at the center of the six microtopographic locations from 11 May to 3 June 2009. Samples were taken at six categorical distances based upon roadside micro-topography along each transect: a) the road shoulder edge; b) the middle of the sideslope; c) the ditch trough ; d) the middle of the backslope ; e) 10 meters into the forest from the forest edge ; f) and 50 meters from road crown (Fig. 2-3). In sum, 216 samples (3 road types x 12 transects x 6 distances) were taken to analyze chemical and physical soil properties. In addition, soil nematode communities were taken along 10 of the 12 transects totally 180 samples. In the forest, leaf duff and large woody debris were gently removed to reveal the organic horizon (O2) before sampling.

2.2.1 Soil Chemistry. At each sampling location, two soil cores were collected using an intact soil corer (5 cm diameter, 7.6 cm length) at 1 m on either side of the predetermined location parallel to the road. Each of these soil cores were placed in a plastic bag, labeled and stored at 4 °C until they could be processed. The samples were air-dried and passed through a 2-mm sieve prior to analysis.

Soil nutrients were extracted for analysis using a Modified Morgan method [24, 25]. Roadside soils were analyzed for nutrients, including available 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), chromium (Cr), cation exchange capacity (CEC) and cation ratios of calcium, potassium and magnesium (% Ca, % K, % Mg). The pH was determined using a Mehlich buffer method with water. CEC was calculated from the % Ca, % K and % Mg. The percent organic matter (% OM) was determined by loss on ignition and converted to a Walkley-Black equivalence [26]. Chemical analysis was performed at the University of Vermont Agricultural and Environmental Testing Lab (http://www.uvm.edu/pss/ag_testing/).

2.2.2 Soil Biology. Nematodes were collected using a Dutch soil auger (5-cm diameter) to the depth of 30-cm, or as deep as possible in the case of compaction or gravel. An Oakfield probe was highly ineffective with roadside soils due to compaction and the high content of large rocks and gravel. Each nematode sample was a composite of five soil cores taken approximately one meter apart (one pace), in a line parallel to the road and perpendicular to the transect (one on the transect and two in either direction from the transect). Given the roadside conditions, some shoulder samples required more than five cores to obtain an equivalent volume of soil to reduce any bias associated with sampling effort or volume.

Soil nematode samples were mixed in a bucket, and approximately 600 g were then placed in plastic resealable bags and stored in an insulated container to maintain field temperatures and moisture. In the laboratory, soil samples were stored at 16° C in a mechanical convection incubator until soil extraction was completed.

Nematodes were extracted from 200 cm^3 of each soil sample using a modified Cobb's decanting and sieving method [27], followed by cotton-wool filter extraction method tray [28] for 48 hrs. To extract nematodes, the soil sample was mixed with tap water to suspend the nematodes. The soil slurry was passed through progressively finer mesh sieves (with sieve sizes mesh size 600, 250, 150, 75, 44 μm), 3 times for each sieve. The nematodes and some soil debris were caught on the sieves, and each time after sieving gently back-washed into a metal basin using a mister. Lastly, the content of the metal basin, which contained the nematodes, was poured over a cotton filter. Nematodes were identified to genus and genera were assigned to trophic groups (algal feeders, bacterivores, fungivores, plant-parasites, omnivores, and predators) according to Yeates et al. [29].

2.2.3 Vegetation. GPS coordinates were used to enable 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 the shoulder, sideslope, or ditch, 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 (Appendix 1). A 10x 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 [19].

2.2.4 Road Attributes. Road attribute data (e.g., daily traffic, age of the road) were collected through database mining and interviews with Public Works officials [J. Cota personal communication, [31, 31]]. 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 yearly weather differences and carryover of product from year to year. The average mass of product purchased was divided by the length of applicable roads in a maintenance jurisdiction to get a kilogram per meter estimation of chemical application. It is assumed for calculation purposes that all roads receive pickled sand, only two-lane paved roads and highways receive sodium chloride (NaCl), and only gravel roads receive calcium chloride ($CaCl_2$) dust suppressant. These products are not necessarily applied evenly across all miles of roads in the district; in practice they are applied as the conditions of the road warrant [J. Cota, personal communication]. However, for analysis purposes, we assume even product distribution.

2.3 Analytical Methodology

Nematode community composition was quantified using three complementary indices: 1) maturity which is a measure of ecological succession, 2) trophic diversity that measures the complexity of food webs, and 3) ratio of fungivorious to bacterivorous nematodes that reflects the dominant decomposition pathway. This suite of indices was chosen because they were complementary in characterizing the condition of soil food webs [18].

A 3-way analysis of variance (ANOVA) using the GLM procedure, with LSMEANS, utilizing type III sum of squares was used to determine whether soil chemistry, physical properties, or nematode communities varied by topography, road type and road distance. Means comparisons of nematode samples were computed as orthogonal contrasts, and chemistry samples by a Tukey-Kramer Honestly Significant Difference (HSD). Data were analyzed using the statistical program SAS Version 9.3 (SAS Institute Inc., Cary, NC).

3. Results

The main ecological effects from roads on vegetation appears to be related to construction modifications required for a roadway (i.e., vegetation clearing and topography modification). The spatial extent of these modifications was correlated positively with road use intensity. Highways have the greatest ecological impact and gravel roads the least impact. The cleared area defined the type of plant community and the distance that road pollutants travel. Secondarily, road presence affected soil chemistry. Heavy metals (e.g., Pb, Cd, Cu, and Zn) correlated positively with road use intensity. In contrast, gravel roads have higher calcium content in nearby soil when compared to other road types (Fig. 3-1). Proximity to all road types made the soils more alkaline relative to the acidic soil of the adjacent native forest (Table 3-1).

Microtopography next to the road had marked effects on the composition of plant communities based on the direction of water flow. Ditch areas supported wetland plants, and had 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.

Soil chemistry and physical properties displayed a few general patterns (Table 3-2). One common pattern was higher values closer to the road and with increasing road use intensity class. This included lead (Pb), which had greatest mean values near the shoulder and in the case of highway roads (Fig. 3-1). Spatial patterns of zinc (Zn) and copper (Cu) were similar to Pb, with concentrations greatest near the roadside and with most intense road use. A second common pattern was higher values at greater distances from the road which included organic matter, cation exchange capacity and nutrients.

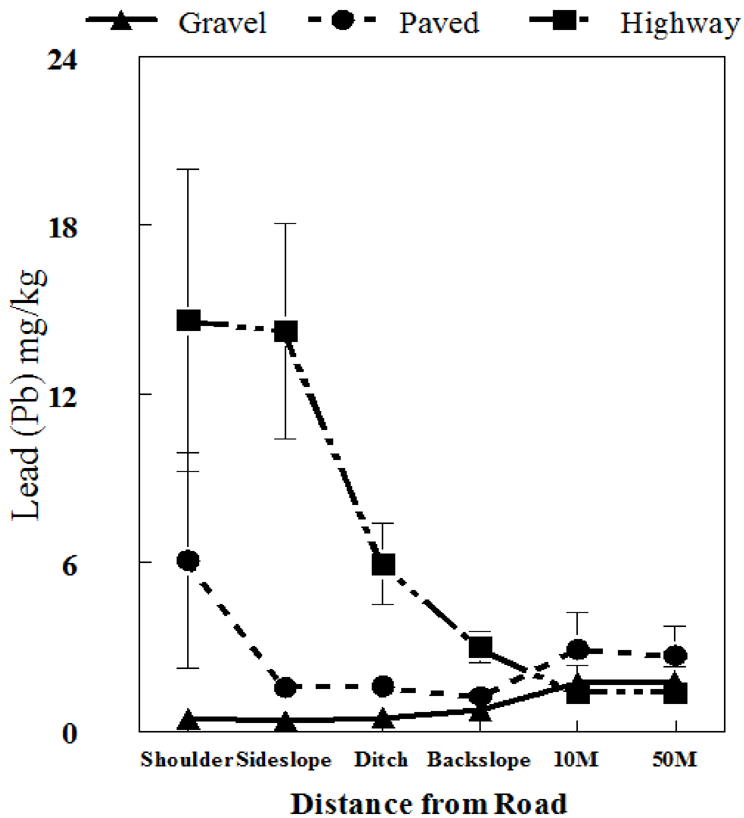


Figure 3-1. Mean levels of lead (mg/kg) in roadside soil based upon categorical distance from road. Error bars represent standard error. Paved refers to 2-lane paved roads. 10M is 10 meters into the forest from the forest edge, and 50M is 50 meters from the road crown.

A second group of measurements also had higher values near the road, but with highest values in the case of gravel roads, and lowest in the case of highways (Table 3-1). Mean calcium (Ca) values were greatest in gravel road samples near the roadside, with 2-lane paved roads being second highest, and highway samples smallest (Fig. 3-3). Calcium varied by road type, distance and topography, as well as interaction term of road and distance (all cases $p < 0.0001$).

Similar to Ca, pH exhibited higher means near the shoulder with gravel roads, however the differences between the road types was not as pronounced. As expected, gravel roads also had the highest amount of rocky debris (particles >2mm), particularly in cases of the sideslope and ditch. Mean bulk density was greatest near the roadside and decreased with distance. There was an interaction by road type and topography with 2-lane paved and highway alternating as the smallest means, but the overall trend showed higher gravel bulk density in the sideslope, ditch and backslope, and convergence at 50m. Percent clay was also highest in the case of gravel roads, particularly at the shoulder and in case of up-sloping transects.

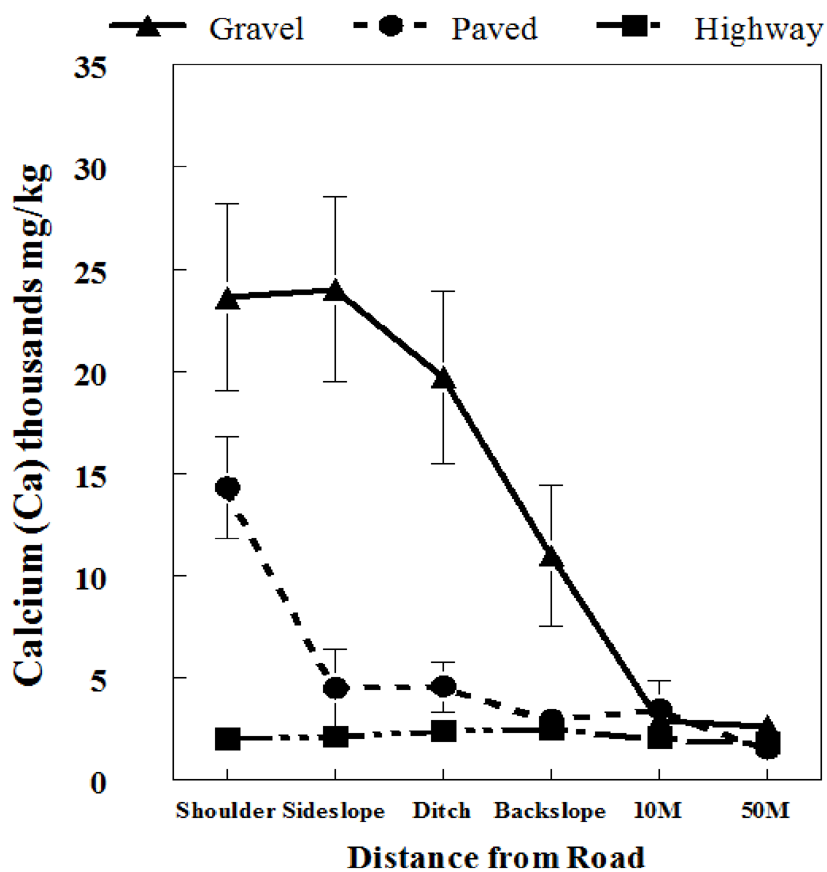


Figure 3-2. Mean levels of calcium (mg/kg) in roadside soil based upon categorical distance from road. Error bars represent standard error. Paved refers to 2-lane paved roads. 10M is 10 meters into the forest from the forest edge, and 50M is 50 meters from the road.

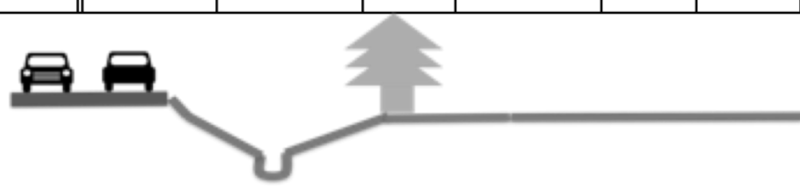
Table 3-1. Soil properties for each of three road types that correspond with increase travel intensity: gravel, two-laned paved, and highway.

Soil Component	Road Type 1	>=<	Road Type 2	p-value
% Organic Matter	Gravel	<	Two-Lane Paved	0.0304
	Two-Lane Paved	=	Highway	0.2553
	Highway	>	Gravel	0.0001
Nickel	Gravel	=	Two-Lane Paved	0.2898
	Two-Lane Paved	<	Highway	0.0001
	Highway	>	Gravel	0.0001
% Potassium	Gravel	=	Two-Lane Paved	0.0752
	Two-Lane Paved	<	Highway	0.0484
	Highway	>	Gravel	0.0001
% Magnesium	Gravel	=	Two-Lane Paved	0.1005
	Two-Lane Paved	<	Highway	0.0001
	Highway	>	Gravel	0.0001
Calcium	Gravel	>	Two-Lane Paved	0.0001
	Two-Lane Paved	=	Highway	0.0769
	Highway	<	Gravel	0.0001
Manganese	Gravel	>	Two-Lane Paved	0.0001
	Two-Lane Paved	=	Highway	0.9981
	Highway	<	Gravel	0.0001

Table 3-2. Mean values of soil component from all road types separated into components that decrease with distance from the road, and those that increase with distance from the road. Metrics not listed had a less defined gradient

High  **Low**

Soil Component	Shoulder	Sideslope	Ditch	Backslope	10m	50m	ANOVA *p*-value std err
>2mm (g/cm^3)	0.59	0.45	0.32	0.22	0.09	0.07	<0.0001 0.029
Bulk Density (g/cm^3)	1.37	1.78	0.99	0.84	0.70	0.68	<0.0001 0.039
pH	7.76	7.70	7.22	6.93	5.88	5.64	<0.0001 0.120
Ca (mg/kg)	13324	10213	8905	5484	2826	1996	<0.0001 1638.929
Zn (mg/kg)	9.04	4.34	3.49	2.24	2.50	2.41	<0.0001 0.721



Low  **High**

Soil Component	Shoulder	Sideslope	Ditch	Backslope	10m	50m	ANOVA *p*-value std err
Organic Matter (%)	2.57	3.13	5.73	8.09	12.12	12.13	<0.0001 1.297
K (mg/kg)	24.47	38.47	56.11	81.28	84.22	88.31	<0.0001 7.225
Mg (mg/kg)	137.7	147.6	193.9	229.0	202.8	200.4	<0.0079 19.608
Al (mg/kg)	7.78	6.03	14.33	19.11	60.78	72.36	<0.0001 6.952
Moisture (%)	10.1	20.8	53.5	59.4	60.1	69.5	<0.0001 8.526
CEC (cmol+/kg)	6.47	8.05	12.36	19.00	27.41	26.80	<0.0001 2.583

Sodium concentration, as well as electrical conductivity (EC), exhibited a unique pattern. Sodium (Na) was highest in 2-lane paved soil samples, specifically at the ditch and backslope (Fig. 3-3).

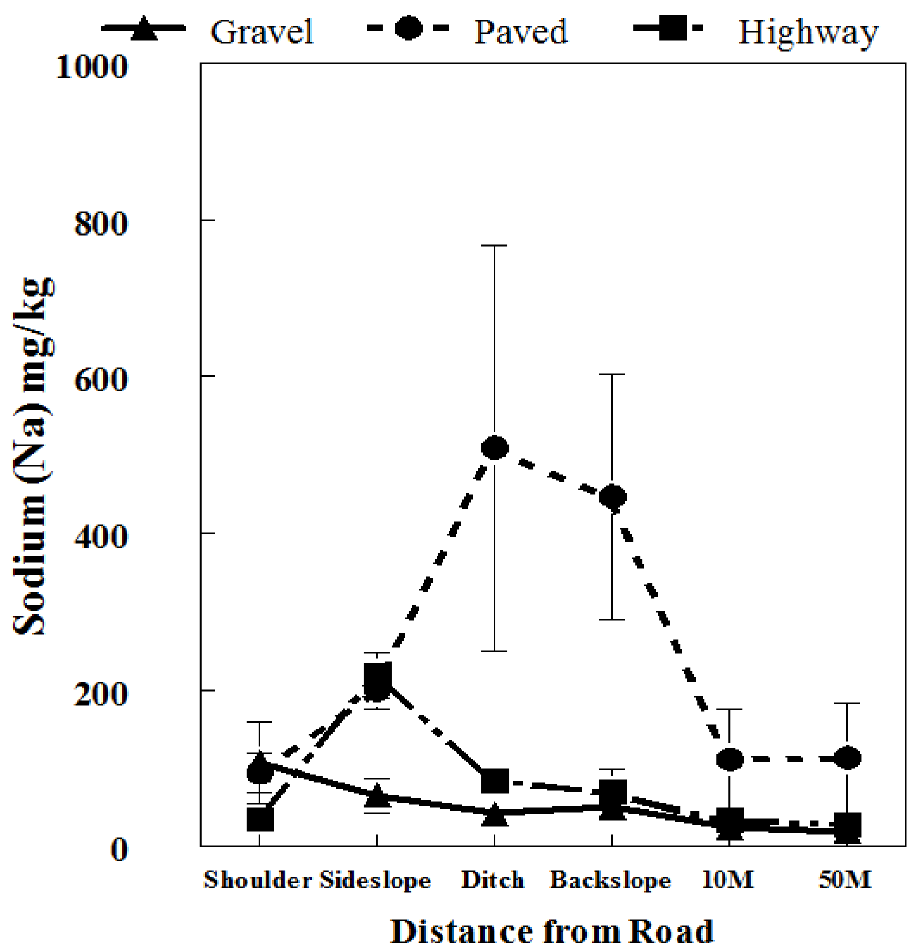


Figure 3-3. Mean levels of sodium (mg/kg) in roadside soil based upon categorical distance from road. Error bars represent standard error. Paved refers to 2-lane paved roads. 10M is 10 meters into the forest from the forest edge, and 50M is 50 meters from the road.

Nematodes. The nematode community proved to be a useful bioindicator of soil condition. A total of 119 genera were identified in the entire data set (Appendix 2). The range of samples contained between 0 and 37 genera, while the average number of genera across all samples (richness) was 18.8. Over the entire data set there was only one algal feeder found, 36 bacterivore genera, 21 fungivore genera, 29 plant-parasitic genera, 11 omnivore genera, 20 predator genera. Values of the MI were greater for highway than paved or gravel regardless of distance from the road (Fig 3-4). Values were lower near than further from the road

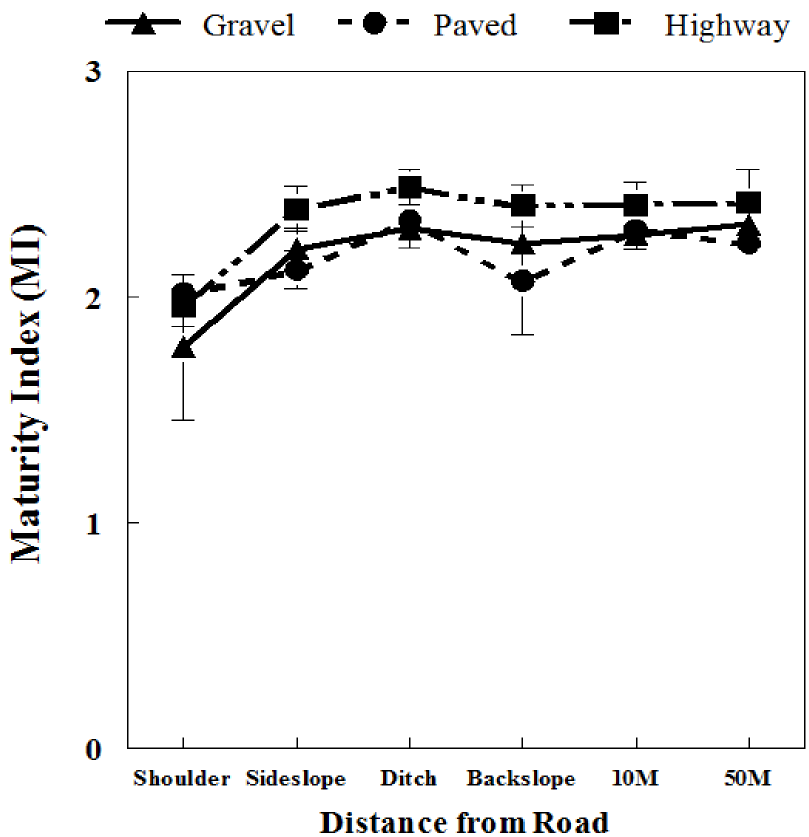


Figure 3-4. Mean Maturity index of nematode communities in roadside soil based upon categorical distance from road. Error bars represent standard error. Paved refers to 2-lane paved roads. 10M is 10 meters into the forest from the forest edge, and 50M is 50 meters from the road.

Reflective of the trends with bacterivore and fungivore fractions, the overall trend in the *F:F+B* ratio was least nearest the roadside and increased with distance from the road (Figure 3-5). Interestingly, the 2-lane paved roads had consistently lower ratios than both gravel and highway roads. The means were significantly different by road type and distance ($p < 0.0001$).

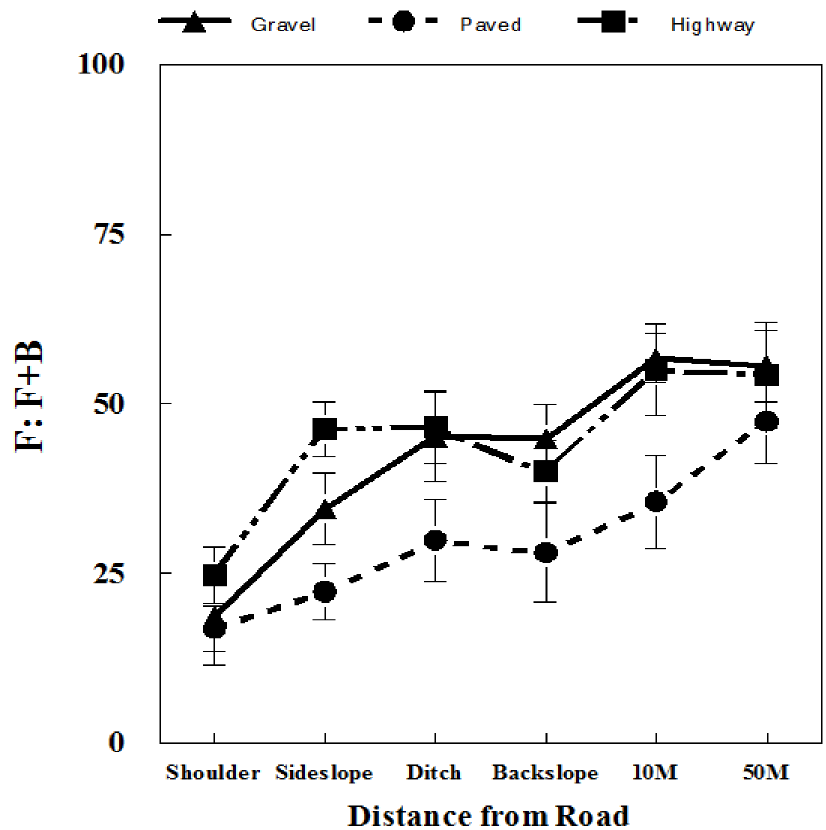


Figure 3-5. Mean ratio of fungal feeding to fungal and bacterial feeding nematodes in roadside soil based upon categorical distance from road. Error bars represent standard error. Paved refers to 2-lane paved roads. 10M is 10 meters into the forest from the forest edge, and 50M is 50 meters from the road.\

4. Implementation/Tech Transfer

This research is part of the University of Vermont Transportation Center Signature Project entitled "Integrated Land-use, Transportation and Environmental Modeling: Complex Systems Approaches and Advanced Policy Applications", into which the results of this research will eventually be incorporated (Fig. 4-1). The signature project has brought together research from both transportation and environmental science, with the intention of integrating research results into new models. These models will be created by enhancing existing traffic modeling software (UrbanSim and TRANSIMS). This project was developed with the aim of being a national showcase for the testing and validation of integrated models and for more sustainable transportation planning.

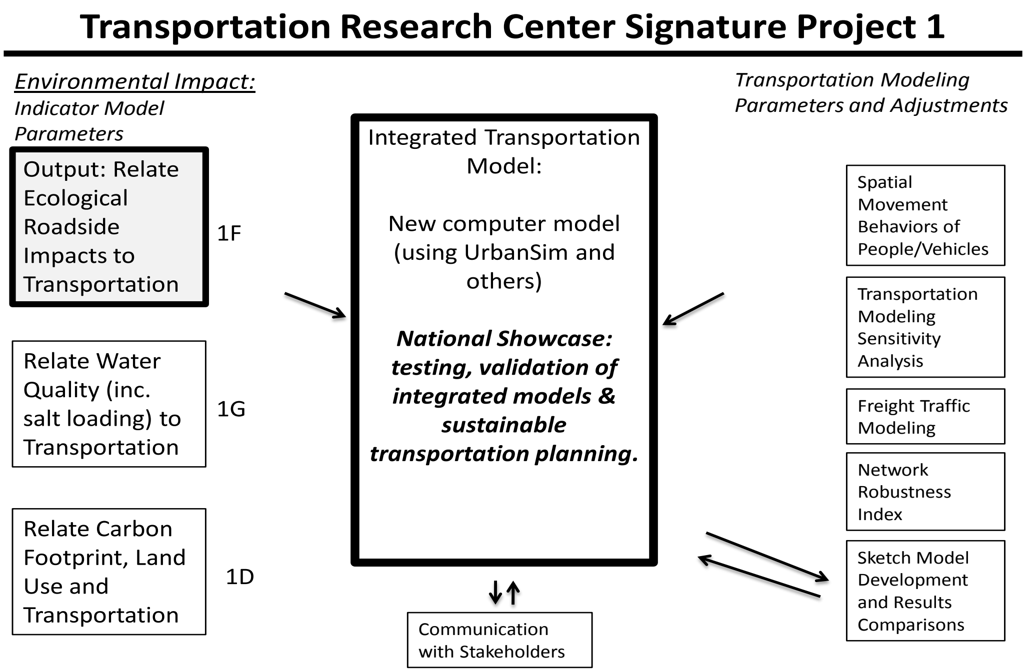


Figure 4-1. Schema of projects integrated together under TRC Signature 1. This study, 1F, is highlighted.

The results of the primary objective were presented at the UVM Student Research Conference:

- 2009- Spatial extent of the impact of transported road materials on the ecological function of forested landscapes, Kristin Williams
- 2012 - Spatial effects of roads on soil nematode communities in forested areas of Vermont, Kristin Williams and David Asmussen

Two M.S. theses were based on analysis of the data gathered in this project:

- The spatial effects of road use intensity on forest plant communities and soil chemistry: does the road less traveled by, make all the difference? – Dave Asmussen, 2010
- Spatial effects of roads on soil nematode communities in forested areas of Vermont – Kristin Williams, 2012

5. Conclusions

The results of both abiotic and biotic soil results present a complex picture of roadside soil ecology in Vermont. These results did suggest the accumulation of pollutants near the roadside, and the combined effects of these pollutants and habitat alterations of the roadside are associated with changes in the soil nematode community, based upon both distance from the roadside and road type. Results suggest that pollutants and most of the ecological effects are concentrated near the roadside, and with higher intensity roads. However, each road type had a unique effect with different pollutants being more prominent.

The roadside grass-verge community was substantially different from the forest in terms of soil nematodes, and plant habitat is probably an influencing factor in these results in addition to chemical and physical soil alteration. Ultimately roadside effects are linked to road type due to the nature of road building, such that highway roads have a much broader roadside verge, 2-lane paved roads a moderate size road verge, and gravel roads a relatively narrow roadside verge. Specific local roadside conditions influence this distance and considerations of local conditions may help designers reduce road effects on the surrounding landscape.

This research supports findings that within an established forest environment, the use-intensity effects of roads on soil and vegetation are contained within the corresponding right-of-way. Increased traffic contributes to higher levels of heavy metals in roadside soil, but these effects do not extend past the forest edge. However, more traffic is correlated positively with wider maintained roadside areas, so the forest edge is effectively farther back compared to lesser-used roads.

Maintained roadside area width is the most significant factor responsible for the roadside environment's deviation from native plant and soil composition. Large maintained areas close to the road are more similar to grassland communities than they are 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, we can maintain natural plant communities and stem the introduction of chemicals into the environment.

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7. Appendix 1.

List of plant species and their coverage for road type and distance. Nomenclature follows Magee and Ahles, [32].

Family	Genus	Species	Gravel Shoulder	Gravel Sideslope	Gravel Ditch	Gravel Backslope	Gravel 10m	Gravel 50m	Paved Shoulder	Paved Sideslope	Paved Ditch	Paved Backslope	Paved 10m	Paved 50m	Highway Shoulder	Highway Sideslope	Highway Ditch	Highway Backslope	Highway 10m	Highway 50m
Aceraceae	Acer	saccharum					▥					▥	▒							
Acoraceae	Acorus	calamus									▒	▥					▥			
Alismataceae	Sagittaria	latifolia		▥	▒															
Alliaceae	Allium	tricoccum																	▥	▥
Anacardiaceae	Rhus	typhina		▥	▥															
	Toxicodendron	rydbergii							▒	▥	▥	▥	▒	▥						▥
Apiaceae	Daucus	carota	▥	▒	▥	▥			▒	▥		▥			▥	▒	▥	▒		
	Pastinaca	sativa				▥									▥	▥	▥	▥		
	Sium	suave			▒															
	Zizia	aurea										▥								
Aquifoliaceae	Ilex	verticillata						▥												
Araceae	Arisaema	triphyllum				▥		▥												
Araliaceae	Aralia	nudicaulis											▒	▥						
Asclepiadaceae	Asclepias	syriaca	▥	▥	▥										▥					
Asteraceae	Achillea	millefolium															▥	▥	▥	
	Ambrosia	artemisiifolia	▥		▥				▒	▥	▥				▒		▥			
	Arcticum	minus		▒	▒					▥	▒	▒								
	Artemisia	vulgaris	▥		▥				▒	▒	▥				▒		▥			
	Aster	cordifolius			▥	▒		▥			▒	▒		▥						
	Aster	lateriflorus			▥	▒				▥	▒	▒							▒	
	Aster	sp.					▥								▥					
	Bidens	frondosa	▥						▥	▥	▥									
	Cichorium	intybus		▥		▥				▥					▒		▥			
	Cirsium	vulgare			▥	▥				▥						▥		▥	▥	
	Conyza	canadensis								▥										
	Erigeron	philadelphicus			▥															
	Eupatorium	maculatum										▒							▥	
	Euthamia	graminifolia	▥		▥	▥					▒	▒					▥	▥		
	Hieracium	caespitosum								▥										
	Hieracium	sp.				▒				▥										
	Leucanthemum	vulgare			▥				▥	▥								▥		
	Matricaria	discoidea							▥						▥					
	Prenanthes	alba				▥														
	Prenanthes	trifoliolata				▥						▥								
	Rudbeckia	hirta																▥		
	Solidago	caesia		▥	▥	▒						▒	▥							
	Solidago	canadensis	▥	▥	▥	▥				▒	▒	▒	▥							
	Solidago	flexicaulis					▥													
	Solidago	gigantea	▥	▒	▥	▥			▥		▥	▒					▥	▥	▥	
	Solidago	rugosa		▥	▥	▥				▒	▒	▒	▥							
	Sonchus	oleraceus				▥			▒	▒					▒	▒	▒	▒		
	Taraxacum	officinale	▒	▒	▒	▒			▒	▒	▥	▥			▥	▥	▥	▥		
	Tussilago	farfara	▒	▒	▒	▒			▒	▒	▒	■								
Balsaminaceae	Impatiens	capensis	▥	▒	▒	▒	▒	▥		▒	▒	▥				▥	▥			▥
Berberidaceae	Caulophyllum	thalictroides						▒					▥						▥	▥
Betulaceae	Ostrya	virginiana																	▥	
Caprifoliaceae	Lonicera	morrowii			▒	▒						▥								
	Sambucus	canadensis									▥									
	Viburnum	acerifolium											▥							▒
	Viburnum	dentatum												▥				▥	▥	▥
	Viburnum	lentago																	▥	
Caryophyllaceae	Silene	vulgaris							▥	▥										
	Stellaria	graminea								▥					▒	▥	▥	▥		
Chenopodiaceae	Chenopodium	album	▥						▥											
	Chenopodium	sp.							▥											

Family	Genus	Species	Gravel Shoulder	Gravel Sideslope	Gravel Ditch	Gravel Backslope	Gravel 10m	Gravel 50m	Paved Shoulder	Paved Sideslope	Paved Ditch	Paved Backslope	Paved 10m	Paved 50m	Highway Shoulder	Highway Sideslope	Highway Ditch	Highway Backslope	Highway 10m	Highway 50m
Clusiaceae	Hypericum	perforatum				▥					▥	▥						▥		
Convallariaceae	Clintonia	borealis											▩							
	Maianthemum	canadense					▥					▥	▩	▩						▥
	Polygonatum	pubescens					▥													
	Smilacina	racemosa				▩	▥	▥					▥	▥						
Convolvulaceae	Calystegia	sepium													▥					
Cornaceae	Cornus	amomum								▥	▩									
	Cornus	racemosa															▥	▥		
	Cornus	sericea			▥															
Cupressaceae	Thuja	occidentalis				▥														
Cyperaceae	Carex	arctata						▥						▥						
	Carex	gracillima					▥						▥							
	Carex	grayi									▥		▥							
	Carex	gynandra															▥			
	Carex	hystericina									▥									
	Carex	intumescens											▥	▥						
	Carex	ovalis									▥									
	Carex	plantaginea											▥							
	Carex	rosea				▩		▥												
	Carex	sp.																		▥
	Carex	swanii				▥	▥	▥												
	Carex	vulpinoidea															▥			
	Eleocharis	tenuis														▩	▩	▥		
	Scirpus	atrovirens		▥													▩			
	Scirpus	microcarpus		▥													▩			
	UID	UID		▥	▥															▥
Dennstaedtiaceae	Pteridium	aquilinum											▥							
Dryopteridaceae	Athyrium	filix-femina				▥	▩					▥						▩	▩	▩
	Cystopteris	bulbifera						▥												
	Deparia	acrostichoides					▥					▥							▥	
	Dryopteris	intermedia					▩	■					▥	▩						
	Dryopteris	marginalis										▥	▥	▥						
	Matteuccia	struthiopteris			▥															
	Onoclea	sensibilis		▩	▥	▩	▥	▥	▥	▩	▩	▩	▥	▩	▥	▩	▩	■	■	■
	Polystichum	acrostichoides				▥	▥	▩						▩						▥
Equisetaceae	Equisetum	arvense	▩	▩	▩	▩					▩	▩	▥		▩	■	▩	▩	▥	▥
	Equisetum	hyemale					▥													
Ericaceae	Gaultheria	procumbens											▥							
	Vaccinium	corymbosum												▥						
Fabaceae	Amphicarpaea	bracteata	▥	▩	▩	▩														
	Lotus	corniculatus	▩			▥			▩	▥						▥	▥	▩		
	Medicago	lupulina			▥				■	▩		▥			▩	▥				
	Melilotus	alba	▩	▥								▥								
	Trifolium	arvense													▩					
	Trifolium	pratense	▥	▥	▥	▥			▥			▥								
	Trifolium	repens								▥										
	Vicia	cracca		▥	▥										▩	▩	▩	▩	▥	
Gentianaceae	Centaurium	erythraea							▥	▥										
Geraniaceae	Geranium	robertianum		▥	▥	▥		▩			▥	▥								▩
Grossulariaceae	Ribes	cynosbati																	▥	
Juncaceae	Juncus	effusus									▥	▥								
	Juncus	sp.		▥		▥											▩	▥		
Lamiaceae	Glechoma	hederacea	▥	▥	▥															
	Prunella	vulgaris	▥	▥	▥	▥														
Lycopodiaceae	Lycopodium	obscurum											▥	▥						

Family	Genus	Species	Gravel Shoulder	Gravel Sideslope	Gravel Ditch	Gravel Backslope	Gravel 10m	Gravel 50m	Paved Shoulder	Paved Sideslope	Paved Ditch	Paved Backslope	Paved 10m	Paved 50m	Highway Shoulder	Highway Sideslope	Highway Ditch	Highway Backslope	Highway 10m	Highway 50m
Lythraceae	Lythrum	salicaria			▒						▥						▥	▥		
Melanthiaceae	Veratrum	viride											▥							
Monotropaceae	Monotropa	uniflora					▥													
Nyctaginaceae	Mirabilis	nyctaginea													▥		▥			
Oleaceae	Fraxinus	americana		▥	▥	▒	▥	▒				▥	▥						▒	▒
Onagraceae	Circaea	lutetiana		▥	▒		▥	▥		▥	▥	▥				▥		▒		
	Oenothera	biennis								▥										
Orchidaceae	Epipactis	helleborine			▥		▥	▥					▥	▥					▥	▥
Osmundaceae	Osmunda	cinnamomea										▒								
	Osmunda	claytoniana										▥						▒	▒	
	Osmunda	regalis																	▥	
Oxalidaceae	Oxalis	europaea	▥	▥	▥				▒	▥		▥				▥				▥
	Oxalis	stricta	▥	▥	▥	▥				▥		▥			▥	▥		▥		▒
Plantaginaceae	Plantago	major	▒	▒	▥				▥	▒					▥		▥			
Poaceae	Bromus	inermis							▒	▥	▥	▥			■	■		▒		
	Carex	hirtifolia				▥														
	Dactylis	glomerata	▥	▒	▥				▒	▒	▒	▥			■	▥				
	Echinochloa	sp.							▒	▥										
	Elymus	repens													▒	▥				
	Festuca	sp.								▒						▒	▒			
	Glyceria	striata			▒										▥		▒	▒		
	Phalaris	arundinacea	▥	▒	▒	▥			▒	■	■	▒			▥	▒	▒	▥		
	Phleum	pratense							▥		▥	▥				▥				
	Setaria	glauca			▒				▒	▥										
	Setaria	pumila													▥					
	UID	UID	▥	▒	▒	▥			▒	■	▒	▒			■	■	■	■	▒	
Polyganaceae	Polygonum	aviculare	▥																	
	Polygonum	persicaria							▒		▥									
	Polygonum	sagittatum															▒	▥		
	Rumex	crispus		▒								▥				▥	▥			
Polypodiaceae	Polypodium	virginianum						▥												
Primulaceae	Lysimachia	ciliata									▥							▥		
	Lysimachia	nummularia	▒	▒	▥	▥			▥	▒	▥	▒							▥	
	Lysimachia	terrestris				▥					▥									
	Trientalis	borealis											▥	▥						
Pyrolaceae	Moneses	uniflora				▥														
Ranunculaceae	Anemone	virginiana			▥	▥												▥	▥	
	Aquilegia	canadensis				▒														
	Caltha	palustris									▥		▒							
	Ranunculus	acris	▥	▥	▒	▥				▥				▥	▥	▥	▥	▥		▥
	Thalictrum	dioicum		▥	▥								▒							
Rhamnaceae	Rhamnus	cathartica					▥	▒			▥		▥						▒	▒
Rosaceae	Fragaria	virginiana											▥				▥	▒	▥	▥
	Geum	canadense				▥	▥							▥				▥	▥	▥
	Prunus	virginiana												▥					▥	
	Rosa	multiflora																		▥
	Rubus	allegheniensis	▒	▒	▒	▒	▥				▥	▒						▥	▒	
	Rubus	idaeus																▥		
	Rubus	odoratus	▒	▒	▒	▒					▥	▒		▥				▒		
	Rubus	pubescens									▒									▒
	Spiraea	alba										▥					▥	▥	▒	▥
Rubiaceae	Galium	palustre		▥	▥															
	Galium	triflorum				▥							▥	▥		▥				
	Galium	mollugo								▥	▒	▥			▒	▒	▒	▒		▥
	Mitchella	repens					▒	▒					▥	▒						▥

Family	Genus	Species	Gravel Shoulder	Gravel Sideslope	Gravel Ditch	Gravel Backslope	Gravel 10m	Gravel 50m	Paved Shoulder	Paved Sideslope	Paved Ditch	Paved Backslope	Paved 10m	Paved 50m	Highway Shoulder	Highway Sideslope	Highway Ditch	Highway Backslope	Highway 10m	Highway 50m
Salicaceae	Populus	tremuloides																|||		
	Salix	nigra		|||																
Saxifragaceae	Tiarella	cordifolia											|||						|||	
Scrophulariaceae	Chelone	glabra									|||									
	Verbascum	thapsus										|||								
	Veronica	officinalis			|||							|||	▒							
Solanaceae	Solanum	dulcamara								|||	▒	|||								
Thelypteridaceae	Thelypteris	noveboracensis	|||		|||	▒												|||		
	Thelypteris	palustris									|||	|||						|||		
Trilliaceae	Trillium	erectum					|||	|||											|||	|||
	Trillium	undulatum					▒	|||											|||	
Typhaceae	Typha	latifolia									▒	|||					|||			
Urticaceae	Pilea	pumila							▒	|||	|||									
Verbenaceae	Verbena	hastata															|||			
Violaceae	Viola	sp.			|||	|||											|||			|||
Vitaceae	Parthenocissus	quinquefolia	|||	▒	|||	|||				▒	|||	|||	▒	|||				▒	▒	|||
	Vitis	riparia	|||	|||	|||	▒		|||		|||	▒	|||			|||	|||	▒	▒	▒	
Unknown Forb #1	UID	UID		|||	|||					|||	|||	|||				▒	|||	▒		
Unknown Graminoid #1	UID	UID		|||																
Unknown Graminoid #2	UID	UID	|||	▒	|||															
Unknown Graminoid #3	UID	UID			|||															
Other Ground Cover																				
Bare Soil			■	■	■	▒	|||	▒	■	▒	■	|||	▒	|||	■		■		■	▒
Leaf Duff			|||	▒	■	■	■	■		|||	▒	■	■	■					■	■

Appendix 2.

Classification of nematode genera by c-p value of the Maturity Index and trophic group, and the percentage of samples with nonzero abundance of specified genera by road type.

				Road Type		
Genus	Family	*c-p*	Trophic	Gravel[a]	2-laned paved[b]	highway [a]
Achromadora[d]	Achromadoridae	3	A	42	50	50
Acrobeles	Cephalobidae	2	B	7	19	12
Acrobeloides	Cephalobidae	2	B	77	83	72
Ailaimus[c d]	Alaimidae	4	B	58	31	38
Anaplectus[d]	Plectidae	2	B	20	17	10
Anatonchus	Anatonchidae	4	P	0	0	3
Anomyctus	Aphelenchoididae	2	B	18	19	3
Aphelechoides	Aphelenchoididae	2	F	87	84	85
Aphelenchus[c d]	Aphelenchidae	2	F	40	40	57
Aporcelaimellus	Aporcelaimidae	5	P	15	7	12
Aporcelaimium	Aporcelaimidae	5	O	0	0	2
Aporcelaimus	Aporcelaimidae	5	P	8	7	7
Axonchium	Belondiridae	5	PP	3	3	8
Basiria	Tylenchidea	2	F	3	5	8
Bastiania	Bastianiidae	3	B	8	9	0
Bitylenchus	Dolichoridae	3	PP	0	5	8
Boleodorus[c]	Tylenchidae	2	F	57	31	50
Bunonema	Bunonnematidae	1	B	3	0	0
Bursaphelenchus	Aphelenchoididae	2	F	0	0	2
Carcharolaimus	Discolaimidae	5	P	0	0	2
Cephalenchus[d]	Tylodoridae	2	PP	12	10	12
Cephalobus	Cephalobidae	2	B	87	88	68
Cervidellus[c]	Cephalobidae	2	B	38	31	17
Chiloplacus	Cephalobidae	2	B	7	3	8
Chronogaster	Leptolaimidae	2	B	2	7	0
Clarkus[d]	Monochidae	4	P	30	19	17
Coomansis	Monochidae	4	P	0	3	2
Coslenchus	Tylenchidae	2	F	6.7	16	17
Criconema	Criconematidae	3	PP	0	0	2
Criconemella	Criconematidae	3	PP	2	0	5
Criconemoides	Criconematidae	3	PP	2	0	2
Croossonema	Criconematidae	3	PP	0	7	5
Cylindrolaimus	Diphtherophoridae	3	B	0	2	0
Dactyluraxonchium	Belondiridae	5	PP	2	0	2
Diphtherophora	Diphtherophoridae	3	F	17	17	18

Diplogaster	Diplogasteroididea	1	B	7	0	0
Diplogasteritus	Diplogasteroididea	1	B	0	2	0
Discolaimus	Discolaimidae	5	P	2	0	2
Ditylenchus	Anguinidae	2	F	62	55	65
Dorydorella	Qudsianematidae	4	O	3	0	0
Dorylaimellus	Belondiridae	5	F	5	2	3
Dorylaimoides	Leptonchidae	4	O	0	0	2
Dorylaimus	Dorylaimidae	4	O	2	0	0
Echphyadophoroides	Tylenchidae	2	F	0	0	2
Echphyadophorus	Tylenchidae	2	F	0	2	0
Enchodellus	Nordiidae	4	O	0	2	0
Epidorylaimus	Qudsianematidae	4	O	23	5	7
Etamphidelus	Alaimidae	4	B	0	3	0
Eucephalobus	Cephalobidae	2	B	92	86	83
Eudorylaimus	Qudsianematidae	4	O	32	29	18
Eumonhystera	Monhysteridae	2	B	80	84	80
Euteratocephalus	Teratocephalidae	3	B	0	0	3
Filenchus	Tylenchidae	2	F	93	88	93
Fraglenchus	Tylenchidae	2	F	0	0	2
Geomonhystera	Monhysteridae	2	B	0	0	2
Helicotylenchus[c]	Hoplolaimidae	3	PP	43	41	70
Hemicycliphora[d]	Hemicyliophoridae	3	PP	13	19	10
Heterocephalobus[d]	Cephalobidae	2	B	15	7	10
Heterodera	Heteroderidae	3	PP	0	2	0
Ironus	Ironidae	4	P	0	0	2
Lelenchus	Tylenchidae	2	F	0	10	7
Leptolaimus	Leptolaimidae	2	B	17	5	3
Leptonchus	Leptonchidae	4	F	3	0	2
Longidorus	Longidoridae	5	PP	8	2	2
Loofia	Hemicyliophoridae	3	PP	2	2	0
Macroposthnia[d]	Criconematidae	3	PP	8	9	17
Malenchus	Tylenchidae	2	F	27	21	18
Meloidogyne	Meloidogynidae	3	PP	3	9	10
Merilinus	Dolichoridae	3	PP	0	2	0
Mesodorylaimus[d]	Thornenematidae	5	O	18	5	13
Metateratocephalus	Teratocephalidae	3	B	3	7	0
Miconchus	Anatonchidae	4	P	0	0	2
Microdorylaimus	Qudsianematidae	4	O	5	0	0
Monhystera[d]	Monhysteridae	2	B	15	17	17
Mononchoides	Neodiplogasteroidid	1	B	2	0	0
Mononchus	Monochidae	4	P	7	0	5
Mylonchulus	Monochidae	4	P	20	31	13
Neopsilenchus	Tylenchidae	2	F	13	14	60
Nygolaimus	Nygolaimidae	5	P	2	0	2
Ogma	Criconematidae	3	PP	0	2	2

Oxydirus	Belondiridae	5	PP	2	2	5
Panagrobellus	Panagrolaimidae	1	B	0	5	2
Panagrolaimus[d]	Panagrolaimidae	1	B	20	24	22
Paractinolaimus	Actinolaimidae	5	P	0	0	2
Paramphidellus[c d]	Alaimidae	4	B	42	32	52
Paraplectonema	Leptonchidae	4	B	0	0	2
Paratrichodorus	Trichodoridae	4	PP	0	2	0
Paratylenchus[d]	Paratylenchidae	2	PP	15	24	17
Paravulvus	Nygolaimidae	5	P	2	0	0
Paraxonchium	Aporcelaimidae	5	P	2	0	0
Plectus	Plectidae	2	B	92	84	85
Pleurotylenchus	Tylodoridae	2	PP	0	5	7
Pratylenchoides	Pratylenchidae	3	PP	0	2	2
Pratylenchus[c]	Pratylenchidae	3	PP	15	29	35
Prismatolaimus	Prismatolaimidae	3	B	35	50	37
Pristionchus	Neodiplogasteroidid	1	B	0	3	2
Prodorylaimus[c]	Thornenematidae	5	O	45	24	47
Protodiplogasteroides	Diplogasteroididea	1	B	2	0	0
Psilenchus	Psilenchidea	2	PP	10	3	15
Pungentus	Nordiidae	4	PP	17	28	18
Rhabditidae[+ d]	Rhabditidae	1	PP	30	38	37
Rhabdolaimus[c d]	Rhabdolaimidae	3	B	15	21	38
Rotylenchus[d]	Hoplolaimidae	3	PP	13	16	5
Scutylenchus	Dolichoridae	3	PP	0	0	5
Seinura	Aphelenchoididae	2	P	0	5	5
Stenonchulus	Onchulidae	3	P	2	0	0
Teratocepahlus	Teratocephalidae	3	B	43	52	32
Thonus[d]	Qudsianematidae	4	O	48	41	30
Tobrilus	Tobrilidae	3	P	2	2	0
Tripyla	Triplylidae	3	P	0	0	2
Trischistoma	Triplylidae	3	P	0	0	2
Tylencholaimellus	Leptonchidae	4	F	8	9	22
Tylencholaimus	Leptonchidae	4	F	50	45	52
Tylenchus	Tylenchidae	2	F	83	72	73
Tyocephalus	Plectidae	2	B	7	12	2
Wilsonema	Plectidae	2	B	17	33	17
Xiphinema[d]	Longidoridae	5	PP	13	9	5
Zanenchus	Tylenchidae	2	F	0	0	2

a. $n = 60$, b. $n = 58$,

chi squared test $p < 0.05$: c. for road type; d. for topography, percent nonzero not listed.

Trophic Groups defined as: A. Algal Feeder, B. Bacterial Feeder, F. Fungal Feeder,

O. Omnivores, P. Predators, PP. Plant (Root) Feeders

road type df=2, topography df=1, + Rhabditidae only identified to family.

8. Equations

Equation 2. Nematode maturity index
$MI = \sum [(v_i f_i) / n]$ where v_i equals the *c-p* value of the *i*th family, f_i equals the frequency of the *i*th family in the sample, and *n* equals the total number of individual nematodes in a sample.

Equation 3. Nematode trophic diversity index
$Hills\ N1 = exp\ [- \Sigma P_i\ (ln\ P_i)$ where P_i is the proportion of trophic group *i.*

Equation 4. Ratio of fungivorous nematodes (FN) to bacterivorous nematodes (BN)
$F{:}F{+}B = (no.\ FN)/(no.\ FN + no.\ BN)\ X\ 100.$