WHERE DO SALAMANDERS CROSS THE ROAD? DEVELOPMENT OF A GIS MODEL TO IDENTIFY AMPHIBIAN ROAD-CROSSING HOTSPOTS

Final Report Submitted to the Vermont Agency of Transportation

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Cover photo – Monkton Road, Monkton, Vermont, 2012 Vermont Orthophotography

Introduction

Amphibian populations are susceptible to direct mortality during spring and autumn movements, when individuals migrate between breeding and terrestrial habitats. In the Vermont landscape, with its complex mosaic of forest patches, agriculture, and developed features, migratory movements and dispersal often induces individual amphibians to cross roads of varying width, substrate, and traffic volume. This movement across roads is an inevitable byproduct of the intersection of anthropogenic land-use pattern and life-cycle biology: roads located in valleys and other lowlands separate low-lying breeding habitat such as vernal pools and wetlands from upland terrestrial and overwintering habitat. Depending on the quality of the adjacent habitat and the volume of vehicle traffic, local amphibian populations may be impaired by high road-crossing mortality rates.

Amphibian mortality along roads has been studied in various landscapes. In the Netherlands, a flow of 10 vehicles/hour (240 vehicles/day) produced 30% mortality in migrating common toads (*Bufo bufo*), and a flow of 60 vehicles/hour (1,440 vehicles/day) was projected to incur 90% mortality (van Gelder 1973). In New Brunswick, Canada, Mazerolle (2004) detected interspecific variation in mortality rates at traffic flows as low as 5-26 vehicles per hour (120-624 vehicles/day). A Danish study by Hels and Buchwald (2001) showed that the probability of road-crossing mortality ranged from 34% to 98% across traffic volumes, depending on various attributes of a given species. Their model was adapted to assess mortality probabilities for spotted salamanders (*Ambystoma maculatum*) by Gibbs and Shriver (2005), who found that mitigation efforts such as tunnels and road closures would be justified in Massachusetts in areas with road densities >2.5 km/km^2 of landscape and traffic volumes >250 vehicles/lane/day.

More recently, Patrick et al. (2012) predicted road mortality “hotspots” for amphibians and turtles in a 12-county area of New York, using habitat-resistance models to examine specific-specific probabilities of occurrence on roads. Their models were most effective for habitat specialists with limited movement ranges, including spotted salamanders and wood frogs (*Lithobates sylvaticus*). For these species, it was easier to model specific habitat characteristics that influence movement across roads and thus were also more effective in assessing associated mortality risk. Patrick et al. concluded that traffic intensity and the length of individual hotspot locations were effective variables in ranking road segments for conservation-related mitigation.

In Vermont, no studies have quantified mortality rates across multiple road classes and habitat conditions, but anecdotal evidence suggests that road mortality is no less important than in other locations with amphibian populations. This is especially true in suburbanizing locations where backroads with low historic traffic volumes have become important commuting routes. However, it is possible to mitigate amphibian mortality by modifying roads with culverts and fencing that funnel animals underneath busy crossing locations (Dodd et al. 2004, Aresco 2005), and the Vermont Agency of Transportation (VTRANS) has developed specific management practices to encourage and guide road-alteration projects (VTRANS 2012). Indeed, video monitoring of two recently-installed wildlife culverts in Monkton, Vermont has documented successful transit of thousands of amphibians during spring dispersal (VRAA 2016).

To better understand the location and distribution of important crossing locations, the Vermont Reptile & Amphibian Atlas actively solicits records of both live and dead amphibians observed on roadways (VRAA 2018). This citizen science is essential for understanding movement patterns and planning for effective mitigation efforts. However, the growing availability of high-resolution remote-sensing datasets and their derivative products (e.g., comprehensive land-cover maps) suggests that direct observation can be supplemented with modeling exercises that identify and rank crossing locations across large geographic extents. Landscape-level modeling would in turn facilitate efficient planning and allocation of funds for road-alteration projects that support wildlife conservation.

This pilot study thus focused on development of a modeling approach that would capitalize on existing public investments in high-resolution data and provide a fine-scale assessment of important crossing locations. Previous studies such as Patrick et al. (2012) used coarse-scale habitat inputs (e.g., 30-m National Land Cover Dataset) that could not resolve site-specific heterogeneity or were based on widely-used but dated methods of manual interpretation (e.g., National Wetlands Inventory) that similarly miss many small features. Multispectral orthoimagery and LiDAR are now available for the entirety of Vermont, at a resolution of 1 meter or finer, making it possible to capture fine-scale topographic features such as vernal pools (Faccio et al. 2016) and to map forest cover to the scale of individual trees (O'Neil-Dunne et al. 2014). These datasets thus have the dual advantage of facilitating fine-grained mapping across large geographic areas, permitting multiple-scale analysis of wildlife habitat and the anthropogenic features that affect it.

Methods

STUDY AREA

The study area encompassed most of Addison County, Vermont and a part of adjacent Chittenden County (Figure 1). This area conformed to the boundary of the LiDAR dataset for Addison County, collected in 2012, available at the time of project commencement (a newer collection has since been collected for the county). Addison County spans a diversity of biophysical regions and habitat conditions, including Champlain Valley lowlands dominated by agriculture and mountainous uplands with large, contiguous forest blocks. This mix of landscapes is known to support many amphibians native to western Vermont, including four species of salamander that are listed as Species of Greatest Conservation Need in Vermont's Wildlife Action Plan (Kart et al. 2005): spotted salamander, Jefferson salamander (*A. jeffersonianum*), blue-spotted salamander (*A. laterale*), and four-toed salamander (*Hemidactylium scutatum*). In addition, several anurans are common in this region, including spring peeper (*Pseudacris crucifer*), American toad (*Anaxyrus americanus*), and wood frog (VRAA 2018).

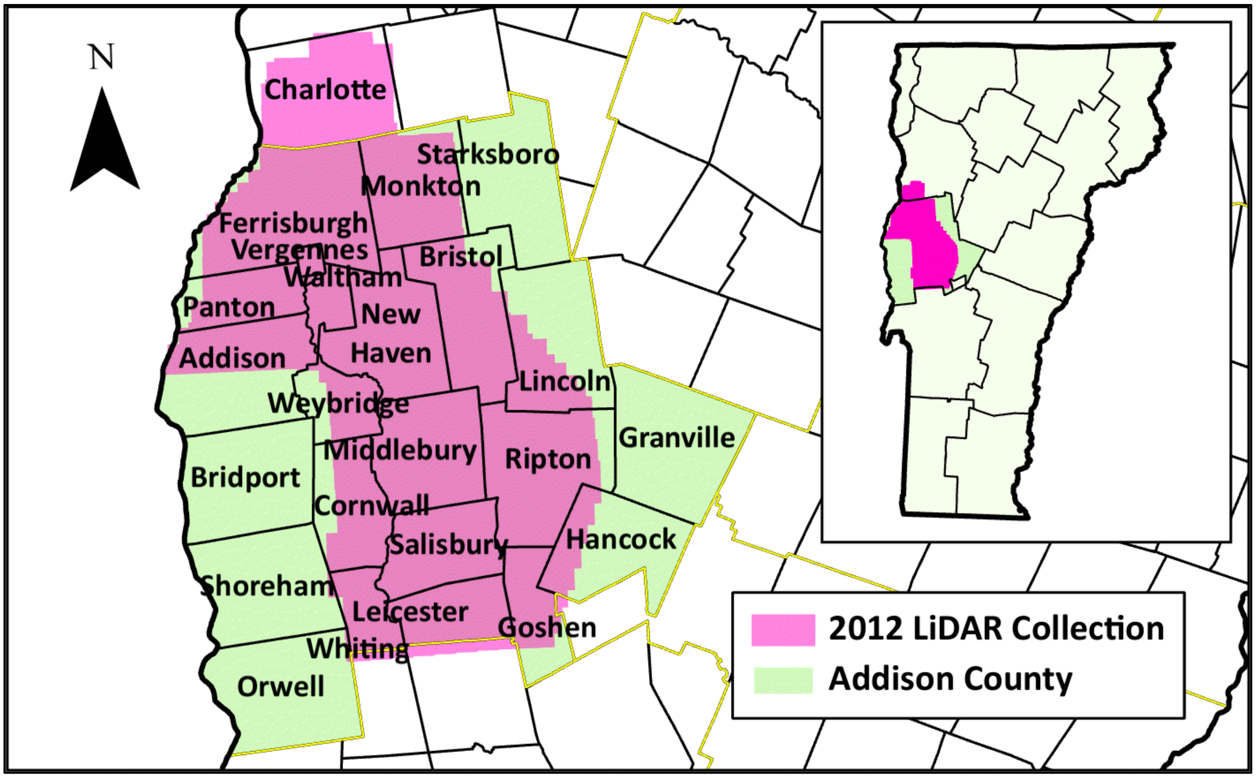

Figure 1. Study area for pilot amphibian-crossing hotspot analysis, Addison County, Vermont (and adjacent Chittenden County). The exact study-area boundary confirms to the LiDAR collection acquired in 2012.

HIGH-RESOLUTION LAND-COVER MAPPING

The analysis of amphibian movement patterns depended on effective delineation of not only key breeding and terrestrial habitats, but also on topographies and anthropogenic features that separate them. This process was expedited by past projects that focused on one or more of the specialized habitat features on which amphibian life cycles depend, capitalizing on other investments in ecological mapping. Accordingly, existing land-cover products were adapted for use with crossing-hotspot modeling and supplemented as necessary to represent additional features of interest.

Lake Champlain Land Cover

This project coincided with a separate effort to map high-resolution land cover for the Lake Champlain Watershed (LCBP 2018). For Addison County, the new map was based on a combination of LiDAR, leaf-off multispectral orthoimagery, and thematic GIS datasets (Table 1). With a 1-m resolution, this new land-cover contained the following classes: Deciduous, Coniferous Forest, Herbaceous, Shrub, Water, Emergent Wetland, Scrub\Shrub Wetland, Forested Wetlands, Crops, Pasture, Hay, Barren, Buildings, Roads\Railroads, Other Impervious, and Orchards. Wetlands mapping followed an automated mapping routine first described by Rampi et al. (2014) and later adapted by Raney et al. (2016) for use in Pennsylvania. Using object-based image analysis techniques (OBIA), this method relied on a LiDAR-derived compound topographic index (CTI) to identify areas with the flow and slope characteristics typical of wetland features. This work was performed in

Table 1. Input datasets for amphibian-crossing hotspot modeling in Addison County, Vermont.

Input Dataset	Type	Source	Processing
Digital Elevation Model (DEM)	LiDAR derivative, 1.6-m ground sample distance (GSD)	Original LiDAR data (LAS format) from U.S. Geological Survey (2013)	Filtered ground returns and exported to surface (Quick Terrain Modeler)
Normalized Digital Surface Model (nDSM)	LiDAR derivative, 1.6-m GSD	Vermont Center for Geographic Information (derived from original LiDAR data, U.S. Geological Survey 2013)	None
LiDAR Intensity	LiDAR derivative, 1.6-m GSD	Original LiDAR data (LAS format) from U.S. Geological Survey (2013)	Filtered last returns and exported to surface (Quick Terrain Modeler)
Flow Accumulation	LiDAR derivative, 1.6-m GSD	Original LiDAR data (LAS format) from U.S. Geological Survey (2013)	Flow directions modeled from DEM (SCALGO Hydrology – Flow Directions) and in turn used to model flow accumulation (SCALGO Hydrology – Flow Accumulation)
Compound Topographic Index (CTI)	LiDAR derivative, 3-m GSD	Original LiDAR data (LAS format) from U.S. Geological Survey (2013)	Gradients calculated from DEM (SCALGO) and then used with flow accumulation to calculate index (ERDAS IMAGINE)
Orthoimagery	Multispectral imagery (4-bands: Red, Green, Blue, Near Infrared), leaf off, 0.5-m GSD	Vermont Center for Geographic Information (2012)	Mosaic tiles (ERDAS IMAGINE)
National Agricultural Imagery Program (NAIP)	Multispectral imagery (4-band), leaf on, 1-m GSD	USDA Farm Service Agency (2016)	Mosaic tiles (ERDAS IMAGINE)
Study Area Boundary, Based on LiDAR Index (Index_LAS_2013_Addison County.shp)	Thematic GIS layer (polygons)	U.S. Geological Survey (2013)	None
Vermont Road Centerlines (TransRoad_RDS)	Thematic GIS layer (lines)	Vermont Agency of Transportation (2013)	None
Vermont Hydrography Dataset – Lakes and Ponds	Thematic GIS layer (polygons)	U.S. Geological Survey (2010)	None
Vermont Annual Average Daily Traffic (AADT)	Thematic GIS layer (lines)	Vermont Agency of Transportation (2016)	None
Vermont Hydrography Dataset - Streams	Thematic GIS layer (lines)	U.S. Geological Survey (2010)	None
Impervious Surfaces (roads, buildings, other pavement)	Thematic GIS layer (polygons)	University of Vermont Spatial Analysis Laboratory (2011)	None
Lake Champlain Basin Land Cover	Thematic GIS layer (raster)	University of Vermont Spatial Analysis Laboratory (2018)	None
Modeled Potential Vernal Pools	Thematic GIS layer (polygons)	Faccio et al. (2016)	Modeled using object-based image analysis techniques

Table 1. Input datasets for amphibian-crossing hotspot modeling in Addison County, Vermont (continued).

Input Dataset	Type	Source	Processing
Vermont Surficial Geologic Map	Thematic GIS layer (polygons)	Vermont Geological Survey (1956-1970)	Exposed bedrock extracted
Bedrock Geology, Northern Appalachians/Acadians	Thematic GIS layer (polygons)	The Nature Conservancy (2014)	Calcareous bedrock extracted
Landforms component of Ecological Land Units	Thematic GIS layer (raster)	The Nature Conservancy (2003)	Cove landforms extracted

eCognition (Trimble), state-of-the-art OBIA software. The CTI-based method was further adapted for the specific topography and available data inputs for western Vermont and northeastern New York. All features, including wetlands, were also subject to manual review and editing to eliminate obvious errors of omission and commission.

Modeled Roads

The new Lake Champlain land-cover map served as a starting point for habitat mapping but additional modeling was needed to refine some features pertinent to amphibian movement. To better gauge the characteristics of individual road segments, an OBIA model in eCognition was used to delineate the edge of actual road surfaces. This technique relied on a LiDAR-derived digital elevation model (DEM) to locate the sharp transition from a road to the drainage ditch typically present on one or both sides. Once the actual road surface was identified, the resulting features were divided into 50-m sections and assigned estimated physical attributes: width and maximum slide slope. This modeling was performed for both automobile-designed roads and railroads. For automobile-designed roads only, road class (FUNCL) was also assigned from the road centerline layer developed by VTRANS (Table 1). In areas where roads did not have ditches that demarcated surface edges (e.g., densely-settled residential and commercial neighborhoods), the roads were adapted from an existing impervious surfaces layer for the Lake Champlain Watershed (Table 1).

Although the available road-class (e.g., interstate, principal arterial, local) designations imply a range of traffic intensities, average annual daily traffic (AADT) data collected by VTRANS was used to estimate actual traffic volume for each road segment. For roads represented in the AADT database, traffic volumes were assigned directly to each coincident 50-m segment. However, traffic counts are performed for only a subset of Vermont's roads, requiring extrapolation from AADT roads to non-AADT segments. First, summary statistics (minimum, maximum, mean, median) were compiled for AADT roads in the Addison County study area: Principal Arterial-Other (FUNCL = 3); Minor Arterial (4); and Major Collector (5). For road classes with no AADT data in Addison County, the summary statistics were calculated statewide: Minor Collector (6) and Local (7). Segments in the Other (0) category were assumed to be equivalent to Local roads. Roads in the study area were then designated as "Rural" or "Urban" using building density as an approximate indicator of likely traffic volumes (i.e., roads with multiple adjacent buildings received the Urban designation). Finally, all rural roads were assigned the minimum value from the class-specific summary statistics while all urban segments were assigned the median value (Table 2). Given that the available literature has suggested amphibian

Table 2. Estimated daily traffic volume by functional class for roads in Addison County, Vermont (and adjacent Addison County).

Road Class (FUNCL)	Numeric Code (FUNCL)	Rural Roads (cars\day)	Urban Roads (cars\day)
Other[a]	0	90	290
Principal Arterial - Other	3	5,100	9,000
Minor Arterial	4	1,200	4,300
Major Collector	5	360	1,900
Minor Collector	6	90	970
Local	7	90	290

[a]This class not represented in the AADT database for the Addison County study area; assumed to have same traffic volume as Local class.

mortality can be high on roads with relatively little traffic, the lower estimate for rural roads was intended to ensure a realistic assessment of mortality risk across all road classes.

Vernal Pools

The wetlands mapping performed for the Lake Champlain Basin sometimes captured vernal pools, but the modeling approach was not specifically designed to map these features. However, vernal pools had previously been modeled for the Addison County study area using a customized OBIA approach (Faccio et al. 2016). This model first identified landscape depressions and then evaluated them for the presence of water using multispectral imagery and LiDAR intensity. Candidate pools were then evaluated relative to known or potential vernal pools represented in the Vermont Vernal Pools Mapping Project (Faccio et al. 2013). Pools not represented in the mapping project were evaluated manually relative to the source imagery and LiDAR. For the current project, all confirmed pools and other pools with strong evidence of water were selected for subsequent use in an Addison County-specific land-cover map.

Compiled Land Cover Map

To compile a map appropriate for amphibian-crossing modeling, the agricultural classes from the Lake Champlain land-cover map were consolidated into a single class, and buildings and other impervious surfaces were similarly combined into one class. Modeled roads and vernal pools were then burned into a final layer to produce the following 14 classes: Tree Canopy-Deciduous; Tree Canopy-Coniferous; Low Vegetation; Shrubs; Water, Wetlands-Deciduous; Wetlands-Coniferous; Wetlands-Scrub\Shrub; Wetlands-Emergent; Potential Vernal Pools; Roads\Railroads; and Other Impervious Surfaces (Figure 2).

GIS-based Hotspot Modeling

Hotspot modeling first focused on the proximity of appropriate overwintering sites (i.e., contiguous forest and forest patches) and breeding habitat (i.e., vernal pools, persistent wetlands) to roads and railroads. Using ArcGIS Pro (2.2.3), and following methods

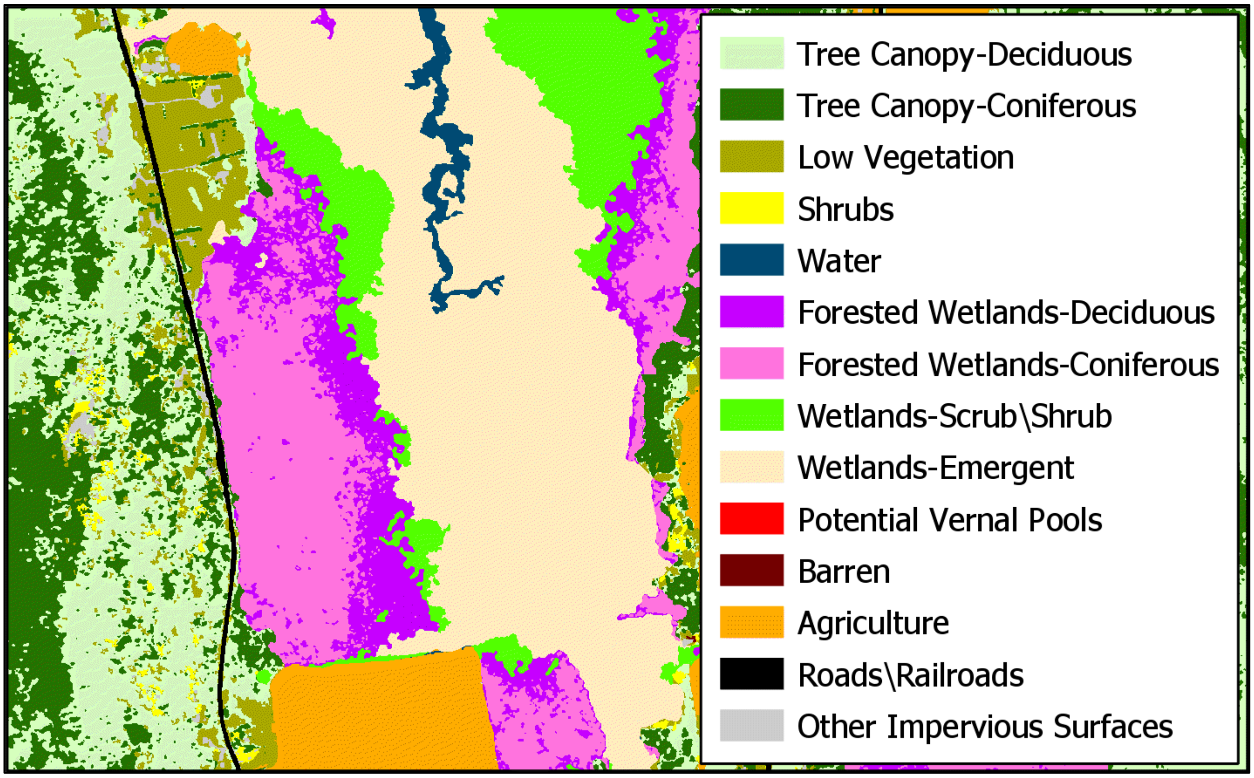

Figure 2. Comprehensive, high-resolution (1 m) land-cover map for amphibian-crossing hotspot modeling in Addison County, Vermont (and adjacent Chittenden County).

used by Patrick et al. (2012), separate cost distance grids (Cost Distance tool) were calculated for: 1) all upland forest types merged into a single class; 2) all wetland classes merged into a single class. The cost distance grids were subsequently used to model upland areas offering potential migration routes between overwintering and breeding habitat. These areas were identified by using a cost distance threshold of 2,745 m, which is equivalent to 183 m (600 ft) – the likely maximum migration distance under forest cover for the focal amphibian species in Vermont (Jim Andrews, personal communication). The cost-distance approach accounted for lower likelihood of migration through developed or other open, upland cover types, but it over-identified open uplands adjacent to large wetlands (due to the zero cost of moving through wetland habitats). These marginal areas were removed using a Euclidean distance limit of 183 m from overwintering habitat. The potential migration areas were in turn used to select an initial set of 50-m road/railroad segments that could serve as crossing locations, eliminating segments that were too distant from the necessary pairing of habitat features.

After isolating the appropriate habitat types, a second step focused on landscape context, or the combination of topographic-position variables and special habitat features that determine likely hotspot locations (Table 3). For this analysis, the difference in elevation between nearest upland forest patch and nearest wetland was calculated using the LiDAR-derived DEM and the angle of approach between these features was estimated using the Euclidean Direction tool. Specific geological features known to affect amphibian movement or enhance habitat quality were extracted from available bedrock geology and landform layers (Table 1), including calcareous bedrock, exposed bedrock, and cove landforms. The

Table 3. Landscape-context variables used to select potential amphibian road-crossing hotspots in Addison County, Vermont (and adjacent Addison County).

Variable	Description	Range of Values	Source
Orientation_majority	Primary orientation between wetlands and upland forest	0-180°	Modeled from Euclidean direction grids
ELEV_CHANGE	Mean elevation of forest patches above wetlands	-169-155 m	LiDAR-derived DEM (Table 1)
NEAR_DIST_FORGRID	Distance to forest patches	0-183 m	Modeled using the "Near" tool
NEAR_DIST_VP	Distance to vernal pools	0-183 m	Modeled using the "Near" tool
Calcareous	Calcareous soil	0-1 (unit-less index)	Bedrock Geology (Table 1)
Bedrock	Bedrock exposure	0-1 (unit-less index)	Bedrock Geology (Table 1)
Cove	Cove landform	0-1 (unit-less index)	Landform (Table 1)

presence of these features was summarized with Focal Statistics (Mean) modeling, producing grids with index values ranging from 0 (not present) to 1 (prevalent). All distance, topographic, and special-habitat variables were summarized for each 50-m road segment and incorporated as searchable fields in the initial selection set.

Hotspot locations were then identified by iteratively querying the 50-m road segments that have landscape characteristics favorable to migrating amphibians. The locations of known hotspots in Addison County (Jim Andrews, personal communication) were used to guide experimentation. The overall goal was to isolate road segments that: 1) separated breeding habitat from nearby upland overwintering habitat; 2) occurred in a relatively direct path between these features; 3) occurred along an elevation gradient preventing inundation of upland sites during non-breeding periods; and 4) were positioned near favorable bedrock and landform characteristics (Figure 3). To help guide subsequent field work, multiple scenarios were constructed with different variables and selection thresholds (e.g., Orientation_majority *and* ELEV_CHANGE vs. Orientation_majority *and* ELEV_CHANGE *or* Cove *or* Calcareous *or* Bedrock).

RISK ASSESSMENT

To aid subsequent field efforts, the preliminary results of the hotspot modeling were ranked according to variables describing both the physical characteristics of roads and the traffic they accommodate: road width (m), maximum side slope on either side of a road segment (%), and estimated daily traffic volume. These variables were used individually and in combination to apportion classes describing approximate risk of mortality for amphibians crossing at specific 50-m road segments: *Low Risk*, *Moderate Risk*, and *High Risk*. Risk criteria were adjusted arbitrarily to produce a negative, linear distribution of road segments among the three classes (i.e., the *High Risk* class was designed to have the smallest number of segments.

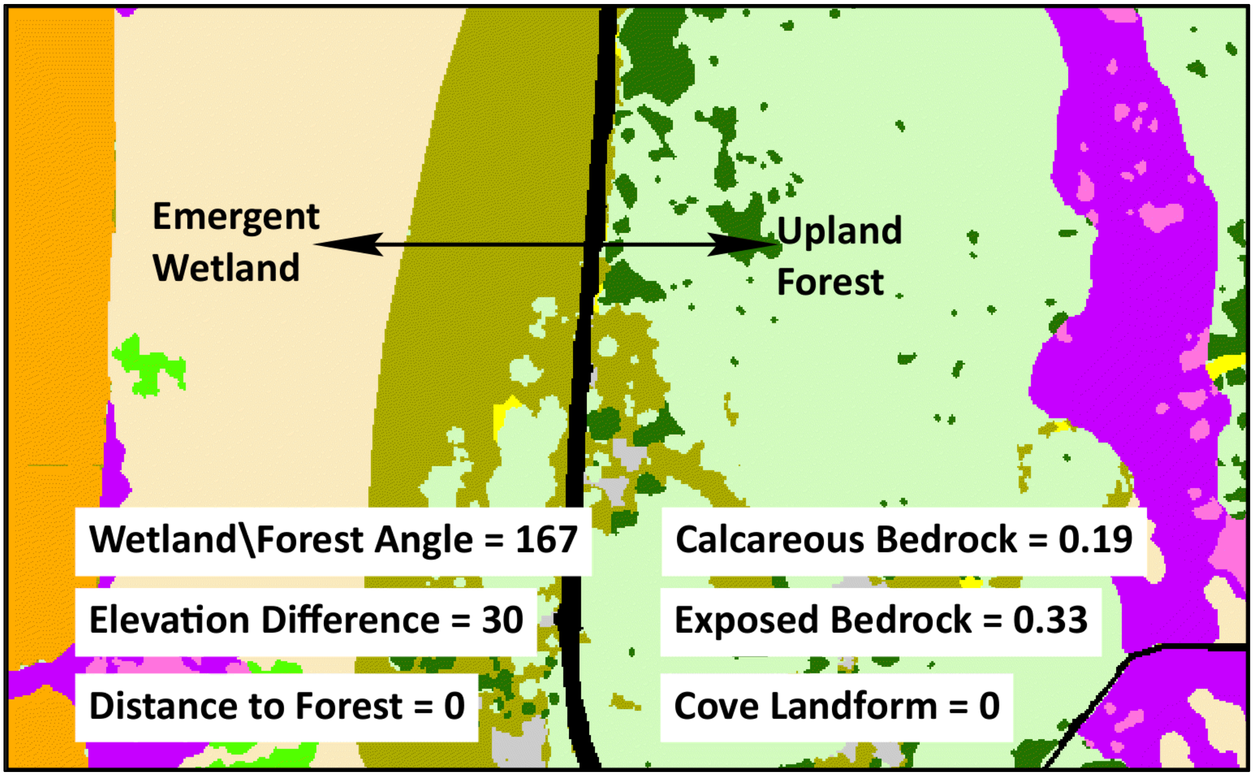

Figure 3. Example crossing location with characteristics favorable to amphibian migration, including juxtaposition of upland overwintering habitat and breeding sites, an elevation gradient between habitat types, and a direct movement path.

FIELD VERIFICATION DATA COLLECTION

The preliminary hotspot and risk assessments were used to plan prospective survey routes in Addison County and immediately-adjacent portions of Chittenden County. Site selection was designed to capture a range of habitat and road classes, and assumed mortality risk. Individual locations were visited during daylight hours following nights with favorable conditions for amphibian movement: rain with temperatures above 40° F. Field-validation occurred on four days during spring 2018 (4, 13, 26 April and 1 May), during which individual road segments were searched by walking up one travel lane and returning on the other while searching for alive and dead amphibians in the roadway. All amphibians encountered were photographed and identified to species when possible (genus, family, or order otherwise) and their locations recorded by GPS. For each road segment surveyed, the starting and ending points were recorded using GPS, potential breeding and adjacent terrestrial habitat was assessed qualitatively, and the probability that the site was an amphibian crossing hotspot was subjectively ranked based on visual cues as *Low, Medium-low, Medium, Medium-high,* or *High*.

REVISED HOTSPOT MODELING AND RISK ASSESSMENT

The field-verification data were used to refine and finalize the hotspot-modeling and risk-assessment protocols. For hotspot modeling, the field observations served as reference data in additional site-selection experimentation, with new thresholds and combinations of landscape-context variables used to maximize correspondence between modeled output and known crossing locations. Similarly, risk-assessment thresholds were adjusted to ensure an informative distribution of sites among the three risk classes.

In addition to the original set of modeled road characteristics (road width, maximum side slope, and daily traffic volume), the final risk assessment included the two risk variables used by Patrick et al. (2012): road class and length of crossing hotspots (m). Functional class (FUNCL) as derived from the available road centerline layer provided the road-class designation. The length of individual hotspots was determined by filling small gaps between otherwise contiguous 50-m sections, buffering, and then clipping the road centerline layer.

Results

FIELD VERIFICATION DATA

A total of 46 sites were visited during the spring 2018 field season, encompassing 730 whole or partial 50-m modeled road segments (Figure 4). In total, 57 individual amphibians of at least eight species were identified, including spotted salamander, blue-spotted salamander, four-toed salamander, eastern newt (*Notophthalmus viridescens*), green frog (*Lithobates sylvaticus*), spring peeper, American toad, and wood frog (Table 4). Most of the specimens were dead, presumably crushed by vehicle traffic, but four live eastern newts were also observed on roads.

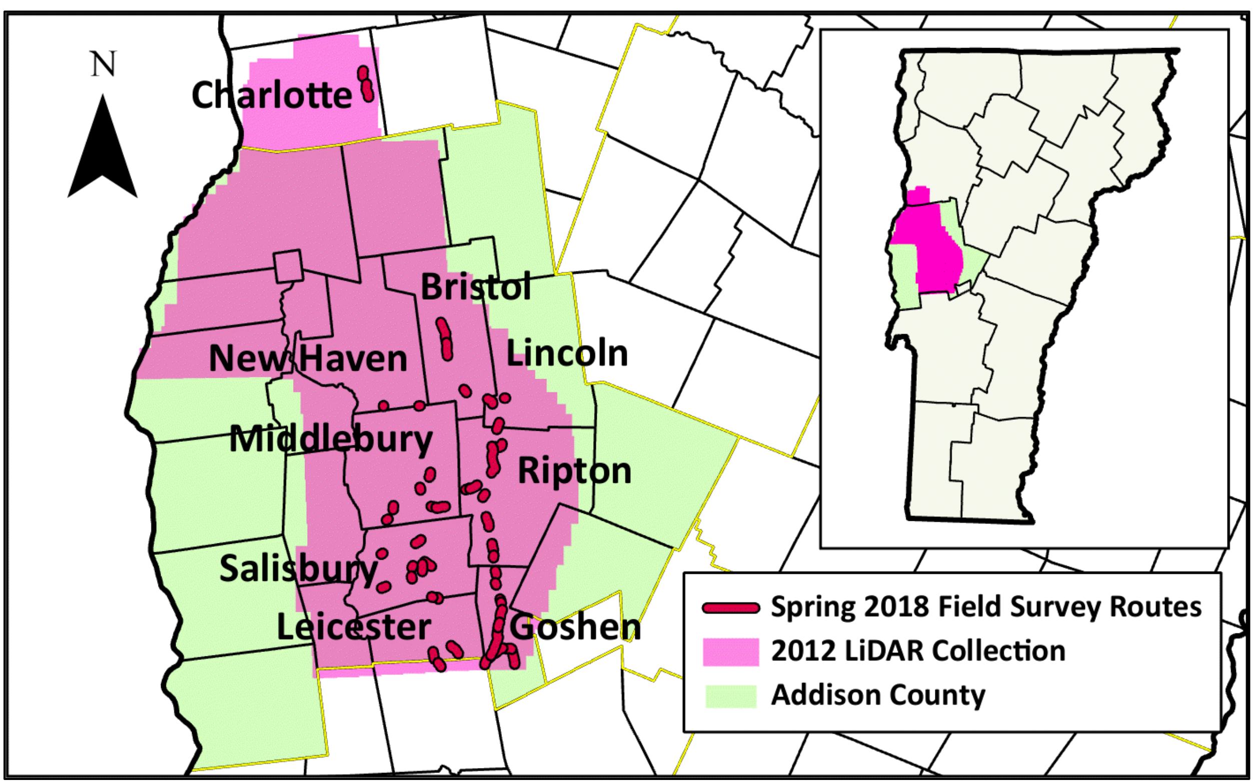

Figure 4. Road segments surveyed during spring 2018 amphibian movement period in Addison County, Vermont (and adjacent Chittenden County).

Table 4. Amphibians identified during spring 2018 field surveys in Addison County, Vermont (and adjacent Chittenden County).

Species	Scientific Name	#	Description
Ambystoma spp.	*Ambystoma* spp.	1	Dead On Road (scavenged egg mass remains)
Ambystoma spp.	*Ambystoma* spp.	7	Dead on Road
American Toad	*Anaxyrus americanus*	2	Dead on Road
Amphibian spp.		1	Dead on Road
Anuran spp.		1	Dead on Road
Blue-spotted Salamander	*Ambystoma laterale*	2	Dead on Road
Caudata spp.	*Caudata* spp.	1	Dead on Road
Eastern Newt	*Notophthalmus viridescens*	4	Alive on Road
Eastern Newt	*Notophthalmus viridescens*	3	Dead on Road
Four-toed Salamander	*Hemidactylium scutatum*	2	Dead on Road
Green Frog	*Lithobates clamitans*	1	Dead on Road
Spotted Salamander	*Ambystoma maculatum*	5	Dead on Road
Spring Peeper	*Pseudacris crucifer*	21	Dead on Road
Wood Frog	*Lithobates sylvaticus*	4	Dead on Road
Wood Frog	*Lithobates sylvaticus*	2	Dead on Road (Gravid Female)
Total		**57**	

Of the 730 visited road segments, only 30 (4%) showed direct evidence of amphibian movement, and all observations were recorded on Local or Minor Arterial roads (Table 5). Most segments without observations were also from the Local and Minor Arterial road classes, but 100 (14%) were from the Principal Arterial – Other, Minor Arterial, and Major Collector classes (Table 5). The road segments with dead or alive amphibians were mostly backroads with relatively narrow width, low maximum side slope, and low estimated traffic volume. The physical attributes of segments without observations varied widely but even the Local and Minor Arterial classes tended to be wider with steeper adjacent slopes.

Table 5. Road characteristics for 50-m segments visited during spring 2018 field verification, Addison County, Vermont (and adjacent Chittenden County).

Segments With Amphibian Observations										
		Width (m)			Traffic (cars/day)			Max. Side Slope (%)		
Road Class	**# Segments**	**Min**	**Max**	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**	**Mean**
Minor Collector (6)	3	11.7	12.6	11.7	90	90	90	11.9	25.1	18.7
Local (7)	26	7.8	11.3	11.3	90	90	90	5.9	55.4	25.2
Total	**30**									
Segments Without Amphibian Observations										
		Width (m)			**Traffic (cars/day)**			**Max. Side Slope (%)**		
Road Class	**# Segments**	**Min**	**Max**	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**	**Mean**
0ther (0)	19	3	46	14.5	90	1,900	217	7.7	89.5	31.6
Minor Arterial (4)	6	11.1	45.5	20.9	2,200	2,600	2,267	29.9	46	39.1
Major Collector (5)	75	8.9	50	14	1,000	3,200	1,916	6.5	116.5	38.1
Minor Collector (6)	69	7	47	12.2	90	970	103	9.5	96.5	32.8
Local (7)	531	1	55	12.9	90	2,500	122	0	118.9	33
Total	**700**									

The most significant “hotspot” documented during field verification was on Bean Rd. in Charlotte, where 33 dead amphibians (62% of all dead amphibians encountered) and 2 live newts were discovered over a 1.5 km section of a low-traffic dirt road. Another “hotspot” was located along a 25-m section of the Goshen-Ripton Rd. (FR-32) in Goshen, about 350 m north of the road to Sugar Hill Reservoir. At this site, a large vernal pool on the east side of the road supports significant populations of wood frogs, spotted salamanders, and Jefferson salamanders. Although only 3 dead amphibians were found at this site (wood frog and spotted salamander), it is a very low-traffic, rural dirt road, and given that Jefferson salamander is considered a rare species of “Special Concern” (S2) in Vermont, the site has the potential to be a significant "hotspot" if traffic increases.

HOTSPOT MODELING

Initial selection of potential crossing locations based on habitat proximity (i.e., breeding habitat near upland forest) identified 17,596 of 33,027 50-m road segments in the study area, or 53% of the total. The other 47%, considered to be unlikely hotspots, were excluded from subsequent analysis. Application of landscape-context variables further reduced the selection set, capturing 8,226 segments (25%). The selection criteria included a combination of habitat orientation and elevation difference in locations where forest patches were at least 10 m distant (Table 6). A forest-distance criterion was necessary because the orientation parameter became uninformative when surrounded by matrix forest (i.e., suitable habitat is found in multiple directions). This restriction is conceptually compatible with hotspot modeling, however, because migrating amphibians presumably will not be concentrated on roads surrounded by ample breeding and overwintering habitat. In contrast, roads separating breeding habitat from remnant forest patches may offer the only feasible movement route. In addition to land-cover configuration, road segments were also selected when special habitat characteristics (calcareous or exposed bedrock, cove landforms) were nearby (Table 6).

Table 6. Criteria for landscape context-based selection of road segments in final hotspot analysis for Addison County, Vermont (and adjacent Chittenden County).

Selection Criteria	Comment
(Orientation_majority > 130 *and* ELEV_CHANGE > 1 *and* NEAR_DIST_FORGRID > 10)	Direct path across road segment. Positive elevation gradient between upland sites and breeding habitat. Relatively distant forest patch (i.e., not a matrix forest site).
or (NEAR_DIST_VP > -1 *and* NEAR_DIST_VP < 183)	Near known vernal pools
or (Calcareous > 0.1)	Near calcareous bedrock
or (Bedrock > 0.1)	Near exposed bedrock
or (Cove > 0.01)	Near cove landform

These criteria helped refine the selection set while ensuring capture of exceptional crossing locations. For example, Figure 3 shows a location (Bean Rd. in Charlotte) at which more than 30 amphibians were observed during field verification. Wetlands and a large matrix forest occur on the east side of the road, suggesting that migrating amphibians can find acceptable breeding and overwintering habitat without crossing the road. And indeed, the road segments in that location were not selected despite favorable orientation and elevation characteristics because of the close proximity of forests. However, the segments were captured by the calcareous and exposed bedrock variables, essentially overriding the other criteria.

RISK ASSESSMENT

The field verification data suggested that high road mortality can occur on even low-intensity roads (Table 5), supporting previous studies that observed significant mortality on relatively quiet transportation networks. Accordingly, road width, maximum side slope, and traffic volume were not used in the final risk assessment. However, some type of risk assessment was necessary to isolate the most important crossing locations and inform subsequent mitigation efforts. Instead, an alternative assessment based on the variables used by Patrick et al. (2012) identified 2,134 road segments as *High Risk* based on the combined length of contiguous segments, or 27% of 8,078 hotspots (Table 7). When combined into single units, these segments identified 31 separate sites across the study area (Figure 5). As designed, the *Moderate Risk* and *Low Risk* classes contained larger proportions of the modeled hotspots by length, with 30% and 43% of the total road segments, respectively. These classes represented 94 (*Moderate Risk*) and 862 (*Low Risk*) different sites when merged into single units. When summarized by road class, the distribution of road segments was more heavily skewed toward the lower risk classes, with the *High Risk* class capturing only 507 segments (6%). However, these segments represented a larger number of individual contiguous sites (86). The combined length X road class category was even more restrictive, capturing 97 segments (1%) in 7 contiguous segments.

Table 7. Risk assessment for road and railroad segments identified as potential hotspots in Addison County, Vermont (and adjacent Chittenden County. Highlighted roads were grouped into risk groups according to the combined length of contiguous road segments, road class, and a combination of these two variables (length only for railroads).

Roads						
			Risk Criteria			
Risk Group	**Length (m)**	**# Segments**	**Road Class (FUNCL)**	**# Segments**	**Length X Road Class**	**# Segments**
Low	>0<=1,000	3,502 (43%)	0, 7	6,360 (79%)	Low, Low	2,890 (36%)
Moderate	>1,000<=2,500	2,442 (30%)	5, 6	1,211 (15%)	All Others	5,091 (63%)
High	>2,500	2,134 (27%)	3, 4	507 (6%)	High, High	97 (1%)
Total		**8,078 (100%)**		**8,078 (100%)**		**8,078 (100%)**
Railroads						
			Risk Criteria			
Risk Group	**Length (m)**	**# Segments**	**Road Class (FUNCL)**	**# Segments**	**Length X Road Class**	**# Segments**
Low	>0<=1,000	84 (57%)	—[a]	—	—	—
Moderate	>1,000<=2,500	30 (20%)	—	—	—	—
High	>2,500	34 (23%)	—	—	—	—
Total		**148 (100%)**	—	—	—	—

[a]All railroads coded as a single class.

For railroads, the *High Risk* class captured 34 of the 148 segments (23%) represented in the study area (Table 7). Although the *Moderate Risk* class contained slightly fewer

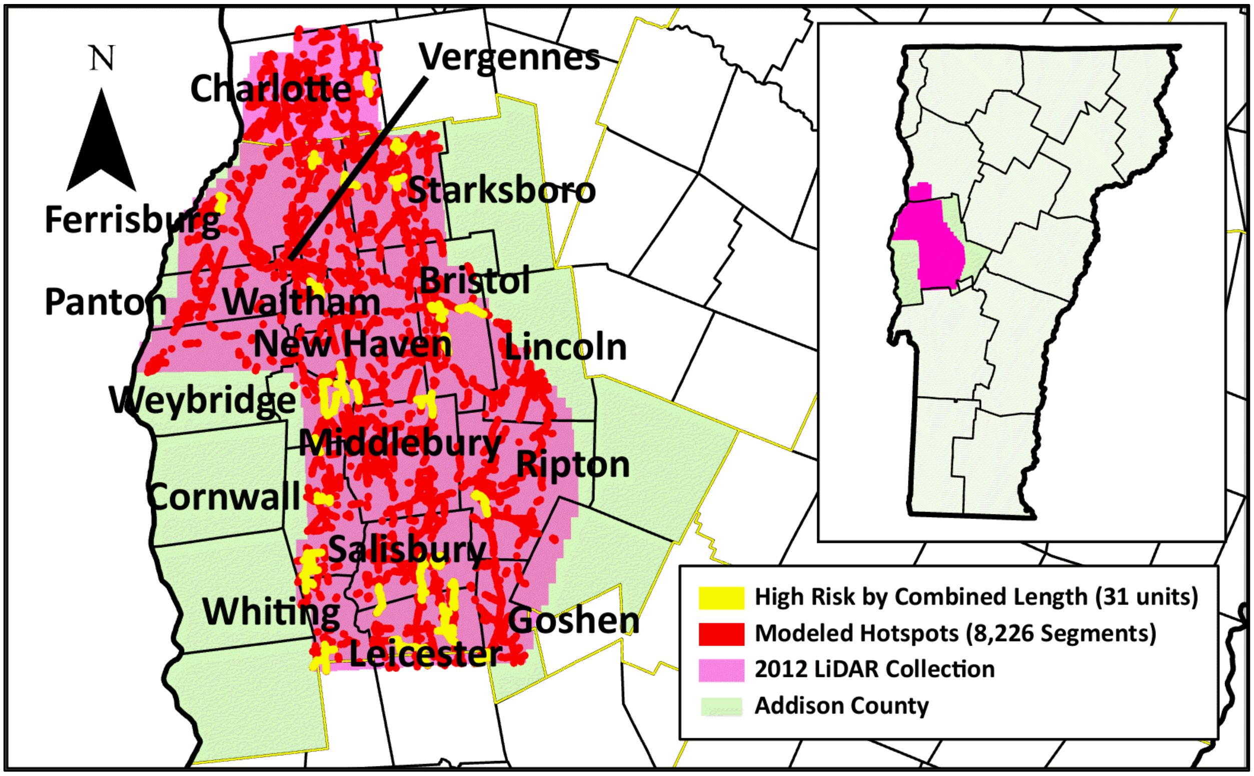

Figure 5. Modeled hotspot road segments in Addison County, Vermont (and adjacent Chittenden County). Of more than 8,000 total segments, a risk assessment performed by combined length identified 2,134 (27%) segments that represented 31 individual sites.

segments (20%), as designed the *Low Risk* class contained the largest proportion of segments (57%). No risk assessment was performed by class because railroads were coded as a single entity.

Discussion

Use of 1-m land cover in habitat modeling provided a fine-grained analysis of some features that affect amphibian movement patterns. These variables include areas with suitable forest cover to support terrestrial amphibian populations adjacent to wetlands suitable for breeding. When these two critical habitat components are bisected by roadways, the potential for mortality increases. Given the widespread occurrence of amphibians in the study area and the relative abundance of wetlands, the model could be improved by being better able to identify those wetlands that provide the most suitable breeding habitat for significant populations of amphibians and/or breeding sites with high species diversity. Nevertheless, our model provides broad-scale data that can be used to identify potential road segments that may negatively impact amphibian populations. While this provides a good starting point for potential mitigation projects, field visits will be essential to verify the presence and significance of individual crossing locations.

Two-step identification of hotspots based first on habitat proximity and secondly on landscape context effectively reduced the set of potential sites to a number appropriate and manageable for further analysis. This approach recognized the importance of habitat pattern and configuration, with topographic characteristics playing an equal role in site selection. Accordingly, the best *habitats* for amphibians were not necessarily captured by the selection criteria; rather, the most likely *crossing locations* were selected. In particular, the modeling often skipped matrix forest locations unless adjacent habitats contained special features known to influence amphibian migration (i.e., specific bedrock characteristics and cove landforms).

The physical road variables designed for risk assessment did not support an effective ranking of Addison County sites. This failure was at least partly attributable to the reality that high mortality can occur on backroads with relatively low traffic volumes; above a certain low threshold of traffic, road width and side-slope characteristics apparently become irrelevant. Maximum side slope was generally low for roads with amphibian observations but it is unclear whether the steeper slopes of other roads impeded movement and hence reduced mortality. More research is needed to understand the interaction of width and side slope in facilitating or impeding amphibian dispersal. More comprehensive traffic-count data would also improve risk-assessment sensitivity, providing a better indicator of mortality risk for backroads and minor collector segments.

Although specific road characteristics were uninformative in this analysis, an alternative risk assessment based on segment length and road class provided a reasonable basis for prioritizing remediation efforts. The length variable in particular identified a modest number of sites that could be examined in the field to: 1) confirm the frequency of amphibian crossings; and 2) isolate specific road segments that could be effectively modified to minimize mortality. Note that both the hotspot analysis and risk assessment presented here are starting points for additional study; the final output datasets provided as part of this project have the full set of habitat and road variables and can be manipulated to provide different modeling scenarios.

Field verification could be expanded in subsequent projects by replicating site visits across multiple dates. Replication would help accommodate variability in the meteorological conditions affecting movement, including precipitation and temperature. It would also help compensate for potential removal of dead specimens by scavenging birds and mammals. Similarly, sampling across a more even distribution of road classes would help gauge mortality on higher-intensity roads and provide better discrimination of hotspots across the full study area.

The methods developed for this pilot can be readily adapted for other sections of Vermont. The Lake Champlain land-cover map is currently being extended to the entirety of the state, and most of the other input datasets are already available at the statewide scale (Table 1). The one exception is modeled vernal pools; these features have not been mapped statewide but it would be possible to burn in known and probable pools represented in the Vermont Vernal Pool Mapping Project and any other local data that may exist. It may also be possible to incorporate expanded vernal pool modeling into future hotspot-modeling projects. Depending on stakeholder need, subsequent analyses could be conducted on either individual regions or the entire state.

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