

Articles

Influence of Natural Gas Pipeline Right-of-Ways on Eastern Red-Backed Salamander Occurrence in the Northern Appalachians

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Abstract

Road and pipeline infrastructure development for natural gas extraction often results in forest fragmentation, which could negatively influence habitat quality for many amphibian species. We investigated occurrence dynamics of the eastern red-backed salamander *Plethodon cinereus* in relation to natural gas pipeline rights-of-way (ROWs) and forest structure characteristics in northern Pennsylvania, USA. We sampled 80 sites across two study areas by using cover-boards, with each site containing sampling plots at the center of the ROW, the edge of the ROW, and 10 m and 30 m into the adjacent forest. We assessed the influence of ROW age, ROW width, distance from ROW, and five forest structure characteristics on plot occupancy probability. Eastern red-backed salamander occupancy probability decreased with ROW age and increased with distance from ROW. Our results indicate that eastern red-backed salamanders are negatively influenced by forest fragmentation for natural gas ROWs. Moreover, responses were time dependent, with occupancy probability declining with ROW age. Due to low detections, we were unable to analyze data for the other amphibians and reptiles encountered during the study. Our capture data indicate that ROWs could improve habitat quality for some snake species, but additional research is needed to better understand the influence of ROWs on reptile species. To reduce future forest fragmentation and impacts on eastern red-backed salamander populations, managers could consider placing pipelines along existing linear clearings and enhancing the habitat quality of ROWs for salamanders.

Keywords: amphibian; energy; forest; occupancy; Pennsylvania; reptile; snake

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Introduction

Natural gas extraction in the Appalachian region has increased following technological developments in the use of horizontal drilling and hydraulic fracturing (Carter

et al. 2011; Slonecker et al. 2012). Production of natural gas from Pennsylvania and West Virginia now represents more than 29% of the total U.S. production (US EIA 2023), up from only 3.6% in 2010 (US EIA 2011). Surface disturbance related to production is mainly associated

with the drilling of wells and transportation of hydrocarbons to market. Disturbance related to well pad and associated infrastructure is approximately 5.6 ha per pad, which has increased over time (Grushecky et al. 2022). Langlois et al. (2017) estimated that disturbance related to midstream infrastructure can increase disturbance up to 250%. Pipelines are the primary method of midstream conveyance for extracted gas from source to market (Kennedy 1984; Folga 2007). Pipelines routed through agricultural areas can be replanted with crops, but in forested areas the rights-of-way (ROWs) must be maintained as herbaceous ground cover to ensure the integrity of the buried pipe (Kennedy 1984). Pipelines in forested areas are often colocated with existing roads to make construction easier, although the roads are often expanded to allow for large trucks and increased traffic volumes (Langlois et al. 2017). Colocation of pipeline ROWs with roads can increase ROW width from an average of 25.1–27.0 m on public and private lands in Pennsylvania to more than 30.0-m widths (Langlois et al. 2017). Thus, road and pipeline infrastructure has become an increasing source of forest fragmentation in the Appalachian region (Drohan et al. 2012; Slonecker et al. 2012; Donnelly et al. 2017; Liu 2021).

Forest fragmentation creates open canopy environments and can negatively or positively affect individual species (Silva et al. 2003; Andrews et al. 2008; Schutz and Driscoll 2008). For example, forest salamanders are often negatively influenced by fragmentation of forest patches due to edge effects and dispersal barriers (Demaynadier and Hunter 1998; Marsh et al. 2005, 2008; Macneil and Williams 2014). By contrast, snakes and insects are often more prevalent in areas with a patchwork of forest than in contiguous forest (Russell et al. 2005; Patrick and Gibbs 2009; Eldegard et al. 2017). Edge effects from fragmentation influence microhabitat conditions in the adjacent forest (Murcia 1995; Fischer and Lindenmayer 2007), with forest edges typically having higher temperatures and drier soils from increased sun exposure and wind (Phillips and Shure 1990; Murcia 1995; Chen et al. 1999). The intensity of edge effects is strongly influenced by aspect, with the weakest and strongest effects on northeastern and southwestern slopes, respectively (Marsh 2007; Moseley et al. 2009). Duration of exposure to direct solar radiation increases with width of the forest opening, resulting in higher temperatures and drier soil conditions (Phillips and Shure 1990).

The Appalachian region is a global biodiversity hotspot for salamanders (Kozak 2017), and broad concern exists about potential negative influences of forest fragmentation on amphibians (e.g., Demaynadier and Hunter 1998; Marsh et al. 2005; Cosentino and Brubaker 2018). The potential for negative impacts of natural gas pipeline ROWs on amphibian populations can extend well beyond direct habitat loss from forest clearing (Cushman 2006; Andrews et al. 2008; Macneil and Williams 2014). Prior studies have assessed amphibian responses to forest fragmentation, but few have investigated responses specifically for natural gas pipeline ROWs (Icochea et al. 2002; Margenau 2020; Chalfoun 2021). Although powerline and pipeline ROWs are qualitatively similar, differences in vegetation management suggest that microhabitat conditions

may differ between them (Russell et al. 2005, 2018; Wagner et al. 2014), potentially influencing wildlife responses. An avian study of powerline ROWs in the study region found that some can be upwards of 55 m wide (Ross et al. 2022), which is larger than that found for most pipeline ROWs (e.g., median width was 16 m for sites in this study). Pipelines are expected to have relatively long lifespans (up to 30 y; Carter et al. 2011), and it is important to improve our understanding of how their long-term use influences amphibians.

Our objective was to assess the influence of natural gas pipeline ROWs on occurrence of terrestrial amphibians and reptiles in a northern Appalachian forest. We assessed the influence of ROW age (hereafter age), ROW width (hereafter width), distance from ROW (hereafter distance), and five forest structure characteristics on occupancy probability for the most abundant species, the eastern red-backed salamander *Plethodon cinereus*. To our knowledge, this is the first study to investigate the influence of age on amphibian occurrence dynamics. We expected that as pipeline ROWs aged, vegetation within them would increase in density and height. This could improve habitat quality for salamanders by decreasing surface temperature (Green et al. 1984; Sugalski and Claussen 1997; Peterman and Semlitsch 2013; Song et al. 2013). Alternately, if habitat quality associated with ROWs does not improve over time for salamanders, we would expect a negative relation between age and salamander occupancy.

Study Area

We conducted this study on two parcels managed by the state of Pennsylvania that contain natural gas infrastructure: Tiadaghton State Forest (TDSF) and Game-lands 12 (GL12; Figure 1) in northeastern Pennsylvania. Both parcels are in the core forest region of northern Pennsylvania (Ritters et al. 2002) where natural gas development is occurring (Drohan et al. 2012; Langlois et al. 2017). Mean annual maximum, minimum, and average temperatures from 1991–2020 were 13.3, 2.8, and 7.8°C for GL12 and 13.9, 3.3, and 8.3°C for TDSF, respectively, and mean annual precipitation was 99.1 and 111.8 cm for GL12 and TDSF, respectively (National Oceanic and Atmospheric Administration 2021). The dominant forest type is northern hardwood, with American beech *Fagus grandifolia*, red maple *Acer rubrum*, black cherry *Prunus serotina*, white oak *Quercus alba*, chestnut oak *Quercus montana*, white pine *Pinus strobus*, and eastern hemlock *Tsuga canadensis* being most common (Hough and Forbes 1943).

The TDSF is located primarily in Lycoming County and encompasses 59,300 ha. Development of ridgetops within the forest with infrastructure for natural gas extraction were in place in 2012 and 2013. As of 2018, approximately 76 km of pipeline was present, with 42 well pads and 254 wells. The GL12 is located 65 km northwest of TDSF in Bradford and Sullivan counties and encompasses 10,350 ha; initiation of natural gas development on GL12 was in 2016. As of 2018, the main southern pipeline was 11 km and contained 5 well pads and 32 wells and the northern trunk line was 18 km and contained 3 well pads and 3 wells. We obtained natural gas well permit data from the Pennsylvania Department

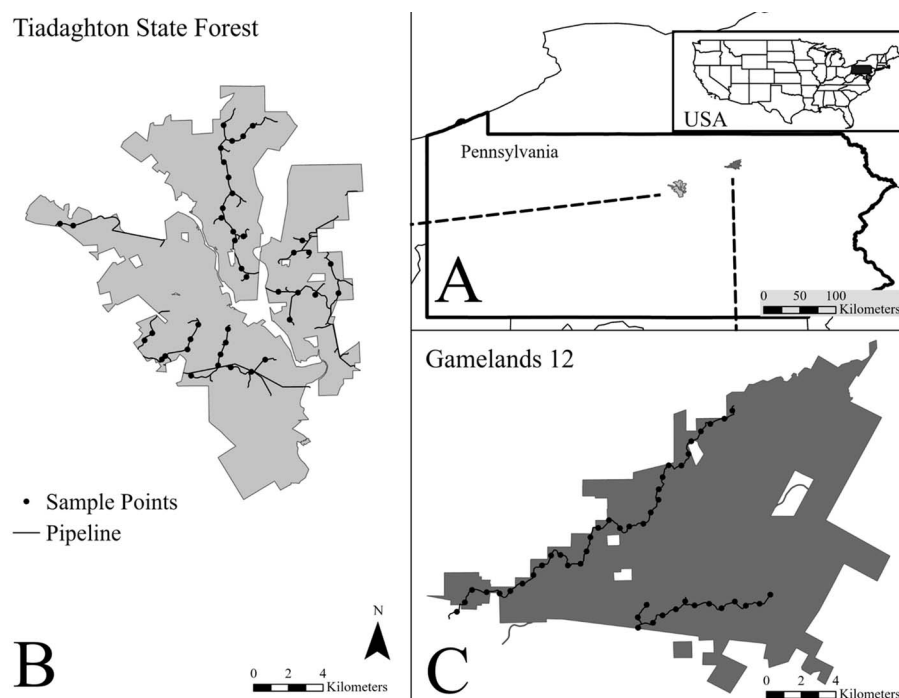


Figure 1. Locations of study areas in northern Pennsylvania, USA (A) used for this study assessing the influence of natural gas pipeline rights-of-way (ROWs) and forest structure characteristics on occurrence of terrestrial salamanders and snakes. Study areas included the Tiadaghton State Forest (TDSF; B) and Gamelands 12 (GL12; C). We distributed 80 sampling sites across TDSF and GL12. Creation of all pipeline ROWs in TDSF was in 2013. Creation of the northern and southern pipeline ROWs in GL12 was in 2019 and 2017, respectively. In each study area, we collected data on forest structure characteristics and sampled the herpetofaunal communities in 2019 and 2020, respectively.

of Environmental Protection to locate all pipeline ROWs within the study area. We identified and hand-digitized pipeline ROW infrastructure by using National Agriculture Imagery Program imagery from 2007 to 2016.

Methods

Sampling sites and plots

We randomly placed 40 sampling sites along pipelines in TDSF and GL12, respectively, with random locations restricted to greater than or equal to 500 m from the nearest site (Figures 1 and 2A). Because GL12 contained only 29 km of pipeline at the time of sampling, this resulted in nearly even spacing of sites along the two pipelines. We placed four sampling plots perpendicular to the ROW at each site, including in the center of the ROW, on the forest side of the edge of the ROW, and 10 and 30 m into the adjacent forest perpendicular to the ROW (Figure 3). We assumed that the forest edge, 10-m plots, and 30-m plots experienced strong, weak, and minimal edge effects, respectively (Marsh 2007; Moseley et al. 2009; Dantas de Paula et al. 2016). We randomly selected which side of the ROW contained sampling plots unless a road was present adjacent to a ROW, in which case we placed sampling plots on the opposite side.

Amphibian and reptile sampling

We used coverboards to sample the terrestrial salamander and snake communities (Moore 2005; Hesed

2012). At each of the plots, we sampled salamanders by using a grid of six $15 \times 30.5 \times 2.5$ cm untreated yellow poplar *Liriodendron tulipifera* boards and sampled snakes by using one $60 \times 60 \times 1.27$ cm untreated plywood board (Hyde and Simons 2001; Halliday and Blouin-Demers 2015; Margenau et al. 2020), for a total of 2,240 coverboards across all plots. We placed the salamander and snake coverboards 2 m apart, parallel to the ROW. We deployed coverboards in summer 2019 to allow them to weather before initiation of sampling in spring 2020 (Hesed 2012). When herpetofaunal sampling began, we found that 36 (1.9%) and 17 (5.3%) of the small and large boards were missing, respectively. For salamanders, because each plot had multiple small boards, we assumed the small percentage of missing boards would have little or no effect on study results. For snakes, because each plot had only one large board, we adjusted our sample sizes in the analyses to reflect unequal sampling effort among sites. We surveyed each of the 320 plots four times between May and August 2020. We identified all salamanders and snakes encountered under coverboards to the species level. We did not mark captured animals; thus, the number of animals detected may not represent the number of unique individuals.

Site, plot, and survey variables

At each site, we recorded age at the time of sampling. We derived age by using environmental plans obtained



Figure 2. Aerial image of a natural gas pipeline right-of-way (ROW; **A**) used for this study assessing the influence of ROWs and forest structure characteristics on occurrence of terrestrial salamanders and snakes in northern Pennsylvania, USA, and the focal species, eastern red-backed salamander *Plethodon cinereus* (**B**). Photo credits: Shawn Grushecky (A) and Donald Brown (B)

from the Pennsylvania Game Commission and Department of Conservation and Natural Resources and verified the ages by using National Agriculture Imagery Program imagery. All ROWs included in this study received significant terrestrial disturbance during the development phase. At each plot, we recorded width and measured several forest structure characteristics in 2019. We recorded quantity of woody stems in two 4-m² vegetation plots (one centered on the large coverboard and one centered on the small coverboard grid). We recorded the percentage of canopy cover in the center of each vegetation plot by using a spherical densitometer. For each variable, we computed the mean from the two vegetation plots to represent the sampling plot. Within 10 m of the sampling plot, we recorded the number and basal area of trees with a diameter at breast height greater than 15.24 cm. We used a 3 × 3 m digital elevation model to estimate heat load index at each plot. We used the equation in McCune and Keon (2002), which accounts for aspect, slope, and latitude. We recorded survey variables at the start of each survey, including day of year, time of survey, temperature (in

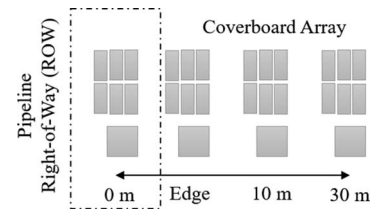


Figure 3. Coverboard array placement in relation to natural gas pipeline rights-of-way (ROWs) for this study assessing the influence of natural gas pipeline ROWs and forest structure characteristics on occurrence of terrestrial salamanders and snakes. Study areas included the Tiadaghton State Forest and Gamelands 12 in northern Pennsylvania, USA. At each of 80 sites, we placed four sampling plots using one 60 × 60 × 1.27 cm untreated plywood coverboard to survey snakes and an array of six 15 × 30.5 × 2.5 cm untreated yellow poplar *Liriodendron tulipifera* coverboards to survey salamanders. We placed sampling plots at the center of the ROW, the forest side of the edge of the ROW, and 10 and 30 m into the adjacent forest. We collected data on forest structure characteristics and sampled the herpetofaunal communities in 2019 and 2020, respectively. Schematic elements not to scale. Pale gray polygons represent individual coverboards.

Celsius), wind speed (in kilometers per hour), and overhead weather conditions (full sun, partly cloudy, overcast, light rain, medium rain). We conducted no surveys under heavy rain. We recorded temperature and wind speed in the shade at breast height and averaged over a 2-min period by using a hand-held weather meter (Kestrel Meter 3000, Kestrel Instruments, Boothwyn, PA). Additional details on the study variables are available online (Data S1, *Supplemental Material*).

Statistical analyses

We assessed relationships between forest structure characteristics and ROW characteristics, including age (1, 4, or 7 y since completion) and distance (0, 10, or 30 m), by using redundancy analysis. This multivariate model is an extension of principal components analysis to include explanatory variables. Specifically, each response variable is regressed on each explanatory variable and then a principal components analysis is performed on the matrix of fitted values (Legendre and Legendre 2012). We chose redundancy analysis rather than canonical correspondence analysis because the gradient length was short (1.7; Legendre and Legendre 2012). We determined whether forest structure characteristics had an association with ROW characteristics by using a global permutation test and visually assessed relationships by using a correlation biplot. We excluded ROW center plots for this analysis because these plots did not contain woody vegetation.

Frequency of observations for salamanders and snakes, except for the eastern red-backed salamander, were too low to model the influence of ROW variables on occurrence probability of individual species. For all salamanders and snakes, we report species-specific capture summary statistics in relation to study area, age, and distance. For the eastern red-backed salamander (Figure 2B), we used a

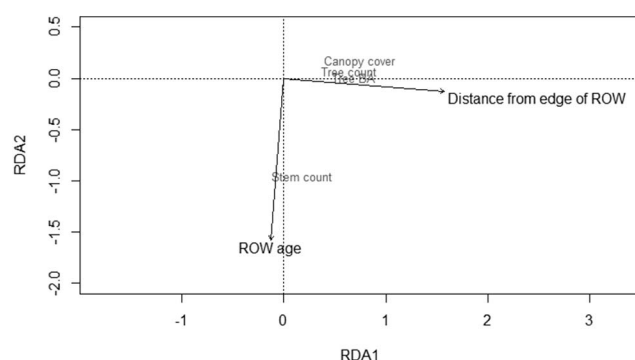


Figure 4. Redundancy analysis (RDA) correlation biplot showing relationships between forest structure characteristics and natural gas pipeline rights-of-way (ROWs) characteristics at Tiadaghton State Forest and Gamelands 12 in northern Pennsylvania, USA. We sampled 320 plots across 80 sites in northern Pennsylvania in 2019. Forest structure characteristics are number of trees (tree count) and basal area of trees (tree BA) > 15.24 cm diameter at breast height within 10 m of salamander sampling plots, canopy cover (%) in the center of salamander sampling plots, and counts of woody stems (stem count) averaged across two 4-m² vegetation plots located within salamander sampling plots. The ROW characteristics are ROW age (1–7 y) and distance from ROW edge (0–30 m). We excluded ROW center plots for this analysis, which did not contain woody vegetation.

single-season occupancy model to quantify the influence of ROW variables and forest structure characteristics on occurrence probability at the plot level. Occupancy models are hierarchical models that account for imperfect detection by jointly estimating probability of detection (p) and probability of site occupancy (Ψ) by using replicated survey data (Kéry and Royle 2016). We assumed that plots were independent of one another and closed to births, deaths, immigration, and emigration during the sampling period.

We ranked candidate models using Akaike's Information Criterion corrected for small sample size (AICc) and assessed model goodness of fit by using a 1,000-

replication parametric bootstrap of the Pearson χ^2 statistic (Kéry and Royle 2016). During preliminary model fit tests, we found that plot encounters during the first survey were substantially higher than expected and not explained by the survey variables that we collected; we addressed this by including survey number as a candidate p variable. The c -hat value for our most complex candidate model with support indicated some overdispersion (c -hat = 3.37). To account for this overdispersion, we ranked focal analyses candidate models by using Quasi AICc (QAICc; Symonds and Mousalli 2011). We considered models with $\Delta(Q)AICc$ scores less than 2 to have strong support and models with $\Delta(Q)AICc$ scores less than 5 to have moderate support (Burnham et al. 2011).

Because of the relatively small sample size and large number of potential models, we used a multistage model selection process to identify important variables for p and Ψ . In the first stage, we ranked candidate p models, which included each individual survey variable and additive models containing variables that received moderate or strong support individually. We tested air temperature as both a linear and quadratic variable. We retained the most parsimonious p model as the null model for focal analyses. We conducted two focal analyses: one assessing occurrence relations with ROW variables and one assessing occurrence relations with forest structure characteristics. For the ROW variable analysis, we ranked the following models: age, width, distance, age + distance, age $\times$ distance, age + distance + width, and age $\times$ distance + width. For the forest structure analysis, we ranked each variable individually, but did not include additive or interaction models because most of the variables had high covariance.

For strongly supported Ψ models, we assessed the direction (negative or positive), magnitude (slope), and strength of the effect (85% confidence interval; Arnold 2010) for predictor variables and we plotted relationships. We conducted all analyses by using program R (version 4.1.1). We performed the redundancy analysis and created biplots by using the package vegan (version

Table 1. Mean number of captures per plot for terrestrial salamander and snake species observed during coverboard surveys in 2020 at Tiadaghton State Forest (TDSF; $n = 40$ sites) and Gamelands 12 (GL12; $n = 40$ sites) in northern Pennsylvania, USA. We computed captures per plot by study area, years since construction of natural gas pipeline right-of-way (ROW age), and distance to edge of the pipeline ROW (distance to ROW). We placed coverboards in the center of the ROW, on the forest side of the ROW edge, 10 m from the edge, and 30 m from the edge.

	Study area		ROW age			Distance from ROW			
	GL12	TDSF	1	5	7	Center	Edge	10 m	30 m
Salamanders									
<i>Notopthalmus viridescens</i>	0.025	0.013	0.005	0.067	0.013	0.025	0.006	0	0.006
<i>Plethodon cinereus</i>	0.375	0.144	0.431	0.260	0.144	0.05	0.081	0.147	0.240
<i>Plethodon glutinosus</i>	0.003	0.013	0	0.010	0.013	0	0	0.003	0.012
Snakes									
<i>Diadophis punctatus</i>	0.006	0.019	0.009	0	0.019	0.009	0.009	0.003	0.003
<i>Lampropeltis triangulum</i>	0	0.003	0	0	0.003	0	0.003	0	0
<i>Opheodrys vernalis</i>	0.003	0	0.005	0	0	0.003	0	0	0
<i>Storeria dekayi</i>	0.006	0.003	0	0.019	0.003	0.006	0.003	0	0
<i>Storeria occipitomaculata</i>	0.006	0.003	0.009	0	0.003	0.009	0	0	0
<i>Thamnophis sirtalis</i>	0.009	0.028	0.005	0.010	0.028	0.025	0.006	0	0.006

Table 2. Model selection results for the influence of environmental variables on detection probability (p), influence of natural gas pipeline rights-of-way (ROW) characteristics on occupancy probability (Ψ), and influence of forest structure characteristics on Ψ for eastern red-backed salamanders *Plethodon cinereus* surveyed between May and August 2020 at Tiadaghton State Forest ($n = 40$ sites) and Gamelands 12 ($n = 40$ sites) in northern Pennsylvania, USA. We used Akaike's Information Criterion corrected for small sample size (AICc; detection probability models) or Quasi AICc (QAICc; occupancy probability models) to rank candidate models. We recorded survey variables at the start of each survey, including day of year, time of survey, air temperature ($^{\circ}\text{C}$), wind speed (km/h), and overhead weather conditions (full sun, partly cloudy, overcast, light rain, medium rain). Survey number refers to the order of the salamander survey (1–4). The ROW characteristics include ROW age, distance from edge of ROW (including a negative distance for center ROW plots), and ROW width. Forest structure characteristics include canopy cover (%), heat load index value (0–1), number of trees with a diameter at breast height (DBH) > 15.24 cm (tree count), basal area of trees with a DBH > 15.24 cm (tree basal area), and total woody stem count. Intercept-only models are shown as (.).

Model	AICc/QAICc	$\Delta\text{AICc}/\Delta\text{QAICc}$	ω
Detection probability (p)			
Survey number + air temperature (linear)	815.30	0	0.78
Survey number	817.88	2.58	0.22
Air temperature (linear)	853.29	37.99	0
Overhead weather conditions	892.49	77.20	0
(.)	895.64	80.35	0
Time of survey	897.21	81.91	0
Wind speed	914.45	99.15	0
Day of year	1037.09	221.80	0
ROW characteristics (Ψ)			
Age + distance	245.12	0	0.43
Age $\times$ distance	246.67	1.55	0.20
Age + distance + width	247.22	2.10	0.15
Distance	248.35	3.22	0.09
Age + distance $\times$ width	248.79	3.67	0.07
Age	249.33	4.20	0.05
(.)	252.65	7.52	0.01
Width	253.11	7.99	0.01
Forest structure characteristics (Ψ)			
Canopy cover	248.27	0	0.43
Tree basal area	249.41	1.15	0.24
Tree count	249.59	1.32	0.22
(.)	252.65	4.38	0.05
Woody stem count	253.44	5.17	0.03
Heat load index	254.60	6.33	0.02

2.6–4). We estimated heat load index by using the package spatialEco (version 2.0-0). We performed occupancy model analyses by using the package unmarked (version 1.1.1) and created model plots by using the packages ggplot2 (version 3.4.0) and cowplot (version 1.1.1). We assessed model goodness of fit and ranked candidate models by using the package AICcmodavg (version 2.3-1).

Results

Forest structure characteristics

The redundancy analysis indicated that age and distance were significant predictors of forest structure characteristics ($P = 0.001$; adjusted $r^2 = 0.071$), with distance being the strongest predictor (Figure 4). Tree count, basal area, and canopy cover increased with distance. Woody stem count increased with age. Site-level forest structure data are available online (Data S2, Supplemental Material).

Salamander and snake encounters

We encountered three salamander species on both study areas during coverboard sampling: eastern newt

Notophthalmus viridescens ($n = 12$), eastern red-backed salamander ($n = 166$), and northern slimy salamander *Plethodon glutinosus* ($n = 5$; Table 1). Relationships between captures and age varied among the three species, with eastern red-backed salamander captures decreasing with age, northern slimy salamander captures increasing with age, and eastern newt captures being highest for the middle age. Northern slimy salamander and eastern red-backed salamander captures increased with distance, but eastern newt captures were highest in the center of the ROW. Plot-level salamander capture data are available online (Data S3, Supplemental Material).

We encountered six snake species during coverboard sampling: ring-necked snake *Diadophis punctatus* ($n = 8$), eastern milksnake *Lampropeltis triangulum* ($n = 1$), smooth greensnake *Opheodrys vernalis* ($n = 1$), Dekay's brownsnake *Storeria dekayi* ($n = 3$), red-bellied snake *Storeria occipitomaculata* ($n = 3$), and common garter-snake *Thamnophis sirtalis* ($n = 12$; Table 1). We captured four of six species at both GL12 and TDSF, with smooth greensnake only captured at GL12 and eastern milksnake only captured at TDSF. Common gartersnake captures



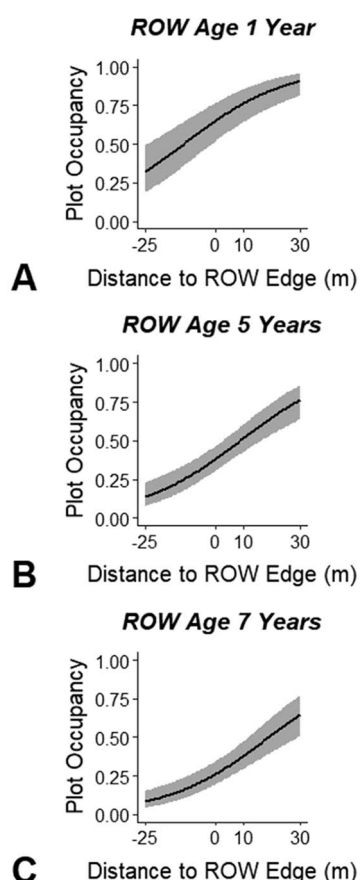


Figure 5. Predicted eastern red-backed salamander *Plethodon cinereus* occupancy probability (Ψ) in relation to natural gas pipeline rights-of-ways (ROWs) age 1 [A], 5 [B], and 7 [C] y and distance to edge of the ROW. Between May and August 2020, we surveyed for salamanders four times at 320 coverboard plots across 80 sites in Tiadaghton State Forest and Gamelands 12 in northern Pennsylvania, USA. At each site, we placed coverboard plots in the center of the ROW, on the forest side of the edge of the ROW, and 10 and 30 m into the adjacent forest perpendicular to the ROW. For the x-axis, 0 represents the ROW edge and negative values represent plots within the ROW. All models included survey number and temperature as predictors of detection probability (p). Solid lines represent the mean Ψ prediction and gray bands encompass the 85% confidence intervals.

increased with age, but the remaining species did not show a clear pattern related to age. Captures decreased with distance for all species except eastern milksnake, which we encountered only at the ROW edge. Plot-level snake capture data are available online (Data S3, *Supplemental Material*).

Eastern red-backed salamander

Survey number + linear air temperature was the most supported model for p ($\omega = 0.78$; Table 2), and we used this model as the null model for focal analyses. Survey number alone had moderate support ($\Delta\text{AICc} = 2.58$, $\omega = 0.22$). Estimated p was highest for the first survey and decreased with air temperature, and p ranged from 0.10

Table 3. Beta coefficient (β) and 85% confidence interval (CI) for strongly supported models estimating the influence of rights-of-way (ROW) and forest structure characteristics on occupancy probability (Ψ) for eastern red-backed salamanders *Plethodon cinereus* surveyed between May and August 2020 at Tiadaghton State Forest ($n = 40$ sites) and Gamelands 12 ($n = 40$ sites) in northern Pennsylvania, USA.

Model	β	85% CI
ROW characteristic		
Age + distance		
Intercept	0.906	0.268 to 1.545
Age	-0.277	-0.381 to -0.173
Distance	0.055	0.036 to 0.074
Age $\times$ distance		
Intercept	0.897	0.195 to 1.600
Age	-0.263	-0.376 to -0.149
Distance	0.091	0.043 to 0.139
Age $\times$ distance	-0.007	-0.015 to 0.001
Forest structure characteristic		
Canopy cover		
Intercept	-0.977	-1.433 to -0.520
Canopy cover	0.021	0.014 to 0.028
Tree basal area		
Intercept	-0.591	-0.986 to -0.197
Tree basal area	0.018	0.009 to 0.027
Tree count		
Intercept	-0.577	-0.976 to -0.178
Tree count	0.219	0.102 to 0.335

to 0.55 during salamander surveys. Survey-level weather data are available online (Data S4, *Supplemental Material*). For the ROW variable analysis, the most supported model was age + distance ($\omega = 0.43$; Table 2), with age $\times$ distance also receiving strong support ($\Delta\text{QAICc} = 1.55$, $\omega = 0.20$). The models estimated that Ψ decreased as age increased and Ψ increased with distance (Figure 5; Table 3). For the forest structure analysis, canopy cover was the most supported model ($\omega = 0.43$; Table 2), with two additional variables receiving strong support: tree basal area ($\Delta\text{QAICc} = 1.15$, $\omega = 0.24$) and tree count ($\Delta\text{QAICc} = 1.32$, $\omega = 0.22$). Predicted Ψ showed a positive association with all three variables (Figure 6; Table 3).

Discussion

Our results indicate that eastern red-backed salamanders are negatively influenced by forest fragmentation from natural gas ROWs, consistent with our expectations based on the natural history of this species and previous studies assessing responses to forest fragmentation (e.g., Silva et al. 2003; Marsh and Beckman 2004; Yahner 2004). Edge effects from increased sunlight penetration and wind that create a warmer and more arid forest floor are diminished as distance from forest edge increases (Wright et al. 2010). Our findings indicated that eastern red-backed salamanders responded to these edge effects through decreased occupancy probability closer to ROWs. As predicted based on previous research (e.g., DeGraaf and Yamasaki 2002; Marsh 2007; Moseley et al. 2009), we also found that eastern red-backed

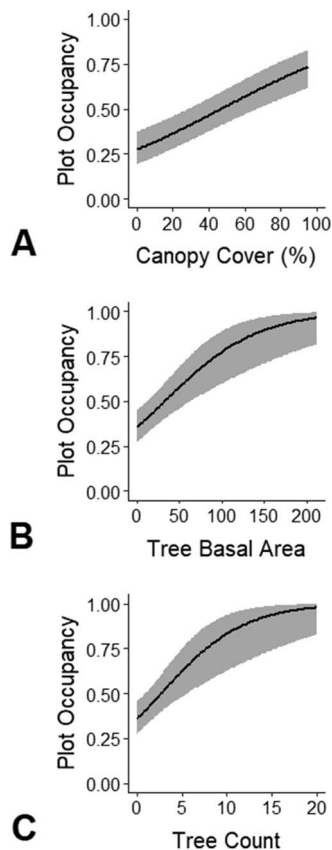


Figure 6. Predicted eastern red-backed salamander *Plethodon cinereus* occupancy probability (Ψ) in relation to forest structure characteristics, including canopy cover (%; **A**), basal area of trees with a diameter at breast height (DBH) > 15.24 cm (tree basal area; **B**), and number of trees with a DBH > 15.24 cm (tree count; **C**). Between May and August 2020, we surveyed for salamanders four times at 320 coverboard plots across 80 sites in Tiadaghton State Forest and Gamelands 12 in northern Pennsylvania, USA. At each site, we placed coverboard plots in the center of the ROW, on the forest side of the edge of the ROW, and 10 and 30 m into the adjacent forest perpendicular to the ROW, and we recorded forest structure characteristics at each plot location. All models included survey number and temperature as predictors of detection probability (p). Solid lines represent the mean Ψ prediction and gray bands encompass the 85% confidence intervals.

salamander occupancy was positively associated with canopy cover, tree basal area, and tree count, conditions that are representative of mature forests.

In general, previous research has shown that occurrence and abundance patterns of wildlife in postdisturbance energy production landscapes follow expectations based on the natural history of individual species (Margenau et al. 2019; Lituma et al. 2021). However, our study indicates that amphibian responses are time dependent; we found that eastern red-backed salamander occupancy probability continued to decline as age increased. This finding is consistent with previous studies focused on responses to timber harvest (Demaynadier and Hunter 1998; Macneil and Williams 2014). We

hypothesize that construction of natural gas ROWs decreased habitat quality for eastern red-backed salamanders in the adjacent forest, resulting in a population decline through reductions in survival or fecundity. However, additional research is needed to understand whether vital rates declined or individual salamanders dispersed from the sampling area and whether the species will eventually be extirpated from plots adjacent to the ROWs. Additional studies focused on reproductive success and survival rates would improve our understanding of the impact of ROWs on this species. For example, Riedel et al. (2012) found a significantly higher proportion of juvenile eastern red-backed salamanders in woodlands than meadows, potentially indicating higher reproductive success or juvenile survival rates in closed canopy environments. In addition, we emphasize that our results for eastern red-backed salamanders should not be extrapolated to other salamander species due to biological and ecological differences among species (Petranka 1998). The limited encounter data for other salamanders documented in our study point to contrasting patterns that may reflect such differences.

Although extremely limited (1–12 observations per species), our count data indicated that captures of individual snake species showed a positive association with ROWs. Reptiles are not as sensitive to desiccation as amphibians (Reinert 1993; Mullin and Seigel 2009), and canopy removal increases thermoregulatory potential for reptiles (Andrews et al. 2008; Patrick and Gibbs 2009; Reinert et al. 2011). In addition, food resources for snakes, such as invertebrates and small mammals, may be higher along ROWs than in the interior forest (Yahner 2004). Although not a focus of our study, we found evidence of meadow vole *Microtus pennsylvanicus* nests or encountered live individuals under 53% of large coverboards placed in the center or edge of the ROW, in comparison with 7% of large coverboards placed 10 or 30 m into the adjacent forest, indicating that meadow vole use showed a positive association with ROWs. However, there were limited snake captures during this study and additional research should aim to quantify the influence of natural gas ROWs on snake populations. Using multiple sampling methods, such as active searches, coverboards, and drift fences with funnel traps, could result in captures that are sufficient for statistical modeling (Fitzgerald 2012).

Based on our results, locating future pipelines along existing roads may be a strategy to minimize potential impacts on eastern red-backed salamander populations. Expanding the width of an existing road would generally be preferable to creating new clearings through interior forest patches that are free of edge effects, because new disturbances will degrade the quality of interior forest, decrease forest cover, and increase total forest fragmentation (Murcia 1995; Moran et al. 2015). In addition, retaining or adding woody debris or large rocks within the ROWs could benefit amphibians and reptiles that occupy or traverse them (Marsh et al. 2005). Coarse woody debris has been found to improve salamander habitat quality when canopy cover is removed, and surveys of powerline ROWs with coarse woody debris have

documented salamanders using these objects (Brannon et al. 2014; O'Donnell et al. 2014).

In conclusion, our study supports that eastern red-backed salamanders are negatively influenced by natural gas ROWs and that impacts increase over time. To minimize negative effects on eastern red-backed salamander populations, managers could consider placing pipelines along existing linear clearings when possible and enhancing habitat quality for salamanders. We recommend that additional research be conducted to better understand how ROW characteristics influence eastern red-backed salamander population vital rates, as well as how ROW width influences dispersal probabilities to provide additional guidance on ROW creation and management.

Supplemental Material

Please note: The *Journal of Fish and Wildlife Management* is not responsible for the content or functionality of any supplemental material. Queries should be directed to the corresponding author for the article.

Data S1. README file for interpreting column headers in site, survey, and capture data used to assess the influence of rights-of-way (ROWs) and forest structure characteristics on herpetofaunal captures and eastern red-backed salamander *Plethodon cinereus* occupancy probability. Study sites were within the Tiadaghton State Forest and Game-lands 12 in northern Pennsylvania, USA. We measured forest structure characteristics in 2019 and conducted herpetofaunal surveys between May and August 2020 at 80 sites containing a total of 320 sampling plots.

Available: <https://doi.org/10.3996/JFWM-22-032.S1> (16 KB XLSX)

Data S2. Site data used to assess the influence of rights-of-way (ROWs) and forest structure characteristics on herpetofaunal captures and eastern red-backed salamander *Plethodon cinereus* occupancy probability. Study sites were within Tiadaghton State Forest and Game-lands 12 in northern Pennsylvania, USA. We measured forest structure characteristics in 2019 and conducted herpetofaunal surveys between May and August 2020 at 80 sites containing a total of 320 sampling plots.

Available: <https://doi.org/10.3996/JFWM-22-032.S2> (27 KB XLSX)

Data S3. Capture data used to assess the influence of rights-of-way (ROWs) and forest structure characteristics on herpetofaunal captures and eastern red-backed salamander *Plethodon cinereus* occupancy probability. Study sites were within Tiadaghton State Forest and Game-lands 12 in northern Pennsylvania, USA. We measured forest structure characteristics in 2019 and conducted herpetofaunal surveys between May and August 2020 at 80 sites containing a total of 320 sampling plots.

Available: <https://doi.org/10.3996/JFWM-22-032.S4> (20 KB XLSX)

Data S4. Survey data used to assess the influence of rights-of-way (ROWs) and forest structure characteristics

on herpetofaunal captures and eastern red-backed salamander *Plethodon cinereus* occupancy probability. Study sites were within Tiadaghton State Forest and Game-lands 12 in northern Pennsylvania, USA. We measured forest structure characteristics in 2019 and conducted herpetofaunal surveys between May and August 2020 at 80 sites containing a total of 320 sampling plots.

Available: <https://doi.org/10.3996/JFWM-22-032.S3> (27 KB XLSX)

Reference S1. Slonecker E, Milheim L, Roig-Silva CM, Malizia AR, Marr DA, Fisher GB. 2012. Landscape consequences of natural gas extraction in Bradford and Washington counties, Pennsylvania, 2004–2010. Open-File Report 2012–1154. Reston, Virginia: U.S. Geological Survey.

Available: <https://doi.org/10.3996/JFWM-22-032.S5> (3.292 MB PDF)

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