Salamander Abundance along Road Edges and within Abandoned Logging Roads in Appalachian Forests

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Abstract: *Roads may be one of the most common disturbances in otherwise continuous forested habitat in the southern Appalachian Mountains. Despite their obvious presence on the landscape, there is limited data on the ecological effects along a road edge or the size of the "road-effect zone." We sampled salamanders at current and abandoned road sites within the Nantahala National Forest, North Carolina (U.S.A.) to determine the road-effect zone for an assemblage of woodland salamanders. Salamander abundance near the road was reduced significantly, and salamanders along the edges were predominantly large individuals. These results indicate that the road-effect zone for these salamanders extended 35 m on either side of the relatively narrow, low-use forest roads along which we sampled. Furthermore, salamander abundance was significantly lower on old, abandoned logging roads compared with the adjacent upslope sites. These results indicate that forest roads and abandoned logging roads have negative effects on forest-dependent species such as plethodontid salamanders. Our results may apply to other protected forests in the southern Appalachians and may exemplify a problem created by current and past land use activities in all forested regions, especially those related to road building for natural-resource extraction. Our results show that the effect of roads reached well beyond their boundary and that abandonment or the decommissioning of roads did not reverse detrimental ecological effects; rather, our results indicate that management decisions have significant repercussions for generations to come. Furthermore, the quantity of suitable forested habitat in the protected areas we studied was significantly reduced: between 28.6% and 36.9% of the area was affected by roads. Management and policy decisions must use current and historical data on land use to understand cumulative impacts on forest-dependent species and to fully protect biodiversity on national lands*

Keywords: amphibian, edge effects, land use, logging, *Plethodon*, road-effect zone

Abundancia de Salamandras a lo Largo de Bordes de Caminos y en Caminos Madereros Abandonados en Bosques Apalaches

Resumen: *Los caminos pueden ser una de las perturbaciones más comunes en bosques otrora continuos en los Montes Apalaches. No obstante su obvia presencia en el paisaje, hay datos limitados sobre los efectos ecológicos a lo largo de un borde de camino o del tamaño de la "zona de efecto del camino." Muestreamos salamandras sitios en caminos vigentes y abandonados en el Parque Nacional Nántala, Carolina del Norte (E.U.A.) para determinar la zona de efecto del camino para un ensamble de salamandras de bosque. La*

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abundancia de salamandras cerca del camino disminuyó significativamente, y las salamandras a lo largo de los bordes eran individuos grandes predominantemente. Estos resultados indican que la zona de efecto de camino para estas salamandras se extiende 35 m a ambos lados de los caminos relativamente angostos, poco utilizados que muestreamos. Más aun, la abundancia de salamandras fue significativamente menor en caminos viejos, abandonados, en comparación con sitios en laderas contiguas. Estos resultados indican que los caminos en los bosques y los caminos madereros abandonados tienen efectos negativos sobre especies dependientes de bosques como las salamandras pletodóntidas. Nuestros resultados se pueden aplicar a otros bosques protegidos en los Apalaches y pueden ejemplificar un problema causado por formas de uso de suelo actuales y pasadas en todas las regiones boscosas, especialmente las relacionadas con la construcción de caminos para la extracción de recursos naturales. Nuestros resultados muestran que el efecto de los caminos rebasó el límite de los mismos y que el abandono de caminos no revirtió los efectos ecológicos perjudiciales; más bien, nuestros resultados indican que las decisiones de gestión tienen repercusiones significativas para las generaciones futuras. Más aun, la cantidad de hábitat boscoso adecuado se redujo significativamente en las áreas protegidas que estudiamos: entre 28.6% y 36.9% de la superficie fue afectada por caminos. Las decisiones políticas y de gestión deben recurrir a datos actuales e históricos sobre el uso de suelo para entender los impactos acumulativos sobre especies dependientes de bosques y para proteger integralmente a la biodiversidad en terrenos nacionales.

Palabras Clave: anfibios, corte de árboles, efectos de borde, *Plethodon*, uso de suelos, zona de efecto de camino

Introduction

Species declines are often due to decreases in population size, increases in isolation, and edge effects (Kareiva & Wennergren 1995). Edge effects in forests reduce the effective size of remaining patches by creating unsuitable habitat along the boundary due to factors such as increased sunlight, air temperature, wind, soil drying, and the presence of invasive species and predators (reviewed extensively in Saunders et al. 1991; Murcia 1995; Harper et al. 2005). Thus, forest-dependent species, which are sensitive to such factors, may shift activity away from edges and be less abundant or even absent along edges.

Roads may be one of the most common disturbances in otherwise continuous forested habitat, such as protected national forest lands. Most paved roads are used for public transportation (6.2 million km of public roads used by 200 million vehicles in the United States; Forman 2000), but many unpaved roads intersect large areas of forest for access to and removal of natural resources such as timber. Roads can have direct effects on species (e.g., mortality from construction and roadkill; e.g., Langton 1989; Fahrig et al. 1995) or indirect effects due to modification of animal behavior, disruption of the physical environment, alteration of the chemical environment, spread of exotic species, and changes in human use of natural resources (e.g., Trombulak & Frissell 2000). Roads create long and narrow edges that may extend well beyond the road surface or roadsides (Forman 2000). Furthermore, roads may persist for >40 years after abandonment and can be embedded in seemingly continuous forest (Vora 1988). Despite their obvious presence on the landscape, there is limited data on the ecological effects of roads along their edges or on the size of the "road-effect zone" (Forman et al. 1997; Forman & Alexander 1998; Forman & Deblinger 2000). The ecological effects of roads may be just as severe as other edge effects created by habitat loss and alteration (Murcia 1995), both of which have important implications for disrupting the function and diversity of forest ecosystems (Saunders et al. 1991; Harper et al. 2005).

We sought to determine the extent of road effects on an assemblage of woodland salamanders in the southern Appalachian Mountains. Woodland salamanders are small, lungless, sedentary, and strongly dependent on cool, moist forest habitat (e.g., Spight 1968; Spotila 1972), and these characteristics make them excellent indicators of environmental stress or change (e.g., Welsh & Droege 2001; Wyman 2003). We assumed woodland salamanders would be highly sensitive to alterations in the physical environment along roads. We hypothesized that declines in salamander abundance near road edges is due to the reduction of suitable habitat and might correlate with physical changes and lower abundance of macroinvertebrate prey at road edges found in previous studies (e.g., Haskell 2000). Furthermore, because results from the first part of our study on edge effects showed a nonlinear response of salamanders, we tested whether abandoned logging roads embedded in seemingly continuous forest might further fragment the forest by creating linear strips of less-suitable habitat relative to adjacent forested areas. Finally, to determine the loss of habitat by varying sizes of the road-effect zone, we used a GIS analysis to estimate the total area of forest that could be classified unsuitable for woodland salamanders.

Methods

Sampling Design

Our study area was centered within the Highlands Ranger District of the Nantahala National Forest, North Carolina

Table 1. Description of 11 road sites from which salamanders were sampled in the Nantahala National Forest, Highlands, North Carolina.

Site	*Road surface*	*Road width (m)*	*Clearing width (m)*	*Aspect*	*Canopy cover (%)*	*Light (lux)*	*Elevation (m)*	*Cars/ hour*
Norton branch	gravel	3.7	6.4	SSW	57	1030	769	9
Chestnut Mt.	gravel	4.1	7.2	W	32	108,600	831	2
Fodderstack Mt.	dirt/grass	1.9	3.4	NE	55	1482	923	(gated)
Cole gap	paved	6.2	36.1	NW	0	2667	1261	50
Highland Ctr.	paved	5.2	11.4	W	0	32,300	1231	10
Cemetery	paved	6.3	12.1	NNW	0	105,266	769	5
Slick rock	gravel	4.6	9.6	ESE	60	2422	985	12
N. Rich Mt.	gravel	4.8	10.3	SE	12	6200	1200	7
Rattlesnake knob	gravel	4.7	8.6	S	52	134	1231	7
Granite city	gravel	6.2	11.6	SSE	8	2500	923	14
Horse cove	gravel	5.8	12.4	ENE	0	6066	969	7
Mean	—	4.86	11.7	—	25.1	24,424	1008	11.2

(U.S.A.) and encompassed primarily a mature (all >75 years since last logging) southern Appalachian hardwood forest dominated by oaks. To examine edge effects, we used area-constrained searches and cover boards to sample salamanders at 11 road sites within the forest. We selected sites along existing low-use gravel ($n = 8$) and paved ($n = 3$) roads, where mature forest bordered the road, that were at least 200 m away from other active roads or other human activities and had low road banks (<30 cm high; Table 1). Sites were selected haphazardly across the area but were representative of roads commonly found throughout the Nantahala National Forest. From 6 to 12 June 2000, we established paired transects to maximize the area sampled and the number of salamanders collected at each road site. Our sampling protocol followed that of Haskell (2000): transects ran perpendicular from the road edge 100 m into the forest and consisted of six sampling stations at 1, 5, 15, 35, 60, and 100 m along the transect. Transects were started at the road edge, which was defined by the presence of a tree line (trees >30 cm circumference). The paired transects ran parallel to each other and were on average 40 m apart. We revisited transects, opportunistically, six times from June 2000 through August 2003, when surface activity of forest-dwelling plethodontid salamanders is generally high (e.g., Petranka et al. 1993; Ash 1997).

During the initial sampling in June 2000, we laid out a 1.5 × 1.5 m quadrat (2.25 m^2) at each of the sampling stations and conducted a thorough search of the leaf litter and all cover objects (e.g., rocks, bark, tree limbs) within the plot down to the mineral soil or rock. Subsequently, we installed a pair of cover boards (30.5 × 122 × 3.75 cm untreated rough-cut lumber) next to each sampling station in October 2000. At each subsequent sampling date we restricted our salamander sampling to checking beneath the cover boards. The cover boards allowed us to sample stations repeatedly, were less destructive to the habitat, and yielded data on the same species assemblage as raking through natural cover objects in June 2000 (deGraaf & Yamasaki 1992; Marsh & Goicochea 2003), albeit at a lower capture rate (e.g., Smith & Petranka 2000; Hyde & Simons 2001). We recorded the species, sex (if discernable by secondary sexual characteristics), and snout-vent length (SVL in mm: distance from the tip of the snout to the posterior margin of the cloacal aperture) for each individual. All measurements were taken in the field and individuals were released within 5 minutes of capture. All sampling was conducted between the hours of 0800 and 2000 and regardless of weather.

To examine the effects of old, abandoned logging roads, we sampled terrestrial salamanders during May 2005 with area-constrained searches at eight sites within the same area of the Nantahala National Forest. All sites were in closed-canopy forest and were last logged at least 80 years ago. We selected sites haphazardly as they were encountered near our edge transects but they appeared representative of old logging roads in the area. We established two replicate sampling arrays at least 50 m apart at each road site. Each array had two stations on the roadbed separated by 10 m, one off-road station 10 m upslope and one station 10 m downslope adjacent to the road. At each site, we laid out a 1.5 × 1.5 m quadrat (2.25 m^2) at each sampling station on and off the roadbed and conducted a thorough search of the leaf litter and all cover objects (e.g., rocks, bark, tree limbs) within the plot down to the mineral soil or rock. We recorded the species, sex (if discernable by secondary sexual characteristics), and whether the individual was an adult or juvenile based on relative body size. Individuals were released within 5 minutes of capture. All sampling was conducted between 0800 and 1800 hours, regardless of weather.

Physical and Biotic Factors

In the road-edge study at each site, we measured width of the road surface used by vehicles and road shoulder (i.e., edge of the road surface to the treeline), clearing width (road surface plus shoulder), road type (paved or gravel), traffic volume (count of vehicles during the sampling period), and light transmission (determined with a digital EXTECH Instruments light meter) and percent canopy cover (GRS Densitometer) at the center of the road. At each sampling station we measured light transmission (lux), percent soil moisture, litter depth, coarse woody debris (CWD), and macroinvertebrate abundance (number per sample) and richness (number of taxa).

To sample invertebrates we used a corer (4.7 cm diameter; 14.76 cm^2 area) at each station to collect three soil-litter subsamples that were combined in one plastic bag and returned to the laboratory for processing within 4–6 hours (methods after Haskell 2000). Each sample was sifted through a 6.25-mm mesh screen to remove rocks, woody debris, and leaves, and then searched exhaustively by hand to find all invertebrates >1 mm in size. We identified all invertebrates to the level of order except Chilopoda and Diplopoda, which were identified to class.

Using a corer, we collected three soil subsamples at each station and placed samples in a plastic bag. Soil samples were weighed, dried at 45° C for 24 hours, and reweighed to determine percent soil moisture. During one sample period, we estimated stem density along each transect by counting all stems rooted within two 1-m^2 plots at each sampling station and classifying stems as small (<10 cm circumference), medium (10–30 cm circumference), or large (>30 cm circumference).

In the study on abandoned logging roads we measured several characteristics of the road and several physical and biotic parameters at each sampling station on or off the roadbed. At each site we measured width of the road surface and road shoulder. At each sampling station we measured percent soil moisture, soil density (dry soil weight per volume), percent litter moisture, and litter depth with the same methods as in the road edge study.

Statistical Analysis

We initially used Haskell's (2000) correlation analytical method to evaluate whether roads influenced salamander abundance along our transects. We pooled our observations from the paired transects at each site and across all sampling periods to increase sample size for each distance. To account for site differences in the correlations, we calculated the proportion of the total number of captures recorded at each sampling station at each site and tested for differences among sites and distances with a two-way analysis of variance (ANOVA with Type III sums of squares). In this analysis distance from the road was a fixed effect, and sites were treated as blocks yielding a randomized complete block design. To eliminate dependence in the proportions among distances, we dropped the data from 100-m stations. Data from the 100-m stations was also dropped because of biases created by nearby abandoned logging roads. We used the angular transformation to make the proportional values normally distributed. Following Haskell (2000) we conducted correlation analyses for five distances versus invertebrate abundance (number of individuals) and richness (number of taxa) at each site ($n = 11$), with means of the two transects as a response variable. We then tested whether the mean correlation coefficient differed significantly from zero with a one-sample two-tailed t test. Last, to help explain the distribution of salamander along our transects, we conducted Spearman's rank correlations of the abundance of salamanders with invertebrate abundance, invertebrate richness, stem density by size class, light transmission, soil moisture, litter depth, and CWD.

GIS Analysis

To determine the loss of habitat due to the road effect zone, we used a GIS analysis to estimate the total area of forest that could be classified unsuitable for woodland salamanders. We used GIS coverage of forest and roads for the Highlands Ranger District of the Nantahala National Forest (446.76 km^2 = 110,396.9 acres of forest; 1222.8 km of all roads and trails). By using road-effect zones of varying sizes 0, 1, 5, 10, 15, 35, 60, 80, and 100 m (times two sides of the road plus 12 m for the average road clearing from Table 1), we calculated the percentage of forest that was unsuitable for a range of road-effect sizes.

Results

Road Edge Effects

Over the six sampling periods, we collected 199 salamanders at our six sampling stations at each of the 11 paired road transects. A total of seven species was represented in these samples, with the southern gray-cheeked salamander (*Plethodon metcalfi*) representing the majority (77%; Table 2). Of the 11 sites there were 3 negative correlations and 8 positive correlations of salamander abundance with distance, only 2 of which were significant at $p < 0.05$ (Cole Gap and Chestnut Mountain), but the average value was marginally significantly different from zero ($t = 2.03$, df = 10, $0.1 > p > 0.05$).

The absence of a strong correlation among transects, however, did not preclude the presence of edge effects because the relationship might be nonlinear and the sampling stations were not continuously distributed. Again, pooling both transects across all sampling periods, we calculated the proportion of the total number of captures recorded at each of the first five sampling stations at each site. We found significant variation both among sites ($p < 0.0001$) and distances ($p = 0.048$) along the transect (Table 3; Fig. 1). Tukey's post hoc comparisons of distance indicated the only significant differences between stations 1 m and 35 m from the road ($p = 0.050$) and between 1 m and 60 m from the road ($p = 0.066$; Fig. 1).

Because *P. metcalfi* was the most common species collected along the transects, the results of the distribution

Table 2. Summary of species and the number of salamanders collected at 11 road sites in the Nantahala National Forest, Highlands, North Carolina during six sampling periods.

Species	*2000* June	*2001* April	May	June	July	August	Total	Proportion
Ambystoma maculatum	0	0	1	0	0	0	1	0.005
Desmognathus ocoee	0	0	1	0	1	1	3	0.015
Eurycea wilderae	1	0	0	1	0	0	2	0.010
Notophthalmus viridescens	2	0	0	1	0	0	3	0.015
Plethodon metcalfi	16	15	41	10	30	41	153	0.769
Plethodon oconalufti	2	8	5	3	4	1	23	0.116
Plethodon serratus	11	2	0	0	0	0	13	0.065
Other (unknown)	1	0	0	0	0	0	1	0.005
Total	33	25	48	15	35	43	199	
Proportion	0.166	0.126	0.241	0.075	0.176	0.216		

analysis were largely due to one species. For this reason we repeated the analysis with only *P. metcalfi* in the ANOVA. Eliminating the other species from the data matrix reduced several site–distance combinations with no observations. Therefore prior to the analysis, we dropped three sites from the data matrix that had fewer than 5% of the total observations of *P. metcalfi*. As in the previous analysis, both the sites ($p = 0.001$) and distances ($p = 0.020$) were significant (Table 3). The pairwise comparisons indicated that the abundance of *P. metcalfi* was significantly lower 1 m from the road compared with 60 m from the road ($p = 0.009$; Fig. 1). Body size of *P. metcalfi* did not differ among sites ($p = 0.720$) but did vary significantly with distance ($p = 0.022$; Table 3). Tukey's pairwise comparisons revealed that individuals found 35 m from the road were significantly smaller than those found 60 m ($p = 0.030$) and 1 m from the road ($p = 0.049$). Notably, these larger salamanders 1 m from the road had relatively little variation in body size (CV = 5.95), whereas all the other sampling distances displayed a much greater degree of variation in body size (CV range 13.86–20.98).

We collected 396 samples for the invertebrate analysis. Neither abundance ($t = 0.352$, df = 10, $p > 0.1$) nor richness ($t = 0.414$, df = 10, $p > 0.1$) was significant. According to goodness-of-fit tests, we could not reject the null hypothesis that an equal number of sites should produce negative and positive correlations for either abundance ($\chi^2 = 0.25$, df = 1, $p > 0.1$) or richness ($\chi^2 = 0.25$, df = 1, $p > 0.1$). Only 5 of 11 sites had positive correlation coefficients for abundance, and the same 5 had positive correlation coefficients for richness. Although six correlation coefficients for individual sites were significant at $p < 0.05$ for abundance, three of these were positive and three were negative correlations. Only three correlation coefficients for individual sites were significant at $p < 0.05$ for richness (two negative and one positive).

The results of the nonparametric regression analysis showed that the abundance of salamanders along the transects was not significantly related to either invertebrate abundance (Spearman $r = 0.20$, $p > 0.05$) or richness ($r = 0.55$, $p > 0.05$). Simple correlation analysis demonstrated that salamander abundance was also not related

Table 3. Summary of analysis of variance statistics for salamander proportion (all salamanders combined; *P. metcalfi* alone) and body size collected along roads in the Nantahala National Forest, Highlands, North Carolina.*

Analysis and source	*df*	*Adjusted SS*	*Adjusted MS*	F	p
All salamanders					
distance	4	0.01450	0.00362	2.64	0.0480
site	10	0.06676	0.00668	4.86	<0.0001
error	40	0.05490	0.00137		
total	54	0.13616			
Plethodon metcalfi					
distance	4	0.02188	0.00547	3.47	0.0200
site	7	0.05312	0.00759	4.81	<0.0001
error	28	0.04418	0.00158		
total	39	0.11918			
Body size					
distance	4	0.06932	0.01733	3.48	0.0220
site	7	0.02224	0.00318	0.64	0.7200
error	25	0.12442	0.00498		
total	36	0.21598			

**Analyses differ in degrees of freedom because some samples were eliminated (see Methods).*

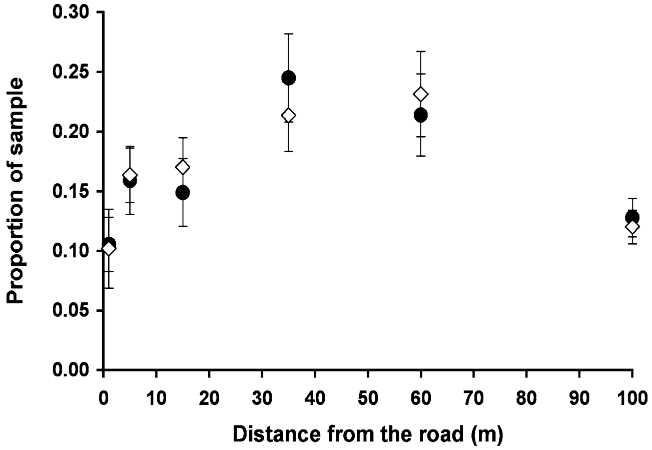

Figure 1. Abundance of salamanders at six distances (1, 5, 15, 35, 60, 100 m) from roads in the Nantahala National Forest, Highlands, North Carolina. Filled circles represent means (+1 SE) of all species combined; open diamonds represent means (+1 SE) of only Plethodon metcalfi *captures.*

to stem density of any size class (Pearson's $r = -0.311$, -0.234, -0.131 for small, medium, and large stem-size classes, respectively; all $p > 0.4$). In a stepwise multiple regression, with the abiotic variables tested against salamander abundance, only litter depth ($t = 3.10, p = 0.053$) and coarse woody debris ($t = 3.87, p = 0.020$) appeared significantly related. None of the abiotic factors were significantly correlated (either positively or negatively) with distance from the road (all $p > 0.05$).

Logging-Road Effects

The eight abandoned roads we sampled were narrow ($\bar{x} = 5.4$ m road width) and varied in elevation from 738 m to 1200 m. During the May 2005 sampling period, we collected only 27 salamanders of five species in 64 sample plots. There were no significant differences in the number of salamanders between on- and off-road plots (two-tailed, unpaired t test; $t = 0.8808$, df = 62, $p = 0.3818$). Nevertheless, when we compared the proportion of salamanders collected per plot (to account for twice as many sample plots on roads) on up- and downslope plots separately with on-road plots, there was a significant difference. The upslope plots had significantly higher proportions of salamanders than those on the road ($t = 2.778$, df = 46, $p = 0.0079$), whereas the proportion of salamanders collected downslope was higher but not significantly different than the proportion on the road ($t = 1.3533$, df = 46, $p = 0.1826$). Furthermore, soil density was significantly lower and depth of leaf litter and soil moisture were significantly higher at down- and upslope sites compared with on the road (Table 4). Leaf-litter moisture was also higher at down- and upslope sites compared with the road sites, but not significantly (Table 4).

Reduction in Habitat

After accounting for the average road clearing of 12 m, there was a large initial loss of suitable habitat with a road-edge effect of just 1 m (3.2–15.4%; Fig. 2). After this initial loss there was a steady and linear decrease of suitable habitat (up to a 28.6% loss) using a minimum road-edge effect of 35 m. This edge effect was significant for all salamanders. If we used a road-edge effect of 60 m, which was significant for *P. metcalfi* alone, the loss of suitable habitat increased to 36.9% (Fig. 2).

Discussion

Woodland salamanders showed a significant reduction in abundance near the road, and individuals along the edge were predominantly large in body size. Furthermore, salamander abundance was significantly lower on old, abandoned logging roads compared with adjacent upslope sites. These results indicate that active forest roads and abandoned logging roads have negative effects on forest-dependent species such as lungless plethodontid salamanders.

Although we predicted that based on invertebrate abundance (Haskell 2000), salamander abundance would be lowest next to roads (i.e., 1 m distance) and increase

Table 4. Summary of four physical characteristics (mean + 1 SE) and percent effect of down- and upslope samples compared with those taken from abandoned logging roads in the Nantahala National Forest, Highlands, North Carolina.

Characteristic	*Downslope (% effect)*	*Road (% effect)*	*Upslope (% effect)*
Soil density (g/mL)	0.2519 + 0.0467 (−38.0)*	0.4061 + 0.0758 —	0.2336 + 0.0446 (−42.5)*
Litter depth (cm)	3.09 + 0.20 (+30.3)*	2.38 + 0.19 —	3.44 + 0.19 (+44.7)*
Soil moisture (%)	35.6 + 3.72 (+27.9)*	27.8 + 2.20 —	39.0 + 3.78 (+44.8)*
Litter moisture (%)	30.5 + 4.20 (+12.5)	27.1 + 2.78 —	35.1 + 4.84 (+38.3)

**A* t *test was used to compare road samples with downslope or upslope (*$p < 0.05$*).*

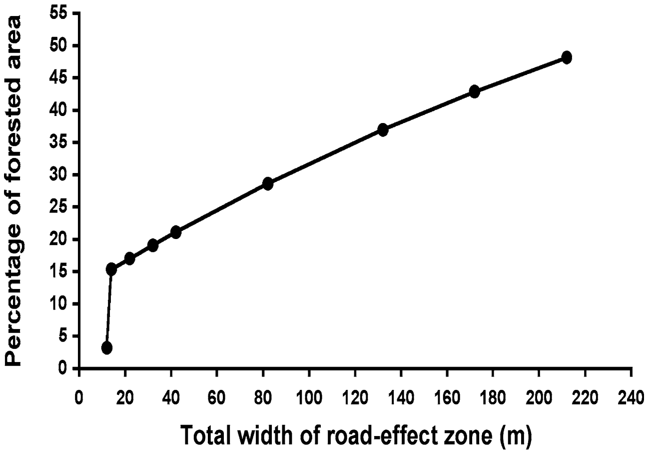

Figure 2. Summary of a GIS analysis showing the percentage of forest area affected by varying sizes of road-effect zone (simulated road edge effects = 0, 1, 5, 10, 15, 35, 60, 80, 100 m) in the Nantahala National Forest, Highlands, North Carolina.

or level off 100 m from roads, abundance was lowest at 1 m, peaked at 35 m from roads for all species and at 60 m for *P. metcalfi*, and declined out to 100 m (Fig. 1). This lack of a correlation with distance and no correlation with invertebrate abundance or richness indicates a road effect is unlikely due to food resources alone.

If one assumes that the scale of road effects in our study was conservatively 35 m, ignoring for the moment the decline at 100 m, this distance was very close to the 20-m road effect found for red-backed salamanders (*Plethodon cinereus*) at two out of three study sites in Virginia but was <the 80-m road effect found at a third site (Marsh & Beckman 2004). Thirty-five meters is also very similar to the edge effects of 20 m found for red-backed salamanders in New Hampshire forests (deGraaf & Yamasaki 2002). Because of such close agreement among three independent studies on the scale of edge effects for salamanders, we suggest that a conservative road-effect zone for terrestrial salamanders likely extends 35 m on either side of these relatively narrow, low-use forest roads (Table 1). We also suggest that the unsuitable habitat for salamanders created by the presence of road clearings plus this road-effect zone (35 m + 12 m road clearing + 35 m = 82 m) can fragment seemingly continuous forest into smaller blocks of suitable habitat.

To illustrate one consequence of a reduction in habitat road edge effects, we conducted a post hoc GIS analysis of the area of forest affected by roads to estimate the area of forest that would be unsuitable for salamanders (Fig. 2). Our estimate, based on the minimum road-effect size of 35 m, was 12,782 ha or 28.6% of the entire Highlands Ranger District. Estimates based on larger values taken from our study (60 m) or Marsh and Beckman (2004) (80 m) show that the amount of forest land that is potentially unsuitable is 36.9–42.8% of this tract of national forest.

Reduced soil moisture and leaf litter or some complex interaction of the two variables appears to decrease the availability of moisture to salamanders near roads. Moisture availability is an important factor for suitable habitat (Jaeger 1971, 1980; Ash 1995, 1997) and is the most likely proximate mechanism driving changes in salamander abundance near edges or limiting use by smaller species and smaller individuals (Ash et al. 2003; Marsh & Beckman 2004; our study). In addition, although data are limited to 1 year, drought conditions can decrease suitability even farther away than 35 m from roads (up to 80 m; Marsh & Beckman 2004), which illustrates the importance of moisture availability as a mechanism driving edge effects. Although explicit tests of this mechanism and further studies are needed, the current data for a broad-range of road effects (e.g., Trombulak & Frissell 2000) would permit a prediction that larger roads with more traffic and a greater drying effect would generate a larger road-effect zone for salamanders (see arguments in Fahrig et al. 1995; Hels & Buchwald 2001; Mazerolle 2004) and likely create even smaller patches of suitable forest habitat.

What is puzzling about our results and those of Marsh and Beckman (2004) is that salamander abundance actually declined after distances of 60 m in our study and 80 m for Marsh and Beckman (2004) from forest roads. A preliminary attempt to explain the declining abundance in our study failed to show any relationship to food resources such as invertebrate abundance or richness, or abiotic factors. Furthermore, salamander abundance did not correlate with shrub cover, as measured by stem density, which might have reflected changes in the availability of night-time foraging surfaces for salamanders (Jaeger 1978). We speculate that two explanations related to habitat change are likely responsible but would require further study. First, our sampling sites at 100 m were often farther up or down a ridge from the road such that the habitat may have been significantly different (e.g., drier on ridges or near outcrops) than at 30–60 m. Nevertheless, our measurements of habitat variables did not detect changes. Second, at 4 of 11 of our initial study sites, old, abandoned logging roads crossed or were adjacent to our transects somewhere between 60 and 100 m into the forest compartment. Although initially the area adjacent to these abandoned roads appeared visually similar to the surrounding forest, data from our study comparing abundance of salamanders on these old roads with samples from up- and downslope sites indicated long-lasting negative effects of roads. The stronger downslope effects relative to upslope sites may be the result of runoff (e.g., chemical pollutants and siltation). Thus, not only do active forest roads have an effect on salamanders but long-abandoned logging roads have an effect as well.

The implications of decreased salamander abundance at distances of 100 m from active roads is that the extraction of timber 80 years ago has created a significant ecological "footprint" in seemingly continuous forest that supercedes regeneration of the forest itself. Such long-lasting ecological effects perpetuate fragmentation of forest habitats and maintain smaller patches of suitable habitat for species than indicated by the presence of mature trees alone. Assuming current timber management practices harvest trees at intervals of 80–100 years in southern Appalachian forests, footprints of logging roads from past harvests will not be gone before a new footprint is laid down, and effects will accumulate over time. Thus, eventually forests could become increasingly fragmented into ever-smaller patches of suitable habitat for salamanders.

We suggest that our results directly apply to other protected forests in the southern Appalachians and exemplify a problem created by current and past land use activities in all forested regions, especially those related to road building for natural resource extraction. The problem we revealed here points to a potential failure of forest managers and policy makers to realize that the effect of roads reaches well beyond their boundary and that abandonment or the decommissioning of roads does not mean detrimental ecological effects disappear. Rather, our results indicate that current management decisions have significant repercussions for generations to come. Furthermore, the quantity of suitable forested habitat in protected areas like national forests is significantly reduced, perhaps as much as 42.8%, when the area encompassed by road effects is taken into account. Thus, we believe that management and policy decisions must use current and historical data on land use to understand accumulative impacts on forest-dependent species and to fully protect biodiversity on national lands.

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