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Research Paper

Factors driving minimal focal species response to the implementation of habitat guidelines on private lands

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ABSTRACT. Effective conservation of breeding habitat for migratory birds benefits from the development and use of science-based management guidelines. The Cerulean Warbler (*Setophaga cerulea*) is a rapidly declining migratory songbird whose decline is understood to be driven, in large part, by breeding grounds habitat loss. In 2013, science-informed habitat management guidelines were developed that described a series of silvicultural techniques to enhance Cerulean Warbler nesting habitat in the Appalachian Mountains. From 2016–2020, the Natural Resources Conservation Service (NRCS) and several partners implemented these guidelines across more than 3800 ha of privately owned forest. From 2017–2020, we surveyed for Cerulean Warblers and sampled vegetation at 139 locations on private forests enrolled in NRCS programs in Pennsylvania and Maryland. Cerulean Warbler occupancy probability was low ($\Psi = 0.16$) and appeared to decline with increasing distance to the nearest Cerulean Warbler subpopulation (especially beyond 2 km). Even after guideline implementation, only 25% of posttreatment locations we monitored met guideline targets for average tree diameter. The lack of large-diameter trees is characteristic of prior unsustainable harvest practices (e.g., high grading) that commonly occurred on private lands in eastern deciduous forests. Although most opportunities to manage Cerulean Warbler habitat in Appalachia exist on private lands, Cerulean Warbler habitat guidelines were developed from studies conducted on public lands, where a history of sustainable management is more common; this disparity appears to drive drastic differences in how the species responds to conservation on private vs public lands. Future efforts to implement Cerulean Warbler habitat guidelines should prioritize sites that are proximate to existing Cerulean Warbler breeding populations and those where exploitative timber harvests have not recently occurred. Our work also provides a cautionary example of recognizing that habitat recommendations developed on public lands may not yield similar results on comparable private lands, especially if guidelines were not designed with private lands in mind.

Facteurs déterminant la réponse minimale d’espèces focales à la mise en œuvre de lignes directrices concernant l’habitat sur terres privées

RÉSUMÉ. La conservation efficace de l’habitat de nidification d’oiseaux migrateurs bénéficie de l’élaboration et de l’emploi de lignes directrices de gestion fondées sur la science. La Paruline azurée (*Setophaga cerulea*) est un passereau migrateur en rapide diminution, et on attribue cette baisse, en grande partie, à la perte d’habitat de nidification. En 2013, des lignes directrices de gestion de l’habitat fondées sur des données scientifiques ont été élaborées et décrivent une série de techniques sylvicoles visant à améliorer l’habitat de nidification de la Paruline azurée dans les Appalaches. De 2016 à 2020, le Natural Resources Conservation Service (NRCS) et plusieurs partenaires ont mis en œuvre ces lignes directrices sur plus de 3 800 hectares de forêts privées. De 2017 à 2020, nous avons recensé les Parulines azurées et échantillonné la végétation à 139 sites dans des forêts privées inscrites aux programmes du NRCS en Pennsylvanie et au Maryland. La probabilité d’occupation de la Paruline azurée était faible ($\Psi = 0{,}16$) et semblait diminuer avec l’augmentation de la distance à la sous-population la plus proche (en particulier au-delà de 2 km). Même après la mise en œuvre des lignes directrices, seuls 25 % des sites post-traitement que nous avons contrôlés ont atteint les cibles prescrites pour le diamètre moyen des arbres. L’absence d’arbres de grand diamètre est caractéristique de pratiques antérieures d’exploitation non durable (par exemple, l’écrémage) qui avaient cours couramment sur les terres privées dans les forêts caducifoliées de l’Est. Bien que la plupart des occasions de gestion de l’habitat de la Paruline azurée dans les Appalaches se trouvent sur des terres privées, les lignes directrices relatives à l’habitat ont été élaborées à partir d’études menées sur des terres publiques, où les antécédents de gestion durable sont plus courants; cette disparité semble être à l’origine des différences radicales dans la manière dont l’espèce réagit à la conservation sur terres privées par rapport à celle sur terres publiques. Les futurs efforts de mise en œuvre des lignes directrices relatives à l’habitat de la Paruline azurée devraient prioriser les sites proches de populations nicheuses existantes de l’espèce et ceux où il n’y a pas eu de récolte de bois commerciale récemment. La présente étude fournit également un exemple de prudence en reconnaissant que les recommandations en matière d’habitat élaborées sur des terres publiques peuvent ne pas donner de résultats similaires sur des terres privées comparables, en particulier si les lignes directrices n’ont pas été conçues en tenant compte des terres privées.

Key Words: *forestry; habitat; migratory birds; nesting habitat; shelterwood; timber harvest*

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INTRODUCTION

Over the past half-century, migratory birds that breed in deciduous forests of eastern North America are increasingly in crisis (Rosenberg et al. 2019). Widespread declines across many avian species appear to be driven by a wide suite of factors, including loss/degradation of their habitats (breeding/wintering grounds, migration routes, etc.; La Sorte et al. 2017), climate change (Matthews et al. 2011), invasive species (Catling 2005), and many other threats (Loss et al. 2015). As a result, many forest-dependent bird species that were once common have become rare and, in some cases, patchily distributed (Rosenberg et al. 2016, Sauer et al. 2020). For species limited by the availability/quality of breeding habitat, restoring/enhancing forests represents one of the most straightforward ways that land managers can benefit affected species (King and Schlossberg 2014). For example, the Kirtland's Warbler (*Setophaga kirtlandii*) is a Nearctic-Neotropical migratory songbird that winters in the Bahamas and breeds in early successional jack pine (*Pinus banksiana*) in northern Michigan (Bocetti et al. 2020). Although a lack of fire-maintained young pine habitat landed this warbler on the Endangered Species List, intensive management of breeding sites has allowed the species to rebound such that it is no longer listed (Bocetti et al. 2012). Similar successes have been reported in several waterfowl species, which have recovered in many regions because of wetland restoration efforts (Baldassarre and Bolen 2006).

Effective conservation of breeding sites for Nearctic-Neotropical migratory birds benefits from science-based guidelines detailing strategies for habitat management (hereafter, habitat management guidelines; Bottrill et al. 2011). Habitat management guidelines are usually publications generated through the coalescence of extensive peer-reviewed bodies of literature, sometimes also accompanied by the addition of novel datasets (e.g., Brudvig et al. 2017). For example, the Golden-winged Warbler (*Vermivora chrysoptera*) is a declining Nearctic-Neotropical migratory songbird threatened by the degradation of early successional nesting habitat via disturbance suppression (Confer et al. 2020). Informed by monitoring data collected largely on public lands, a set of habitat management guidelines were drafted (Bakermans et al. 2011, Roth et al. 2019) that described how to restore habitat using practices like shrub management, prescribed fire, prescribed grazing, and overstory removal timber harvests (McNeil et al. 2017). Since the initial publication of these management guidelines, implementation of management is gaining momentum (McNeil et al. 2020a, Litvaitis et al. 2021), and the management guidelines have iteratively been revised to incorporate lessons learned in an adaptive framework (Roth et al. 2019).

Although habitat management guidelines are usually developed with data collected on public lands (Bakermans et al. 2011, Wood et al. 2013), effective conservation of species that breed in eastern forests of North America will require management of private lands (Ciuzio et al. 2013, North American Bird Conservation Initiative [NABCI] 2013). Although conservation efforts focused on public lands have proven beneficial in many instances (Cooper et al. 2019, McNeil et al. 2020a), 84% of the forest land in the eastern United States is in private ownership, highlighting that public land alone is insufficient for the conservation of a wide suite of species (NABCI 2013, McNeil et al. 2020b). Still, there are many challenges associated with private forest lands conservation. For example, forest landowners often possess diverse attitudes and motivations and coordinating concerted management efforts among them may be time consuming and expensive (Barbour et al. 2007). Additionally, in many regions, parcellation of lands is increasing, further complicating the capacity of conservation efforts to coordinate widespread management implementation (Brooks 2003). Fortunately, in the United States, agencies like the United States Department of Agriculture's Natural Resources Conservation Service (NRCS) have established programs to provide funding and technical assistance for landowners interested in creating habitat for migratory birds on their properties (Ciuzio et al. 2013, Litvaitis et al. 2021). Although many of these private lands programs have only gained momentum over the past decade, initial research suggests that they may be beneficial to a wide variety of avian and non-avian taxa (e.g., Litvaitis et al. 2021, Mathis et al. 2021, Keele et al. 2023).

One species of enormous conservation need is the Cerulean Warbler (*Setophaga cerulea*). The Cerulean Warbler is a long-distance Nearctic-Neotropical migratory songbird that winters throughout parts of South America and breeds in mature deciduous forests across eastern North America (Buehler et al. 2020). Cerulean Warblers, like many migratory animal species, are threatened by stressors across the full annual lifecycle (Raybuck 2022), with breeding grounds loss/degradation among the most important conservation actions that may reverse declines in the species, which have been sustained at 1.9%/year since at least the 1960s (Sauer et al. 2020). With an estimated 75% of its breeding distribution on private lands, according to NABCI (2013), the role private forests can play in the conservation of this at-risk species is imperative. During the breeding season, Cerulean Warblers nest in mature timber stands characterized by large-diameter trees and sporadic canopy gaps that promote structural heterogeneity (Buehler et al. 2020). As with a growing list of other forest bird species, habitat management guidelines were drafted using public lands monitoring data and describe methods of creating nesting habitat for the species using conservation practices like shelterwood timber harvest (Wood et al. 2013). To implement these practices, a program by NRCS (Regional Conservation Partnership Program [RCPP]) was established in 2015 (Adusumilli 2019). Part of the aim of the RCPP is assisting private landowners in the conservation of Cerulean Warblers on their forestlands (Shaffer 2022). To help understand the extent to which Cerulean Warblers benefit from breeding grounds conservation efforts on private lands, we monitored sites treated and planned to be treated through the RCPP effort from 2017-2020 in Pennsylvania and Maryland. Specifically, we established the following aims: (1) quantify Cerulean Warbler occupancy rates on private forest sites both before and after management implementation, and (2) relate Cerulean Warbler occupancy probability to microhabitat and landscape characteristics on private lands in central Appalachia.

METHODS

Habitat management guidelines

Under the guidance of the Cerulean Warbler Technical Group, a series of experimental timber harvests were implemented on public lands (e.g., Daniel Boone National Forest) to elucidate Cerulean Warbler habitat needs (Boves et al. 2013a). Using the results from those experimental timber harvests and relevant findings from previous research, the Cerulean Warbler habitat management guidelines were created (Wood et al. 2013). In those guidelines, basal area, tree size, and tree species composition were identified as the most critical habitat components for this bird species. Cerulean Warbler response to guideline implementation on public lands was most positive at intermediate harvest intensities (e.g., shelterwood harvests) where basal area was between 9.2 and 20.7 m²/ha. Along with basal area, Cerulean Warblers displayed a strong preference for large trees (≥ 40.6 cm DBH) and tree species composition; selecting for white oak (*Quercus alba*), chestnut oak (*Q. montana*), hickories (*Carya* spp.), and sugar maple (*Acer saccharum*), while avoiding species from the red oak group and red maple (*Acer rubrum*). In a later study that evaluated the Cerulean Warbler guidelines, population growth was positive when > 50% of basal area was comprised of preferred tree species or trees ≥ 40.6 cm DBH (Nareff et al. 2019).

Study area

Our study was conducted within the central Appalachian Mountains where management on private forest lands was guided by Cerulean Warbler habitat management guidelines (e.g., shelterwood, single-tree selection, group-tree selection, etc.; Wood et al. 2013) through NRCS conservation programs. We surveyed 139 sites across several counties in Pennsylvania (n = 26) and western Maryland (n = 2) at elevations ranging from 192–853 m above sea level (Fig. 1A). All study sites were within the Appalachian Mountains Bird Conservation Region, which hosts > 70% of the Cerulean Warbler breeding population (Rosenberg et al. 2016). Forests in this region of the central Appalachians vary depending on topographic and other edaphic conditions but are dominated by either mixed oak, mixed hardwoods, or northern hardwoods communities (McCaskill et al. 2014). Forest cover in this region was largely regenerated in the early 1900s after landscape-scale logging and thus were dominated by 80–110 years old forest with minimal forest older than this age range (McCaskill et al. 2014).

We defined a site as the boundary or planned boundary of a treatment area (i.e., shelterwood timber harvest). We obtained shapefiles for treatment boundaries from NRCS partner biologists and then used QGIS (https://qgis.org) to randomly generate avian survey point locations within each treatment polygon. Sites ranged from 2–177 ha in size and contained between 1–2 avian survey points. Each point was > 250 m apart to help ensure spatial independence (Ralph et al. 1995). Additionally, when possible, all points were ≥ 80 m from a treatment edge, but this was not always possible because of irregular treatment boundary shapes (McNeil et al. 2018). When harvest boundaries precluded point establishment > 80 m from an edge, we placed the survey location at the geometric center of the treatment area, and observers were careful to determine if Cerulean Warbler were detected inside the treatment area to ensure that detections were assigned to the appropriate vegetation conditions.

Point count locations

From 2017–2020, we conducted point count and vegetation surveys across 139 individual locations. Of these 139 locations, 21 were monitored during both the pretreatment and posttreatment periods, resulting in 56 points monitored at pretreatment and 100 at posttreatment locations. Because we monitored some points for multiple years (n = 127 of 139), our final sample consisted of 337 point x year combinations, with repeated point count and vegetation surveys at each. Of these 337 point x year combinations, 103 were pretreatment, whereas 82 experienced < 1 year since treatment, 75 one year since treatment, 58 two years since treatment, and 19 three years since treatment. Average distance between points was 3314 m.

Point count surveys

We conducted 10-minute passive point count surveys at each location twice per breeding season between 15 May and 15 June (Ralph et al. 1995). The first and second round of surveys were separated by approximately 14 days. All point count surveys were conducted between a half hour before sunrise and four hours post sunrise. Prior to each survey, we recorded conditions that could influence avian detection, including: (1) Beaufort wind index (0–5), (2) sky condition (% cloud cover), (3) Precipitation (none, fog, mist, or light rain), (4) minutes since sunrise (mss), and (5) ordinal date. For each detected bird, we also noted whether it was present inside the treated area (not applicable for pretreatment points).

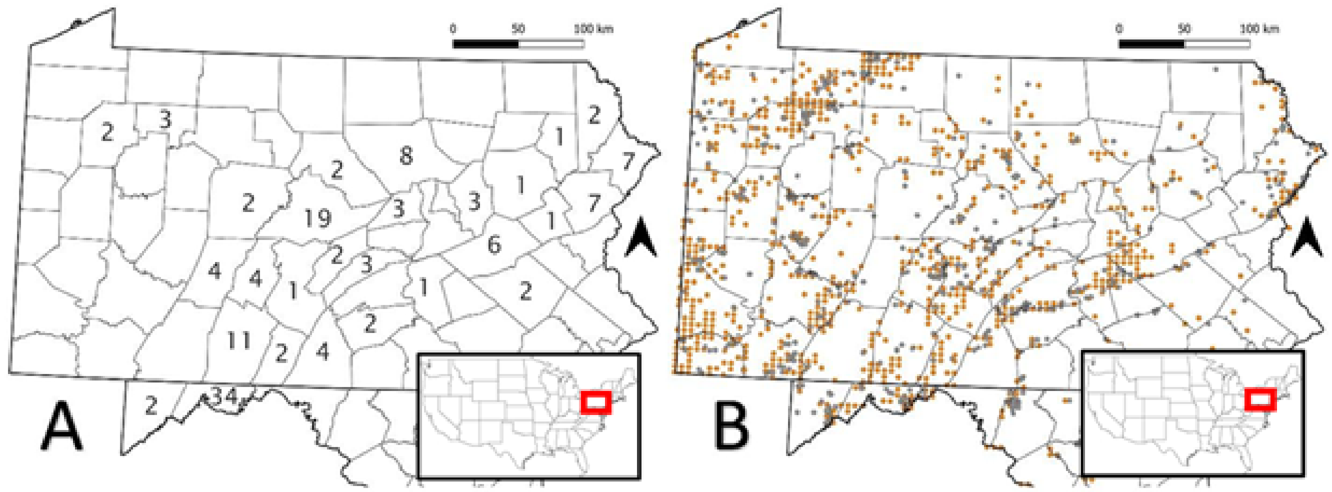
Microhabitat vegetation surveys

We conducted vegetation surveys at each point count location between 15 June and 15 July, annually. We quantified vegetation characteristics that are known to be ecologically important to Cerulean Warblers. All vegetation data were collected along three, 35 m radial transects oriented at 0°, 120°, and 240°, originating from point-center (McNeil et al. 2020a). Along each 35 m transect, we recorded vegetation strata at 7 stops using an ocular tube, each of which was 5 m apart on a given transect (n = 21/point; James and Shugart 1970). Basal area of living trees (≥ 10 cm diameter at breast height [DBH]) was quantified using a 10-factor basal area (converted to m²/ha) prism at the 0 m and 35 m locations along each transect (n = 4 prism swings/avian survey point). We identified each tally tree to species and measured their DBH to the nearest 0.1 cm. At each stop, we recorded the presence/absence of vegetation strata in the following categories: canopy tree (≥ 10 cm DBH), sapling (< 10 cm DBH), shrub, forb, fern, grass (graminoid), coarse woody debris, leaf litter, and bare ground (McNeil et al. 2018, 2020b). We quantified vegetation cover by dividing the sum of present recordings by the number of stops, resulting in a proportion of cover for each stratum. Vegetation cover was analyzed as % cover. At each prism location, we further classified in tree species as preferred, avoided, or neutral based on Cerulean Warbler nesting and foraging ecology (Boves et al. 2013b, Wood et al. 2013). We analyzed tree species composition as percent of basal area consisting of preferred and avoided tree species.

Remote-sensed data

We used the National Land Cover Database ([NCLD] 2016 dataset; Yang et al. 2018) to summarize land cover at the 1 km spatial extent centered around each avian survey location known to be ecologically important to Cerulean Warblers (Boves et al. 2013a, 2013b). Within the 1 km buffer, we quantified the proportion of deciduous forest, mixed forest, coniferous forest, shrubland, forested wetland, emergent wetland, pasture, row crops, and human development. Additionally, we used the Global Multi-resolution Terrain Elevation Data (GMTED2010; Danielson et al. 2011) to extract topographic characteristics including elevation, slope, and aspect. Slope was analyzed as percent slope. Aspect was transformed into Beers' aspect prior to analysis (Beers et al. 1966).

Fig. 1. Map of counties in Pennsylvania and Maryland where private forest enrolled in NRCS's Regional Conservation Partnership were surveyed for *Setophaga cerulea*, Cerulean Warblers (A). Each county includes a count of the number of Natural Resources Conservation Service (NRCS) survey locations that occurred within that county; they are not mapped here to protect private landowner identities. Across the study area, we also mapped centroids of Breeding Bird Atlas Occupied USGS Quadrangles (orange circles) Merged with eBird Data (gray circles) from Pennsylvania and Maryland into a single point layer (B). The insets depicts where, within the continental United States, the study area occurred (red bounding boxes).



Cerulean Warbler regional occurrence dataset

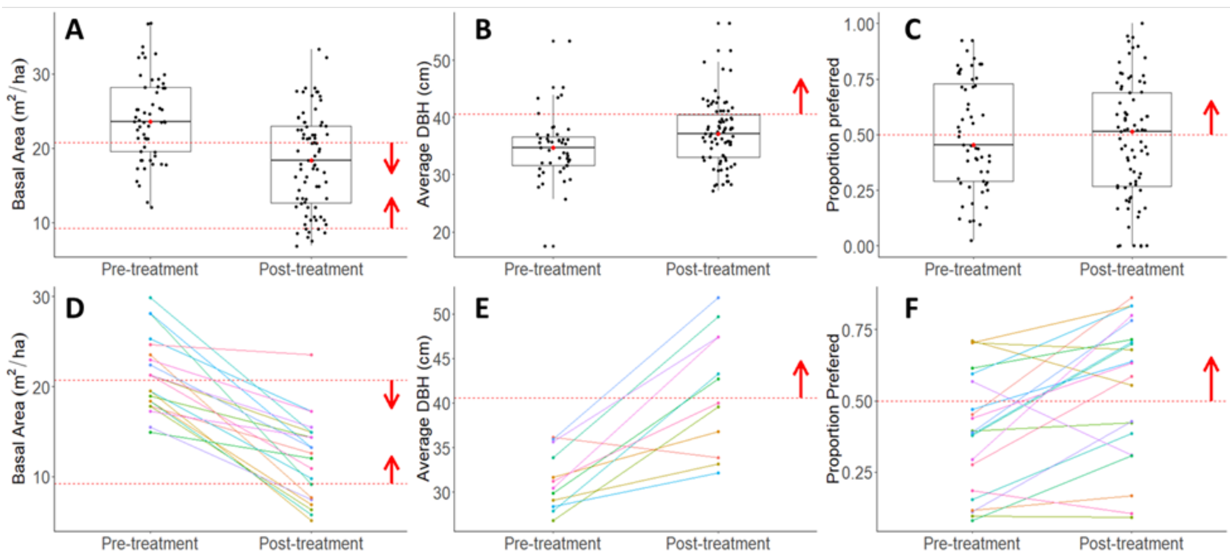
Previous research has identified proximity to other Cerulean Warbler populations as an important factor predicting management outcomes for the species (Roth and Islam 2007, Wood et al. 2013). We created a single Cerulean Warbler breeding population occurrence map for Pennsylvania and western Maryland by combining presence data from three datasets: (1) The Second Pennsylvania Breeding Bird Atlas (PA-BBA; Wilson et al. 2013); (2) the Second Maryland Breeding Bird Atlas (MD-BBA; Ellison et al. 2011); and (3) eBird citizen science data (http://www.ebird.org). To create a map from these datasets, we first used QGIS to extract all USGS quadrangles (24 km²) that had evidence of breeding activity from PA-BBA and MD-BBA (Fig. 2B). Next, we obtained all Cerulean Warbler observations for Pennsylvania and western Maryland from eBird and filtered those data to only include detections in June from 2013–2020. We only used observations from June to maximize the likelihood that eBird observations were associated with breeding Cerulean Warblers (not migrating). Additionally, we restricted June observations to stationary checklists to ensure each observation was a single accurate location. We extracted the centroid of each BBA quadrangle and merged it with the eBird points to create a single layer. Lastly, we used the QGIS plugin NNJoin to calculate the distance from each point surveyed to the nearest BBA-centroid or eBird point (Fig. 1B).

Occupancy modeling analysis

All data analyses were conducted in the statistical program R (R Core Team 2021). We used single-season occupancy models to analyze Cerulean Warbler detection histories with the R package unmarked (Fiske and Chandler 2011, MacKenzie et al. 2017). We ranked models in descending order of Akaike's Information Criterion adjusted for small sample size (AIC_c; Akaike 1973) and accounted for overdispersion, were it present, by using the Quasi-AIC_c adjustment ($QAIC_c$; Lebreton et al. 1992, Anderson 2007). Linear covariates were considered informative if they were competing ($\Delta AIC_c < 2.0$) and had β 95% confidence intervals that did not include zero. To incorporate data from multiple years, we utilized a stacked format (McClure and Hill 2012, Fogg et al. 2014). We first modeled which survey covariates might influence detection probability (*p*) from the list of five survey covariates noted above. We fit univariate detection models for each of our four detection covariates and kept occupancy constant across all points.

After accounting for imperfect detection, we fit occupancy models to evaluate the influence of covariates on occupancy probability (Ψ). To avoid overfitting due to low naïve occupancy, we began with univariate models for a regional, landscape, and microhabitat model set. We then retained the top-ranking model from each model set in the subsequent model sets. We started with a regional model set that included latitude, longitude, elevation, and distance to the nearest Cerulean Warbler population (km). Additionally, we ran latitude and longitude models with quadratic relationships. Next, we generated a landscape model set that consisted of univariate models including proportion of land cover within 1 km of a point for the following cover types: deciduous forest, mixed forest, coniferous forest, shrubland, woody wetland, emergent herbaceous wetland, barren, pasture, row-crops, and human development. Our last model set was for microhabitat and included years since treatment, treatment status (i.e., pretreatment or posttreatment), Beers' aspect, slope, basal area, proportion of preferred trees, percent sapling, and percent shrub cover. Beers' aspect and slope were included in the microhabitat model set

Fig. 2. Basal area of locations enrolled in Natural Resources Conservation Service (NRCS) programs on private lands for pre-treatment and post-treatment locations (A). Each black dot represents an individual location, and the red dotted lines represent Cerulean Warbler (*Setophaga cerulea*) habitat management guideline targets with red arrows indicating desired direction (Wood et al. 2013). Also shown are average DBH in cm (B) and proportion of tree species preferred by Cerulean Warblers (C). Additionally, for a subset of locations, we measured basal area at pre-treatment locations and again after treatment (D). Also shown for the subset of locations are average DBH in cm (E) and proportion of tree species preferred by Cerulean Warblers (F).



because of their effects on microhabitat vegetation conditions (e.g., northeast slopes tend to be more productive in the Appalachians; Werling and Tajchman 1984, Fekedulegn et al. 2003). In the microhabitat model set, we also included basal area with a quadratic relationship. To assess model adequacy, we ran a MacKenzie and Bailey (2004) goodness-of-fit test with 5,000 bootstrap samples from package AICcmodavg (Mazerolle 2023) on our most parameterized model. Prior to analyses, we tested for multicollinearity by calculating Pearson's correlation coefficient (correlation > 0.7; Sokal and Rohlf 1969), variance inflation factor (VIF), and examined scatter plots among all pairwise sets of variables. We used the top-ranked models to evaluate functional relationships between habitat covariates and Cerulean Warbler occupancy rather than model averaging given the challenges regarding interpretability associated with model averaging (Cade 2015).

Vegetation comparison analysis

We compared pretreatment and posttreatment vegetation conditions to evaluate the influence of treatment on within-stand characteristics known to be important to Cerulean Warblers (Boves et al. 2013a, 2013b). Specifically, we compared total basal area, percent basal area consisting of tree species preferred by Cerulean Warblers (hereafter, proportion preferred trees), and mean DBH. We conducted two vegetation comparisons: (1) a comparison between all pretreatment (n = 56) vs all posttreatment (n = 79) survey locations, and (2) a comparison between pretreatment and posttreatment data collected at locations that were surveyed during both periods (n = 21 pre/post pairs). Pretreatment data from these 21 sites were also included in the first comparison; however, the post treatment data from these sites were not included to avoid violating spatial independence. Points that had data for both pretreatment and posttreatment stages were sometimes monitored for > one year during either stage. In this case, we used those data collected the year prior to treatment and the year immediately following treatment. Preliminary analysis revealed that our microhabitat data were not normally distributed for comparison (1) but were normally distributed for comparison (2). Thus, we used non-parametric Wilcoxon rank-sum tests for all comparisons where our data were not normally distributed. We used a two-tailed t-test for comparisons with normally distributed data. To evaluate how well each point met Cerulean Warbler habitat guidelines, we categorized whether they met the three forest characteristics most important to Cerulean Warblers and summed up how many of the three each met. The three guideline targets were: (1) basal area between 9.2 and 20.7 m²/ha, (2) average DBH ≥ 40.6 cm, and (3) over 50% of tree species composition of preferred species. We then calculated the proportion of points that met each guideline and the proportion of points that met none, one, two, or all three guidelines, respectively. Note, we did not have DBH data from nine pretreatment locations. Thus, we did not include those in the analysis for average DBH.

RESULTS

Comparing vegetation at pre and posttreatment sites

We conducted vegetation surveys at 56 pretreatment and 79 posttreatment locations. Median basal area was higher at pretreatment (23.5 m²/ha, 95% CI: 21.2–23.7) than posttreatment locations (18.4 m²/ha, 95% CI: 16.1–20.66; Wilcoxon test, W =

1144, $p < 0.01$; Fig. 2A), whereas median DBH was higher at posttreatment (37.2 cm, 95% CI: 35.7–38.1) than pretreatment locations (34.7 cm, 95% CI: 32.3–35.9; Wilcoxon test, W = 2376, $p < 0.01$; Fig. 2B). Median proportion preferred trees did not differ significantly between pretreatment (0.453; 95% CI: 0.389–0.579) and posttreatment locations (0.513, 95% CI: 0.397–0.567; Wilcoxon test, W = 2119, $p = 0.68$; Fig. 2C). Many pretreatment locations (19 of 56, 33.9%) did not attain any guideline metrics, 26 of 56 (46.4%) locations attained one metric, 11 of 56 (19.6%) locations attained two metrics, and no pretreatment locations attained all three guideline metrics. Proportion of preferred trees was the guideline metric most often attained at pretreatment locations (26 of 56, 46.4%), followed by basal area (16 of 56, 28.6%). posttreatment locations did not attain any guideline metrics at 18 of 79 (22.8%) locations, whereas attaining one guideline metric at 27 of 79 (34.2%) locations, two metrics at 35 of 79 (37%) locations, and three metrics at 5 of 79 (6.3%) locations. Posttreatment locations most often satisfied the guideline metric for basal area (40 of 79, 51%; Fig. 2A) and proportion of preferred trees (40 of 79, 51%; Fig. 2C). Average DBH ≥ 40.6 cm was the metric least attained at both pretreatment (6 of 47, 12.8%; note: we lacked DBH data for nine locations) and posttreatment (20 of 79, 25%) locations (Fig. 2B).

Comparing vegetation before and after treatment at the same sites

We monitored 21 locations for which we collected data during both pre and posttreatment (DBH was only measured at 12 of these locations). For the complete set of 21 pre/post locations, median basal area was reduced from 21.3 m^2/ha (95% CI: 19.6–23.0) to 12.0 m^2/ha (95% CI: 10.2–14.1; Paired t-test, t = 9.68, DF = 20, $p < 0.01$; Fig. 2D). For the 12 pre/post locations where we measured tree diameters, average DBH increased following treatment from 31.4 cm (95% CI: 29.8–33.2) to 41.5 cm (95% CI: 38.1–45.3; Fig. 2E). Finally, at the complete set of 21 pre/post locations, the proportion of preferred tree species rose from 0.39 (95% CI: 0.306–0.481) to 0.55 (95% CI: 0.44–0.65; paired t-test, t = -3.79, DF = 20, $p < 0.01$) after management (Fig. 2F). Prior to treatment, 8 of 21 (38.1%) locations did not attain any guideline metrics, one metric was attained at 10 of 21 (47.6%) locations, and two metrics at 3 of 21 (14.3%) locations. No pretreatment site attained all three metrics. Following treatment, 4 of 21 (19%) locations did not attain any guideline metrics, one metric was attained at 6 of 21 (28.6%) locations, two metrics at 7 of 21 (33.3%) locations, and all three metrics were attained at 4 of 21 (19%) locations. Basal area (Fig. 2D) and proportion of preferred trees (Fig. 2F) were most often either improved (i.e., attained metric target; n = 8 each) or maintained metric target (n = 5 each). At sites with tree diameter data before and after treatment, attainment of the DBH value recommended in the habitat management guidelines was at 50% (6 of 12; Fig. 2E).

Cerulean Warbler response

We detected a total of 31 individual Cerulean Warblers. Eight of the 31 individual Cerulean Warblers were detected at pretreatment locations, whereas the remaining 23 were detected at posttreatment locations. Naïve occupancy was 0.14 and 0.17 at pretreatment (8/56 sites) and posttreatment (14/100 sites) locations, respectively. At the 21 survey locations for which we collected both pre and posttreatment data, 3 Cerulean Warblers were detected at 3 locations prior to treatment and 7 at 5 locations following treatment. Of the 3 pretreatment locations occupied, Cerulean Warblers were detected at 1 following treatment. Of the 5 posttreatment locations occupied, Cerulean Warblers were only detected at 1 location prior to treatment. Our most parameterized occupancy model was overdispersed ($\hat{c} = 2.79$), so we adjusted all models using $QAIC_c$. The best-ranked detection model was the null model and, therefore, no detection covariates were used in subsequent models. Detection probability was $p = 0.28$ (95% CI: 0.17–0.38). After accounting for imperfect detection, mean Cerulean Warbler occupancy probability was 0.16 (SE: 0.06–0.26). In the regional model set, Ψ(distance-to-nearest-Cerulean Warbler) best predicted occupancy probability and there were no competing models (Table 1). This top model, Ψ(-2.32–1.78 * distance), indicated that, as distance to the nearest Cerulean Warbler population increased from 0.36–27.4 km, occupancy probability declined from 0.43–0.00. This pattern was linear with steep declines occurring between 0.36 and 5 km, where occupancy probability declined most sharply from 0.43 to 0.11. With this pattern in mind, the estimate on distance to the nearest Cerulean Warbler population (-1.78) and standard error (0.57), when adjusted for overdispersion (SE*), indicated weak effects at the 95% confidence level (95% CI: ± 1.87) but was biologically meaningful at the 85% level (± 1.37; Arnold 2010).

The best-ranked Landscape model was the null model. Our best-ranked Microhabitat model was Ψ(basal area). However, Ψ(basal area) was competing (within < 2 $QAIC_c$) with the null model and therefore was not considered informative. No model indicated support for a treated (yes/no) covariate in predicting Cerulean Warbler occupancy probability. Our top regional model, ` (distance-to-nearest-Cerulean Warbler) was our only model that was not competing with a null model and thus was our top model overall.

DISCUSSION

This study is among few concerted efforts to monitor Cerulean Warbler responses to the implementation of its species-specific management guidelines on private lands (Oliver et al. 2024) and the first to focus on Pennsylvania and Maryland. These results are important not only because we detail how this bird responds to conservation implementation in the private land context, but also because we provide insights that may be used to revise habitat management guidelines (Wood et al. 2013). Cerulean Warbler occupancy was relatively low on treated private lands, contrasting with similar monitoring work that has taken place on public lands elsewhere (e.g., Daniel Boone and Monongahela National Forests; Boves et al. 2013b). Furthermore, we expected to see an effect of treated vs untreated in our occupancy models (Sheehan et al. 2014) but did not find support for this covariate. This was especially surprising considering that Cerulean Warblers, in previous studies on public lands, had a significant response within the first two years of treatment (Boves et al. 2013a). With that in mind, one important habitat feature that often cannot be obtained easily in the short-term (i.e., by implementing habitat management) is large-diameter trees preferred by Cerulean Warblers. To obtain the average diameter of tree species preferred by Cerulean Warblers, there must be enough large diameter (≥ 40.6 cm) trees present prior to treatment. Moreover, during guideline implementation in such stands, managers should target smaller-diameter stems of non-preferred species to attain desired basal area values (9.2–20.7 m^2/ha; Wood et al. 2013). Management

Table 1. Top occupancy models for Cerulean Warblers (*Setophaga cerulea*) on private lands in Pennsylvania and western Maryland, surveyed 2017. Models are ranked in descending order of Quasi Akaike's Information Criterion (QAICc). Covariate β 95% confidence intervals that did not include zero are bolded and those overlapping zero are non-bold. Shown for each model are: number of model parameters (k), change in QAICc (ΔQAICc) from the top model, model weight (w), and β coefficients on occupancy probability. Our top detection and landscape models were null models.

Model	k	$\Delta QAIC_c$	w	β coefficients
Detection probability				
p(.), Ψ(.)	3	0	0.37	
p(msss), Ψ(.)	4	0.21	0.34	
p(julian date), Ψ(.)	4	2.02	0.14	
p(wind), Ψ(.)	5	2.16	0.13	
p(precipitation), Ψ(.)	7	6.02	0.02	
p(cloud cover), Ψ(.)	7	7.32	0.01	
Regional occupancy probability				
p(.), Ψ(distance-to-nearest-Cerulean Warbler)	**4**	**0**	**0.8**	$\boldsymbol{\beta_1 = -1.78}$
p(.), Ψ(.)	3	4.68	0.08	
p(.), Ψ(latitude)	4	4.99	0.07	
p(.), Ψ(longitude)	4	6.71	0.03	
p(.), Ψ($latitude^2$)	5	7.00	0.02	
Landscape occupancy probability				
p(.), Ψ(.)	3	0	0.14	
p(.), Ψ(% developed)	4	0.35	0.12	
p(.), Ψ(% grassland)	4	0.73	0.1	
p(.), Ψ(% open)	4	1.1	0.08	
p(.), Ψ(% barren)	4	1.26	0.08	
p(.), Ψ(% deciduous forest)	4	1.37	0.07	
p(.), Ψ(% mixed forest)	4	1.41	0.07	
p(.), Ψ(% woody wetland)	4	1.64	0.06	
p(.), Ψ(% evergreen forest)	4	1.68	0.06	
p(.), Ψ(% herbaceous wetland)	4	1.81	0.06	
p(.), Ψ(% water)	4	1.92	0.05	
p(.), Ψ(% pasture)	4	1.97	0.05	
p(.), Ψ(% row-crops)	4	1.97	0.05	
Microhabitat occupancy probability				
p(.), Ψ(basal area)	4	0	0.18	$\beta_1 = -0.61$
p(.), Ψ(.)	4	0.31	0.16	$\beta_1 = -1.69$

efforts that implement Cerulean Warbler habitat guidelines should be tempered when working on lands (e.g., private forests) where mean diameter of preferred tree species cannot be increased to ≥ 40.6 cm after treatment. As habitat management guidelines for birds like Cerulean Warblers are developed/revised, our results demonstrate the immense danger of ignoring private lands and the unique challenges presented thereof (Capano et al. 2019, Oliver et al. 2024).

Whereas conservation outcomes of habitat management guidelines are highly tied to the starting conditions of a site before implementation, our study provides one potential example of a straightforward way to bolster management recommendations: target implementation near existing subpopulations of Cerulean Warblers. Although the current guidelines published by Wood et al. (2013) recommend that sites should be within 10 km from known populations, our results might suggest that sites within two km should be given the highest priority. A similar (albeit clearer) trend was observed in Golden-winged Warblers (McNeil et al. 2020b), another at-risk wood-warbler species that requires private lands conservation for persistence in many regions (Litvaitis et al. 2021). Golden-winged Warblers appear to cluster territories in a metapopulation structure to maximize opportunities for obtaining mates and extrapair copulation (Roth et al. 2014), and it seems reasonable that Cerulean Warblers engage in a similar behavior. Indeed, Cerulean Warblers have been reported by other studies to cluster their territories near conspecifics, even when vacant habitat is available nearby (Roth and Islam 2007, Kaminski and Islam 2013). Given the apparent importance of conspecific attraction to Cerulean Warbler territory establishment observed in our study area and elsewhere, we suggest habitat management should aim to prioritize management within two km of known Cerulean Warbler populations, at least as priority areas to maximize the probability of colonization. It is important to keep in mind that treatments more than 2 km from known Cerulean Warbler populations are still potentially worthwhile; implementation can improve vegetation conditions (e.g., tree species composition; Wood et al. 2013) and place stands on a trajectory capable of developing the structural components Cerulean Warblers require. However, this is a long-term perspective because many stands will need decades for trees to achieve preferred Cerulean Warbler diameter. Additionally, whereas Cerulean Warbler occurrence has been positively associated with understory cover that develops in the first several years following treatment (Wood et al. 2013), by 13-years post harvest, increased midstory conditions will develop that Cerulean Warblers will avoid (Raybuck 2022). Once stands with adequate amounts (more than 50%) of tree species preferred by Cerulean Warbler achieve preferred diameter, they will be capable of meeting Cerulean Warbler breeding conditions with further management. With these recommendations in mind, our findings highlight the need for future work with larger sample sizes to more clearly describe the relationship between Cerulean Warbler use of managed forests and distance to nearest neighboring population.

Perhaps the most important implication from our study is as a cautionary tale against developing species habitat management guidelines while ignoring the unique challenges presented on private lands (Cuizio et al. 2013, Proctor et al. 2022) hampered by a legacy of poor forest management. Indeed, whereas implementation of the habitat management guidelines on public lands often results in robust responses by Cerulean Warblers (Nareff et al. 2019), responses to private lands management are relatively weaker. Even after the habitat management guidelines were implemented, we often observed stands with small tree diameters composed heavily of tree species not preferred by Cerulean Warblers (e.g., red maple, black birch [*Betula lenta*]). Such characteristics are indicative of high-grading, an unsustainable timber harvest practice, whereby the largest and most valuable trees are selectively cut, and smaller and less desirable trees are left behind (Fajvan et al. 1998). High-grade harvests, also called selective harvests or diameter-limit cuts, are recognized to employ a philosophy of "take the best, leave the rest" (Coufal et al. 2011), with those trees selected for harvest often being those which Cerulean Warblers prefer most (e.g., large-diameter white oak species, etc.; Newell and Rodewald 2011, Boves et al. 2013b). Unfortunately, high-grading continues to be prominent on private lands throughout eastern forests (Fajvan et al. 1998, Metcalf et al. 2012, Belair and Ducey 2018). Therefore, private lands' conservation value for Cerulean Warblers will be limited until exploitative harvests are drastically reduced. Beyond birds, high-grading has several long-term negative consequences for a stand, including lower residual tree quality, reduced canopy tree species diversity, and poor regeneration of less shade-tolerant tree species (e.g., oaks and hickories; Schuler et al. 2017, Curtze et al. 2022). Future work assessing the extent to which private land sites selected for Cerulean Warbler habitat management had been treated with unsustainable logging practices—and quantifying the effects of those practices on stand trajectories—would be valuable.

CONCLUSION

Although Cerulean Warbler responses to the implementation of habitat management guidelines on private lands were relatively weak, restoration of Cerulean Warbler breeding habitat in private forests is nevertheless critical given the overwhelming regional importance of private land tenure in the forest landscape of eastern United States. Future work targeting shelterwood harvests, or similar practices, on private lands where large-diameter preferred tree species already exist might be an important next step in exploring how best to conserve Cerulean Warblers on private lands. Furthermore, monitoring timelines beyond what we conducted here (i.e., only a couple years) would allow estimation of dynamic parameters (e.g., colonization and persistence rates; MacKenzie et al. 2006), which can vary widely over time and space (Raybuck 2022), as well as improving static parameters (i.e., site occupancy) as estimated by this study. In sum, our results indicate that reevaluation of the Cerulean Warbler habitat management guidelines (Wood et al. 2013) is necessary in the central Appalachians and, likely, other parts of the species' breeding range. This is particularly true given that degraded forest conditions on private lands are not unique to Pennsylvania and western Maryland and are likely to be widespread throughout eastern forests (Belair and Ducey 2018).

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Data Availability:

These data are protected because they are from private lands.

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