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Assessing longer-term effectiveness of forest management guidelines on breeding habitat for cerulean warblers

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ABSTRACT

Widespread clear-cutting in the late 19th and early 20th centuries and subsequent regrowth has resulted in homogenous, closed-canopy forest structure across much of eastern deciduous forests in temperate North America. Forest management prescriptions designed to diversify stand structure have been increasingly applied with the goal of improving breeding habitat for declining species that require heterogenous forest structure, including Cerulean Warblers (“ceruleans”; *Setophaga cerulea*). Although a few studies have documented positive short-term (1–4 years post-treatment) responses of ceruleans to forest management prescriptions in the Appalachian Mountains region, longer-term responses have yet to be assessed. In 2019–2020, we followed the same spot-mapping methods as used previously (2005–2006 pre-harvest and 2007–2010 post-harvest) and compared territory density with previous estimates at each of 4 treatment levels (reduced basal area and overstory canopy by 0–75 %) across four forest stands on study sites in Tennessee, Kentucky and Ohio ($n = 12$ stands total) that had exhibited short-term positive density responses. Ceruleans did not exhibit consistently positive longer-term responses compared with pre-treatment densities when all stands were analyzed together. Compared with pre-treatment surveys, after 13–14 years post-harvest we documented density decreases of 1.0–3.1 territories per 10 ha at 5/9 stands, and positive responses of 1.8–2.2 territories per 10 ha at 3/9 treated stands. Over this period, midstory cover changed significantly (increased) during the 10 years since these stands were last surveyed. Thus, sustaining the short-term (1–4 year) positive response of cerulean warbler territory density to timber harvest may require periodic follow-up treatments that reduce the development of a dense midstory; we recommend that this hypothesis, along with the methods to achieve these conditions, should be tested.

1. Introduction

Avian abundance in eastern North American forests has severely declined over the past half century (Rosenberg et al., 2019), despite a trend of increasing forest cover (Johnson and Govatski, 2013). The decline of some forest species’ populations may be related to the lack of tree age-class diversity and stand structural complexity in second-generation forests (Fiss, 2023; Grinde et al., 2017; Shifley et al., 2014). This may be perpetuated by reduced frequencies of natural disturbances such as tree senescence and fire (Long, 2009; Shifley et al., 2014); prior to the 20th century, vast expanses of open woodland conditions (i.e., well-spaced trees with large crowns and open spacing) were prevalent (Hanberry and Thompson, 2019; Hanberry et al., 2020). In recent decades, forest management efforts have been designed and implemented across North America to emulate natural disturbance regimes (Long, 2009; Shaffer et al., 2025) with the intent to restore forest heterogeneity and biodiversity (Brawn et al., 2001; Franklin et al., 2007; Johnson and Govatski, 2013; Palik and Amato, 2017). However, there is still much to learn regarding how avian species respond to such silvicultural prescriptions as post-disturbance forest regrowth progresses (Sallabanks et al., 2000).

One disturbance-adapted species for which such ecological forestry

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practices have increasingly been used as a habitat management tool is the Cerulean Warbler (*Setophaga cerulea*; hereinafter 'cerulean'). This canopy-dwelling, migratory species breeds in mature deciduous forests across much of the eastern United States and portions of southeastern Canada (Buehler et al., 2020), with the majority (~80 %) breeding in the Appalachian Mountains Bird Conservation Region (Fink et al., 2023; Wood et al., 2013). Cerulean populations have declined by ~75 % over the past half century (Sauer et al., 2024; Wood et al., 2013). Breeding territories are typically in large tracts of mature forest with large-diameter trees and complex overstory structure with canopy gaps (Boves et al., 2013a; Buehler et al., 2020; Nemes and Islam, 2017; Wessels and Boves, 2021). For nesting, females typically use large diameter trees in areas with more understory cover and less midstory cover and basal area (Boves et al., 2013a; Buehler et al., 2020). Fledglings use a variety of forest stand types and age classes and prefer areas with more midstory cover (Raybuck et al., 2020). Together, these habitat preferences make ceruleans prime candidates for benefiting from ecological forest management practices that aim to increase heterogeneity at the local and landscape scale.

The Cooperative Cerulean Warbler Forest Management Project (CWFMP; Boves et al., 2013b; Sheehan et al., 2014) investigated ceruleans' and other target species' short-term (1–4 years post-treatment) population density responses to partial timber harvests of varying intensity at 7 study sites in 4 states throughout the Appalachian region. The CWFMP found positive territory density responses at each of 3 harvest intensities (light, intermediate, and heavy; Boves et al., 2013b), with the greatest increases in intermediate stands, or those with residual basal area (BA) ~16 m^2/ha (~70 ft^2/acre; Boves et al., 2013b; Sheehan et al., 2014). The results from the CWFMP and other studies formed the basis for the "Cerulean Warbler Management Guidelines for Enhancing Breeding Habitat in Appalachian Hardwood Forests" (hereinafter "Cerulean Management Guidelines", Wood et al., 2013). These guidelines recommended reducing basal area to ~9–21 m^2/ha (40–90 ft^2/acre) while retaining large-diameter trees of preferred species (such as white oak, *Quercus alba*) to create or enhance cerulean nesting habitat. However, it remains unclear if stands treated following this prescription continue to provide benefits to ceruleans beyond the initial 4 years post-harvest. This study represents the first effort to track long-term response to conservation measures designed to recover populations of ceruleans through silvicultural techniques. The results of this study will help inform managers of the longer-term effectiveness of various forest management prescriptions and provide insight into potential ways to prolong effectiveness of breeding habitat enhancement efforts through adaptive management.

2. Materials and methods

Of the original 7 study sites from the CWFMP (Boves et al., 2013b), we focused on 3 sites that remained unaltered by major disturbances since experimental timber harvests were implemented in 2006 (further logging or otherwise as of 2019–2020). These sites were located within the North Cumberland Wildlife Management Area (36.356° N, −84.282° W) in Tennessee, the Daniel Boone National Forest (38.069° N, −83.554° W) in Kentucky, and Vinton Furnace State Experimental Forest (formerly referred to as the Raccoon Ecological Management Area; 39.192° N, −82.373° W) in Ohio. Each study site was comprised of 4 plots that consisted of ~10-ha treatments and ~10-ha adjacent, untreated buffers; we used the same boundaries as defined in the previous study (see Fig. 2 in Boves et al., 2013b). Treatments at each site included light (~20 % of basal area and canopy cover removed; single-tree selection), intermediate (~40 % of basal area and canopy cover removed; shelterwood establishment cut), and heavy harvests (~75 % of basal area and canopy cover removed; heavy shelterwood establishment cut) as well as an undisturbed control plot (Boves et al., 2013b; Sheehan et al., 2014). Treatments were all implemented in 2006, except the heavy treatment in Kentucky, which was harvested in 2007 after the breeding season (Sheehan et al., 2014). Thus, all 2005–2006 surveys and the 2007 KY heavy treatment survey were "pre-harvest", and 2007–2010 surveys (except the 2007 KY heavy treatment) were "early post-harvest". We then conducted the present study during 2019 and 2020, 13–14 years after harvest ("latter post-harvest"). Although these sites remained mostly undisturbed since the 2006 treatment implementations, one exception was that, in 2017, transmission lines were removed from the Ohio control plot. In this process, some trees were removed for temporary access roads, but a drastic change in canopy cover was not apparent in aerial imagery or field measurements.

2.1. Temporal avian responses

All plots were originally surveyed yearly from 2005–2010 for Cerulean Warblers (Boves et al., 2013b). We conducted surveys on these plots following identical spot-mapping methodology: 8 visits/plot between 10 May and 09 June in 2019 and 2020. Spot-mapping has been demonstrated to be more accurate as a census of territories than point counts (Bibby et al., 2000; Newell et al., 2013). To reduce the possibility of observer bias affecting results, trained observers (several of whom surveyed the plots from 2005–2010) alternated between plots daily and alternated among different starting locations on each plot.

We delineated and counted territories in the same manner as previous analyses (Boves et al., 2013b; Newell et al., 2013; Sheehan et al., 2014). Territory delineations, based on numerous recorded instances of counter-singing, were performed manually by the same observer for all 2019–2020 data following training (which involved jointly delineating territories for an example plot) by an observer who had performed much of the 2005–2010 delineations. To examine territory density responses over time for each treatment intensity, we compared means by treatments across study sites and examined individual site-specific changes in cerulean densities qualitatively.

2.2. Temporal vegetation responses

In June and July 2019, we collected vegetation measurements ($n = 10$ per treatment and $n = 10$ per treatment buffer at each site) including BA and percent cover of understory, midstory, and overstory strata, following Boves et al. (2013a), to assess how vegetative structure had changed since 2010. Vegetation was sampled at the same locations for each period. Previously, in Kentucky and Tennessee, these locations were sampled in all years from 2005–2010, while in Ohio, these locations were sampled once each in a randomly selected year from 2007–2010. Boves et al. (2013a) initially collected canopy cover data at 7 strata: 0.5–1.5 m, 1.5–3 m, 3–6 m, 6–12 m, 12–18 m, 18–24 m, and > 24 m and later combined these strata into 3 defined layers: 0.5–3 m (understory), 3–12 m (midstory), and > 18 m (overstory), by using the highest number of 'hits' from a stratum within each combined layer. Because we simplified our data collection methodology by directly measuring percent cover within only the 3 defined (0.5–3 m, 3–12 m, and > 18 m) layers in 2019, we calculated and applied correction factors for each of the 3 defined layers for direct comparison between the time periods. These correction factors were calculated from a subset of 50 vegetation plots using data sheets from 2007 by dividing the total of the greater number of hits per vegetation plot among each substratum that composed each of the understory, midstory, and overstory layers (as done by Boves et al., 2013b) by the total sum of hits that could have fallen into at least one of the substrata within each layer (as measured in 2019). We applied these correction factors (0.86, 0.83, and 0.95 for the understory, midstory, and overstory layers, respectively) to all 2019 canopy cover measurements. We compared early (2007–2010) post-harvest vegetation metrics with these latter (2019) post-harvest metrics at the same vegetation plots for each metric with paired Wilcoxon signed-ranked tests (for Kentucky and Tennessee data) and with unpaired Wilcoxon ranked-sum tests (for Ohio data) because locations of vegetation sampling points changed each early post-harvest year in Ohio but not in Kentucky and Tennessee.

3. Results

3.1. Temporal avian response

Cerulean territory densities at control plots declined by 26 % from $\mu = 9.2 \pm 0.8$ territories/10 ha pre-harvest to $\mu = 6.8 \pm 0.9$ territories/10 ha latter post-harvest) and remained relatively stable within buffers (with slight 7 % average decline from $\mu = 7.4 \pm 1.4$ territories/10 ha pre-harvest to $\mu = 6.9 \pm 1.0$ territories/10 ha latter post-harvest). Cerulean densities among light treatment plots ($\mu = 9.5 \pm 0.9$ territories/10 ha across time periods) were relatively unchanged (Fig. 1). However, cerulean densities in intermediate plots differed among time periods, with latter post-harvest period densities ($\mu = 7.3 \pm 1.0$ territories/ha) reduced by 34 % from early post-harvest densities ($\mu = 11.1 \pm 1.8$ territories/10 ha, and by 26 % compared with pre-harvest densities ($\mu = 9.8 \pm 2.5$ territories/10 ha) after an initial 13 % early post-harvest increase. Cerulean densities in heavy treatments reflected a similar pattern, although the mean density was relatively low ($\mu = 4.1 \pm 1.1$ territories/10 ha across time-periods) compared with controls, buffers, and other treatments. After an initial 67 % increase from pre-harvest to early post-harvest densities, the heavy treatment mean was reduced by 52 % in the latter post-harvest period ($\mu = 2.5 \pm 1.2$ territories/10 ha) compared with the early post-harvest densities ($\mu = 5.2 \pm 2.1$ territories/10 ha) and by 20 % compared with pre-harvest densities ($\mu = 3.1 \pm 1.6$ territories/10 ha); Fig. 1).

3.2. Temporal vegetation responses

Structurally, the midstory layer exhibited the largest and most consistent changes between early and latter post-harvest periods across all treatments (Table 1). Conversely, overstory cover remained relatively similar in all treatments (and at all study sites). In Kentucky and Tennessee, across heavy treatments, BA increased and midstory cover increased ($P < 0.01$), while understory cover was relatively unchanged ($P = 0.24$). Across intermediate treatments, midstory cover increased ($P < 0.01$) but understory cover ($P = 0.46$) and BA ($P = 0.76$) were unchanged between survey periods. Across light treatments, midstory cover increased ($P < 0.01$), while BA ($P = 0.08$) and understory cover ($P = 0.35$) remained unchanged. Across control plots, BA ($P = 0.82$), midstory cover ($P = 0.07$), and overstory cover $P = 0.40$) remained unchanged while understory cover increased ($P < 0.01$).

In Ohio, vegetation structural changes generally aligned with those in Kentucky and Tennessee but there were a few exceptions. BA ($P = 0.70$) and understory cover ($P = 0.22$) remained similar within the heavy treatment and midstory cover increased ($P < 0.01$). At the intermediate treatment, BA remained similar ($P = 0.37$) and midstory cover increased ($P < 0.01$). Unlike the intermediate treatments at the other sites, in Ohio understory cover increased ($P < 0.01$). At the light treatment plot, midstory cover increased ($P < 0.01$) and BA did not change ($P = 0.52$), but unlike the Kentucky and Tennessee sites, understory cover increased ($P = 0.01$). At the Ohio control plot, BA decreased ($P < 0.01$), while understory cover $P < 0.01$) and midstory cover ($P < 0.01$) both increased and there was no change in overstory cover ($P = 0.19$).

4. Discussion

Recent forest management to enhance cerulean habitat has been predicated on the hypothesis that increasing canopy structural complexity will increase abundance of breeding ceruleans. In fact, after the Cerulean Warbler Forest Management Guidelines were developed (Wood et al., 2013), a large regional conservation effort was implemented throughout the Appalachian region based on this hypothesis (e.g., Shaffer et al., 2025; Oliver et al., 2024). Although previous studies documented positive short-term increases in cerulean density in response to forest management prescriptions (Boves et al., 2013b; Nareff et al., 2019), our results demonstrate that those increases may be relatively short-lived within managed stands.

Across plots that previously exhibited short-term cerulean density increases following harvests, densities at most plots had reverted to or below original levels by 13–14 years post-harvest. In part, these declines may have been influenced by declining global and regional trends across the study periods (Fink et al., 2023; Sauer et al., 2024), especially considering the 26 % and 7 % declines we observed at control plots and buffers. However, the general pattern of increased early post-harvest density responses followed by latter post-harvest period density reductions are likely affected by the dynamism of vegetative structure in response to increased light conditions created by the canopy reduction; specifically, they seem to be most associated with changes in the midstory. Early post-harvest cerulean density increases in harvested plots may have been affected by the increase in canopy gaps, which may be associated with increases in insect prey density (Blake and Hoppes, 1986; Gorham et al., 2002; Dodd et al., 2012) in residual overstory trees exposed to newly formed gaps (Boves et al., 2013a; Perkins and Wood, 2014). But after 13 years, the midstory below these canopy gaps became filled with an increasingly dense layer of vegetation (e.g., 61–82 % mean cover within intermediate and heavy treatment plots). Indeed, other studies have shown that male ceruleans typically select territories where

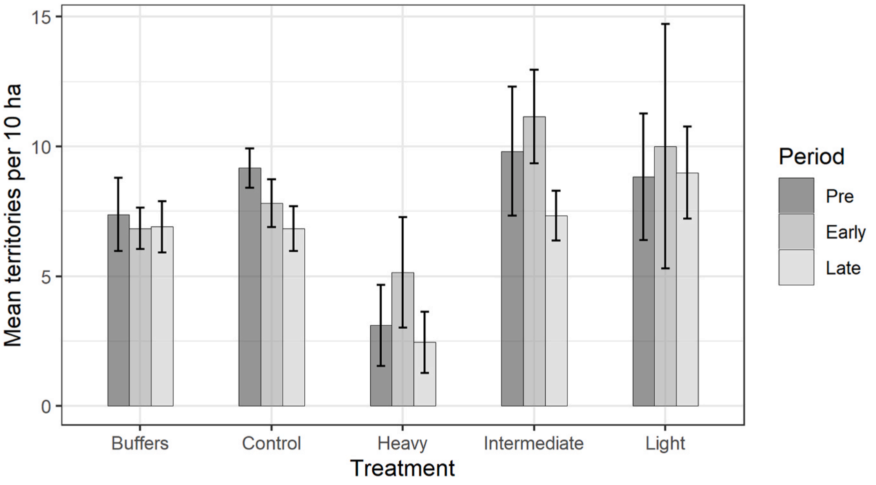

Fig. 1. Cerulean Warbler territory density (mean with standard error) at each treatment intensity for the combined Kentucky, Tennessee, and Ohio sites. Periods covered 2 preharvest years (2005–2006), 4 early post-harvest years (2007–2010), and 2 late (2019–2020) post-harvest years.

Table 1

Vegetation structure comparisons between 2010 (4 years post-harvest) and 2019 (13 years post-harvest) across 3 study sites. Bolded values with superscripts denote differing ($P < 0.05$) measurement distributions (based on paired Wilcoxon signed-ranked tests (Kentucky and Tennessee) and unpaired Wilcoxon ranked-sum tests (Ohio).

Basal Area (m^2/ha)						**Understory Cover (%)**					
Treatment	**Year**	**Mean KY/TN**	**SE**	**Mean OH**	**SE**	**Treatment**	**Year**	**Mean KY/TN**	**SE**	**Mean OH**	**SE**
Control	2010	23.4	0.9	**30.3**^{A}	1.4	Control	2010	24.1^{A}	2.3	**30.7**^{A}	1.4
	2019	23.7	1.4	**19.5**^{B}	1.1		2019	34.3^{B}	3.7	**59.6**^{B}	4.1
Light	2010	22.4	2.3	21.7	1.1	Light	2010	30.3	5.1	**23.6**^{A}	5.7
	2019	16.4	1.2	20.7	2.3		2019	38.4	5.5	**58.4**^{B}	6.0
Intermediate	2010	14.4	1.6	11.9	1.7	Intermediate	2010	59.1	7.8	**13.1**^{A}	4.8
	2019	15.8	2.1	14.4	1.3		2019	68.7	3.1	**77.1**^{B}	3.1
Heavy	2010	**8.5**^{A}	1.3	4.3	2.0	Heavy	2010	50.8	7.6	66.3	4.2
	2019	**13.3**^{B}	1.0	5.2	1.3		2019	62.3	3.9	68.5	3.1
Midstory Cover (%)						**Overstory Cover (%)**					
Control	2010	57.4	3.0	**60.5**^{A}	2.4	Control	2010	78.8	2.7	75.5	2.4
	2019	67.0	3.0	**76.8**^{B}	2.0		2019	81.0	2.6	79.2	3.7
Light	2010	**51.0**^{A}	3.0	**40.3**^{A}	3.2	Light	2010	65.3	6.9	52.0	4.8
	2019	**77.2**^{B}	3.0	**73.0**^{B}	3.9		2019	63.4	7.9	64.3	11.2
Intermediate	2010	**24.6**^{A}	2.6	**21.8**^{A}	3.8	Intermediate	2010	60.8	6.2	44.7	8.2
	2019	**69.7**^{B}	4.1	**61.3**^{B}	6.5		2019	59.0	7.2	57.8	5.9
Heavy	2010	**38.6**^{A}	5.0	**16.9**^{A}	6.8	Heavy	2010	28.3	5.0	12.3	10.9
	2019	**81.8**^{B}	1.0	**74.7**^{B}	4.2		2019	20.0	3.9	7.1	3.7

midstory cover is ~45–65 % and females select nesting locations in areas with further reduced midstory cover (Boves et al., 2013a). Because we did not survey our study sites between 2011 and 2018, it is unknown when initial cerulean density increases began to reverse (timewise or with respect to midstory cover levels).

Changes in vegetation structure were generally consistent with expected forest dynamics. Vegetation growth in sub-overstory layers was greatest across heavy treatment sites, where ample sunlight was available across the entirety of these sites and thus seedlings and saplings (especially shade-intolerant species) grew rapidly (Phillips and Shure, 1990). In heavy treatments in Kentucky and Tennessee, rapidly growing pole-sized stems (including shade-intolerant tulip poplar; *Liriodendron tulipifera*; Fig. 2) resulted in increased BA after 13 years post-harvest. Importantly, overstory cover did not measurably change since early pre-harvest years at any of the treatments, implying that overstory canopy gaps had not closed at the > 18 m stratum over the 13-years since harvests were implemented. Thus, overstory canopy heterogeneity associated with large-diameter residual trees, favorable for nesting ceruleans, was maintained. Regeneration within newly formed canopy gaps in each treatment had already advanced to the understory (0.5–3 m) layer by the 4th year post-harvest, which explains the general lack of change at this stratum between the 4th and 13th year post-harvest.

Although heavy treatments (e.g., even-aged timber harvests with <10 m^2/ha or <44 ft^2/acre BA) may represent the most economically viable forest management options, they did not appear to provide long-term increases in numbers of ceruleans, at least without further management. These heavy treatments fell at (in Tennessee and Kentucky) or below (in Ohio) the lower limit of the recommended 9–21 m^2/ha (40–90 ft^2/acre) Cerulean Warbler Forest Management Guideline's recommendations in early post-harvest years. In Tennessee and Kentucky, although BA at the heavy treatment, after 13 years of regrowth, was within the recommended range, BA increase since the early post-harvest period was largely due to the ingrowth of pole timber-sized trees within the midstory. Thus, these stands did not attract as many nesting ceruleans compared with pre-harvest conditions likely because large-diameter trees remained limited, while ingrowth resulted in a dense, undesirable midstory layer. However, it is possible that this advanced regeneration in harvests may still benefit ceruleans during the post-fledging period when family groups select for denser midstory cover (Raybuck et al., 2020).

White oaks are among the most preferred tree species for cerulean nesting and foraging (Boves et al., 2013a; Buehler et al., 2020) and are particularly difficult to regenerate due to competition with faster-growing species like tulip poplar and red maple (*Acer rubrum*; Dillaway et al., 2007). Carefully implemented shelterwood or group selection techniques that provide enough sunlight to support white oak regeneration have the potential to improve breeding habitat for ceruleans, as well as other wildlife species that benefit from white oak mast and/or nest in the understory layer (Newell and Rodewald, 2012; Wood

Fig. 2. Heavy treatment plot in the North Cumberland WMA in Tennessee, USA. These photos, taken in May 2008 (3 years post-harvest; panel A) and May 2019 (13 years post-harvest; panel B), provide an example of the forest regeneration progression that has resulted in increased canopy cover at the understory (0.5–3 m) and midstory (6–12 m) layers. This stand was harvested in fall of 2006.

et al., 2013). Even though, on average, light- and intermediate-intensity harvests did not effectively lead to longer-term increases in cerulean density from pre-treatment levels to 14 years post-harvest, some sites did indeed appear to maintain increases over the longer-term (2 of 3 in light and 1 of 3 in intermediate plots; Figs. S1, S2, and S3). It is unclear what differed between sites that allowed for some increased densities to be maintained for this longer time frame. Perhaps at these 3 plots (light and intermediate treatment plots in Ohio, and light treatment plot in Kentucky) the midstory layer had not grown as high as the other treatment plots due to less light availability/shorter growing seasons, or there may have been other metrics of sustained high-quality habitat that we did not measure.

It is plausible that various forest management methods to revert the midstory structure back toward early post-harvest conditions or toward open woodland conditions could help prolong the increases in cerulean density that were documented during early post-harvest years. Periodic prescribed fire applications would help maintain open woodland conditions that were historically prevalent across the landscape (Brose et al., 1999; Peterson and Reich, 2001; Hanberry et al., 2020). Alternatively, modification of a crop-tree release that favors preferred tree species, including white oaks, while substantially reducing the midstory may improve habitat by emulating open fire-adapted woodland conditions. If ceruleans are using a first-stage harvest shelterwood stand for nesting, managers could forego the final overstory removal and consider additional treatments focused on midstory reduction that retains some of the midstory-level trees (especially white oaks) while reducing numbers of trees that ceruleans tend to avoid (e.g., red maples). Ideally, these hypotheses should be tested experimentally to document how ceruleans respond.

Although locally high densities of ceruleans may be desired by managers, sustaining long-term increases of cerulean density at specific locations may not be necessary at broader scales (spatially and population-wise). Where landscapes contain extensive mature forest, managers could implement additional light and intermediate treatments to replace existing treatments once they age out of being cerulean nesting habitat. Cerulean prescription harvests could thus be spatially staggered to create a landscape matrix that always includes some (adjacent) stands with large, favorable trees, canopy gaps, and an open midstory during the breeding season and some stands that provide a dense midstory cover that are known to be used by fledglings and post-breeding adults (Raybuck et al., 2020). Ceruleans and other forest-dwelling avian species tend to move to areas with dense subcanopy cover during the critical post-fledging period (Anders et al., 1998; Fiss et al., 2021; Raybuck et al., 2020; Stoleson, 2013; Vitz and Rodewald, 2006). Additionally, maintaining a mosaic of stand conditions and seral stages across forested landscapes are likely to improve avian biodiversity and be beneficial to many species across different periods of the annual cycle (Grinde et al., 2017; Lindenmayer et al., 2000; Sheehan et al., 2014).

Contrary to positive short-term post-harvest responses on public lands documented by Nareff et al. (2019), Oliver et al. (2024) found no differences in cerulean occupancy in managed (1–4 years post-treatment) vs. unmanaged stands on private lands enrolled in the Natural Resources Conservation Service (NRCS) and Appalachian Mountain Joint Venture (AMJV) Cerulean Warbler Appalachian Forestland Enhancement Project in West Virginia. Shaffer et al. (2025) also reported a lack of a treatment effect on cerulean occupancy across Pennsylvania and Maryland private lands enrolled in the program, and their findings elaborated that pre-harvest stand conditions and proximity to existing breeding cerulean populations are highly influential to likelihood of cerulean occupancy of managed stands. Thus, implementation of successful cerulean prescriptions may be especially challenging in situations affected by some combination of habitat fragmentation, a lack of large-diameter trees due to a history of high-grading (Ciuzio et al., 2013; Shaffer et al., 2025), or lack of tree species favored by ceruleans (Boves et al., 2013a; Shaffer et al., 2025).

Based on our results, we recommend further research in other portions of the cerulean's range, and more long-term monitoring of ceruleans' and other wildlife species' responses to forest management to increase our understanding of dynamic responses to changing forest structure. Of particular interest would be an evaluation of the hypotheses that ceruleans are adapted to open canopy, fire-mediated systems, at least within the Appalachian portion of their range. In addition, more targeted studies should be implemented to assess ceruleans' responses to other midstory reduction treatments in stands that are developing a dense mid-story after a decade or more of regrowth. Such studies could compare cerulean responses following various periodic midstory reduction methods designed to result in open woodland conditions.

5. Conclusions

We found that cerulean territory density increases at three study sites in the Appalachians following timber harvest were generally not sustained after 13–14 years post-treatment. Although Cerulean Warbler prescription harvests in this region still can provide short-term benefits for the species, it is important to factor in the ephemeral nature of the benefits into long-term cerulean conservation plans. Reductions in cerulean density > 4 yrs after harvest appears to be affected by the development of the midstory layer, warranting future research that involves midstory reduction within the ~4–13-year post-harvest window to determine if density increases can be maintained with additional disturbance (via fire, chemical, or mechanical means). Careful selection and prioritization of sites with existing conditions favorable to ceruleans may improve the species' response to management. In any event, forest managers should not expect all "Cerulean Warbler prescription" applications to be successful at attracting ceruleans. Thus, the species will likely require extensive, targeted, adaptive, and ongoing forest management efforts if sufficient increases of breeding habitat acreages that result in sustainable regional population increases are to be achieved.

CRediT authorship contribution statement

Douglas W. Raybuck: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **David A. Buehler:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Patrick D. Keyser:** Writing – review & editing, Conceptualization. **Than J. Boves:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Conceptualization. **Jeffery L. Larkin:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

Declaration of Competing Interest

This article is based on our original research, has not been published, is not currently in consideration for publication elsewhere, and it is being submitted exclusively to Forest Ecology and Management. We declare that we have no conflicts of interest regarding this article or its future publication.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.foreco.2025.123005.

Data Availability

Data will be made available on request.

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