



Summary and Synthesis of 15 Years of the Amphibian Vital Sign Monitoring in the National Capital Area Inventory and Monitoring Network

Natural Resource Report NPS/NCRN/NRR—2022/2356





ON THIS PAGE

Northern cricket frog (*Acris crepitans*)
NPS / CHARLIE SHAFER

ON THE COVER

NCRN amphibian monitoring at Chesapeake and Ohio Canal National Historical Park
NPS / CHARLIE SHAFER

Summary and Synthesis of 15 Years of the Amphibian Vital Sign Monitoring in the National Capital Area Inventory and Monitoring Network

Natural Resource Report NPS/NCRN/NRR—2022/2356

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Abstract

The amphibian monitoring program, designed and conducted by the U.S. Geological Survey's Amphibian Research and Monitoring Initiative program, is designed to estimate the status and trends of amphibian populations to assist management decisions in individual parks and across the National Capital Region Network. Detection/non-detection data for stream and wetland habitats has been collected in 2 parks annually since 2005, and recently expanded to 11 units in the network following habitat mapping efforts. Data for all parks were incorporated into an analysis of site-occupancy for each habitat type (e.g. streams, wetlands) to estimate the occupancy rates for each species. This report summarizes the monitoring efforts, changes in the program over time, and findings based on data from 2005-2018. Fifteen species or species complexes within wetland sites and 5 species of salamander in stream sites were encountered during surveys. Across the network, more than half of wetland populations (65%) are estimated to be stable, 2% are increasing, and 33% indicate a negative trend. Stream salamander populations appear to be relatively stable, with observed population fluctuations likely related to availability of surface water in a given year. Although there were among-park differences in baseline occupancy and dynamics, overall factors promoting occupancy and persistence from year to year included sites that are large, well-connected to other breeding habitats, forested, and with low conductivity.

List of Terms and Acronyms

National Park Service Acronyms

- ANTI: Antietam National Battlefield
- CATO: Catoctin Mountain Park
- CHOH: Chesapeake and Ohio Canal National Historical Park
- GWMP: George Washington Memorial Parkway
- HAFE: Harpers Ferry National Historical Park
- MANA: Manassas National Battlefield Park
- MONO: Monocacy National Battlefield
- NACE: National Capital Parks – East
- NCA: National Capital Area
- NCRN: National Park Service National Capital Region Network
- NPS: National Park Service
- PRWI: Prince William Forest Park
- ROCR: Rock Creek Park
- WOTR: Wolf Trap National Park for the Performing Arts

Amphibian Species Acronyms

- ACRE: *Acris crepitans* — northern cricket frog
- AMA: *Ambystoma maculatum* — spotted salamander
- AOPA: *Ambystoma opacum* — marbled salamander
- BUFO: *Anaxyrus americanus/fowleri* — American/Fowler's toad
- DFUS: *Desmognathus fuscus* — northern dusky salamander
- EBIS: *Eurycea bislineata* — northern two-lined salamander
- EGUT: *Eurycea guttolineata* — three-lined salamander
- ELON: *Eurycea longicauda* — long-tailed salamander
- HSCU: *Hemidactylium scutatum* — four-toed salamander
- HYLA: *Hyla versicolor/chrysocelis* — gray treefrog complex
- NVIR: *Notophthalmus viridescens* — eastern red-spotted newt
- PCRI: *Pseudacris crucifer* — spring peeper
- PFER: *Pseudacris feriarum* — upland chorus frog
- PRUB: *Pseudotriton ruber* — northern red salamander
- RCAT: *Lithobates catesbeianus* — American bullfrog
- RCLA: *Lithobates clamitans* — northern green frog
- RPAL: *Lithobates palustris* — pickerel frog
- RSPH: *Lithobates sphenoccephalus* — southern leopard frog
- RSYL: *Lithobates sylvaticus* — wood frog
- SHOL: *Scaphiopus holbrookii* — eastern spadefoot

Other Acronyms and Study-Specific Symbols

AICc: Akaike Information Criterion

NEARMI: Northeast Amphibian Research and Monitoring Initiative

Ψ : Initial occupancy of species in a park

γ : Species colonization likelihood in a particular wetland

ϕ : Species persistence likelihood, the inverse of extinction

ϵ : Local Extinction

$\bar{n}$: Species richness

Glossary

Covariate: An independent variable that can affect a response variable but is not of direct interest in the trial or study

Hydroperiod: A period of time when the soil area is waterlogged

Julian Date: Date format that counts the number of days since the beginning of the year.

Lentic: Wetland habitat

Lotic: Stream habitat

Palustrine: Non-tidal wetlands

Vital Sign: Element in park ecosystem that helps indicate the overall health or condition of park resources

Introduction

Initiated in 2005, the amphibian monitoring program of the National Park Service National Capital Region Network (NCRN) aims to describe the status and trends of amphibian populations and explore factors that may influence these populations. The monitoring program is also designed to provide information to inform management decisions for amphibians for individual parks and for the entire network. Amphibians were chosen as a Vital Sign and priority taxonomic group due to concern for risk of population declines due to both urbanization and climate-induced ecosystem change (NPS 2005). Initial work in the network began in 2005 and included collection of detection/non-detection data for amphibians in stream, terrestrial, and wetland habitats in two parks in the National Capital Region Network (Chesapeake and Ohio Canal National Historical Park, Rock Creek Park). Random, unbiased sampling of lentic (still, e.g., wetland) and lotic (flowing, e.g., stream) habitats and multiple survey techniques were used. Consultation between researchers and park personnel after the first year resulted in the current monitoring program design (NPS 2007) focused on wetlands (lentic habitat) and first-order streams (lotic habitat) in the Chesapeake & Ohio Canal National Historical Park (CHOH), and only lotic habitats in Rock Creek Park (ROCR) and Prince William Forest Park (PRWI). These parks were selected because they had existing maps of stream and wetland habitats, and initial monitoring provided estimates of parameters useful for designing a program that considered every park in the network. Monitoring efforts have since expanded to other parks following mapping efforts, including Catoctin Mountain Park (CATO), George Washington Memorial Parkway (GWMP), Harpers Ferry National Historical Park (HAFE), Manassas National Battlefield Park (MANA), Monocacy National Battlefield (MONO), and National Capital Parks – East (NACE).

The NCRN Parks are in the Washington, D.C. metropolitan region, an area continuing to undergo urbanization and ex-urban development (Lookingbill et al. 2014). Parks here are small in size and therefore vulnerable to factors external to park boundaries (Stottlemeyer 1987). The enabling legislation for each park varies and can include a focus on historic value, recreation value, and/or the preservation of natural resources (NPS 2005), and parks in the region encompass a diverse array of habitat types (e.g., parks are located in at least one of four different physiographic regions). Thus, each park has a unique landscape context (i.e., use and history) and may differ in the amphibian community response to external and internal drivers of ecosystem change (Lookingbill et al. 2014). Additionally, because of differences in park purpose, the management objectives for each park differ, thus complicating the selection of an optimal response to declines in this Vital Sign.

Site-occupancy was selected as the state variable because for amphibians, sites are assumed to represent populations, and the number of occupied sites is more appropriate than changes in abundance for characterizing amphibian population dynamics (Green 1997). Estimating site-occupancy requires repeat visits to a site, during which the state of the species is assumed to be ‘closed’ to changes in occupancy status. During each of these visits, a species may be present and available for detection, or it may be present but undetected. The sequence of detection/nondetection data can be used to estimate the true probability a species is present at a site, accommodating this potential heterogeneity in per-visit detection probability (MacKenzie 2006).

Many species of amphibians have long generation times, thus monitoring programs must include sufficiently long time series to understand the population trends, even when statistically unbiased estimators (such as our use of occupancy probability) are used (Walls 2014). Here we summarize current information on the status and trends of amphibian populations in the National Capital Area. This report details the ongoing monitoring efforts, changes in the program over time, and describes findings based on analysis of the current available data (2005–2018).

Methods

The monitoring program includes a random sub-sample of all mapped wetland (Lentic Habitat; Table 1) and stream (Lotic Habitat; Table 2) habitats within each NCA park. In the beginning phase of the monitoring program (2005–2012), this included lentic and lotic habitats in parts of CHOH and ROCR, and lotic habitats in PRWI – parks where wetland and stream habitats had been previously mapped. Mapping efforts in other NCR parks conducted in 2013–15 allowed for expansion of lentic monitoring to most other NCR parks (Table 1; see below for mapping methods). Data from the initial phase were useful in estimating baseline detection, occupancy, and dynamic parameters for amphibian species (which did not exist prior to this work).

Uneven sampling across sites across parks resulted from logistical constraints and monitoring priorities that have varied over time. Monitoring at CHOH since 2005 has been constrained to the first 16 miles of the canal (including the Potomac Gorge region in the southern section of the park) where wetlands were mapped at the beginning of the monitoring program; otherwise, for all other parks, sampling was not constrained spatially. Monitoring at ROCR from 2005–2015 was limited to just three species (*Ambystoma maculatum*, *A. opacum*, *Lithobates sylvaticus*) as opposed to the entire amphibian community in other years and for other parks (limited sampling is denoted by an # in Table 1). Monitoring at Manassas from 2007–2014 was conducted at sites which were chosen nonrandomly (i.e., based on the presence of one or more of the focal species), and thus were not integrated into the analysis (in which the selection of sites is probabilistic so that status of the species could apply to the entire park and not just the selected sites). Sampling within the NACE administrative unit from 2016 to 2018 occurred in: Greenbelt Park, Kenilworth Park & Aquatic Gardens, Oxon Cove Park/Oxon Hill Park, and Piscataway Park. No sampling was conducted in ANTI or WOTR because these parks do not contain sufficient habitats for estimation of population status.

Table 1. shows the annual monitoring effort in lentic habitats (i.e., the number of wetlands sampled yearly). The number of wetlands known in each park is indicated in the second column. Values with stars (*) indicate a non-random selection of habitats; values with hash tags (#) indicate that only a subset of the community was sampled.

Table 2. shows the annual monitoring effort in lotic habitats (i.e., the number of transects sampled yearly). The total number of established stream transects at a park is indicated in the second column. Monitoring was not conducted at other NCRN parks due to lack of adequate habitat maps for probabilistic site selection and because of an emphasis on wetland amphibian communities. Sites were not sampled in 2018–2019 to allow expanded wetland sampling effort at a greater number of parks (as listed in Table 1).

Table 1. Annual Lentic Habitat Monitoring Effort for Amphibians in the National Capital Area from 2005 to 2019.

Park	Number of Known Wetlands	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
CATO	88	0	0	0	0	0	0	0	0	0	0	19	17	22	20	21
CHOH	274	33	25	31	30	33	61	61	54	29	60	20	20	48	46	21
GWMP	69	0	0	0	0	0	0	0	0	0	0	0	0	17	29	33
HAFE	35	0	0	0	0	0	0	0	0	0	0	9	6	0	0	0
MANA	66	0	0	9*	9*	9*	9*	9*	9*	9*	10*	35	16	34	22	20
MONO	70	0	0	0	0	0	0	0	0	0	0	26	10	13	25	19
NACE	113	0	0	0	0	0	0	0	0	0	0	0	7	0	22	19
PRWI	120	0	0	0	0	0	0	0	0	0	0	0	0	21	22	25
ROCR	10	6 [#]	3 [#]	8 [#]	3 [#]	2 [#]	8 [#]	5 [#]	2 [#]	9 [#]	7 [#]	9 [#]	2	7	10	10

Table 2. Annual Lotic Habitat Monitoring Effort for Amphibians in the National Capital Area from 2005 to 2019.

Park	Stream Transects	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
CHOH	26	24	20	24	24	25	26	24	25	19	26	26	25	18	0	0
PRWI	72	0	72	0	45	70	0	0	61	68	72	0	26	0	0	0
ROCR	19	19	17	18	16	19	19	15	14	17	19	19	17	14	0	0

Mapping Methods

The locations of all amphibian habitat sites available for monitoring can be viewed in a geospatial dataset for NCRN amphibian habitat mapping, completed in 2017, available at:

<https://irma.nps.gov/DataStore/Reference/Profile/2239467>. Of the available sites, the locations of those actually monitored is considered operationally protected data, based on protected data agreements with each park, and are not included in this report. Location data for amphibian sites monitored may be requested from the National Park Service or the authors of this report.

Lentic Habitats

We used two approaches to locate, identify, and map available wetlands at each park unit, depending on park size and complexity. For most (ANTI, CATO, CHOH, GWMP, HAFE, NACE, PRWI, WOTR), we used a probabilistic sampling design to randomly select points throughout the park to search for aquatic habitats (Table 3). For others (MANA, MONO), unmapped sections were walked systematically. Mapped wetlands that were determined to be isolated, palustrine (non-tidal), and < 0.4 ha in area were considered for potential sampling in the monitoring program (Table 4).

Table 3. Number of Random Points Visited in Each Unmapped Park to Discover Lentic Habitats in the NCRN. Unmapped sections of MANA and MONO were traversed systematically (*) to map all potential aquatic habitats present in the park.

Park	2013	2014	2015	2016
ANTI	–	–	–	56
CATO	91	–	–	–
GWMP	–	–	70	–
HAFE	68	–	–	–
MANA	–	*	–	–
MONO	–	*	–	–
NACE	–	–	93	–
PRWI	–	–	–	108
WOTR	–	–	9	–

Table 4. Number of Mapped Lentic Habitats in Each Unmapped NCRN Park 2013–2016. Additional total of mapped habitats that do not fit the definition for this monitoring program (e.g., seeps and floodplain wetlands) are included in parentheses in the table.

Park	2013	2014	2015	2016
ANTI	–	–	–	7
CATO	88 (142)	–	–	–
GWMP	–	–	68 (23)	–
HAFE	35 (15)	–	–	–
MANA	–	66 (70)	–	–
MONO	–	70 (46)	–	–
NACE	–	–	113 (79)	–
PRWI	–	–	–	120 (13)
WOTR	–	–	12 (4)	–

Site Selection/Field Methods

Once a map of wetland habitats was available for a park, a subset of sites were randomly chosen and sampled up to 5 times annually, with 1 or 2 independent observers searching for amphibians at each visit. Over the course of the monitoring within the region, we sampled 243 wetlands. Field methods are detailed in Grant et al. (2011) as well as the published protocols (NPS 2007). Briefly, wetland surveys involve 1–2 independent observers walking the full perimeter of the wetland (once each), starting from opposite ends. All detections of eggs, larvae, juveniles, and adults (via visual encounters or dip-net surveys) of any species encountered are separately recorded by the independent observers.

Lotic Habitats

Site Selection/Field Methods

As maps of stream habitats were available, a subset of monitoring sites were randomly chosen from headwater stream segments that originate within NCR parks. Details of site selection and field methods are described in the protocol (NPS 2007) as well as Grant et al. (2011). Briefly, stream surveys involve multiple temporary removal passes, turning available cover objects in paired 15-m stream sections at both the headwaters and 100 m downstream (Figure 1). Salamanders encountered in each pass are temporarily removed, and after all passes are complete, all salamanders are recorded and returned to their location of capture. Each site was surveyed up to two times per year. Covariates [pH, conductivity (uS), water temperature (°C)] were measured at each visit when water was present.

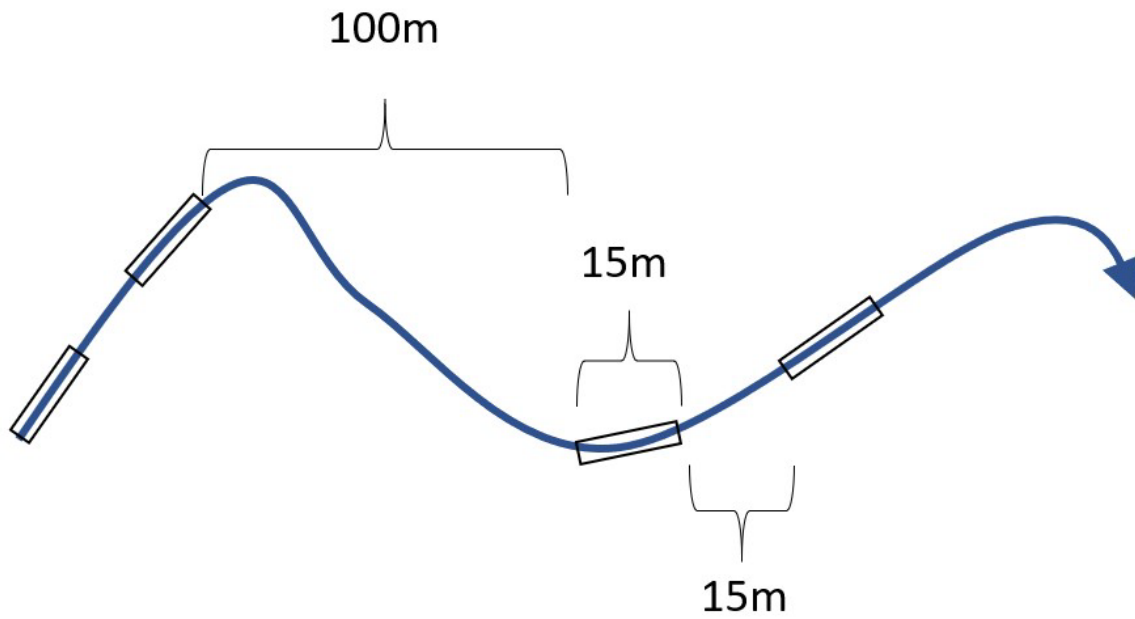


Figure 1. Conceptual figure of lotic sampling design along a single stream. Removal sampling was conducted in 15-m transects, with 4 transects on each stream, with 100 m between transect pairs. Sampling sites were constant among years. Figure not drawn to scale. Arrow indicates flow direction.

Analytic Methods

Lentic Habitats

Initial analysis of the data followed NCRN protocols (NPS 2007) used the program PRESENCE, to fit multi-season occupancy models to estimate the initial occupancy probability and dynamic parameters (extinction and colonization) for each species separately. (The PRESENCE program is used to estimate patch occupancy and related parameters and is described at:

[https://www.usgs.gov/software/presence.](https://www.usgs.gov/software/presence))

Using this approach, we were unable to estimate occupancy and trends for species with few encounters. Subsequently, we fit static community occupancy models to analyze data at each park separately (CHOH; Zipkin et al. 2012), which improved our estimate of species richness and trends within surveyed parks.

To properly account for the hierarchically nested sampling (i.e., sites within parks; parks within the network) and to improve the ability to share information about the species-specific detection probabilities among parks, we developed a dynamic, multi-region, community occupancy model (Dorazio et al. 2010, Sutherland et al. 2016) to analyze the species detection-nondetection data from the lentic habitat sampling of all parks (Wright et al. 2020). Using this hierarchical model, we are able to jointly estimate species-specific occupancy, colonization, extinction, and detection probabilities at each park for each year, in addition to gaining inference on wetland- and park-specific species richness estimates, all in a unified statistical analysis. Importantly, though this approach produces unbiased estimates of the species-specific dynamic parameters, estimates of these parameters will become more precise as more years of data are accumulated. This focus on estimating population dynamic parameters is important, as are the rates where management may affect the system, so it is important to understand what is driving species-specific trends, and to use the model to predict how management may affect future population status (e.g., Grant et al. 2013).

We treat each park as a spatially independent unit in this analysis. We assume the amphibian occupancy status to be open to change across years (i.e., a species can go locally extinct from an occupied site and is free to colonize an empty site between time t and $t+1$), and we assumed closure (i.e., no change in species-specific wetland occupancy) during the repeat sampling visits which occurred during the amphibian breeding season (March–July). This allowed for annual rates to be estimated from the model. We treated each observer during each sampling occasion as an independent replicate, yielding up to 10 repeat sampling events for a wetland each year. We combined detections across all age-classes for each species.

We estimated the number of species present at each park (Table 5) as a function of the total park area, percent forest cover, and isolation (% developed and open water land use classes surrounding park within a 1 km buffer) of each park (see Wright et al. 2020 for additional details on covariates). Given a species occupied a park, we modelled the occupancy (i.e., proportion of wetlands occupied) of that species annually over the duration of the sampling of that park. Initial occupancy (ψ) for each species was estimated at each wetland for the first year of sampling given the hydroperiod status of the wetland. In subsequent years, estimates of species occupancy were derived from estimated probabilities of time-varying site colonization and extinction. The likelihood a given species colonized (γ) a particular wetland was relative to the occupancy status of that species at that wetland

in the previous year, and the following covariates: area of that wetland, its connectivity to other mapped wetlands in the park, and a random effect of year. We hypothesized that hydroperiod had a stronger effect on year-to-year survival, as the time period in which colonization is occurring, most wetlands (regardless of hydroperiod) are inundated. There can be parameter identifiability issues in dynamic models if the separate linear models (colonization, persistence, detection) all have the same covariates (i.e., the model has a harder time parsing out the variation among different processes and individual covariates). While hydroperiod might have a slight effect on colonization, because we expect it to be minor and to have a much larger impact on extinction, we do not include it as a covariate on the colonization process. The likelihood a given species persisted (ϕ ; the inverse of extinction) at a particular wetland was relative to the occupancy status of that species at that wetland in the previous year, and the wetland hydroperiod, area, conductivity, precipitation, and a random effect of year. Precipitation was calculated as the cumulative daily precipitation (01 Feb–31 May, obtained from the regional PRISM model; Daly et al. 2008) for the park centroid location of all surveyed wetlands. (PRISM is the acronym for the Parameter-elevation Regressions on Independent Slopes Model described at: <https://prism.oregonstate.edu/>.) To account for false negatives (i.e., a species is present at a wetland but not detected), we modelled the likelihood of detecting a species during a sampling event at a wetland in a given year of a park assuming a quadratic effect of day of year to account for differences in breeding periods among species, and a random effect of year to account for other variation (such as shifts in phenology over time). We calculated annual wetland-specific species richness ($\bar{n}$) for each park by averaging the number of species estimated to be present at all wetlands at each park in each year. Our site selection allows us to make inference to the entire park, except for those parks and years where site selection was non-random (Table 1).

We estimated model parameters using Bayesian inference within the programs R (R Core Team 2016) and JAGS (Plummer 2001, Kellner 2016) through a data augmentation process (Royle et al. 2007). All continuous covariates were standardized to have a mean of zero and standard deviation of one. We used vague and uninformative priors and determined model convergence using the Gelman and Rubin convergence diagnostic (Gelman & Rubin 1992, Gelman & Shirley 2011).

To estimate trends (mean and 95% credible intervals) in occupancy, we conducted a *post-hoc* analysis on the annual occupancy estimates for each amphibian population (i.e., each species in each park) across all posterior samples from the Bayesian model output, using a linear model to estimate absolute rates of change (Weir et al. 2016, Adams et al. 2013). We standardized year to have a mean of zero. We categorized population trend directions as negative (95% of the posterior mass less than zero), slightly negative (75% of the posterior mass less than zero), positive (95% of the posterior mass greater than zero), or neutral. Posterior mass is the area under the posterior distribution curve produced by the Bayesian model. To estimate correlations with environmental covariates and estimated species richness (at both the park- and wetland-levels), we also calculated *post-hoc* Pearson's correlation coefficients for each posterior sample (organized by the median and 95% credible intervals).

Lotic Habitats

Dry sites were treated as non-visits in all analyses, as stream salamanders are generally not available on the surface for detection when water is not present; therefore, surveys are not performed at sites without surface water. Covariates associated with urbanization and proximity to roads (pH, conductivity, temperature) were included as a standardized mean of all observations at a site.

We ran models in two steps for this analysis. The first set of analyses estimate occupancy for each segment on a stream as separate sites (i.e., 4 segments per stream). We considered the two visits per year as different ‘seasons’ to allow for changes in occupancy between the June and July surveys. This results in 117 site-estimates of occupancy across the three parks with 26 possible visits to each site from 2005–2018. Not all sites were visited in all years, in part because segments may have been dry during a sampling occasion (Table 2). We used a parameterization to estimate occupancy in the first season, with subsequent estimates of occupancy derived from estimated probabilities that a site will go locally extinct (ϵ) or be colonized (γ). This structure allowed investigation of covariates affecting these rates among parks, which are expected to be a target for management actions. We first fit a set of models under a general model structure (i.e., occupancy, colonization and extinction related to season and park; $\Psi(\text{season}+\text{park})$, $\gamma(\text{season}+\text{park})$, $\epsilon(\text{season}+\text{park})$) to determine the best structure for the ‘nuisance’ detection probability parameter for each species, which we hypothesized would be related to the sample pass (3 passes possible at each visit), transect location (headwaters or downstream), month (June or July), or season (i.e., different at each of the 26 visits). Using the best structure for detection, we then examined the effects of water quality (pH, conductivity, temperature), transect location (headwaters or 100m downstream) and frequency of drying (as percent of visits site was dry) on initial occupancy. The covariates in the top model for initial occupancy (and detection) were then used to fit models with varying structures on ϵ and γ . We hypothesized these rates could be constant or vary by season, park, percent of dry visits, transect location, as well as combinations of these variables. Model selection used Akaike Information Criterion, AICc, (Burnham and Anderson 2002), and we calculated AICc weights to estimate the relative support for each candidate model in the set.

Because there is interest in park-specific estimates of annual dynamics in stream salamander occupancy, in a second analysis we combined data within streams and calendar year to separately fit models which estimated occupancy, colonization, and extinction with an interaction among parks over time. All segments on a stream were treated as replicate visits, and we did not include other covariates except segment location on detection (31 models across the three species: Appendix Table 1). The primary objective of the second modeling step was to produce plots of average occupancy for each species over time for each park, to allow for broad comparisons across parks and species.

Results

We encountered 15 species or species complexes (BUFO, HYLE; species acronyms defined in Table 5.) within wetland lentic sites (9 salamanders, 3 toads, and 8 frogs) as well as 5 stream salamander species in lotic sites across the NCR parks. We most frequently encountered three stream salamander species in NCR parks: *Desmognathus fuscus* (DFUS), *Eurycea bislineata* (EBIS), and *Pseudotriton ruber* (PRUB). Two additional *Eurycea* species are infrequently captured (*Eurycea longicauda* and *E. guttolineata*) during stream surveys.

Table 5. Lentic and Lotic Species Encountered at Each Park Across All Sampling Years. Cells containing 'x' indicate presence of the species in the park. Cells containing 'n' indicate a species was not encountered at a park because there has been no lotic sampling, whereas cells containing an en-dash (–) indicate that there has been sampling of a habitat type at a park, but the species has not been detected in the sampling.

Code	Common Name	Scientific Name	Type	CATO	CHOH	GWMP	HAFE	MANA	MONO	NACE	PRWI	ROCR
ACRE	northern cricket frog	<i>Acris crepitans</i>	Lentic	–	x	–	x	x	–	–	x	–
AMAC	spotted salamander	<i>Ambystoma maculatum</i>	Lentic	x	x	x	–	x	x	x	x	x
AOPA	marbled salamander	<i>Ambystoma opacum</i>	Lentic	–	x	x	–	x	–	–	x	–
BUFO	American/ Fowler's toad	<i>Anaxyrus americanus/ fowleri</i>	Lentic	x	x	x	x	x	x	x	x	x
DFUS	northern dusky salamander	<i>Desmognathus fuscus</i>	Lotic	n	x	n	n	n	n	n	x	x
EBIS	northern two-lined salamander	<i>Eurycea bislineata</i>	Lotic	n	x	n	n	n	n	n	x	x
EGUT	three-lined salamander	<i>Eurycea guttolineata</i>	Lotic	n	–	n	n	n	n	n	x	–
ELON	long-tailed salamander	<i>Eurycea longicauda</i>	Lotic	n	x	n	n	n	n	n	–	–
HSCU	four-toed salamander	<i>Hemidactylium scutatum</i>	Lentic	–	x	–	–	–	–	–	–	–
HYLA	gray treefrog complex	<i>Hyla versicolor/ chrysocelis</i>	Lentic	x	x	x	x	x	x	x	x	–
NVIR	eastern red-spotted newt	<i>Notophthalmus viridescens</i>	Lentic	–	x	x	–	x	–	–	x	–
PCRI	spring peeper	<i>Pseudacris crucifer</i>	Lentic	x	x	x	x	x	x	x	x	x
PFER	upland chorus frog	<i>Pseudacris feriarum</i>	Lentic	x	x	–	x	x	x	x	–	–
RCAT	American bullfrog	<i>Lithobates catesbeianus</i>	Lentic	x	x	x	x	x	x	–	x	–
RCLA	northern green frog	<i>Lithobates clamitans</i>	Lentic	x	x	x	x	x	x	x	x	x
RPAL	pickerel frog	<i>Lithobates palustris</i>	Lentic	x	x	x	x	x	x	–	x	–
RSPH	southern leopard frog	<i>Lithobates sphenoccephalus</i>	Lentic	x	x	–	x	x	x	x	x	x
RSYL	wood frog	<i>Lithobates sylvaticus</i>	Lentic	x	x	x	x	x	x	x	x	x
SHOL	eastern spadefoot	<i>Scaphiopus holbrookii</i>	Lentic	x	x	–	x	–	x	–	–	–
PRUB	northern red salamander	<i>Pseudotriton ruber</i>	Lotic	n	x	n	n	n	n	n	–	x

Lentic Habitats

We observed 15 wetland-breeding amphibians (or species complexes) over the course of our study (see Table 5): *Acris crepitans* (northern cricket frog), *Ambystoma maculatum* (spotted salamander), *Ambystoma opacum* (marbled salamander), *Anaxyrus americanus/fowleri* (American/Fowler's toad complex), *Hemidactylium scutatum* (four-toed salamander), *Hyla versicolor/chrysoscelis* (gray treefrog complex), *Lithobates catesbeianus* (American bullfrog), *Lithobates clamitans* (northern green frog), *Lithobates palustris* (pickerel frog), *Lithobates sphenoccephalus* (southern leopard frog), *Lithobates sylvaticus* (wood frog), *Notophthalmus viridescens* (eastern newt), *Pseudacris crucifer* (spring peeper), *Pseudacris feriarum* (upland chorus frog), and *Scaphiopus holbrookii* (eastern spadefoot toad).

Detection

Mean estimated detection probabilities for amphibian species at each park varied non-linearly along each season (by Julian Date), generally peaking in May (Figure 2a.). Species-specific detection probabilities varied widely throughout the sampling season (Figure 2b; here we plot estimates for the amphibians detected in CHOH, the park with most data, as an example). This variation relates to the different breeding periods of each species, for example, estimated detection is highest at the beginning of the sampling season for the spotted salamander and wood frog, as both species are early season breeders, and their eggs are easily detectable.

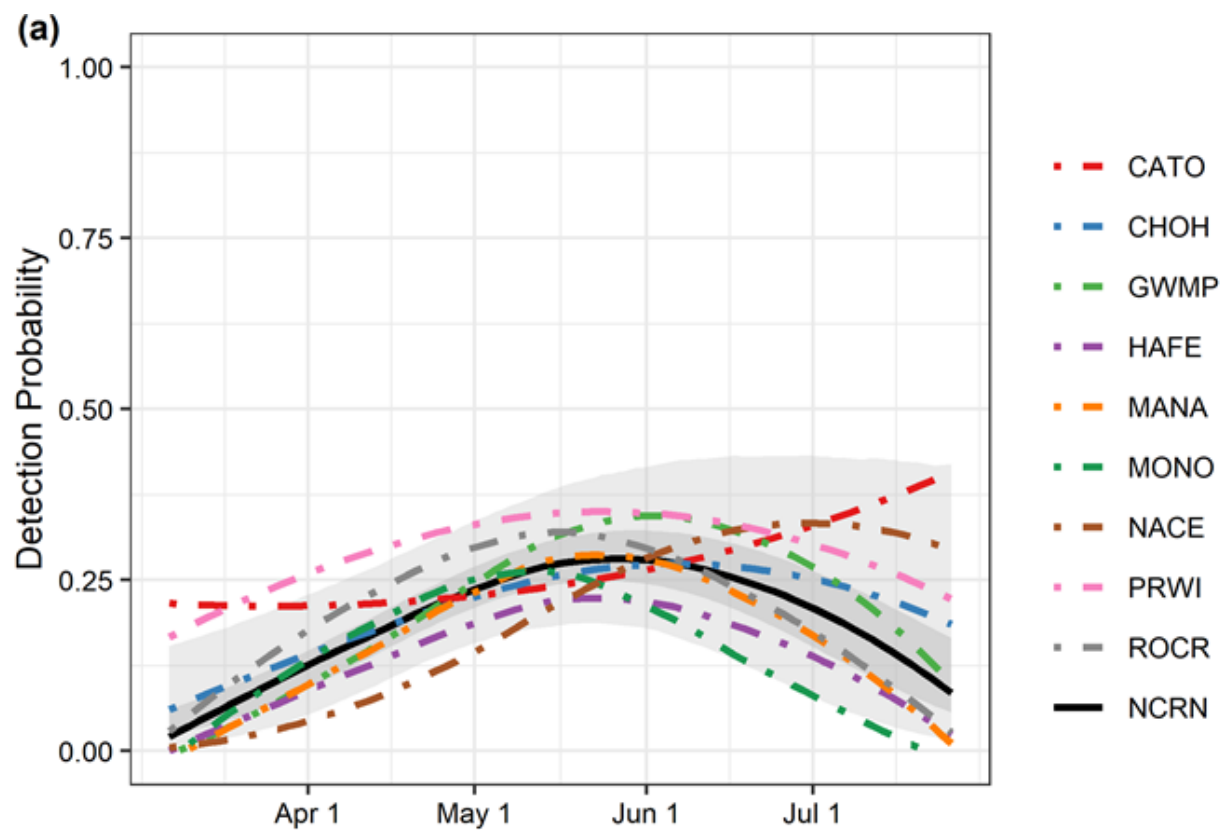


Figure 2a. Mean Park-Level Detection Probability Estimates for Lentic Habitats Across Julian Date. Dashed lines show each park while the solid black line shows the average across parks (with shaded dark grey 50% credible interval [CI] and light grey 95% CI).

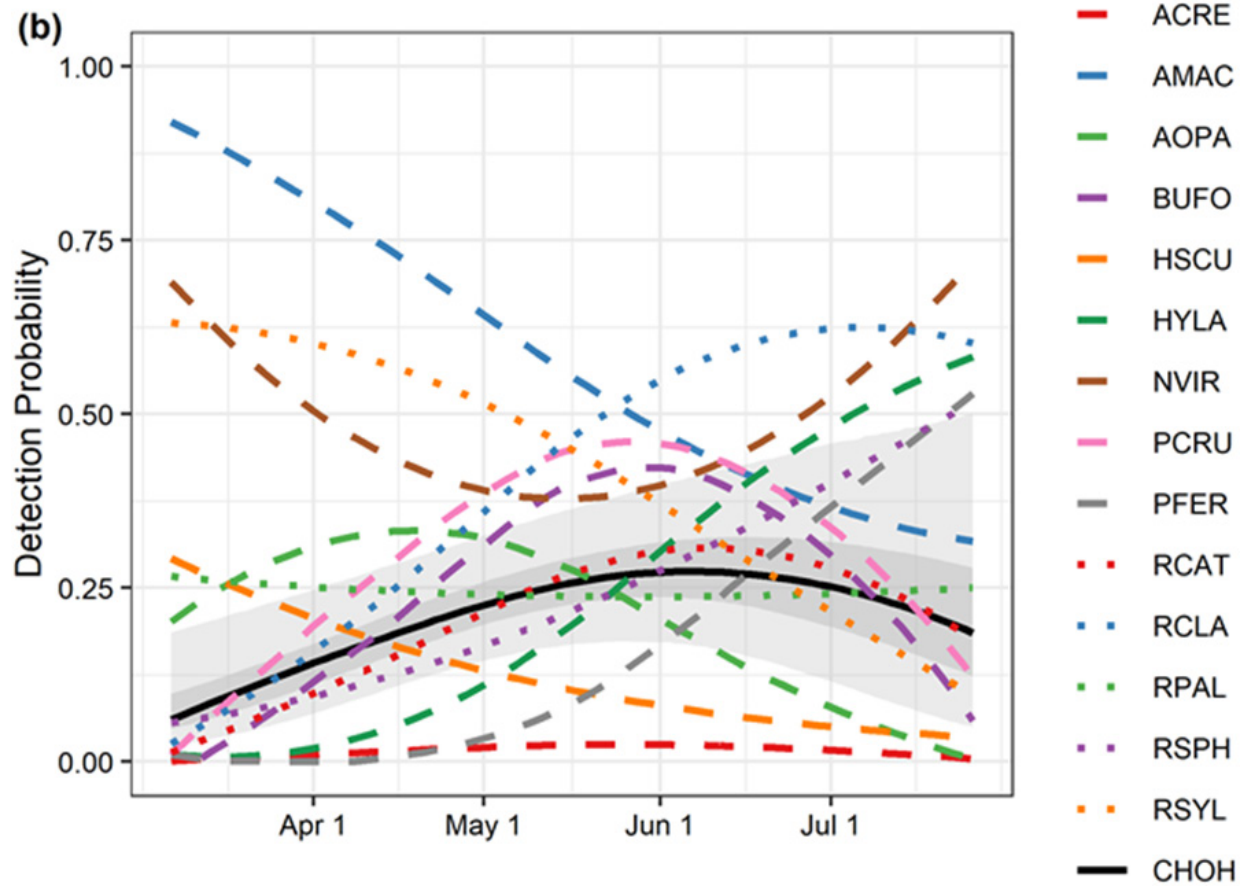


Figure 2b. Mean Species-Specific Detection Probability Estimates Across Julian Date in CHOH, the park with the most data. Dashed lines show the relationship for each species while the solid black line shows the average across all species (with shaded dark grey 50% credible interval and light grey 95%).

Drivers of species richness at the park-level

Overall, estimated and observed species richness varied by park (Figure 3) related to park-level area and isolation (the degree to which habitat surrounding the park is impermeable to amphibian movement). The number of species that were observed in each park varied from six (ROCR) to 14 (CHOH). Estimated park-level richness was higher than observed in most parks given imperfect detection and limited sampling across space and time (excluding CHOH where sampling has been the most intensive). Percent isolation had a strong negative correlation with park-level species richness ($r = -0.700$, 95% credible interval [CI]: $-0.860 - -0.401$ CI, and the largest mean effect on the probability a species occurred within a park (Ω_r ; $-0.268, -0.605 - 0.060$ CI). Park area had a moderate positive correlation with park-level species richness ($r = 0.414$, $0.143 - 0.618$ CI), and a positive mean effect on the probability a species occurred within a park (Ω_r ; $0.135, -0.158 - 0.425$ CI). There was no correlation between percent forest cover and park-level species richness ($r = -0.063, -0.329 - 0.174$ CI), but there was a small, negative effect on the probability a species occurred within a park (Ω_r ; $-0.164, -0.481 - 0.148$ CI). The 95% CIs for all of the park-level covariates overlapped zero, although this is not necessarily surprising given these estimates are the

community-level effects of covariates that encompass the life history diversity of amphibian species within this region.

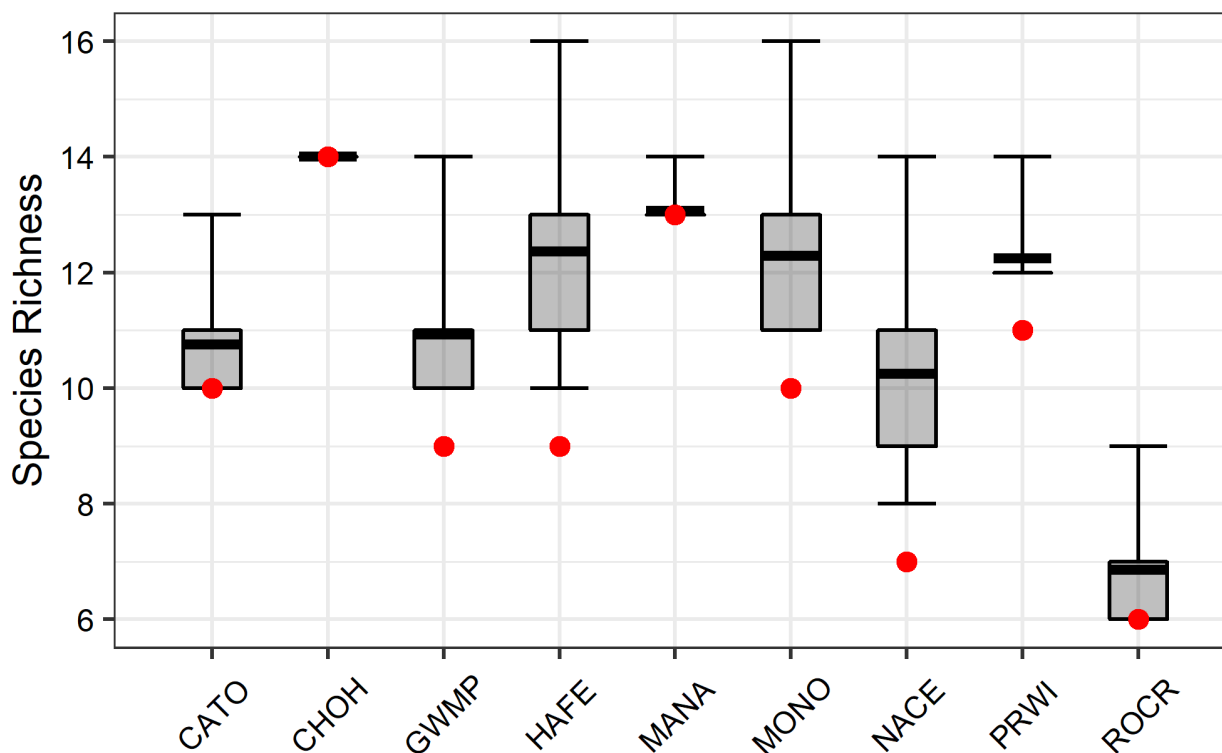


Figure 3. Estimated and Observed Species Richness at Each of the Nine Sampled NCRN Parks. The estimated mean value is indicated with a horizontal line, 50% credible interval (CI) indicated with a box, and 95% CI indicated with the error bars. The observed species richness is indicated by the red dots.

Population Occupancy Status & Trends

We report annual mean wetland-specific species richness for each park in Figure 4, and all annual occupancy and trend estimates for each amphibian population (i.e., each species at each park) in Figures 5–13, organized by park. The fill color of the “Trend” text box indicates the direction of the population trend: blue indicates a positive trend (95% of the posterior mass is greater than zero), white indicates a neutral trend, yellow indicates a slightly negative (75% of the posterior mass is less than zero), and red indicates a negative trend (95% of the posterior mass is less than zero).

Up to this point in the monitoring program, we observe that 5 populations (of 94 total populations – unique species-park combinations) indicate a negative trend, 26 populations indicate a slight negative trend, 2 populations indicate a positive trend, and the remaining 61 populations are stable. At CATO, both the American bullfrog and southern leopard frog indicate population declines (Figure 5). At CHOH, data for the American bullfrog indicates a negative trend, the four-toed salamander indicates a slight negative trend, and the marbled salamander and gray treefrog complex indicate positive trends (Figure 6). At GWMP, data for the spotted salamander, toad complex, spring peeper, northern green frog, and pickerel frog indicate a slight negative decline, and the wood frog indicates a negative decline (Figure 7). At HAFE, no species indicate a slight negative decline (Figure 8). At

MANA, the spotted salamander, toad, complex, gray treefrog complex, spring peeper, northern green frog, pickerel frog, southern leopard frog, and wood frog indicate a slight negative decline, and the upland chorus frog indicates a negative decline (Figure 9). At MONO, data for the pickerel frog and southern leopard frog indicate a slight negative trend, and the toad complex indicates a negative trend (Figure 10). At NACE, data for the spring peeper, upland chorus frog, and southern leopard frog indicate slight negative declines (Figure 11). At PRWI, data for the northern green frog, American bullfrog, and pickerel frog indicate slight negative declines, and the southern leopard frog indicates a negative decline (Figure 12). At ROCR, data for the spotted salamander and wood frog indicate slight negative declines (Figure 13).

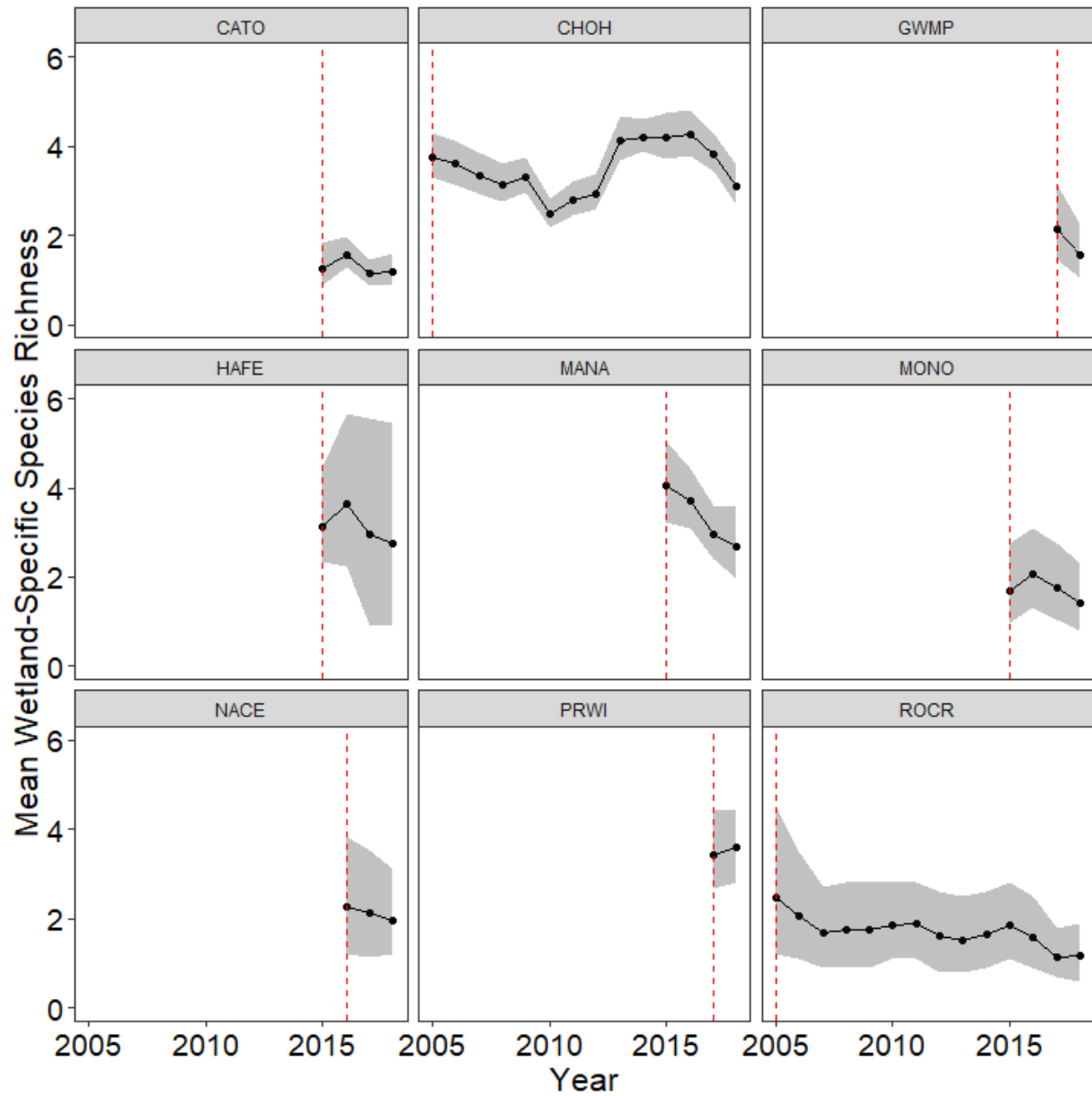


Figure 4. Annual Mean Wetland-Specific Species Richness for Each NCRN Park. Annual mean (black dots) wetland-specific species richness $\bar{\pi}$ of each park, and 95% Credible Intervals. Vertical red dashed lines indicate the first year a park was sampled.

Persistence and Colonization Drivers

Mean colonization probabilities at the network-level (i.e., across all parks and species) was relatively low (γ ; 0.085, 0.044 – 0.151 CI) as compared to mean persistence at the network-level for temporary wetlands (ϕ ; 0.562, 0.347 – 0.745), semi-permanent wetlands (ϕ ; 0.708, 0.433 – 0.888), and permanent wetlands (ϕ ; 0.680, 0.266 – 0.911). Differences in estimated annual wetland richness across hydroperiod categories showed stronger association, with the highest estimated species richness in permanent (n ; 4.700, 4.408 – 5.039), followed by semi-permanent (n ; 3.854, 3.601 – 4.157 CI), and temporary wetlands (n ; 2.190, 2.002 – 2.401 CI). Wetland area had a significant positive effect on persistence at the network-level (ϕ ; 2.097, 0.633 – 3.818 CI), and positive, but not significant, effects on colonization at the network-level (γ ; 0.472, –0.014 – 1.017 CI). Annual wetland-specific species richness was moderately correlated ($r = 0.338$, 0.307 – 0.374 CI) with wetland area. Conductivity had a negative effect on network-level persistence (ϕ ; –1.278, –3.318 – 0.702 CI), but was weakly correlated ($r = -0.129$, –0.153 – –0.102 CI) with annual wetland-specific species richness. Connectivity had almost no effect on mean colonization at the network-level (γ ; 0.017, –0.724 – 0.835 CI), but was moderately correlated ($r = 0.362$, 0.324 – 0.400 CI) with annual wetland-specific species richness. Precipitation had almost no effect on mean persistence at the network-level (ϕ ; –0.013, –0.537 – 0.561 CI), and had no correlation with annual wetland-specific species richness ($r = -0.047$, –0.096 – 0.006 CI).

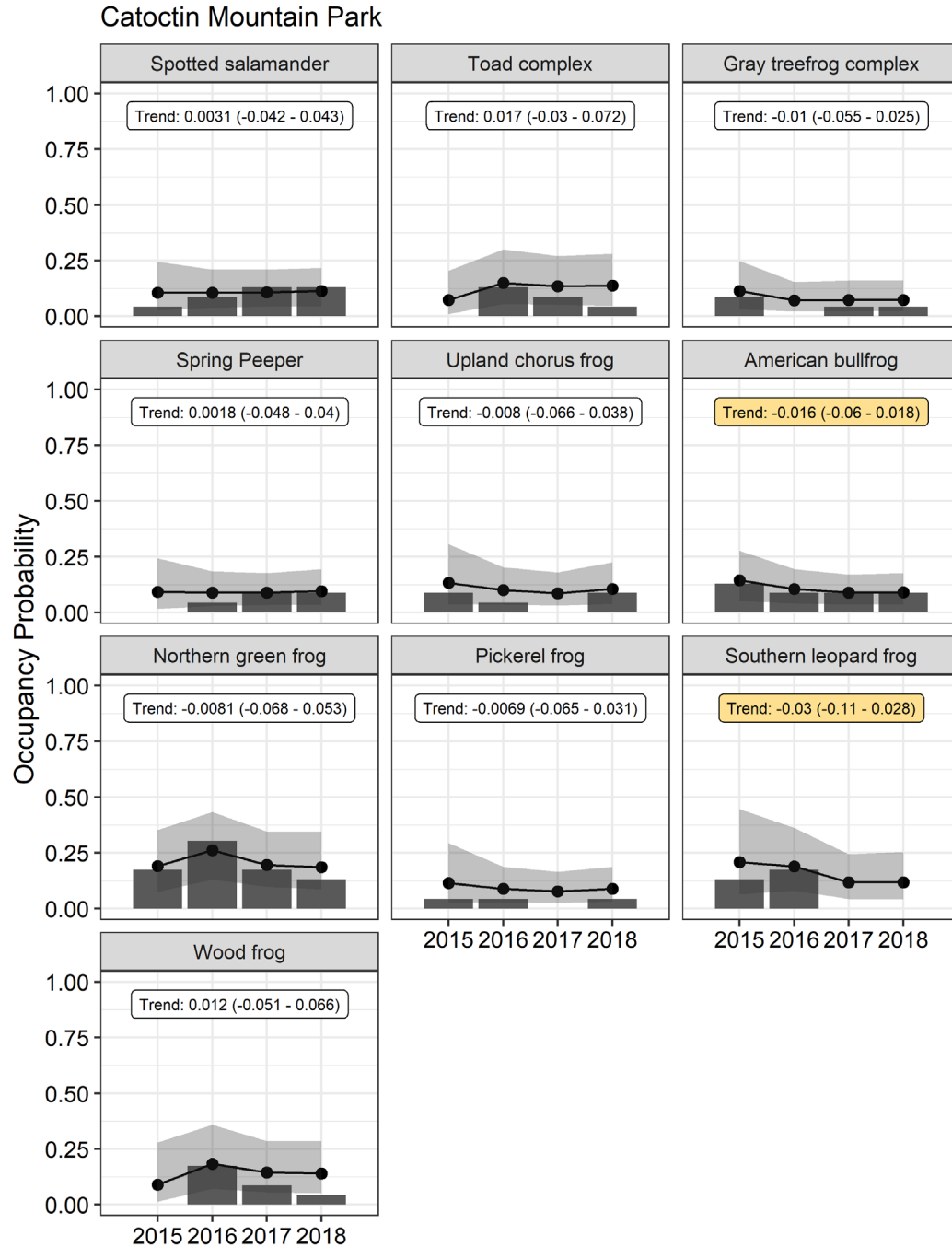


Figure 5. Annual Estimated Occupancy, Raw Occupancy, and Trend Estimates for Each Species Observed in CATO. Black dots (connected by black lines) indicate mean annual occupancy estimates (the number of sites a species was estimated to be present proportional to the total number of sites available for sampling). Light gray shaded areas indicate 95% credible intervals. Dark gray bars indicate raw occupancy (the number of sites a species was observed given the total number of sites available for sampling). The text box in each panel indicates the population trend estimate (mean and 95% credible interval) and the fill color of the text box indicates the direction of the population trend: blue indicates a positive trend (95% of the posterior mass is greater than zero), white indicates a neutral trend, yellow indicates a slightly negative (75% of the posterior mass is less than zero), and red indicates a negative trend (95% of the posterior mass is less than zero).

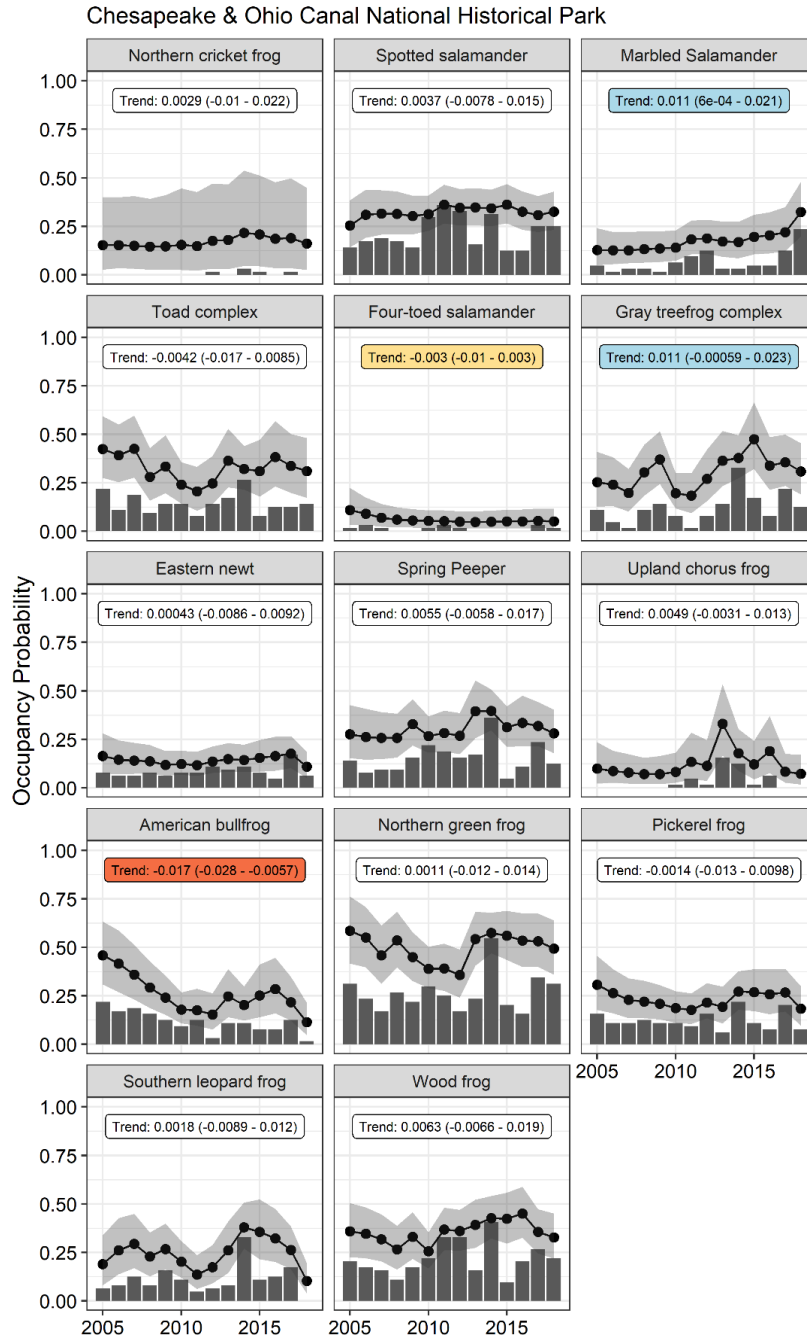


Figure 6. Annual Estimated Occupancy, Raw Occupancy, and Trend Estimates for Each Species Observed in CHOC. Black dots (connected by black lines) indicate mean annual occupancy estimates (the number of sites a species was estimated to be present proportional to the total number of sites available for sampling). Light gray shaded areas indicate 95% credible intervals. Dark gray bars indicate raw occupancy (the number of sites a species was observed given the total number of sites available for sampling). The text box in each panel indicates the population trend estimate (mean and 95% credible interval) and the fill color of the text box indicates the direction of the population trend: blue indicates a positive trend (95% of the posterior mass is greater than zero), white indicates a neutral trend, yellow indicates a slightly negative (75% of the posterior mass is less than zero), and red indicates a negative trend (95% of the posterior mass is less than zero).

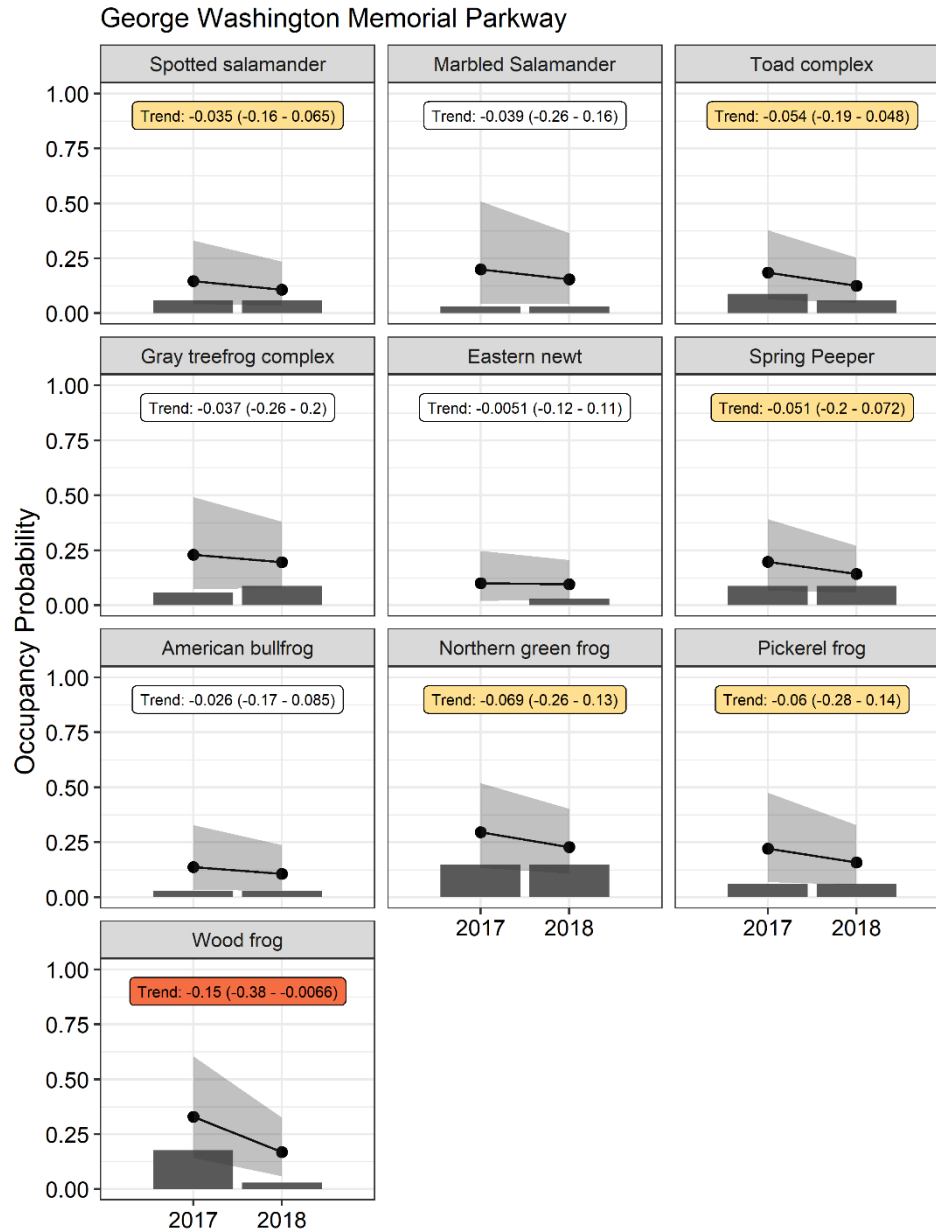


Figure 7. Annual Estimated Occupancy, Raw Occupancy, and Trend Estimates for Each Species Observed in GWMP. Black dots (connected by black lines) indicate mean annual occupancy estimates (the number of sites a species was estimated to be present proportional to the total number of sites available for sampling). Light gray shaded areas indicate 95% credible intervals. Dark gray bars indicate raw occupancy (the number of sites a species was observed given the total number of sites available for sampling). The text box in each panel indicates the population trend estimate (mean and 95% credible interval) and the fill color of the text box indicates the direction of the population trend: blue indicates a positive trend (95% of the posterior mass is greater than zero), white indicates a neutral trend, yellow indicates a slightly negative (75% of the posterior mass is less than zero), and red indicates a negative trend (95% of the posterior mass is less than zero).

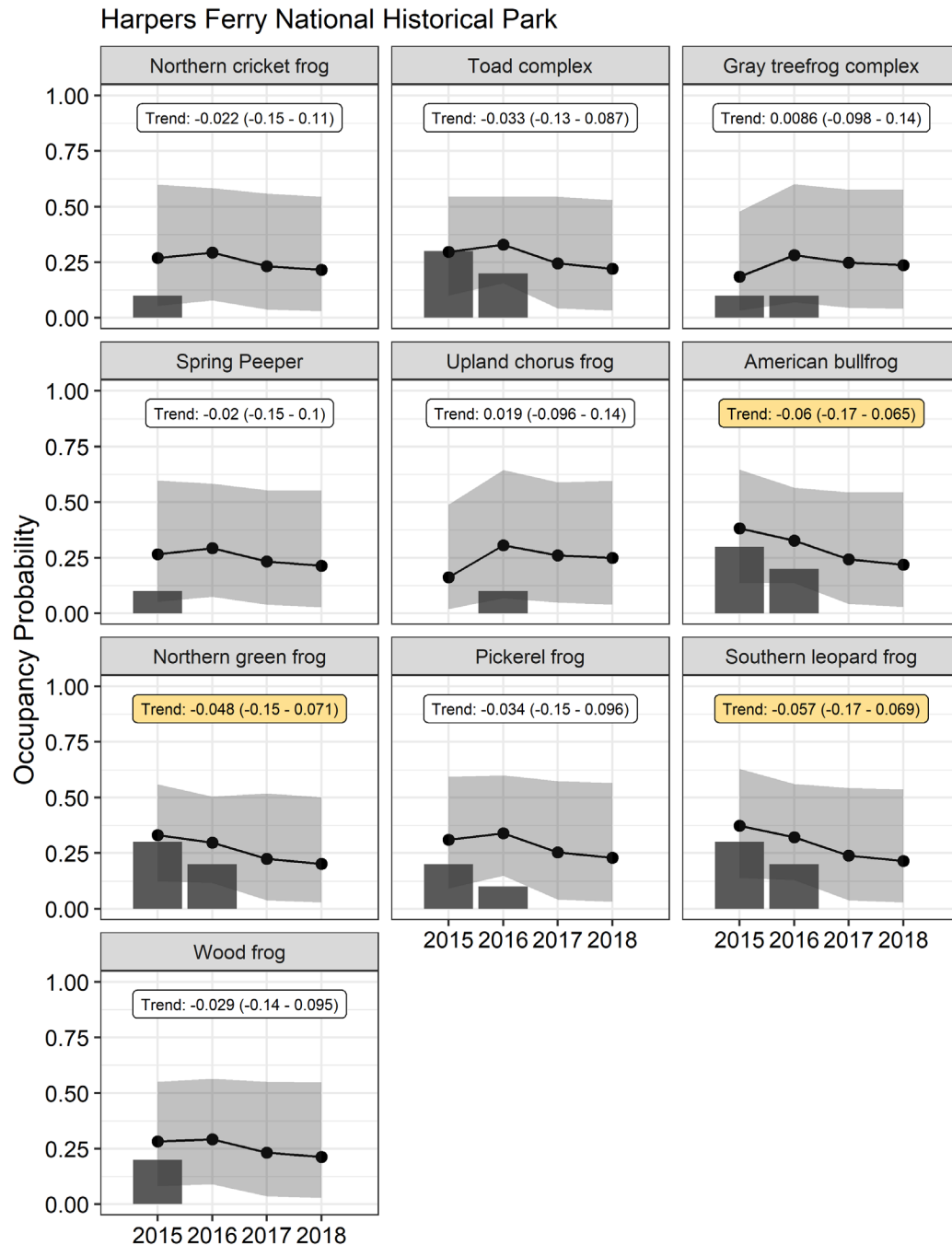


Figure 8. Annual Estimated Occupancy, Raw Occupancy, and Trend Estimates for Each Species Observed in HAFE. Black dots (connected by black lines) indicate mean annual occupancy estimates (the number of sites a species was estimated to be present proportional to the total number of sites available for sampling). Light gray shaded areas indicate 95% credible intervals. Dark gray bars indicate raw occupancy (the number of sites a species was observed given the total number of sites available for sampling). The text box in each panel indicates the population trend estimate (mean and 95% credible interval) and the fill color of the text box indicates the direction of the population trend: blue indicates a positive trend (95% of the posterior mass is greater than zero), white indicates a neutral trend, yellow indicates a slightly negative (75% of the posterior mass is less than zero), and red indicates a negative trend (95% of the posterior mass is less than zero).

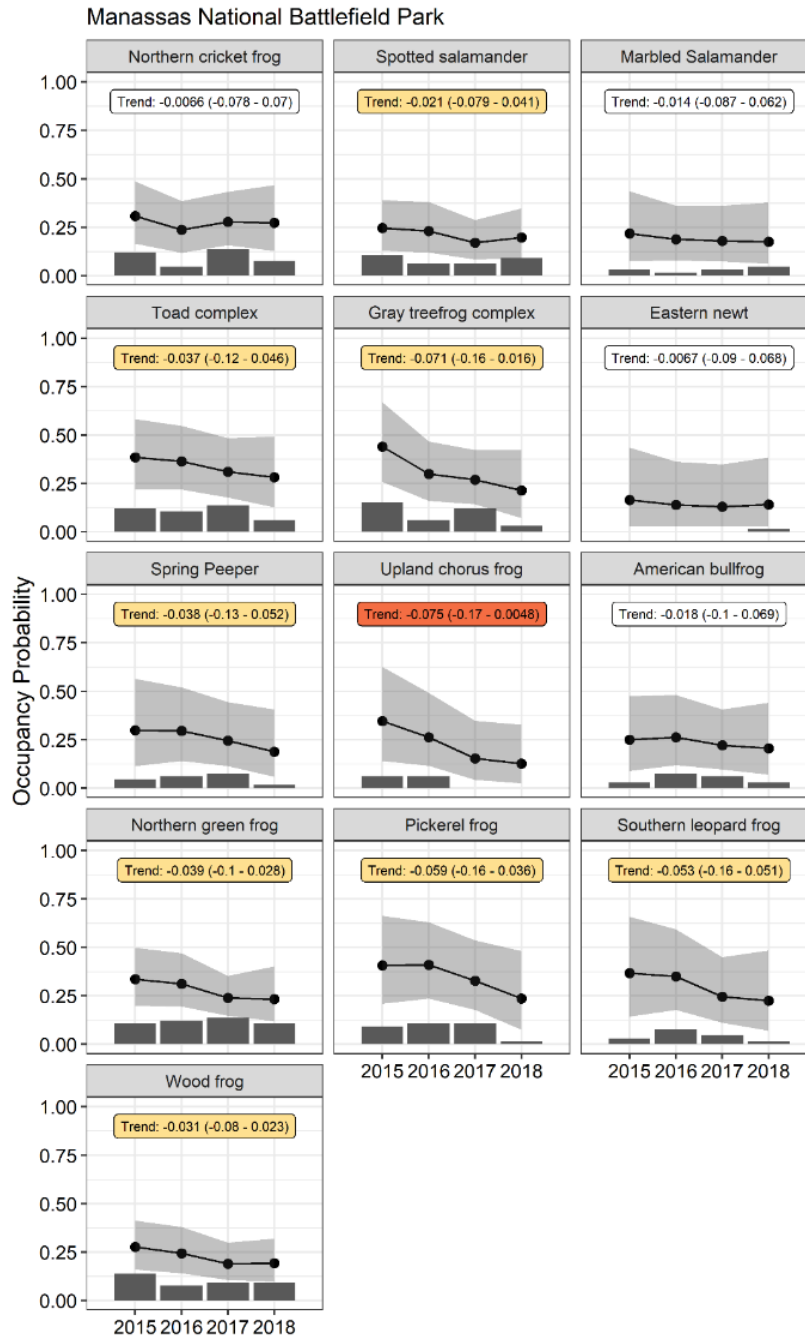


Figure 9. Annual Estimated Occupancy, Raw Occupancy, and Trend Estimates for Each Species Observed in MANA. Black dots (connected by black lines) indicate mean annual occupancy estimates (the number of sites a species was estimated to be present proportional to the total number of sites available for sampling). Light gray shaded areas indicate 95% credible intervals. Dark gray bars indicate raw occupancy (the number of sites a species was observed given the total number of sites available for sampling). The text box in each panel indicates the population trend estimate (mean and 95% credible interval) and the fill color of the text box indicates the direction of the population trend: blue indicates a positive trend (95% of the posterior mass is greater than zero), white indicates a neutral trend, yellow indicates a slightly negative (75% of the posterior mass is less than zero), and red indicates a negative trend (95% of the posterior mass is less than zero).

Monocacy National Battlefield

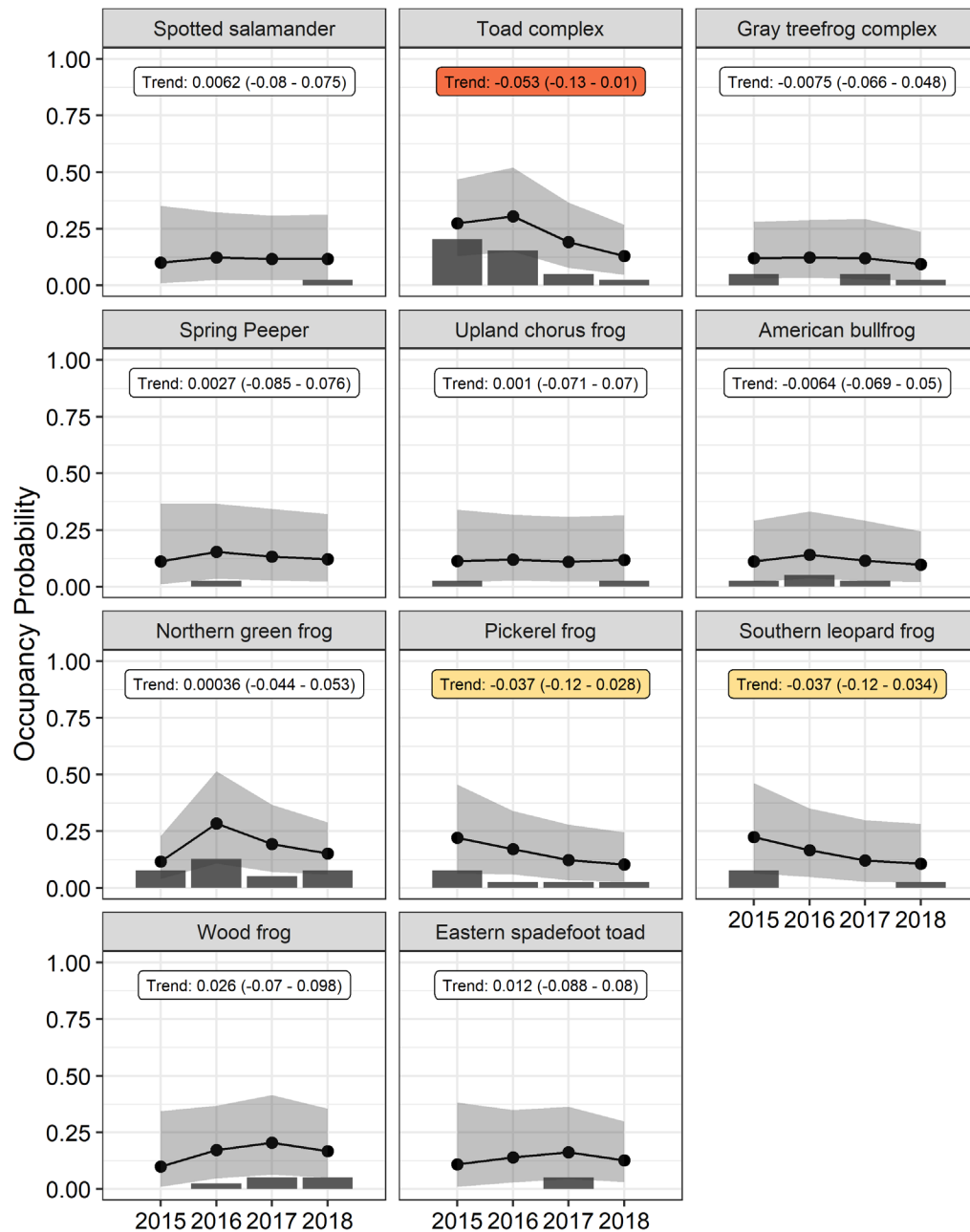


Figure 10. Annual Estimated Occupancy, Raw Occupancy, and Trend Estimates for Each Species Observed in MONO. Black dots (connected by black lines) indicate mean annual occupancy estimates (the number of sites a species was estimated to be present proportional to the total number of sites available for sampling). Light gray shaded areas indicate 95% credible intervals. Dark gray bars indicate raw occupancy (the number of sites a species was observed given the total number of sites available for sampling). The text box in each panel indicates the population trend estimate (mean and 95% credible interval) and the fill color of the text box indicates the direction of the population trend: blue indicates a positive trend (95% of the posterior mass is greater than zero), white indicates a neutral trend, yellow indicates a slightly negative (75% of the posterior mass is less than zero), and red indicates a negative trend (95% of the posterior mass is less than zero).

National Capital Parks - East

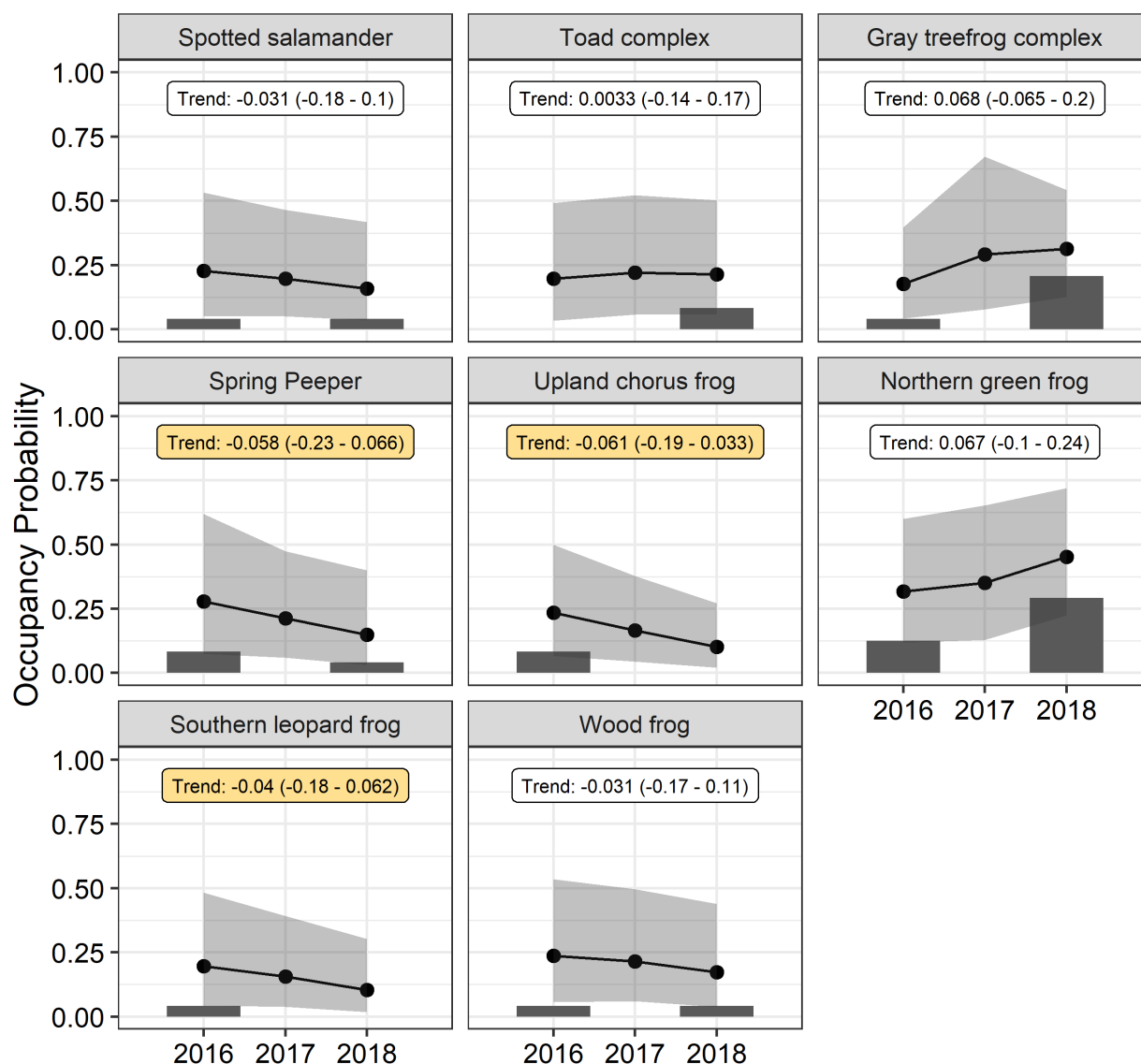


Figure 11. Annual Estimated Occupancy, Raw Occupancy, and Trend Estimates for Each Species Observed in NACE. Black dots (connected by black lines) indicate mean annual occupancy estimates (the number of sites a species was estimated to be present proportional to the total number of sites available for sampling). Light gray shaded areas indicate 95% credible intervals. Dark gray bars indicate raw occupancy (the number of sites a species was observed given the total number of sites available for sampling). The text box in each panel indicates the population trend estimate (mean and 95% credible interval) and the fill color of the text box indicates the direction of the population trend: blue indicates a positive trend (95% of the posterior mass is greater than zero), white indicates a neutral trend, yellow indicates a slightly negative (75% of the posterior mass is less than zero), and red indicates a negative trend (95% of the posterior mass is less than zero).

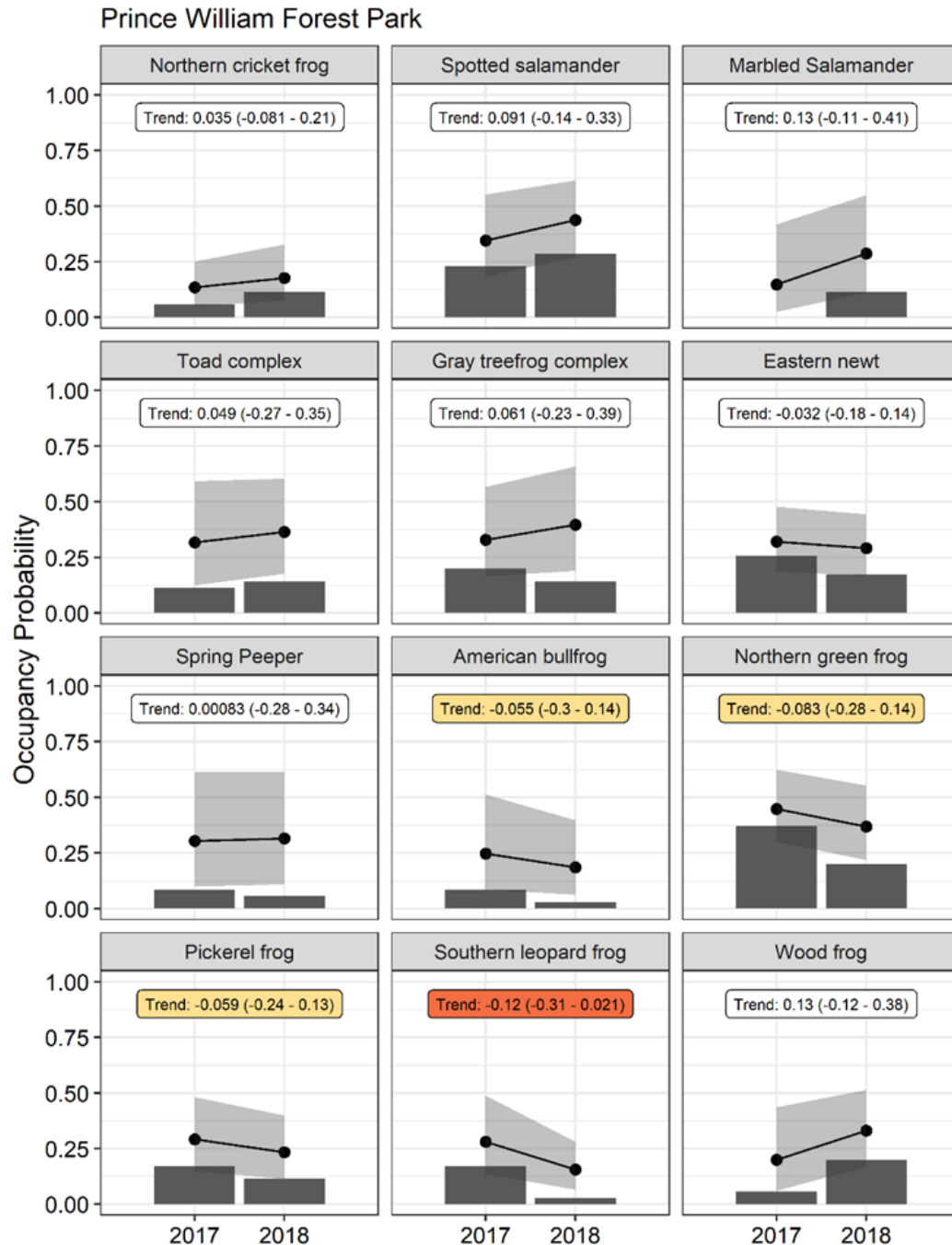


Figure 12. Annual Estimated Occupancy, Raw Occupancy, and Trend Estimates for Each Species Observed in PRWI. Black dots (connected by black lines) indicate mean annual occupancy estimates (the number of sites a species was estimated to be present proportional to the total number of sites available for sampling). Light gray shaded areas indicate 95% credible intervals. Dark gray bars indicate raw occupancy (the number of sites a species was observed given the total number of sites available for sampling). The text box in each panel indicates the population trend estimate (mean and 95% credible interval) and the fill color of the text box indicates the direction of the population trend: blue indicates a positive trend (95% of the posterior mass is greater than zero), white indicates a neutral trend, yellow indicates a slightly negative (75% of the posterior mass is less than zero), and red indicates a negative trend (95% of the posterior mass is less than zero).

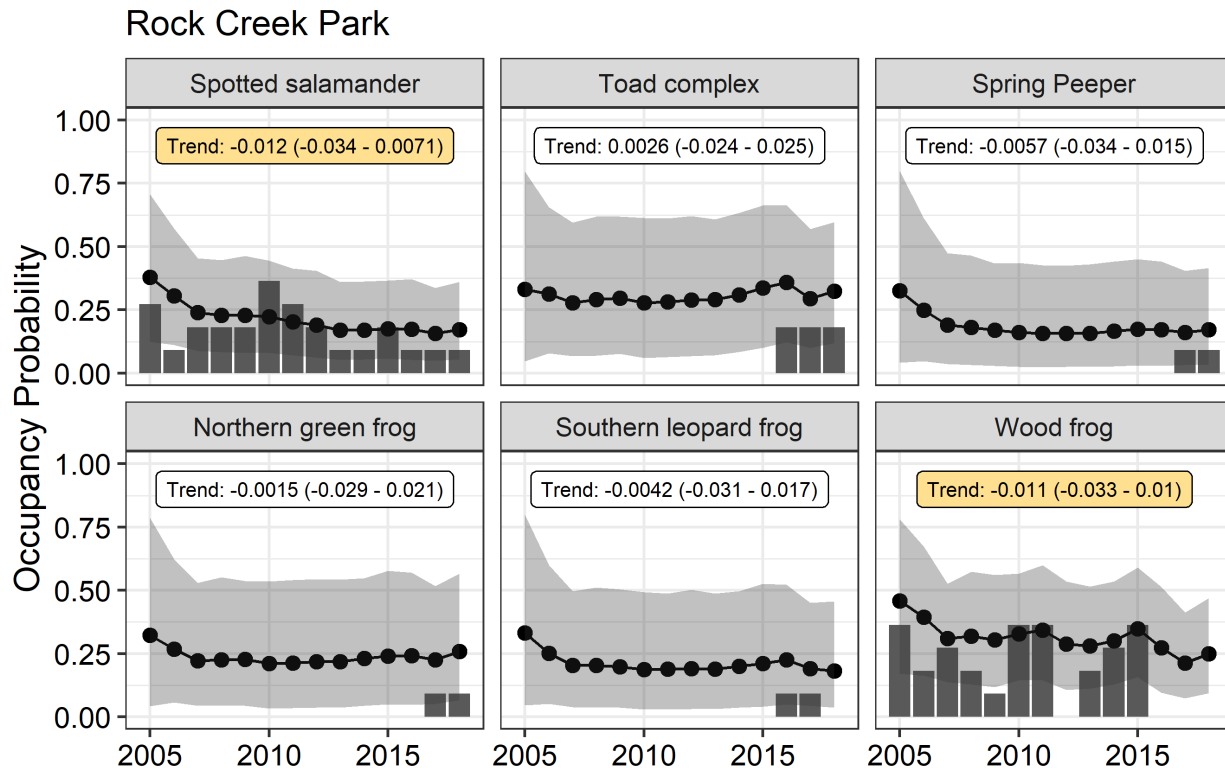


Figure 13. Annual Estimated Occupancy, Raw Occupancy, and Trend Estimates for Each Species Observed in ROCR. Black dots (connected by black lines) indicate mean annual occupancy estimates (the number of sites a species was estimated to be present proportional to the total number of sites available for sampling). Light gray shaded areas indicate 95% credible intervals. Dark gray bars indicate raw occupancy (the number of sites a species was observed given the total number of sites available for sampling). The text box in each panel indicates the population trend estimate (mean and 95% credible interval) and the fill color of the text box indicates the direction of the population trend: blue indicates a positive trend (95% of the posterior mass is greater than zero), white indicates a neutral trend, yellow indicates a slightly negative (75% of the posterior mass is less than zero), and red indicates a negative trend (95% of the posterior mass is less than zero).

Lotic Habitats

We detected 5 species of stream salamanders across all parks: *Desmognathus fuscus*, *Eurycea bislineata*, *Eurycea guttolineata*, *Eurycea longicauda*, and *Pseudotriton ruber*. We did not encounter *E. guttolineata* or *Eurycea longicauda* with enough frequency to include in analyses. Although multiple age classes of each species were available for detection over the course of the study, we combined detections across all age classes for our multi-season analyses to examine species-level differences in occupancy within NCRN parks.

Site covariates collected over the course of the study indicate a few differences among stream sampling sites within NCRN parks. Although some variations were observed among visits, there was little difference in pH among parks overall with mean pH around 6.5 (Figure 14a). Conductivity, however, was high and with large among-site variation within ROCR sites ($286.5 \pm 260.0 \mu\text{S}$) and was lower at CHOH ($144.6 \pm 76.2 \mu\text{S}$) and PRWI ($56.1 \pm 33.9 \mu\text{S}$, Figure 14b). Stream temperatures

tended to be higher at PRWI ($18.8 \pm 1.3^{\circ}\text{C}$) than CHOH ($17.3 \pm 1.3^{\circ}\text{C}$) and ROCR ($17.2 \pm 1.3^{\circ}\text{C}$, Figure 14c). Stream segments at PRWI also were observed dry less often than stream sites at the other two parks (Figure 14d), and had fewer dry segments across all years of sampling (Figure 15).

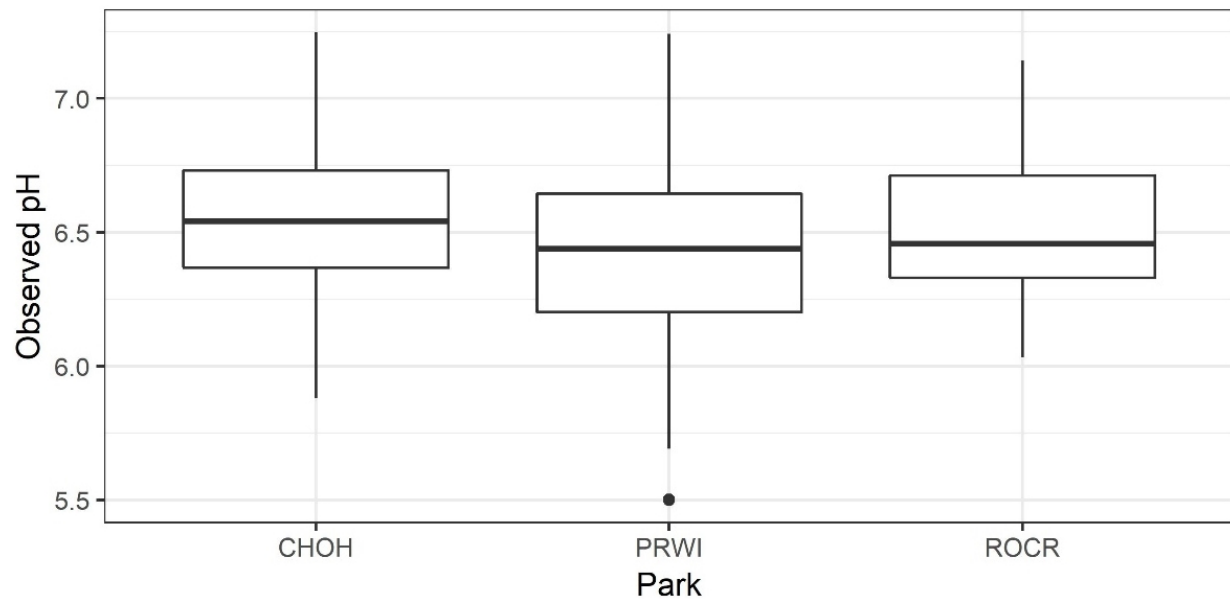


Figure 14a. pH Covariant within Lotic Sampling Sites. The graphs indicate the distribution of pH within the lotic sampling sites at CHOH, PRWI, and ROCR during sampling visits over the course of the study.

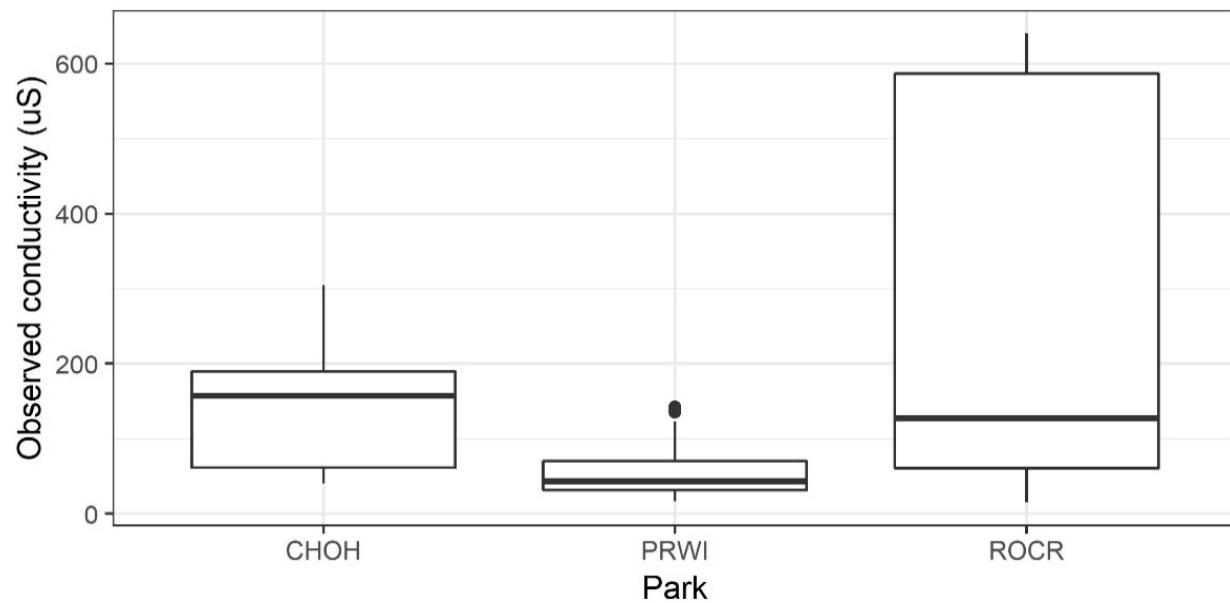


Figure 14b. Observed Conductivity Covariant within Lotic Sampling Sites. The graphs indicate the distribution of observed conductivity within the lotic sampling sites at CHOH, PRWI, and ROCR during sampling visits over the course of the study.

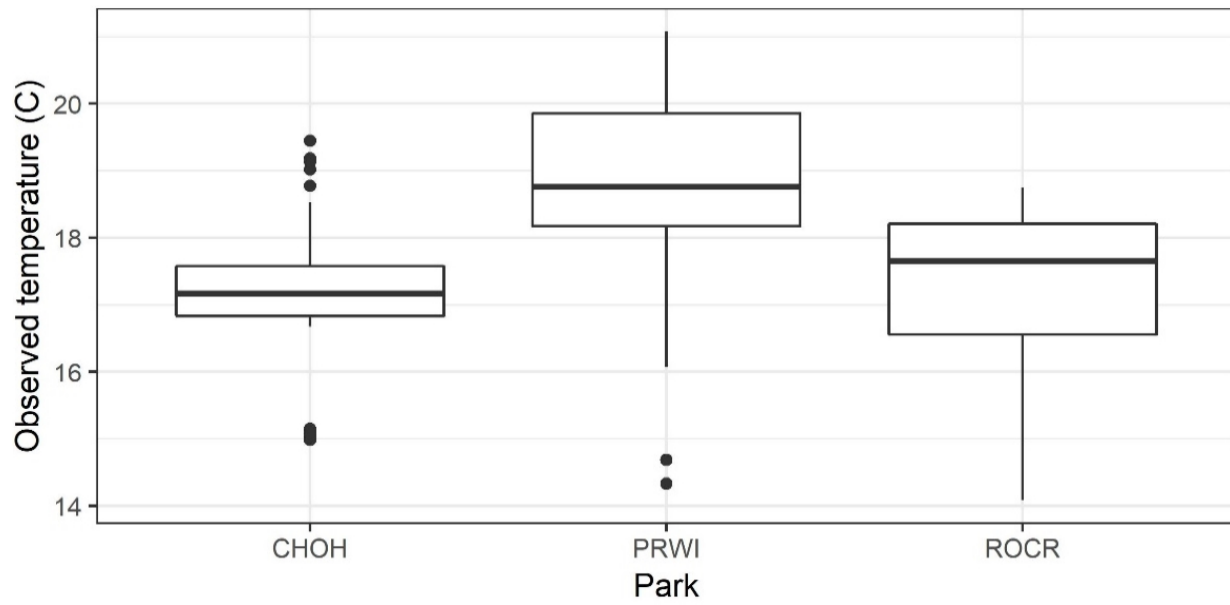


Figure 14c. Observed Temperature Covariant within Lotic Sampling Sites. The graphs indicate the distribution of observed temperature within the lotic sampling sites at CHOH, PRWI, and ROCR during sampling visits over the course of the study.

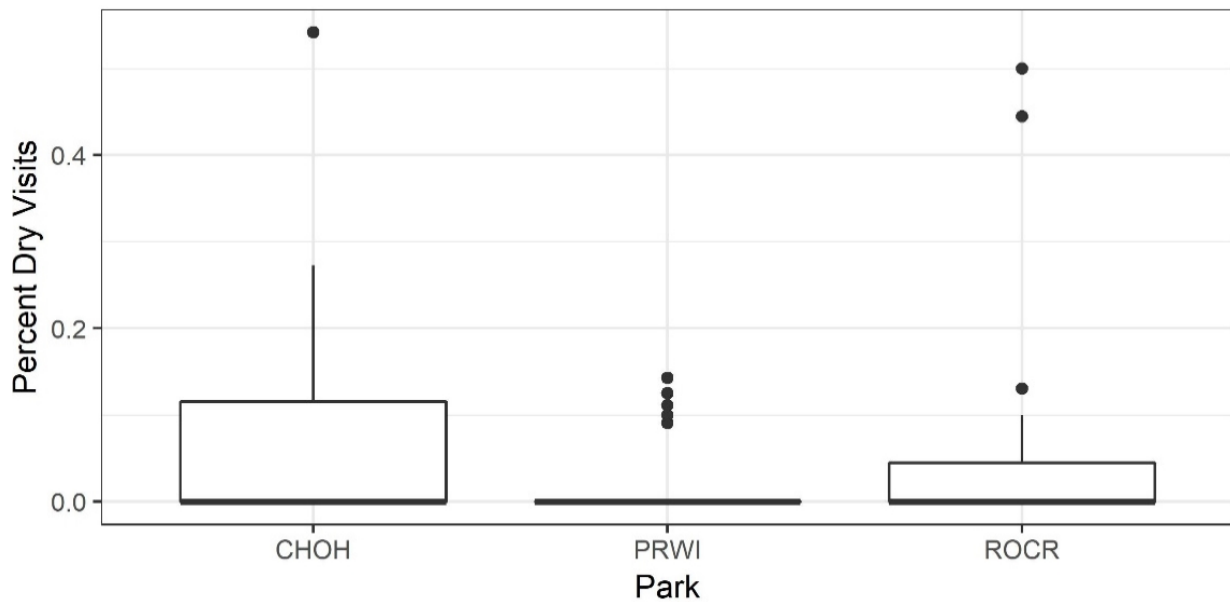


Figure 14d. Percent of Dry Visits Covariant within Lotic Sampling Sites. The graphs indicate the distribution of percent of dry visits within the lotic sampling sites at CHOH, PRWI, and ROCR during sampling visits over the course of the study.

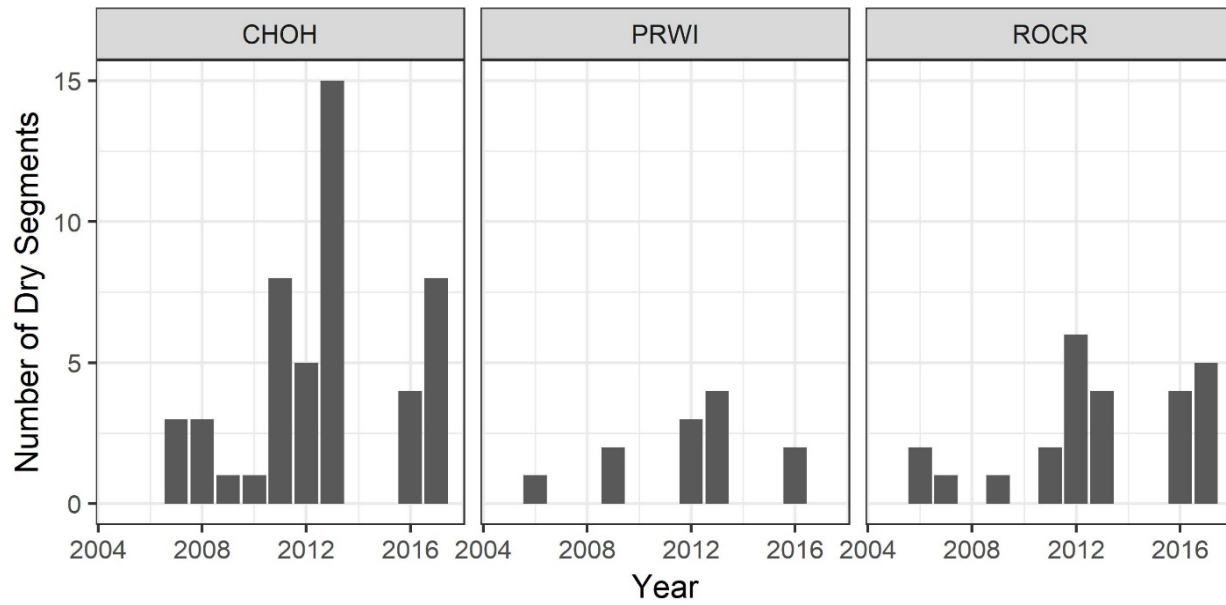


Figure 15. Total Number of Observed Dry Stream Sites within Lotic Sampling Sites. The graphs indicate the total number of observed dry stream sites between the two sampling visits annually from 2005–2017 at CHOH, PRWI, and ROCR. Total number of stream sampling sites at each park are 26, 72, and 19, respectively.

Model selection

The best model for detection of all species included variation among survey events (seasons) as well as between the first sampling pass and the second/third sampling pass. Detection was variable among years, different between the June and July visit, and usually lower on the second and third sampling pass.

The best models (see Appendix Table 1 for model selection table) for *Eurycea bislineata* (EBIS) and *Desmognathus fuscus* (DFUS) included occupancy as a function of park and conductivity, with occupancy increasing as conductivity increased (Figure 16a and 16b). *Pseudotriton ruber* (PRUB) initial occupancy was best modeled by park and transect location, with the upper segments estimated as being occupied while the lower 2 segments were estimated to be unoccupied in any park (Figure 16c).

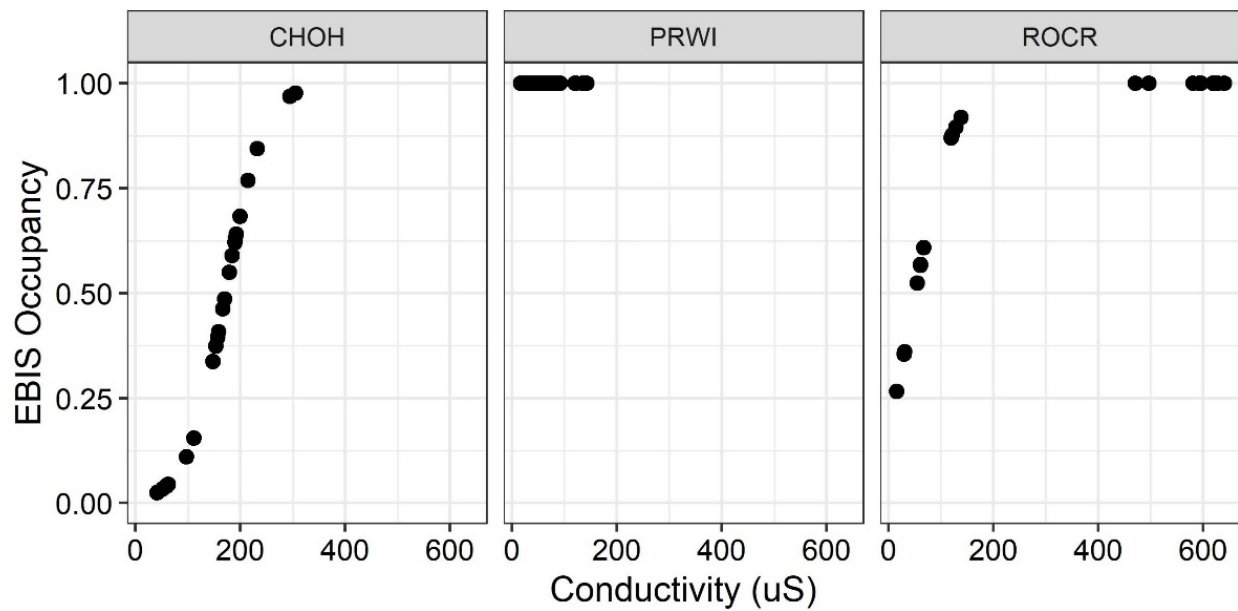


Figure 16a. Initial Occupancy Relationship of *Eurycea bislineata* (EBIS) at Lotic Sampling Sites. The initial occupancy of EBIS as a function of conductivity at CHOH, PRWI, and ROCR parks.

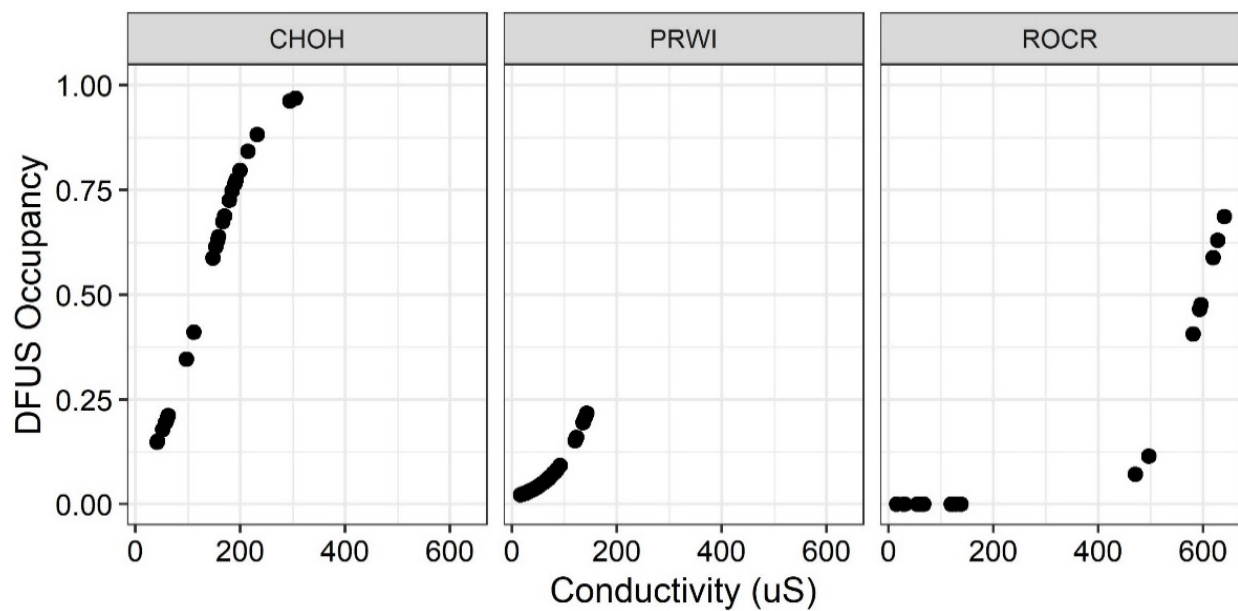


Figure 16b. Initial Occupancy Relationship of *Desmognathus fuscus* (DFUS) at Lotic Sampling Sites. The initial occupancy of DFUS as a function of conductivity at in CHOH, PRWI, and ROCR parks.

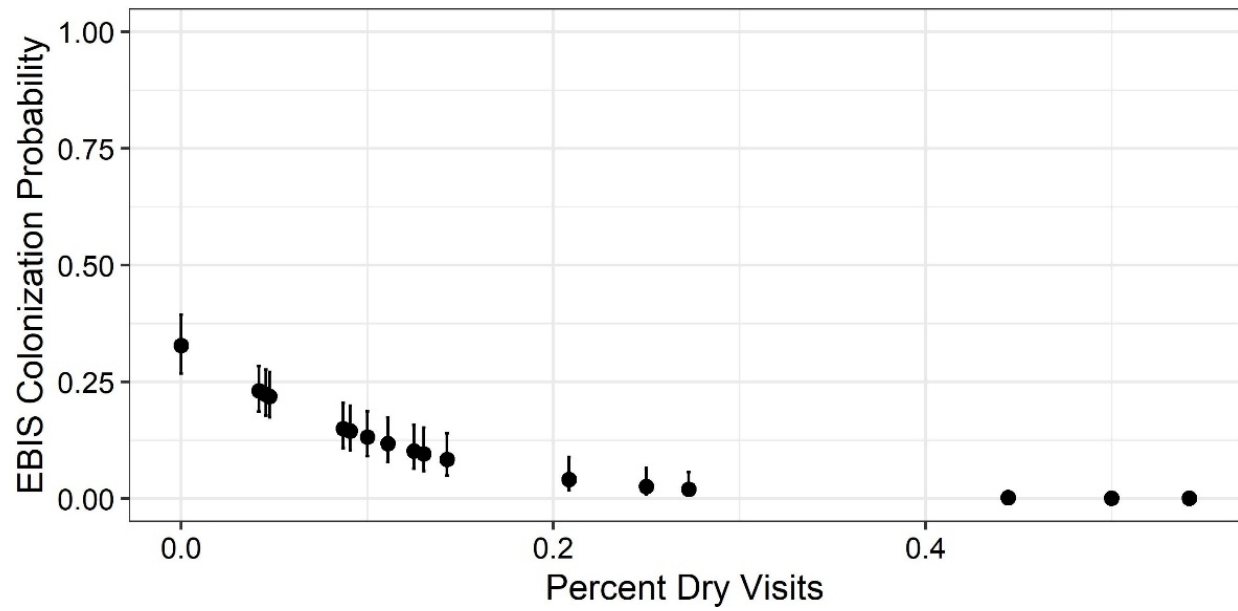


Figure 17a. EBIS Colonization Probability by Percent Dry Visits at Lotic Sampling Sites. Estimates of colonization of *Eurycea bislineata* (EBIS) in streams at estimated colonization probability as a function of percentage of visits where stream segment was dry.

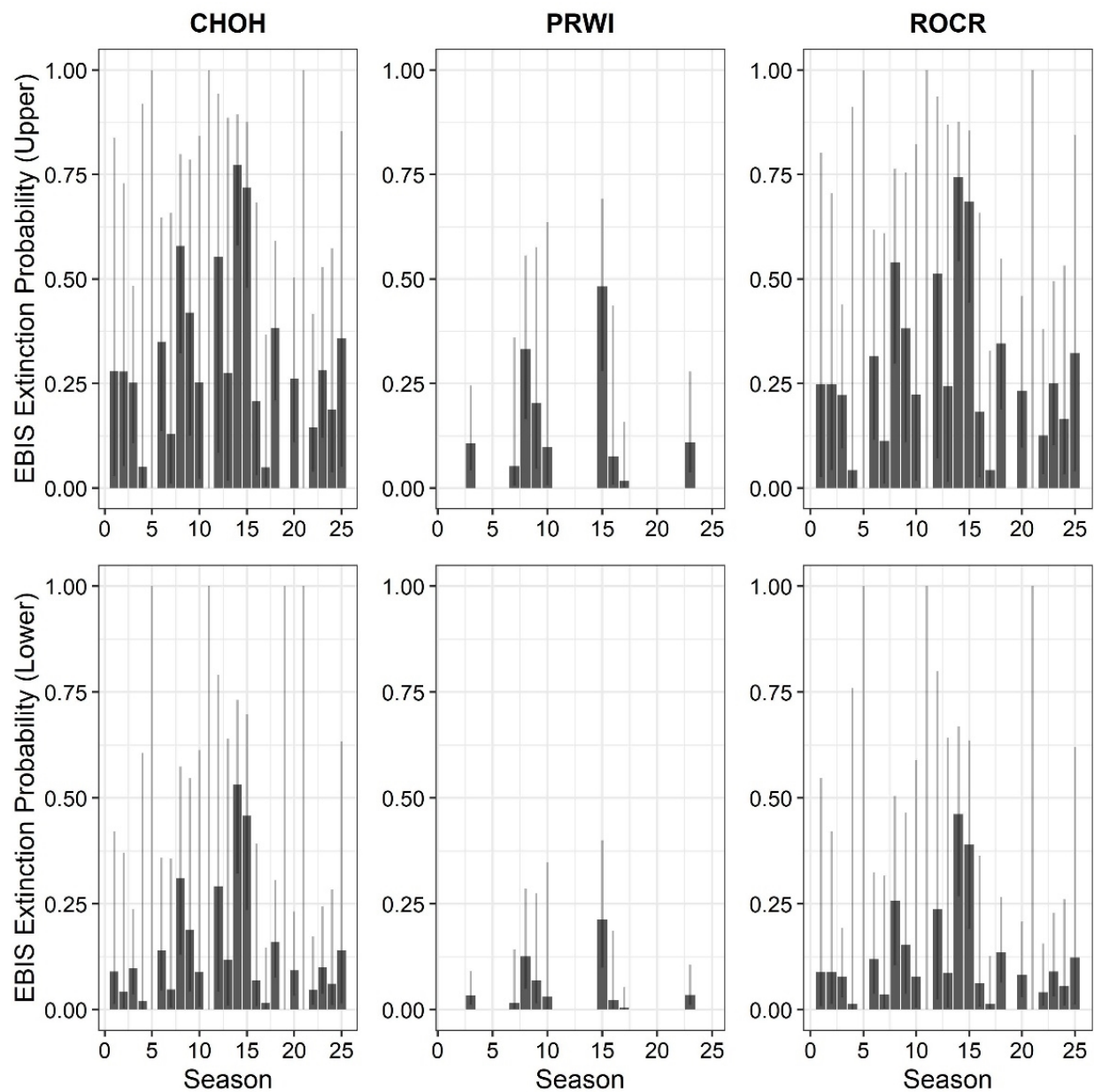


Figure 17b. EBIS Extinction Probability at Lotic Sampling Sites. Estimated extinction of *Eurycea bislineata* (EBIS) probability across 26 seasons and between the upper stream transect locations (top panels) and lower stream transect locations (bottom panels) in CHOH, PRWI, and ROCR.

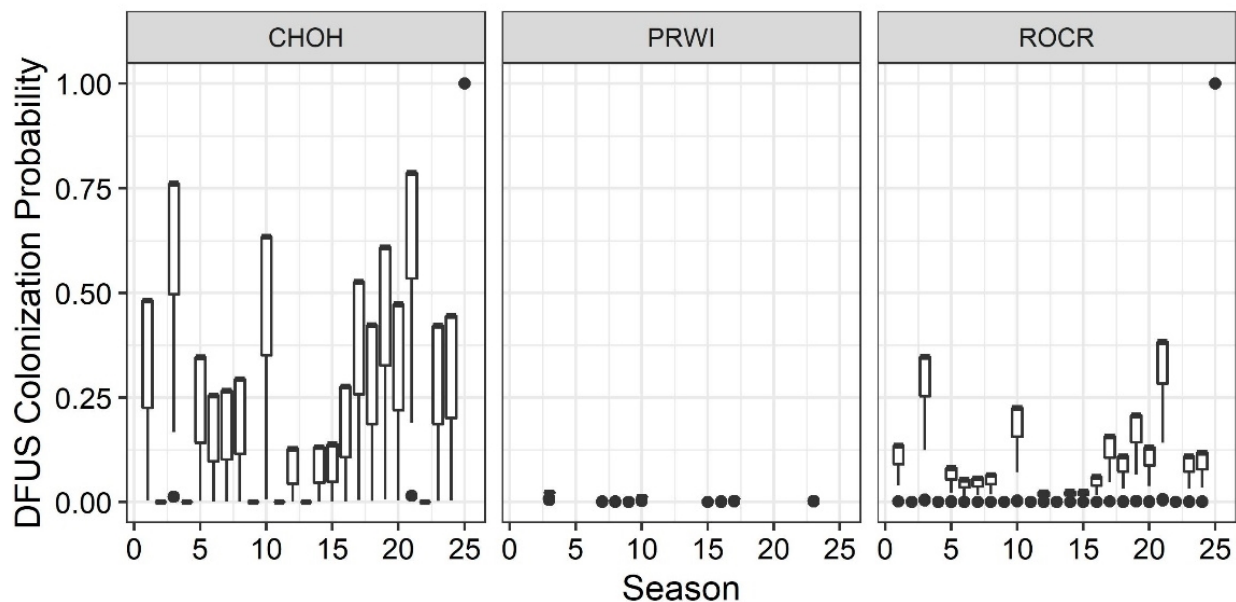


Figure 18a. DFUS Colonization Probability by Season at Lotic Sampling Sites. Estimated colonization probability of *Desmognathus fuscus* (DFUS) as a function of season at CHOH, PRWI, and ROCR. Boxplots represent variation in estimates across observed percent of dry visits in each season.

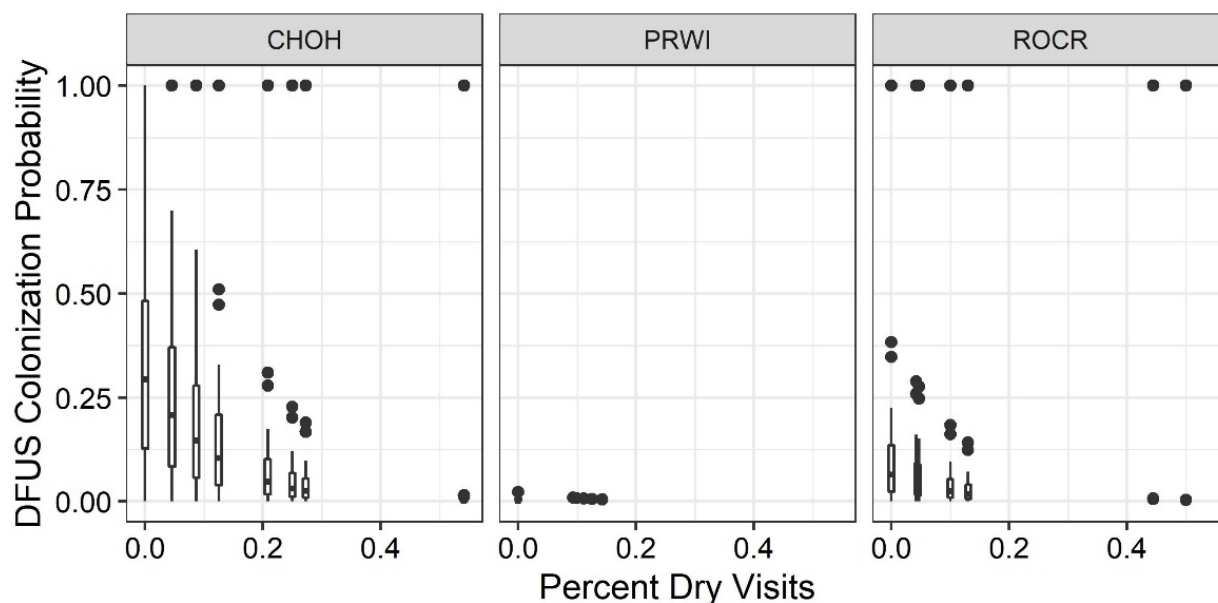


Figure 18b. DFUS Colonization Probability by Percent Dry Visits at Lotic Sampling Sites. Estimated colonization probability of *Desmognathus fuscus* (DFUS) as a function of percentage of visits where stream segment was dry at CHOH, PRWI, and ROCR. Boxplots represent estimates of colonization for each drying frequency value across different seasons of the study.

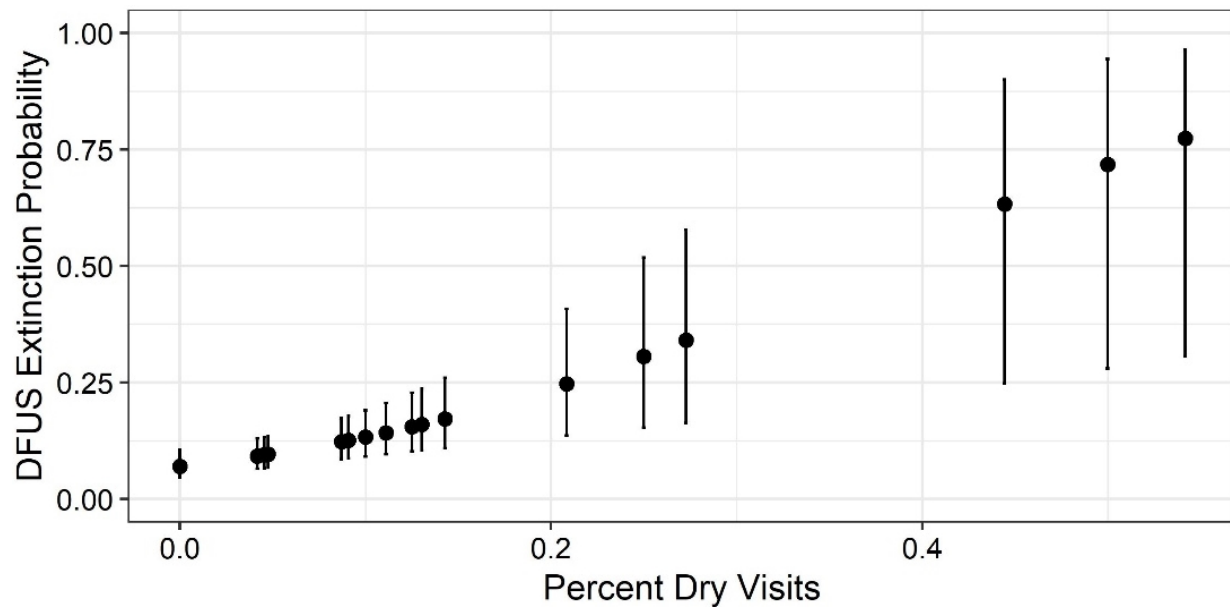


Figure 18c. DFUS Extinction Probability at Lotic Sampling Sites. Estimated extinction probability of *Desmognathus fuscus* (DFUS) as a function of percentage of visits where stream segment was dry.

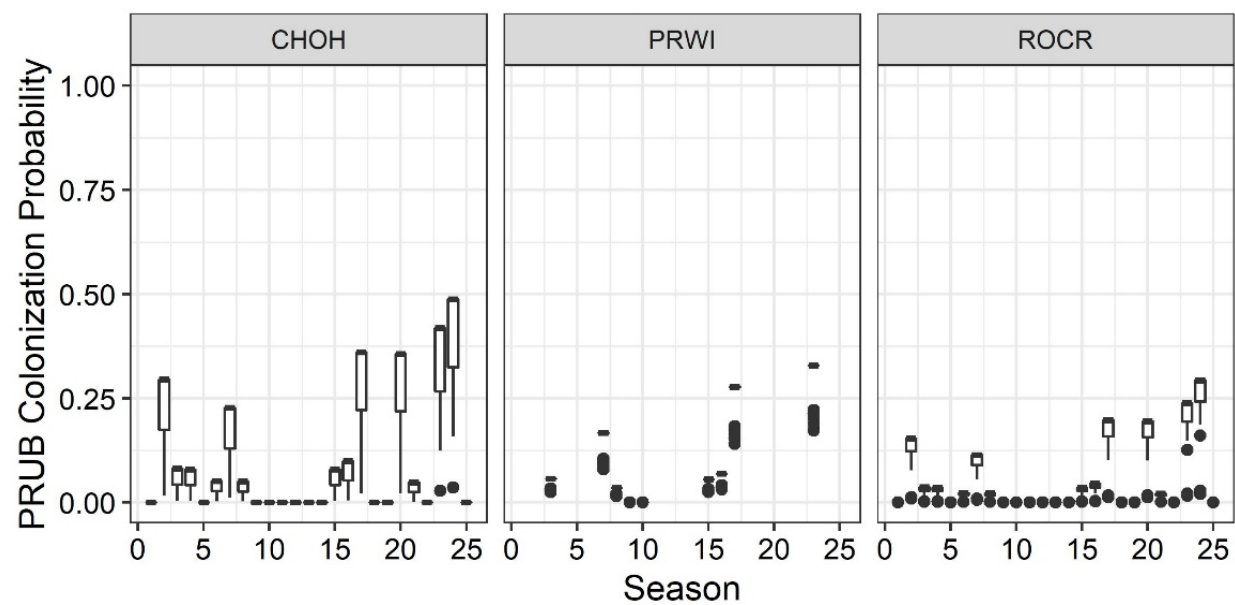


Figure 19a. PRUB Colonization Probability by Season at Lotic Sampling Sites. Estimated colonization probability of *Pseudotriton ruber* (PRUB) as an additive function of season at CHOH, PRWI, and ROCR parks. Boxplots for each season represent variation in estimates with percent of dry visits observed at sites for each park.

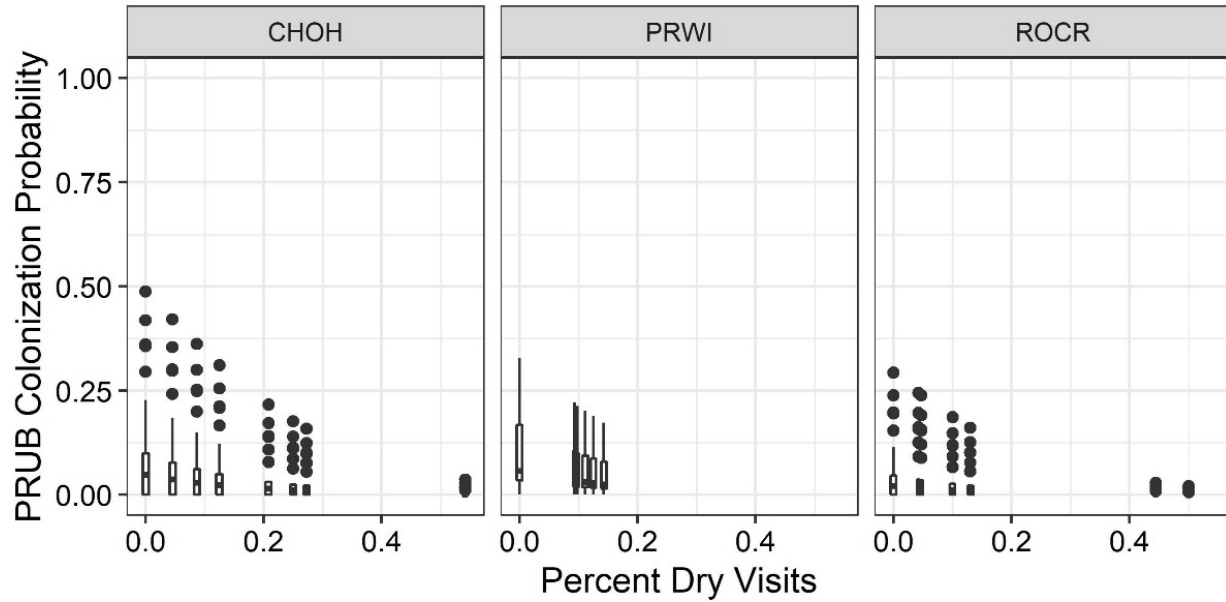


Figure 19b. PRUB Colonization Probability by Percent of Dry Visits at Lotic Sampling Sites. Estimated colonization probability of *Pseudotriton ruber* (PRUB) as an additive function of percent dry visits at CHO, PRWI, and ROCR. Boxplots represent variation in colonization estimates for each value of percent dry visits across all seasons for each park.

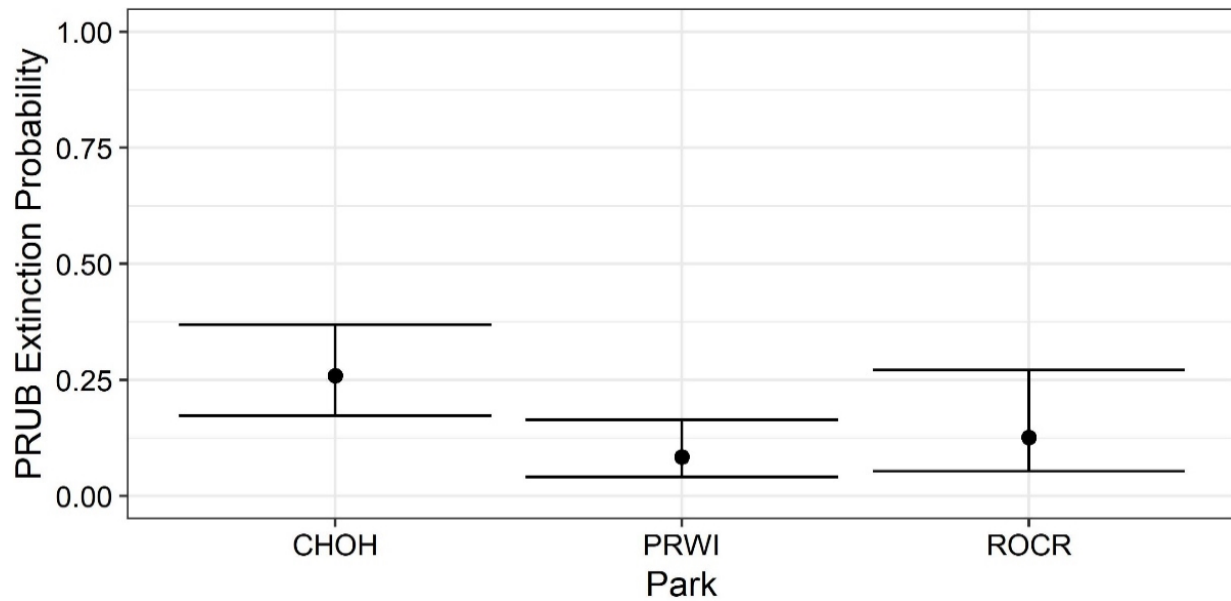


Figure 19c. PRUB Extinction Probability at Lotic Sampling Sites. Estimated extinction probability of *Pseudotriton ruber* (PRUB) was constant across 26 seasons but different at each NCR park.

Annual time-varying occupancy rates of stream salamanders

The dynamic rates were used to calculate the resulting annual occupancy dynamics, which show some variation in occupancy over time, but relatively little change from 2005–2017. Almost all streams in ROCR and PRWI are estimated to be occupied by EBIS, but occupancy at CHOH is only around 0.7 (Figure 20 top panels). In contrast, occupancy of DFUS was highest at CHOH (~0.8), estimated near zero at PRWI, and relatively high at ROCR (~0.7). Occupancy of PRUB was near constant at PRWI, and though occupancy of PRUB at CHOH and ROCR is higher on average, occupancy was more variable across the time series.

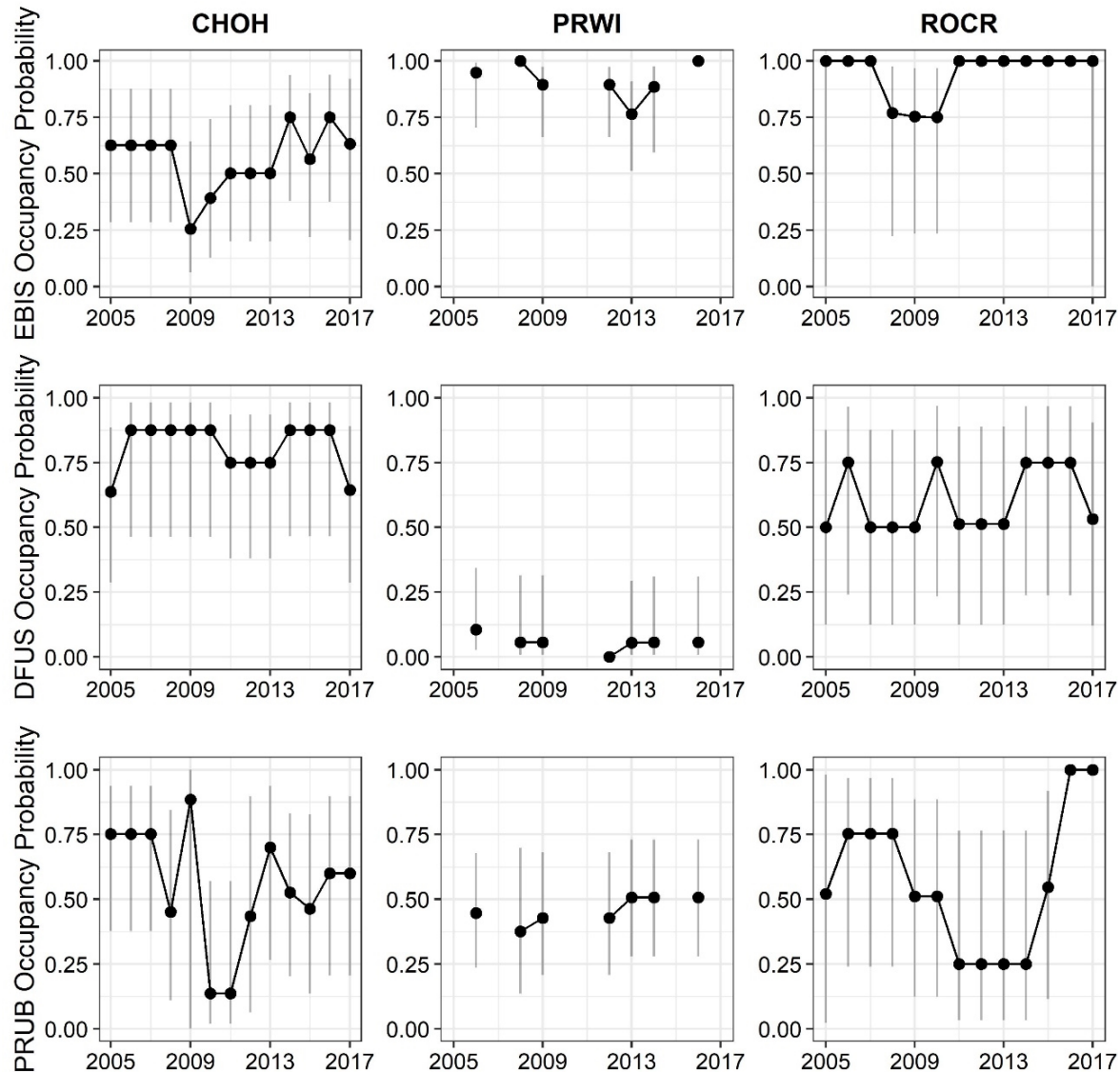


Figure 20. Occupancy Probability Difference of EBIS, DFUS, and PRUB at CHOH, PRWI, and ROCR parks. Occupancy differences (black dots) and 95% credible intervals (gray vertical lines) among parks over time for three salamander species are estimates from a model where all segments on each stream are treated as one site (32 sites) and all visits within calendar year as replicates. Missing estimates at PRWI indicate lack of data in that year. Error for occupancy estimates excluded where inestimable (i.e., when the point estimate was =0 or 1).

Discussion

The monitoring program for the Amphibian Vital Sign of the National Capital Region NPS I&M network focuses on the occupancy trends and dynamics of wetland and stream-associated amphibians. Our monitoring program found variation among species and parks in occupancy trends and dynamics. We expect some species to be more dynamic in their patterns of occupancy because of the competition-colonization tradeoff (Richter-Boix et al. 2007). For example, American toads may be inferior larval competitors (Petranka et al. 2019) and thus may undergo more frequent local extinctions, especially when competitors persist at a site. Other species [i.e., all the stream salamanders; (Green 2003)] are expected to have lower inherent variation in population abundances through time, and may be more persistent in the face of some environmental changes. Overall, wetland-breeding amphibian populations are in decline in parks across the NCRN, though the dynamics revealed through the longer time series at CHOH suggest that more years of data are necessary to confirm this trend. We found evidence for declining trends for 31 of 94 wetland breeding amphibian populations (unique species-park combinations)—but note that some of these declines may not be ‘real,’ i.e., additional years of data will help to identify the true declining trends from those that are an artifact of low sample size. Note that the declines in parks who began sampling later than 2015 match the pattern at CHOH for that time period. For example, current species richness at CHOH and ROCR is lower than when the monitoring program was initiated. Caution should be taken when interpreting the trend results for HAFE, NACE, and PRWI, as each park has only two years of data collected through 2018 (the temporal extent of this analysis). Additionally, a neutral trend does not indicate necessarily that populations are stable, but that additional data may be necessary to make robust inference to the true trend (particularly given that all parks except CHOH have less than 5 years of data on the full amphibian community). Besides the inability to estimate population dynamics precisely with only a few years of data, when occupancy estimates are low, there aren’t sufficient data to estimate precisely persistence probabilities, and when occupancy estimates are high, it is difficult to estimate colonization rates (Martin et al. 2009). For long-lived species, such as many amphibians, changes in wetland occupancy patterns may take many years. For parks with few years of data, we are still able to estimate a trend in occupancy; this trend should be treated with caution. In parks with few years of data, the trend is driven mainly by the network-level data, as our hierarchical model ‘shares’ information among sites to improve estimates at the network-scale.

In contrast, stream salamander occupancy appears to be relatively stable; fluctuations in occupancy may result from availability of surface water, as stream segments were dry in some survey years. Salamanders are not available for detection but may be present belowground where the water table is maintained in the hyporheic zone. This matches expectations for stream salamanders (Green 2003). The state variable that is the focus of this monitoring program, site-occupancy, is more important as a metric for quantifying status (Green 1997), but may be less sensitive to change and environmental drivers. For example, we found that the population of northern dusky salamanders may be declining in abundance at CHOH, even as occupancy remains relatively stable (Zipkin et al. 2014). The environmental conditions in the years of that study (2005–2012) had below-average precipitation,

which may have led to reduced larval and juvenile survival and recruitment, or increased temporary emigration belowground (which would show up in the analysis as reduced survival).

Globally, there are no consistent drivers of amphibian population dynamics; local factors likely influence the effect of regional and global drivers (Miller et al. 2018; Grant et al. 2016). Disease, in particular, has been cited as a prominent driver of amphibian decline; in the NCRN it may be important to some species (e.g., ranavirus to wood frogs; (Earl and Gray 2014), and though some species may be susceptible to the chytrid fungus *Batrachochytrium dendrobatidis* (Gahl et al. 2011), it does not appear to be a principle driver at this time (Grant et al. 2008). The potential introduction of the newly described salamander chytrid fungus (*Batrachochytrium salamandrivorans*) is a concern for species in the network, especially the eastern red-spotted newt, which is highly susceptible to the fungus (Martel et al. 2014). It has yet to be detected in the United States, though the mid-Atlantic is at high risk for introduction and establishment of the pathogen (Richgels et al. 2016). Other factors are hypothesized to be important; amphibian population dynamics may be driven by changes in mean hydroperiod (Blaustein et al. 2001), winter conditions (O'Connor and Rittenhouse 2015), water quality (Houlahan and Findlay 2003), and upland habitat suitability (Jones et al. 2018; Houlahan and Findlay 2003), among other factors. For the community of wetland and stream-breeding species, factors promoting occupancy and persistence included sites that are large, well-connected to other breeding habitats, in forests, and with low conductivity. We found among-park differences in baseline occupancy and occupancy dynamics. However, all of the NCR parks are more forested and have a larger number of breeding habitats than the landscape surrounding the parks, and we expect them to function as refugia for species that could not persist outside of these protected areas.

We identified factors driving species occurrence at the park and wetland scale. Landscape setting is important to amphibian populations in the NCR. We found that more connected and larger parks had higher park-level amphibian richness, though greater forested area of a park was not strongly related to species richness (Wright et al. 2020). The amount and variation in habitat conditions within each park may also be important to species richness, as the diversity of amphibian life histories in the NCR means that high number of habitats, and differences in habitat factors (e.g., temperature, pH, hydroperiod) results in different species occupancy and persistence. For lentic-associated species, among-species differences are likely related to differential sensitivity to habitat and environmental covariates.

An early analysis of stream salamander occurrence data in conjunction with water quality variables indicated that stream water temperature limits stream salamander occupancy in NCRN parks and increases in stream temperature would likely affect some species but not others (Grant et al. 2013). After additional years of data, we now find conductivity to be more important for occupancy, but both conductivity and temperature are expected to covary with urbanization, which is a major potential threat to NCRN amphibian populations, given the small size and fragmented nature of parks in the region. It was surprising that the top model indicated a positive effect of conductivity for EBIS and DFUS, but the observed conductivity at many of our sites may be below levels that would negatively affect occupancy of these species (Barrett et al. 2010). Combined with results from

analyses presented here, NCR decision makers have information on what limits occupancy in NCR stream salamander species that can be used to direct management to achieve management objectives.

Ensuring the monitoring program can meet stated objectives

Since the program began, the Northeast Amphibian Research and Monitoring Initiative (NEARMI) has been committed to not only providing trends and the current understanding of the system, but also evaluating the ability of monitoring designs to robustly estimate trends of interest to resource managers. We evaluated the lentic monitoring design after the first three years (Mattfeldt et al. 2009) and detailed the habitat factors expected to be important to understanding wetland species occurrence at a given site for the expanded monitoring program. Although species composition varies widely among years at a single wetland, occurrence generally is consistent at the park-scale. For wetland species, we found that more than 5 years of data would be required to determine what influences dynamics at a wetland. Current work is underway to evaluate different monitoring program designs that may balance precision in estimates at the network and individual park levels, which may help to inform predictive models of management strategies which may be undertaken to improve the amphibian Vital Sign.

For stream species, we determined that species were not affected by the proximity to the park boundary or roads as expected, and that more than 5 years of data will be needed to estimate what influences presence/absence of stream salamanders (Mattfeldt et al. 2008). As a follow up, in 2010–2011, NCRN funded additional surveys to evaluate the stream monitoring program and its ability to detect declines. Brand and Grant (2017) describe the sampling conducted in three complete stream networks, which provided data to evaluate how the location of monitoring sites and different sampling designs to detect simulated declines. Although the current design will suffice for detecting declines in occurrence over a five-year timeframe, it is not sufficient for concurrently estimating dynamics (colonization/extinction) that may inform the mechanism behind changes in occupancy or offer an understanding of the factors driving population dynamics. The stream monitoring program may be revised in consultation with NPS to better inform management decisions for stream-associated salamanders.

Informing resource management

One of the goals of the NCRN amphibian monitoring program was to inform management decisions for amphibians and other management priorities at the park and network-level. Accordingly, the monitoring program has been used to make inferences specifically for resource managers to guide decision-making in a timely fashion. In a formal context, structured decision-making workshops were held in collaboration with CHOH resource managers to examine management solutions to the expected effects of climate change on wetland amphibian communities in the park (Grant et al. 2013). Grant et al. found that the optimal strategy was to increase the hydroperiod of a set of temporary wetlands; if management was delayed, an increasing fraction of wetlands required management to meet the objectives (Grant et al. 2013). Despite the uncertainty, a focus on short-term management solutions under an adaptive management framework may be more advantageous than inaction. The NCRN amphibian monitoring program has contributed not only to the state of

knowledge on amphibians in the NCRN, but also to the broader understanding of multiple issues and to the variety of scientific techniques available.

Further, detailed models, including those illustrated in this report, can now be used to make predictions about network-level management strategies—an important element in decision-making. Through a structured decision-making approach similar to that used in CHOH (Grant et al. 2013), USGS scientists, the NCRN staff, and park resource managers can develop the necessary components (i.e., objectives, legal constraints, potential actions, tradeoffs) for a conservation management plan for amphibians in the NCRN parks. We can subsequently use these predictive models that incorporate the network- and park-specific management objectives, the impact and uncertainty of important local and regional threats to amphibians, and existing monitoring data describing the current status, trend, and drivers of amphibian populations. This process can evaluate the trade-offs of various proposed management actions to develop an optimal network-level management strategy to maintain amphibian populations in the region, emphasizing strategies to reduce exposure to emerging and present threats. We expect to demonstrate the integration of a large-scale monitoring program with regional-level management objectives, and can provide guidance to managers who desire to protect amphibians in a region experiencing rapid climate change and effects of urbanization.

Management Implications

Of the habitat variables that drive occupancy dynamics of wetland-associated species, hydroperiod (the length in which wetlands hold water) has one of the largest effects and has been considered elsewhere as among the most feasible habitat attributes to manage in NCR parks for amphibians (e.g., Grant et al. 2013). Further, the length of a wetland's hydroperiod is mediated by climate and land use processes, and thus vulnerable to any further urbanization and climate change in the region. Longer and hotter summers, as predicted for this region of the United States (USGCRP 2018), may increase growing-season evapotranspiration, the variability of precipitation patterns, and drought frequency (Hayhoe et al. 2007). These impacts will further affect the hydroperiod wetlands during the amphibian breeding season, reducing available habitat and potentially exacerbating declines. Stream-associated species may also be sensitive to changes in water availability, driven by both climate and landscape change. We find that the upper reaches are more likely to be occupied and may be more sensitive to drought, which we found drives the local extinction of some species of stream salamander.

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Appendix A: Lotic Models

Combined Akaike Information Criterion (AIC) tables from Lotic Models for *Eurycea bislineata* (EBIS), *Desmognathus fuscus* (DFUS), and *Pseudotriton ruber* (PRUB). Covariates for each site include park (P), season (SE), sampling pass (Pass, 1 vs 2/3), Pdry (percent of visits site was observed dry), average pH (pH), average conductivity (cond), transect location (headwaters vs downstream, Sloc).

***Eurycea bislineata* (EBIS)**

Table A-1. *Eurycea bislineata* (EBIS).

EBIS Model	AIC	neg2ll	npar	DAIC	modlike	wgt
psi(P+cond)p(SE+Pass)gamma(SE+P)epsilon(SE+P)	2582.838	2412.838	85	0	1	0.9818
psi(P+temp)p(SE+Pass)gamma(SE+P)epsilon(SE+P)	2590.993	2420.993	85	8.1549	0.017	0.0166
psi(P+Sloc)p(SE+Pass)gamma(SE+P)epsilon(SE+P)	2596.041	2426.041	85	13.2034	0.0014	0.0013
psi(P+PDry)p(SE+Pass)gamma(SE+P)epsilon(SE+P)	2600.145	2430.145	85	17.3066	2.00E-04	2.00E-04
psi(P)p(SE+Pass)gamma(SE+P)epsilon(SE+P)	2602.846	2434.846	84	20.0083	0	0
psi(P+pH)p(SE+Pass)gamma(SE+P)epsilon(SE+P)	2603.793	2433.793	85	20.9547	0	0
psi()p(SE+Pass)gamma(SE+P)epsilon(SE+P)	2611.338	2447.338	82	28.4998	0	0
psi(P+cond)p(SE+Pass)gamma(PDry)epsilon(SE+P+Sloc)	4285.357	4163.357	61	1702.519	0	0
psi(P+cond)p(SE+Pass)gamma(PDry)epsilon(SE+P)	4307.891	4187.891	60	1725.054	0	0
psi(P+cond)p(SE+Pass)gamma(PDry)epsilon(SE+P)	4307.891	4187.891	60	1725.054	0	0
psi(P+cond)p(SE+Pass)gamma(PDry)epsilon(SE+P+PDry)	4309.651	4187.651	61	1726.813	0	0
psi(P+cond)p(SE+Pass)gamma(SE+P+PDry)epsilon(SE+P)	4310.593	4138.593	86	1727.755	0	0
psi(P+cond)p(SE+Pass)gamma(PDry)epsilon(SE)	4312.473	4196.473	58	1729.635	0	0
psi(P+cond)p(SE+Pass)gamma(PDry)epsilon(Sloc)	4313.419	4243.419	35	1730.581	0	0
psi(P+cond)p(SE+Pass)gamma(PDry)epsilon(SE X ROCR+PRWI)	4332.165	4164.165	84	1749.327	0	0
psi(P+cond)p(SE+Pass)gamma(PDry)epsilon()	4340.124	4272.124	34	1757.286	0	0
psi(P+cond)p(SE+Pass)gamma(PDry)epsilon(PDry)	4342.123	4272.123	35	1759.285	0	0
psi(P+cond)p(SE+Pass)gamma(PDry)epsilon(P)	4343.045	4271.045	36	1760.207	0	0
psi(P+cond)p(SE+Pass)gamma(SE+P+Sloc)epsilon(SE+P)	4346.152	4174.152	86	1763.314	0	0
psi(P+cond)p(SE+Pass)gamma(P)epsilon(SE+P)	4349.385	4227.385	61	1766.547	0	0
psi(P+cond)p(SE+Pass)gamma(Sloc)epsilon(SE+P)	4354.214	4234.214	60	1771.376	0	0
psi(P+cond)p(SE+Pass)gamma(SE+P)epsilon(SE+P)	4363.437	4193.437	85	1780.599	0	0
psi(P+cond)p(SE+Pass)gamma()epsilon(SE+P)	4368.708	4250.708	59	1785.87	0	0
psi(P+cond)p(SE+Pass)gamma(SE)epsilon(SE+P)	4371.001	4205.001	83	1788.163	0	0

Table A-1 (continued). *Eurycea bislineata* (EBIS).

EBIS Model	AIC	neg2ll	npar	DAIC	modlike	wgt
psi(P+Sloc)p(SE+Pass)gamma(SE+P)epsilon(SE+P)	4371.377	4201.377	85	1788.539	0	0
psi(P+Sloc)p(SE+Pass+Month)gamma(SE+P)epsilon(SE+P)	4373.377	4201.377	86	1790.539	0	0
psi(P+cond)p(SE+Pass)gamma(SE X ROCR+PRWI)epsilon(SE+P)	4379.955	4161.955	109	1797.117	0	0
psi(P+Sloc)p(Pass+Loc+Month)gamma(SE+P)epsilon(SE+P)	4701.983	4577.983	62	2119.145	0	0
psi(P+Sloc)p(Pass+Loc)gamma(SE+P)epsilon(SE+P)	4704.538	4582.538	61	2121.7	0	0
psi(P+Sloc)p(Pass+Month)gamma(SE+P)epsilon(SE+P)	4708.759	4586.759	61	2125.922	0	0
psi(P+Sloc)p(Pass)gamma(SE+P)epsilon(SE+P)	4711.28	4591.28	60	2128.442	0	0

***Desmognathus fuscus* (DFUS)**

Table A-2. *Desmognathus fuscus* (DFUS).

DFUS Model	AIC	neg2ll	npar	DAIC	modlike	wgt
psi(P+cond)p(SE+Pass)gamma(SE+P+PDry)epsilon(PDry)	2532.078	2410.078	61	0	1	0.9381
psi(P+cond)p(SE+Pass)gamma(SE+P+PDry)epsilon()	2538.975	2418.975	60	6.8975	0.0318	0.0298
psi(P+cond)p(SE+Pass)gamma(SE+P+PDry)epsilon(Sloc)	2539.337	2417.337	61	7.2599	0.0265	0.0249
psi(P+cond)p(SE+Pass)gamma(SE+P+PDry)epsilon(P)	2542.91	2418.91	62	10.8321	0.0044	0.0042
psi(P+cond)p(SE+Pass)gamma(SE+P+PDry)epsilon(SE+P+PDry)	2543.605	2369.605	87	11.527	0.0031	0.0029
psi(P+cond)p(SE+Pass)gamma(SE+P+PDry)epsilon(SE)	2552.626	2384.626	84	20.548	0	0
psi(P+cond)p(SE+Pass)gamma(SE+P+PDry)epsilon(SE+P)	2557.904	2385.904	86	25.8264	0	0
psi(P+cond)p(SE+Pass)gamma(SE+P+PDry)epsilon(SE+P)	2557.904	2385.904	86	25.8264	0	0
psi(P+cond)p(SE+Pass)gamma(SE+P+PDry)epsilon(SE+P+Sloc)	2557.91	2383.91	87	25.8322	0	0
psi(P+cond)p(SE+Pass)gamma(P)epsilon(SE+P)	2573.752	2451.752	61	41.6741	0	0
psi(P+cond)p(SE+Pass)gamma(SE+P+Sloc)epsilon(SE+P)	2581.411	2409.411	86	49.333	0	0
psi(P+cond)p(SE+Pass)gamma(SE+P)epsilon(SE+P)	2582.838	2412.838	85	50.7604	0	0
psi(P+cond)p(SE+Pass)gamma(SE+P)epsilon(SE+P)	2582.838	2412.838	85	50.7604	0	0
psi(P+cond)p(SE+Pass)gamma(SE+P+PDry)epsilon(SE X P)	2586.289	2366.289	110	54.2112	0	0
psi(P+temp)p(SE+Pass)gamma(SE+P)epsilon(SE+P)	2590.993	2420.993	85	58.9153	0	0
psi(P+cond)p(SE+Pass)gamma(Sloc)epsilon(SE+P)	2594.433	2474.433	60	62.3554	0	0
psi(P+cond)p(SE+Pass)gamma()epsilon(SE+P)	2595.322	2477.322	59	63.2441	0	0
psi(P+Sloc)p(SE+Pass)gamma(SE+P)epsilon(SE+P)	2596.041	2426.041	85	63.9638	0	0
psi(P+Sloc)p(SE+Pass)gamma(SE+P)epsilon(SE+P)	2596.041	2426.041	85	63.9638	0	0
psi(P+cond)p(SE+Pass)gamma(PDry)epsilon(SE+P)	2596.158	2476.158	60	64.08	0	0
psi(P+Sloc)p(SE+Pass+Month)gamma(SE+P)epsilon(SE+P)	2596.922	2424.922	86	64.844	0	0
psi(P+PDry)p(SE+Pass)gamma(SE+P)epsilon(SE+P)	2600.145	2430.145	85	68.067	0	0
psi(P)p(SE+Pass)gamma(SE+P)epsilon(SE+P)	2602.846	2434.846	84	70.7687	0	0
psi(P+pH)p(SE+Pass)gamma(SE+P)epsilon(SE+P)	2603.793	2433.793	85	71.7151	0	0

Table A-2 (continued). *Desmognathus fuscus* (DFUS).

DFUS Model	AIC	neg2ll	npar	DAIC	modlike	wgt
psi()p(SE+Pass)gamma(SE+P)epsilon(SE+P)	2611.338	2447.338	82	79.2602	0	0
psi(P+cond)p(SE+Pass)gamma(SE)epsilon(SE+P)	2613.214	2447.214	83	81.1367	0	0
psi(P+cond)p(SE+Pass)gamma(SE X P)epsilon(SE+P)	2617.37	2399.37	109	85.292	0	0
psi(P+Sloc)p(Pass+Loc+Month)gamma(SE+P)epsilon(SE+P)	2712.302	2588.302	62	180.2249	0	0
psi(P+Sloc)p(Pass+Loc)gamma(SE+P)epsilon(SE+P)	2715.012	2593.012	61	182.9346	0	0
psi(P+Sloc)p(Pass)gamma(SE+P)epsilon(SE+P)	2727.197	2607.197	60	195.1195	0	0
psi(P+Sloc)p(Pass+Month)gamma(SE+P)epsilon(SE+P)	2731.484	2609.484	61	199.4066	0	0

***Pseudotriton ruber* (PRUB)**

Table A-3. *Pseudotriton ruber* (PRUB).

PRUB Model	AIC	-2LL	Npar	DAIC	modlike	wgt
psi(P+Sloc)p(SE+Pass)gamma(SE+P+PDry)epsilon(P)	1851.752	1727.752	62	0	1	0.912
psi(P+Sloc)p(SE+Pass)gamma(SE+P+PDry)epsilon()	1857.58	1737.58	60	5.8286	0.0542	0.0495
psi(P+Sloc)p(SE+Pass)gamma(SE+P+PDry)epsilon(PDry)	1859.483	1737.483	61	7.7318	0.0209	0.0191
psi(P+Sloc)p(SE+Pass)gamma(SE+P+PDry)epsilon(Sloc)	1859.51	1737.51	61	7.7581	0.0207	0.0189
psi(P+Sloc)p(SE+Pass)gamma(SE+P+PDry)epsilon(SE+P+PDry)	1868.099	1694.099	87	16.3471	3.00E-04	3.00E-04
psi(P+Sloc)p(SE+Pass)gamma(SE+P+PDry)epsilon(SE+P)	1869.884	1697.884	86	18.1324	1.00E-04	1.00E-04
psi(P+Sloc)p(SE+Pass)gamma(SE+P+PDry)epsilon(SE+P)	1869.884	1697.884	86	18.1324	1.00E-04	1.00E-04
psi(P+Sloc)p(SE+Pass)gamma(SE+P+PDry)epsilon(SE+P+Sloc)	1870.21	1696.21	87	18.4587	1.00E-04	1.00E-04
psi(P+Sloc)p(SE+Pass)gamma(SE+P+Sloc)epsilon(SE+P)	1873.815	1701.815	86	22.0633	0	0
psi(P+Sloc)p(SE+Pass)gamma(PDry)epsilon(SE+P)	1875.357	1755.357	60	23.6058	0	0
psi(P+Sloc)p(SE+Pass)gamma(SE+P)epsilon(SE+P)	1875.54	1705.54	85	23.788	0	0
psi(P+Sloc)p(SE+Pass)gamma(SE+P)epsilon(SE+P)	1875.54	1705.54	85	23.788	0	0
psi(P+Sloc)p(SE+Pass)gamma(SE+P)epsilon(SE+P)	1875.54	1705.54	85	23.788	0	0
psi(P+Sloc)p(SE+Pass+Month)gamma(SE+P)epsilon(SE+P)	1877.429	1705.429	86	25.6776	0	0
psi(P+Sloc)p(SE+Pass)gamma(SE)epsilon(SE+P)	1878.635	1712.635	83	26.8833	0	0
psi(P+pH)p(SE+Pass)gamma(SE+P)epsilon(SE+P)	1879.442	1709.442	85	27.6908	0	0
psi(P+cond)p(SE+Pass)gamma(SE+P)epsilon(SE+P)	1879.96	1709.96	85	28.2079	0	0
psi(P+Sloc)p(SE+Pass)gamma(P)epsilon(SE+P)	1880.255	1758.255	61	28.5029	0	0
psi(P+temp)p(SE+Pass)gamma(SE+P)epsilon(SE+P)	1880.699	1710.699	85	28.9476	0	0
psi())p(SE+Pass)gamma(SE+P)epsilon(SE+P)	1880.809	1716.809	82	29.0571	0	0
psi(P+Sloc)p(SE+Pass)gamma(SE+P+PDry)epsilon(SE)	1881.4	1713.4	84	29.648	0	0
psi(P+PDry)p(SE+Pass)gamma(SE+P)epsilon(SE+P)	1881.556	1711.556	85	29.8045	0	0
psi(P+Sloc)p(SE+Pass)gamma(Sloc)epsilon(SE+P)	1883.099	1763.099	60	31.3469	0	0
psi(P+Sloc)p(SE+Pass)gamma()epsilon(SE+P)	1883.198	1765.198	59	31.4468	0	0

Table A-3 (continued). Pseudotriton ruber (PRUB).

PRUB Model	AIC	-2LL	Npar	DAIC	modlike	wgt
psi(P)p(SE+Pass)gamma(SE+P)epsilon(SE+P)	1884.173	1716.173	84	32.421	0	0
psi(P+Sloc)p(Pass+Month)gamma(SE+P)epsilon(SE+P)	1893.926	1771.926	61	42.1741	0	0
psi(P+Sloc)p(Pass)gamma(SE+P)epsilon(SE+P)	1894.875	1774.875	60	43.1234	0	0
psi(P+Sloc)p(Pass+Loc+Month)gamma(SE+P)epsilon(SE+P)	1895.164	1771.164	62	43.4119	0	0
psi(P+Sloc)p(Pass+Loc)gamma(SE+P)epsilon(SE+P)	1895.73	1773.73	61	43.978	0	0
psi(P+Sloc)p(SE+Pass)gamma(SE+P+PDry)epsilon(SE X P)	1905.158	1685.158	110	53.4068	0	0
psi(P+Sloc)p(SE+Pass)gamma(SE X P)epsilon(SE+P)	1906.845	1688.845	109	55.0931	0	0

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