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RESEARCH ARTICLE

Breeding latitude drives demographic rate variation in wood duck populations, informing banding strategies in eastern North America

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Abstract

Sustainable game management requires effective monitoring of population trends and demography at a biologically relevant scale. As a commonly harvested species that uses forested wetlands throughout their annual cycle, wood ducks (*Aix sponsa*) are challenging to monitor using traditional abundance methods; thus, banding is critical for assessing vital rates. We used capture-mark-recovery data of wood ducks banded during the pre-season period from 2000–2022 to evaluate spatial variation in demographic rates and used the results to provide updated monitoring recommendations. We fit a dead-recovery model with Brownie parameterization within a Bayesian framework at varying spatial scales to characterize demographic rate variability. We identified significant latitudinal gradients in wood duck demography within the Atlantic and Mississippi flyways. Specifically, 3 latitudinal regions maximized inter-region variation and minimized intra-region variation in survival and harvest probabilities. Using simulations of varied band deployment across these latitudinal zones, we found that current deployment distribution was reasonably robust to latitudinal bias, but changing deployments in the future could lead to considerable bias in flyway-wide estimates of survival and harvest probability, which are used to set harvest regulations. We recommend revised banding goals and annual estimation of survival and harvest probabilities by latitudinal region to optimize wood duck harvest management and account for changes in band distribution over time.

KEYWORDS
Aix sponsa, Atlantic Flyway, mark-recovery, Mississippi Flyway, waterfowl management, wood duck

Sustainable harvest strategies aim to strike a balance between present use and long-term conservation goals (Wefering et al. 2000, Heffelfinger et al. 2013). Informed management decisions hinge on the availability of reliable population monitoring data at a biologically relevant scale (Witmer 2005, Runge et al. 2009, U.S. Fish and Wildlife Service 2023), which are often challenging to obtain owing to high costs, the need for specialized equipment, and significant staffing requirements (Thompson et al 1998). For waterfowl, population estimation and modeling are typically conducted using data from aerial surveys, a method that has proven effective for many species across North America for more than a half century (Nichols et al. 2007, U.S. Fish and Wildlife Service 2023). These methods fall short for more cryptic species like the wood duck (*Aix sponsa*); these ducks exhibit extensive geographic breeding ranges and are difficult to detect because of their use of forested wetlands, making aerial surveys impractical at the scale of their North American breeding range (Kelley 1997, Garrettson 2007).

Wood ducks are one of the most commonly harvested and cryptic waterfowl species in eastern North America (Bellrose and Holm 1994, Fronczak 2021, Raftovich et al. 2022); Kelley (1997) claimed that the development of a wood duck population monitoring program in eastern North American was one of the most challenging tasks facing waterfowl managers. Consequently, banding has become the primary method for wood duck monitoring (Kelley 1997, Garrettson 2021), although its effectiveness relies on critical assumptions, such as representative sampling and accounting for unequal survival and recovery rates across subpopulations and migration strategies (Brownie et al. 1985, Alisauskas et al. 2009). Given the extensive range and the existence of both migratory and non-migratory populations of wood ducks (Hepp and Hines 1991, Bellrose and Holm 1994), quantifying these assumptions is essential to reduce bias in harvest and survival rates (Pollock and Raveling 1982, Nichols and Johnson 1990) and any derived population estimates (Alisauskas et al. 2009).

Research indicates substantial spatial variability in wood duck vital rates, with differences in harvest exposure between northern and southern breeding populations (Heusmann and McDonald 2002, Greenawalt et al. 2022). Specifically, wood ducks banded in more northern latitudes seemingly travel farther distances and have greater harvest and lower survival rates (Nichols and Johnson 1990, Bellrose and Holm 1994, Heusmann and McDonald 2002, Garrettson 2007). This heterogeneity in vital rates may result in biased inferences if sampling and banding effort do not adequately capture this diversity or if efforts are inconsistent over time and space (Pollock and Raveling 1982, Brownie et al. 1985). Despite changes in reporting rates, regulations, and available analytical techniques, a spatial analysis of demographic rates and updated banding goals had not been reevaluated in over 20 years (Kelley 1997, Garrettson and Howard 2023).

In the United States portions of the Mississippi and Atlantic flyways, the wood duck daily bag limit was raised from 2 to 3 per hunter in 2008 in response to an assessment of harvest potential (Garrettson 2007) and additional work that suggested this bag increase would not result in harvest rates above allowable take (Balkcom et al. 2014). These assessments relied heavily on banding data. In allowing this regulation change, the United States Fish and Wildlife Service (USFWS) regulations committee required annual monitoring of wood duck kill rates (Garrettson 2021). In the Mississippi Flyway, the general duck season length depends heavily upon the status of mid-continent mallard (*Anas platyrhynchos*) and pond estimates from the Waterfowl Population and Breeding Habitat Survey (USFWS 2023), whereas the Atlantic Flyway uses a multi-stock management approach, with annual regulations informed by harvest rate estimates from several species, including wood ducks, calculated from banding data (Garrettson 2021, USFWS 2023). Greenawalt et al. (2022) demonstrated sufficient spatial variability in wood duck harvest probabilities among some banding locations, in conjunction with Garrettson (2007, 2021), raising concerns that declining banding effort in the southeastern United States could reduce precision of estimates and bias flyway-wide demographic estimates. Declining banding effort could be due to a multitude of factors, which include funding constraints, staff shortages, and locating suitable banding sites. This uneven distribution of banding efforts among states may bias demographic rate estimates if band deployment locations vary over time, potentially leading to sub-optimal harvest management decisions. Thus, identifying and delineating an appropriate geographic scale to update banding goals is critical to ensure valid harvest management decisions.

We present updated benchmarks tailored to wood duck regional demography to optimize monitoring efforts. Because wood ducks remain one of the most harvested waterfowl species in eastern North America without a comprehensive population survey (Fronczak 2021, Garrettson 2021, Raftovich et al. 2022), our objectives were to quantify spatial variation in survival and harvest probabilities of wood ducks at multiple scales across North America, identify appropriate population delineations and monitoring units based on this variation, and provide updated banding goals to support robust inferences for harvest management.

STUDY AREA

Our study included wood ducks banded in the United States and Canadian portions of the Mississippi and Atlantic flyways (Table S1). The states and provinces included in these regions encompass most of the wood duck annual range (i.e., breeding and wintering) in eastern North America (Bellrose and Holm 1994). Although several Canadian provinces were included in our study area, banding stations that capture pre-season wood ducks only occur in the southern portions. The northernmost banding location occurred at 49.5 degrees latitude and the southernmost occurred at 26.5 degrees latitude. This portion of eastern North America is diverse, including 15 Bird Conservation Regions and 9 Migratory Bird Joint Ventures (U.S. North American Bird Conservation Initiative Committee 2000, National Joint Venture Communications, Education, and Outreach Team 2020). Wood ducks breed throughout this entire range but only winter in southern portions of the flyways, generally south of 35 degrees latitude (Dugger and Fredrickson 1992). Birds that breed south of North Carolina, Tennessee, and Little Rock, Arkansas, USA, are essentially nonmigratory (Bellrose and Holm 1994).

METHODS

Band-recovery data

Wood ducks were captured during the July-September (i.e., pre-season period) by state and federal agencies and individually marked with United States Geological Survey (USGS) aluminum leg bands. All capture methods involved using bait with either swim-in traps (Dieter et al. 2009), rocket nets, or walk-in confusion traps (Sharp and Smith 1986). Upon capture, wood ducks were sexed and aged as either hatch year (hereafter juvenile) or after hatch year (hereafter adult) by plumage characteristics and cloacal examination (Carney 1992). These characteristics established 4 cohorts of wood ducks: adult female (AF), adult male (AM), juvenile female (JF), and juvenile male (JM). We obtained recovery data, including location, using citizen science data from the USGS Bird Banding Laboratory (BBL) when banded birds were harvested by waterfowl hunters or found dead and the uniquely marked band was reported.

We downloaded wood duck banding data (deployments and recoveries) from the USGS BBL from 1960–2022 (Celis-Murillo et al. 2022). We limited bandings and recoveries to include birds banded in 2000–2021 during the pre-hunting season (Balkcom et al. 2014) and recovered in 2000–2022, making 2021–2022 the last hunting season included in the analysis. We chose this timeframe to align with the dates of the last major distribution study (Kelley 1997; Garrettson 2007, 2021; Greenawalt et al. 2022) and to limit effects of landscape changes, policy shifts influencing band deployment, and changes in the BBL data collection methodologies or other external factors that may have occurred over a longer period. This timeframe also facilitates comparisons with recently completed work (Garrettson 2021, Greenawalt et al. 2022).

For bandings and recoveries, we excluded birds of unknown age or sex to omit accounts with missing data (Garrettson 2007, 2021; Garrettson and Howard 2023), birds that were banded as local (i.e., flightless) to avoid potentially biasing survival of our focal flighted juvenile cohort (Hestbeck et al. 1989), and birds banded in nest boxes that may bias survival and recovery rates (Balkcom et al. 2014, Garrettson 2021). We chose to exclude these birds based on previous analyses to maintain a conservative approach. Some birds included in the analysis could have been and probably were produced in nest boxes and then later captured in traps during the pre-season period. We included only birds banded under status codes not expected to influence survival or band reporting rates: normal wild (BBL status code = 3), birds that were only marked with federal numbered leg bands (BBL code = 00), thus excluding auxiliary markers (e.g., transmitters, additional bands, geolocators), control birds in a reward band study (BBL code = 04), and birds that were night-lighted (BBL code = 70). We included only recoveries recorded as shot (BBL how code = 1) or found dead (BBL how code = 0; Garrettson 2021).

As each hunting season includes 2 calendar years, we converted recovery year to recovery season. For recoveries with a specified recovery month, birds recovered from September – December were assigned a recovery season that equaled the recovery year. Birds recovered from January – February were assigned a recovery season of the previous year (i.e., recovery year − 1; Garrettson 2021, Garrettson and Howard 2023, Greenawalt 2023). We included recoveries listed as fall (BBL month code = 93) or hunting season (BBL month code = 94), and for these, the recovery season was equal to the recovery year. Recoveries listed as spring (BBL month code = 83) were assigned a recovery season equal to the recovery year − 1. We excluded recoveries with an unknown month of encounter (BBL month code = 99). We included recoveries regardless of who reported them or the reporting method used (e.g., phone or web; Garrettson 2021, Greenawalt et al. 2022). We excluded any birds not meeting recovery criteria from the band release data.

Spatial variation in harvest probabilities

To quantify spatial variation in demographic rates, as an *a priori* hypothesis guided by Garrettson (2007, 2021) and Greenawalt et al. (2022), and based on the results of each subdivision, we created 12 different regional subdivisions (Table 1). We fit a dead-recovery model to each of the 12 regional subdivisions, each with a different number of spatial strata (k) dependent on the number of regions in that division (e.g., Kelley [1997] regions $k = 6$, north vs. south $k = 2$). To quantify the spatial variation in harvest probabilities, we used the coefficient of variation within and among the spatial strata to calculate a ratio for each of the 12 regional subdivisions:

$$\text{Variation ratio} = \frac{\text{Harvest probabilities CV among strata}}{\text{Harvest probabilities CV within strata}}.$$

We wanted to maximize the variation among regions and minimize the variation within a region. This method allows the identification of the most efficient yet scientifically sound geographic scale to assign new banding goals. By identifying the largest demographically homogenous scale, fewer total bands will be needed to be deployed across the flyways, reducing the burden on state and federal banding programs. Therefore, we ranked the 12 different scenarios from best (greatest variation ratio) to worst (smallest variation ratio) to determine the most appropriate scale for estimating banding goals.

Dead-recovery model

Following methods used by Greenawalt et al. (2022), we used a dead-recovery model with Brownie parameterization (Brownie et al. 1985) within a Bayesian framework. For each year (t) and spatial stratum (k), we estimated sex

TABLE 1 The top 5 ranked regional divisions created to assess demographic rate variability of pre-season banded wood ducks in eastern North America from 2000–2022. We provide a description of the subdivisions, the number of strata (*k*) created in each subdivision, and each subdivision coefficient of variation (CV) rank according to our harvest CV ratio. This ratio was calculated by dividing the estimated harvest probability CV among each stratum by the CV within the spatial strata of each subdivision. We then ranked each subdivision from best (greatest variation ratio) to worst (smallest variation ratio).

Subdivision	Description	*k*	Rank
Equal break, 3 latitudinal bins	The U.S. and Canadian portions of the Mississippi and Atlantic flyways divided into 3 bins using an equal break sequence between the minimum and maximum latitude of banding locations.	3	1
Equal break, 3 latitudinal bins, U.S.	The U.S. portion of the Mississippi and Atlantic flyways divided into 3 bins using an equal break sequence between the minimum and maximum latitude of banding locations.	3	2
Three latitudinal regions	The U.S. and Canadian portions of the Mississippi and Atlantic flyways divided into 3 regions by state and province based on the latitudinal lines from 3 latitudinal bins that include Canada.	3	3
Equal break, 5 latitudinal bins, U.S.	The U.S. portion of the Mississippi and Atlantic flyways divided into 5 bins using an equal break sequence between the minimum and maximum latitude of banding locations.	5	4
Three state latitudinal regions	The U.S. portion of the Mississippi and Atlantic flyways divided into 3 regions by state based on the latitudinal lines of 3 latitudinal bins.	3	5
Northern and southern regions	The U.S. and Canadian portions of the Mississippi and Atlantic flyway divided by state and providence from Garrettson 2007.	2	6
North vs. south longitudinal bins	The U.S. and Canadian portions of the Mississippi and Atlantic flyways divided in half latitudinal. Then divided into thirds longitudinally using a separate equal break sequence between the minimum and maximum longitude of banding locations for the north and south half.	6	7
Kelley regions	The wood duck sub-population regions described by Kelley (1997).	6	8
U.S. flyway quadrants	The U.S. portions of the Mississippi and Atlantic flyways divided by state, flyway, and north vs. south region.	4	9
Flyways	The U.S. and Canadian portions of the Mississippi and Atlantic flyways.	2	10
Equal break, 5 longitudinal bins, U.S.	The U.S. portion of the Mississippi and Atlantic flyways divided into 5 bins using an equal break sequence between the minimum and maximum longitude of banding locations.	5	11
Equal break, 10 longitudinal bins, U.S.	The U.S. portion of the Mississippi and Atlantic flyways divided into 10 bins using an equal break sequence between the minimum and maximum longitude of banding locations.	10	12

(*l*) and age (*m*) specific (i.e., cohorts) band-recovery probabilities ($f_{t,k,l,m}$) as a function of hunting mortality (i.e., harvest; $Hm_{t,k,l,m}$), crippling loss (cL), and time-specific band-reporting probabilities (p_t) from 2000–2022:

$$f_{t,k,l,m} = Hm_{t,k,l,m} \times p_t \times (1 - cL).$$

We assumed a constant crippling loss of 0.2 throughout the study period for all cohorts (Martin and Carney 1977, Hicklin and Barrow 2004, Schulz et al. 2006). We used time-specific band reporting probabilities (p_t) from 2000–2017 ranging from 0.714 (SD = 0.017) to 0.833 (SD = 0.30) and calculated a constant rate of 0.841

(SD = 0.03) for 2017–2022 by transforming means and standard deviations of annual band reporting probability estimates to shape parameters of a beta distribution using moment matching (Hobbs and Hooten 2015, Arnold et al. 2020, Greenawalt et al. 2022, Thompson et al. 2022). We then included band reporting probabilities as informative priors to account for the uncertainty in band reporting probability estimates.

We modeled harvest and natural mortality with a grand mean for each cohort, spatial stratum, and random year effects. Harvest includes all mortality associated with hunting (i.e., killed by a hunter regardless of retrieval or reporting status); thus, harvest probability will be higher than recovery rate. Natural mortality includes all other sources of mortality (Brownie et al. 1985, Kéry and Schaub 2012). We modeled cohort- and stratum-specific grand mean hunting and natural mortality using vague priors on the probability scale and transformed to the logit scale to include the random effect:

$$Mean.\ Hm_{t,k,l,m} \sim \text{Beta}(1,\ 1)$$

$$Mean.\ Nm_{t,k,l,m} \sim \text{Beta}(1,\ 1)$$

$$\text{logit}(Hm_{t,k,l,m}) \sim \text{Normal}\left(\text{logit}(Mean.\ Hm_{t,k,l,m}),\ \sigma^2_{Hm,k,l,m}\right),$$

$$\sigma_{Hm,k,l,m} \sim \text{Uniform}(0,\ 2)$$

$$logit\,(Nm_{t,k,l,m}) \sim \text{Normal}\left(\text{logit}(Mean.\ Nm_{t,k,l,m}),\ \sigma^2_{Nm,k,l,m}\right),$$

$$\sigma_{Nm,k,l,m} \sim \text{Uniform}(0,\ 2),$$

where $Mean.\ Hm_{t,k,l,m}$ and $Mean.\ Nm_{t,k,l,m}$ are the grand means for hunting mortality and natural mortality, $\sigma^2_{Hm,k,l,m}$ and $\sigma^2_{Nm,k,l,m}$ are the variances for the random year effect for hunting and natural mortality, and $\sigma_{Hm,k,l,m}$ and $\sigma_{Nm,k,l,m}$ are the standard deviations for the random year effects of hunting mortality and natural mortality for each spatial stratum (k), sex (l), and age (m). We calculated survival as a function of hunting ($Hm_{t,k,l,m}$) and natural mortality ($Nm_{t,k,l,m}$):

$$S_{t,k,l,m} = 1 - Hm_{t,k,l,m} - Nm_{t,k,l,m}.$$

We formatted band-recovery data into m-arrays and analyzed data with a multinomial likelihood to reduce computational requirements (Brownie et al. 1985, Kéry and Schaub 2012). Each row was modeled as a multinomial trial with the number of released individuals in each year as the index (Kéry and Schaub 2012). Multinomial cell probabilities denote the probability of being recovered between the release occasion until the end of the study, and the probability of never being recovered. Therefore, cell probabilities were functions of survival ($S_{k,l,m}$) and recovery ($f_{k,l,m}$) parameters for each stratum (k), sex (l), and age (m), where S_{ahy} and f_{ahy} are the survival and recovery probabilities of adults, and S_{hy} and f_{hy} are the survival and recovery probabilities of juveniles. We assumed birds banded as juveniles had the same survival and recovery probabilities as adults once they progressed into that cohort the following spring. Direct recoveries for adults and juveniles were a function of recovery probabilities ($f_{k,l,m}$) for each cohort. For adults, subsequent indirect recovery cell probabilities were a function of annual survival and recovery:

$$\left(\prod_{t=1}^{t-1} S_{t,k,l,m}\right) f_{t,k,l,k}.$$

For juveniles, subsequent indirect recovery cell probabilities were a function of survival ($S_{hy,k,l}$) in the first year as a juvenile and then survival ($S_{ahy,k,l}$) and recovery probabilities ($f_{ahy,k,l}$) as an adult. Specifically, juveniles harvested their first year as an adult followed the equation:

$$S_{hy,t=1,k,l}\, f_{ahy,t,k,l}.$$

Wood ducks banded as juveniles and then harvested in their t year as an adult followed the equation:

$$S_{hy,t=1,k,l}\left(\prod_{t=2}^{t-1} S_{ahy,k,l}\right) f_{ahy,t,k,l}.$$

We calculated the probability of never being recovered as 1 minus the sum of the probabilities of being recovered for individuals of the same release year.

Simulations

Based on the results of the first phase of our analysis, we then simulated band deployment scenarios at several geographic scales to understand how banding deployment distributions could affect future wood duck demographic estimates. We created band deployment simulation scenarios at 1) the current flyway scale; 2) our third-ranked subdivision scale (3 latitudinal regions, see results below; Figure 1B), which we found to be the best subdivision to create new banding goals; and 3) a smaller, intersected flyway by latitudinal region scale (Figure 1C), which was a hybrid of the 2 other scales. We simulated the effects of varying banding effort across 24 different scenarios at those 3 scales (i.e., flyway, 3 latitudinal regions, and Atlantic or Mississippi flyway latitudinal regions; Table S2). We simulated band-recovery data based on estimated demographic probabilities for each cohort in each region. For each banding scenario, we assigned a total number of bands to each region that varied by scenario. We then calculated the simulated cohort-specific band deployments for each region and scenario based on the cohort's current actual percentage of the banded sample in that region. These cohort percentages were based on the average banding frequency and cohort percentage in each determined region from 2016–2021 (Table 2, S3).

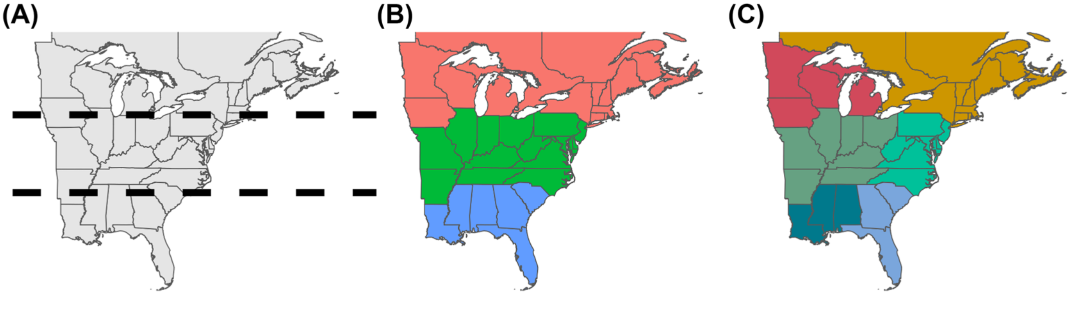

FIGURE 1 We derived wood duck demographic rates from 2000–2022 from banding data in a mark-recovery framework at varying spatial scales to identify possible new wood duck management regions. We divided eastern North America into various strata to compare demographic rates of wood ducks banded in each. We found that divisions based on equal break, 3 latitudinal bins (A) maximized demographic rate variation among each stratum and minimized variation within each stratum. From this we created 3 latitudinal regions (B), dividing states and provinces along those latitudinal lines. We then also divided these regions by flyway (C) to create 6 different regions for flyway administrative purposes.

TABLE 2 The average banding distribution, frequency, and percentage of pre-season banded wood ducks in 3 latitudinal regions (across flyways) and latitudinal regions by flyway in eastern North America from 2016–2021. Banding frequencies are divided by latitudinal regions (north, central, south) within each geographic scale determined using demographic rate variability.

Geographic scale	Region	Average yearly band deployments	Percentage of geographic scale total
Three latitudinal regions	North	11,345	40.09
	Central	11,382	40.09
	South	5,569	19.68
	Total	28,296	
Atlantic Flyway	North	2,314	29.58
	Central	4,230	54.07
	South	1,279	16.35
	Total	7,823	
Mississippi Flyway	North	9,068	44.29
	Central	7,115	34.75
	South	4,290	20.95
	Total	20,473	

TABLE 3 The estimated average harvest probability and standard deviation (SD) from 2000–2022 of pre-season banded wood ducks in 3 latitudinal regions (across flyways) and latitudinal regions by flyway in eastern North America. Harvest probabilities and standard deviations are presented by latitudinal regions (north, central, south) within each geographic scale determined using demographic rate variability.

		Adult female		Adult male		Juvenile female		Juvenile male	
Geographic scale	Region	Harvest	SD	Harvest	SD	Harvest	SD	Harvest	SD
Three latitudinal regions	North	0.101	0.0040	0.136	0.0047	0.166	0.0083	0.202	0.0078
	Central	0.086	0.0047	0.123	0.0048	0.127	0.0060	0.165	0.0041
	South	0.063	0.0053	0.100	0.0042	0.084	0.0079	0.118	0.0080
Atlantic Flyway	North	0.091	0.0049	0.137	0.0067	0.151	0.0081	0.188	0.0086
	Central	0.092	0.0076	0.135	0.0062	0.138	0.0085	0.171	0.0095
	South	0.068	0.0093	0.106	0.0072	0.109	0.0171	0.139	0.0189
Mississippi Flyway	North	0.108	0.0073	0.134	0.0062	0.176	0.0123	0.211	0.0119
	Central	0.083	0.0054	0.118	0.0058	0.125	0.0071	0.163	0.0063
	South	0.060	0.0064	0.095	0.0054	0.078	0.0079	0.112	0.0095

We simulated dead-recovery data using the banding numbers and random values for demographic probabilities drawn from beta distributions of hunting mortality (*Hm*) and natural mortality (*Nm*) that were specific to that geographic region or strata (*k*; Tables 3 and 4).

$$Nm_{k,l,m} \sim \text{beta}(\alpha_{Nm,k,l,m},\ \beta_{Nm,k,l,m}),$$

TABLE 4 Estimated average natural mortality probability and standard deviations (SD) from 2000–2022 of pre-season banded wood ducks in 3 latitudinal regions (across flyways) and latitudinal regions by flyway in eastern North America. Natural mortality probabilities and standard deviations are presented by latitudinal regions (north, central, south) within each geographic scale determined using demographic rate variability.

		Adult female		Adult male		Juvenile female		Juvenile male	
Geographic scale	Region	Natural	SD	Natural	SD	Natural	SD	Natural	SD
Three latitudinal regions	North	0.397	0.0149	0.275	0.0194	0.373	0.0229	0.289	0.0159
	Central	0.402	0.0306	0.268	0.0196	0.380	0.0231	0.279	0.0198
	South	0.421	0.0287	0.285	0.0323	0.413	0.0434	0.233	0.0303
Atlantic Flyway	North	0.399	0.0306	0.283	0.0258	0.365	0.0357	0.288	0.0278
	Central	0.390	0.0409	0.267	0.0335	0.368	0.0438	0.293	0.0370
	South	0.406	0.0756	0.291	0.0458	0.274	0.0703	0.211	0.0767
Mississippi Flyway	North	0.394	0.0205	0.269	0.0235	0.379	0.0224	0.290	0.0196
	Central	0.405	0.0271	0.269	0.0222	0.375	0.0256	0.270	0.0228
	South	0.427	0.0373	0.281	0.0324	0.424	0.0556	0.224	0.0293

$$Hm_{k,l,m} \sim \text{beta}(\alpha_{Hm,k,l,m},\ \beta_{Hm,k,l,m}).$$

For the simulations, we used a reporting rate of 0.841 (SD = 0.030) to calculate shape parameters for a beta distribution (Greenawalt et al. 2022). Including this variability is important to reflect and account for the real-world complexity in reporting probabilities:

$$p_t \sim \text{beta}(\alpha_{p_t},\ \beta_{p_t}).$$

We generated random numbers from a multinomial distribution to create the dead-recovery data for each stratum, age, and sex class.

To obtain estimates for each flyway, we simulated band recovery for each region divided by flyway and then combined the data for the entire flyway (i.e., $k = 1$). For the 3 latitudinal regions and the Atlantic or Mississippi flyway latitudinal regions, we again simulated data for each region but then modeled demographic probabilities separately. We simulated data for each banding scenario 100 times for a 5-year period and fit the simulated banding data to the dead-recovery model. We calculated bias for demographic probabilities from each iteration of the simulation and then summarized across the 100 simulations:

$$\text{Bias} = \left| \frac{\text{demographic parameter estimate} - \text{simulated truth}}{\text{simulated truth}} \right|.$$

We also calculated coefficients of variation (CVs) for estimates of harvest probabilities for each scenario. We sought to provide banding recommendations that met a ≤7% 5-year mean CV precision threshold. This precision goal was determined by Garrettson (2021) through discussions with stakeholders in both flyways. We identified banding goals at the 3 latitudinal regions scale, Atlantic latitudinal regions scale, and the Mississippi latitudinal regions scale based on the banding distributions that reached the desired precision threshold. We used a logarithmic regression to assess how the number of band deployments from simulations related to harvest probability CVs (i.e., band deployments ~ log (harvest probability CV)). We provided banding goals similar to Collins et al. (2023), which is a total banding number across all cohorts and accounts for a given cohort, given that cohort's percentage of the observed banded sample. For example, if 2,000 adult females need to be banded to reach adult female precision levels and this cohort makes up 20% of the banded sample, the recommended goal for the given area would be 10,000 total bands deployed.

We conducted all analyses in JAGS (Plummer 2003) using the jagsUI package (Kellner 2019) in R 4.2.2 (R Core Team 2022). We ran 3 Markov chain Monte Carlo (MCMC) chains for 150,000 iterations and discarded the first 50,000 iterations as a burn-in and then retained every 50th iteration. We then visually assessed trace plots and MCMC chains for convergence and used the Brooks-Gelman-Rubin statistic ($\hat{R}$) < 1.01 as an assessment of convergence (Brooks and Gelman 1998). We assessed model fit using Bayesian *P*-values calculated from the Freeman-Tukey statistic as described by Brooks et al. (2000). A Bayesian *P*-value close to 0.5 suggests the model is adequate (Brooks et al. 2000, Kéry and Schaub 2012).

RESULTS

Over our 22-year analysis period, 611,148 banded wood ducks met inclusion criteria. Of those, 183,018 (29.9%) were banded in the Atlantic Flyway and 428,130 (70.1%) were banded in the Mississippi Flyway. Of bands deployed, 99,777 (16.3% of deployments) were recovered that fit inclusion criteria. Of recovered bands, 13,242 (13.3%) were recovered in a flyway different than their banding flyway; 6,765 (6.8%) birds banded in the Mississippi Flyway were recovered in the Atlantic Flyway, and 3,462 (3.5%) birds banded in the Atlantic Flyway were recovered in the Mississippi Flyway. In addition, 3,015 (3.0%) birds were recovered in the Central Flyway; of those, 110 were banded in the Atlantic Flyway.

Spatial variation in harvest probabilities

The different subdivisions resulted in slightly different estimates of harvest and survival and associated uncertainty (Figures S1 and S12). At the flyway scale, we found similar mean annual survival and harvest probabilities in the Atlantic and Mississippi flyways for each cohort (Tables 5 and 6; Figure S9). At the flyway scale, geographic variability of demographic rates was masked, and the flyway scale ranked poorly in subdivision comparisons

TABLE 5 Average estimated survival rates and coefficients of variation (CVs) of pre-season banded wood ducks from 2000–2022 in eastern North America estimated for each Kelley (1997) region and flyway.

	Adult female		Adult male		Juvenile female		Juvenile male	
Subpopulation region	Survival	CV	Survival	CV	Survival	CV	Survival	CV
North East[a]	0.508	7.18	0.585	3.34	0.485	7.96	0.524	4.88
Mid-Atlantic[a]	0.526	6.24	0.604	5.88	0.560	9.95	0.595	7.58
Southern[a]	0.513	4.07	0.619	2.97	0.508	7.12	0.600	3.33
South East[a]	0.525	22.51	0.609	13.51	0.494	24.88	0.582	14.81
Lake States[a]	0.503	6.44	0.597	5.90	0.498	10.00	0.512	6.14
North Central[a]	0.506	5.46	0.605	2.51	0.468	5.51	0.533	4.10
Mississippi Flyway	0.508	3.29	0.608	2.79	0.486	5.01	0.540	2.50
Atlantic Flyway	0.512	6.99	0.586	4.18	0.514	6.50	0.548	4.15

[a]Kelley (1997) regions.

TABLE 6 Average estimated harvest probabilities and coefficients of variation (CVs) of pre-season banded wood ducks wood ducks from 2000–2022 in eastern North America, estimated for each Kelley (1997) region and flyway.

Subpopulation region	Adult female		Adult male		Juvenile female		Juvenile male	
	Harvest	CV	Harvest	CV	Harvest	CV	Harvest	CV
North East[a]	0.099	5.42	0.142	3.97	0.160	5.87	0.196	4.92
Mid-Atlantic[a]	0.080	9.21	0.125	7.60	0.124	8.42	0.154	9.11
Southern[a]	0.073	7.50	0.106	5.20	0.110	6.32	0.146	5.38
South East[a]	0.067	22.83	0.096	10.66	0.094	30.01	0.124	13.87
Lake States[a]	0.086	7.66	0.132	6.99	0.134	9.12	0.174	7.16
North Central[a]	0.097	7.23	0.128	4.51	0.152	6.43	0.188	5.24
Mississippi Flyway	0.084	5.61	0.122	4.16	0.128	5.00	0.166	4.29
Atlantic Flyway	0.085	6.34	0.131	4.79	0.140	6.22	0.174	5.40

[a]Kelley (1997) regions.

(CV ratio = 2.34; rank = 10; Table 1, S4). The top-ranking subdivision model was the equal break, 3 latitudinal bins scale, which encompassed both flyways (CV ratio = 4.83; rank = 1; Table 1; Figure 1A). At this scale, we observed greater mean annual harvest probability in our northernmost bin (AF = 0.100, AM = 0.136, JF = 0.164, JM = 0.202) and lower mean annual harvest probabilities in our southernmost bin (AF = 0.063, AM = 0.098, JF = 0.084, JM = 0.117), especially in the juvenile cohorts. Our highest performing and pragmatic subdivision model was the 3 latitudinal regions scale (CV ratio = 4.52; Table 1; Figure 1B). This model fit the data moderately well based on our average Bayesian *P*-value of 0.35 (Figure S18).

All subdivisions with bins along a longitudinal gradient (east to west) encompassing both flyways ranked poorly (Table 1). For example, the equal break, 5 longitudinal bins, U.S. scale, which encompassed both flyways, ranked eleventh (Table 1). The Kelley (1997) scale only had notable variation in mean annual harvest probability between northern and southern regions (Table 6), with little variation in harvest elsewhere. Specifically, we only found a 0.008 difference in juvenile male annual harvest probabilities between the North East (0.196; 95% Bayesian credible interval [BCI] = 0.176–0.216) and North Central (0.188; 95% BCI = 0.169–0.208) regions, and only a 0.022 difference between the Southern (0.146; 95% BCI = 0.131–0.162) and South East (0.124; 95% BCI = 0.090–0.160) regions. The Kelley (1997) regions ranked eighth (CV ratio = 2.86) among the subdivisions (Table 1).

Simulations

Flyway scale

Grouping simulated data across the Atlantic Flyway, the current banding distribution and frequency reached mean harvest probability CV targets of ≤7% for 5-year means for all cohorts except adult females (AF = 7.4%, AM = 5.0%, JF = 6.0%, JM = 5.03%; Figure 2). Shifting band distributions northward increased estimated mean harvest probabilities, and shifting band distributions southward decreased estimated mean harvested probabilities; however, the change in mean harvest probability was less intense and there was little change in bias (Figure S13). For example, shifting 70% of band deployments to our identified northern region created only marginally (≤0.03) greater mean annual harvest probabilities (AF = 0.087, AM = 0.133, JF = 0.144, JM = 0.181) than shifting 70% of band deployments to our identified southern region (AF = 0.072, AM = 0.113, JF = 0.121, JM = 0.152; Figure 2)

Grouping simulated data across the Mississippi Flyway, we found the current banding distribution met the mean annual harvest probability CV targets for all cohorts (AF = 5.4%, AM = 3.8%, JF = 4.2%, JM = 3.6%; Figure 2; Table 2). Shifting the banding distribution within the Mississippi Flyway affected mean harvest probability estimates; as band distribution shifted northward, harvest probabilities increased, with the opposite effect occurring if distributions shifted to the south. For example, shifting 70% of band deployments to our identified northern region produced higher mean annual harvest probabilities (AF = 0.10, AM = 0.13, JF = 0.15, JM = 0.19; Figure 2) than the scenario that shifted 70% of band deployments to our identified southern region (AF = 0.07, AM = 0.11, JF = 0.10, JM = 0.13; Figure 2). There was little change in bias of harvest estimates as banding distribution shifted (Figure S14).

Three latitudinal regions scale

There was a slight change in mean estimated annual harvest probabilities across simulations within the 3 latitudinal regions (Figure 1B); however, certainty around parameter estimates varied with regional banding efforts (Figure 3). The current banding distribution at the 3 latitudinal regions scale met desired precision thresholds across all regions and cohorts except in the southern region for adult (CV = 10.42%) and juvenile (CV = 8.87%) females (Figure 3). Based on simulations, the southern region would need to increase band deployments by 115% to at least 11,999 bands to reach ≤7% CV for adult female harvest probability estimates (Figure 3).

At the 3 latitudinal regions scale, there was a slight change in the mean annual bias of parameter estimates as fewer bands were allocated to a given region (Figure S15). For example, allocating 50% of bands to the north, 25%

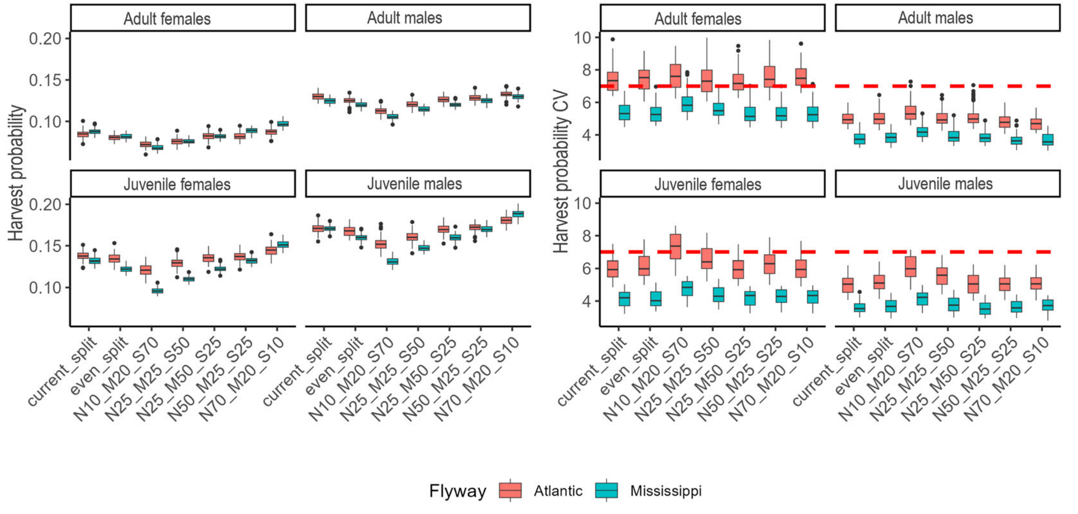

FIGURE 2 Estimated harvest probabilities (left) and associated coefficients of variation (CVs; right) for each Atlantic and Mississippi flyway simulation scenario of each pre-season banded wood duck cohort (adult female, adult male, juvenile female, juvenile male). The red-dashed lines depict the set target of precision for the 5-year mean CV at 7%. We derived estimates by simulating each banding scenario 100 times for a 5-year period based on region- and cohort-specific estimated demographic rates from 2000–2022. We calculated banding frequency for the simulation scenarios based on the average band deployments from 2016–2022. We then fit the simulated banding data to a dead-recovery model with Brownie parameterization (Brownie et al. 1985) within a Bayesian framework to obtain harvest estimates and associated variances. Scenarios are named by the proportion of band deployment in each region (north, middle, south; e.g., N10 means 10% of bands were allocated to the north region). Current split was the current band distribution, and even split was equal band distribution across each region.

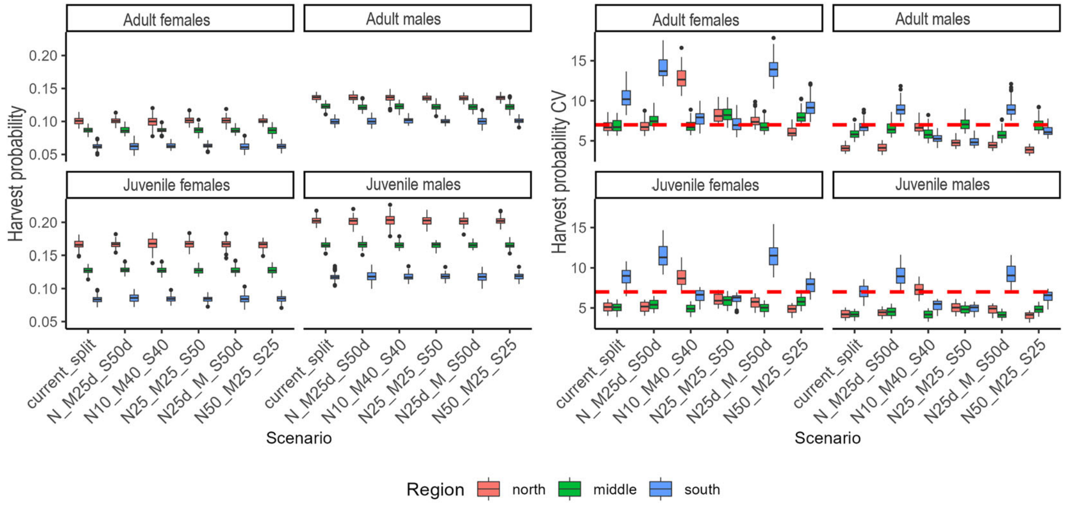

FIGURE 3 Estimated harvest probabilities (left) and associated coefficients of variation (CVs; right) for each simulation scenario for 3 latitudinal regions (across the Mississippi and Atlantic flyways) for each pre-season banded wood duck cohort (adult female, adult male, juvenile female, juvenile male). The red-dashed lines depict the set target of precision for the 5-year mean CV at 7%. We derived estimates by simulating each banding scenario 100 times for a 5-year period based on region- and cohort-specific estimates of demographic rates from 2000–2022. We calculated banding frequency for the simulation scenarios based on the average band deployments from 2016–2022. We then fit the simulated banding data to a dead-recovery model with Brownie parameterization (Brownie et al. 1985) within a Bayesian framework to obtain harvest probability estimates and associated variances. Scenarios are named by the proportion of band deployment in each region (north, middle, south; e.g., N10 means 10% of bands were allocated to the north region). Current split was the current band distribution, and N_M25d_S50d was the current banding total in the north region, a 25% decline of bandings in the middle region, and a 50% decline of bandings in the southern region.

to the central region, and 25% to the southern region led to a mean annual bias of 0.04, 0.07, and 0.08 for each respective region. Shifting 25% of the banding distribution to the north, 25% to the central region, and 50% to the southern region led to a mean annual bias of 0.06, 0.07, and 0.07 for each region. For all scenarios, regions, and cohorts at this scale, the mean annual bias ranged from 0.03 to 0.10, and each female cohort had slightly more bias (Figure S15).

Mississippi Flyway latitudinal regions scale

The Mississippi Flyway on average currently deploys 20,473 bands annually, with the northern region contributing most of the bands (Table 2). The current distribution and frequency did not meet mean harvest CV target levels for the adult female cohort in any region (north 7.54%, central 8.68%, south 17.78%), for adult males in the central (CV = 7.20%) and southern region (CV = 8.53%; Figure 4), or either juvenile cohort in the southern region (JF CV = 9.67%, JM CV = 8.00%). Based on our scenarios, band deployments in the Mississippi Flyway would need to be increased ≥28% (9,090 bands) in the central region, and ≥215% (13,530 bands) in the southern region to reach adult female precision targets (Figure 4).

For simulations at the Mississippi Flyway by latitudinal region scale, we observed small changes in the mean bias of parameter estimates as fewer bands were allocated to a given region (Figure S16). For example, for the adult female cohort, allocating 50% of bands in the north, 25% in the central, and 25% in the southern region led to mean

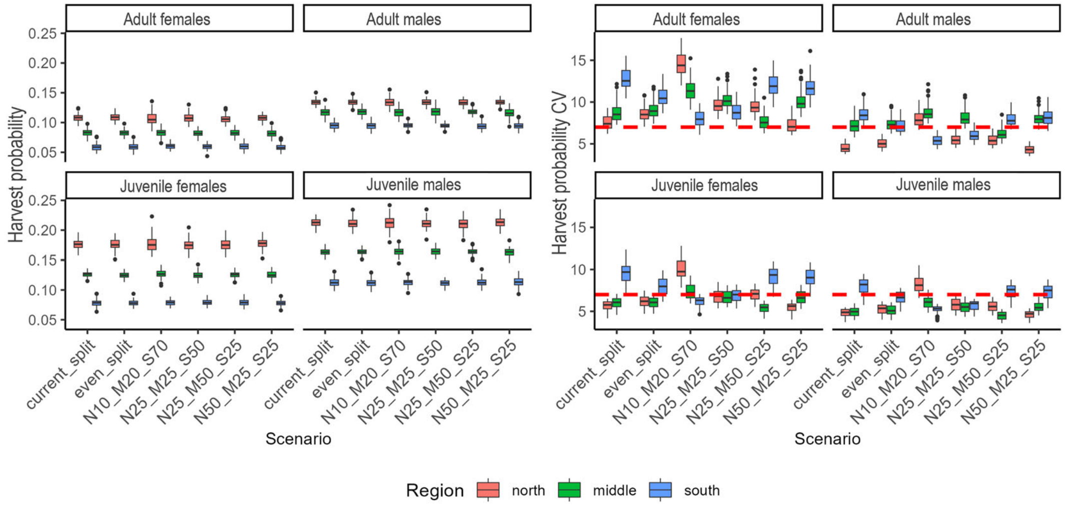

FIGURE 4 Estimated harvest probabilities (left) and associated coefficients of variation (CVs; right) for each simulation scenario for 3 latitudinal regions within the Mississippi Flyway for each pre-season banded wood duck cohort (adult female, adult male, juvenile female, juvenile male). The red-dashed lines depict the set target of precision for the 5-year mean CV at 7%. We derived estimates by simulating each banding scenario 100 times for a 5-year period based on region and cohort specific estimates of demographic probabilities from 2000–2022. We calculated banding frequency for the simulation scenarios based on the average band deployments from 2016–2022. We then fit the simulated banding data to a dead-recovery model with Brownie parameterization (Brownie et al. 1985) within a Bayesian framework to obtain harvest estimates and associated variances. Scenarios are named by the proportion of band deployment in each region (north, middle, south; e.g., N10 means 10% of bands were allocated to the north region). Current split was the current band distribution, and even split was equal band distribution across each region.

annual bias in estimates of 0.06, 0.08, and 0.10 for those regions. Switching this distribution to 25% of bands in the north, 25% in the central, and 50% in the southern region led to mean annual bias in estimates of 0.07, 0.08, and 0.09 for those regions. For all scenarios, regions, and cohorts at this scale, the mean annual bias in parameter estimates ranged from 0.04 to 0.10, with the greatest amount of bias in the adult female cohort and the least for adult and juvenile males.

Atlantic Flyway latitudinal regions scale

The Atlantic Flyway on average currently deploys 7,823 bands annually, with the central region contributing most of the bands (Table 2). Of all cohorts, only juvenile males in the central region (6.26% CV) met desired precision goals. The current banding distribution and frequency did not reach adult female (north 14.36%, central 10.22%, south 16.32% CV) or adult male (north 7.33%, central 7.77%, south 11.93% CV) mean variation targets in any region (Figures 5 and 6). To reach targets for adult females (thus all other cohorts too), the Atlantic Flyway would need to increase banding to at least 9,449 in the north, 8,475 in the central, and 9,279 in the south regions. If the flyway is only concerned with adult males, merely 3,306 bands in the north, 6,397 in the central, and 6,585 in the southern regions would need to be deployed.

The bias in parameter estimates was slightly more than those from simulations at the other scales (Figure S17). For example, for the adult female cohort, allocating 50% of current band numbers in the north, 25% in the central, and 25% in the southern region resulted in mean annual bias estimates of 0.08, 0.11, and 0.13 for those regions.

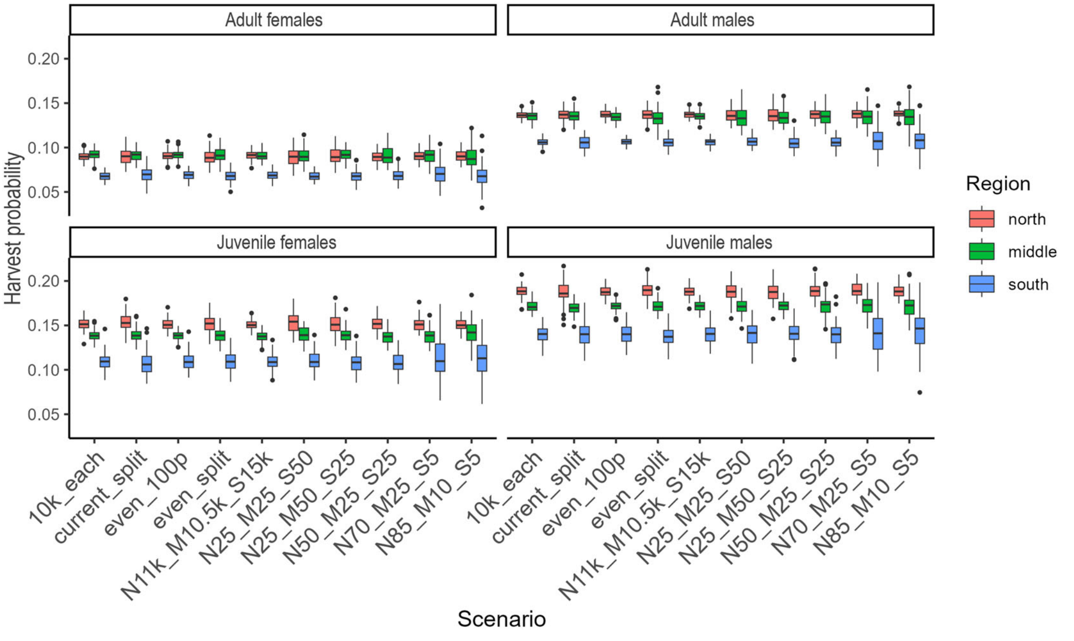

FIGURE 5 Estimated harvest probability for each simulation scenario for 3 latitudinal regions within the Atlantic Flyway for each pre-season banded wood duck cohort (adult female, adult male, juvenile female, juvenile male). We derived estimates by simulating each banding scenario 100 times for a 5-year period based on region and cohort specific estimate of demographic rates from 2000–2022. We calculated banding frequency for the simulation scenarios based on the average band deployments from 2016–2022. We then fit the simulated banding data to a dead-recovery model with Brownie parameterization (Brownie et al. 1985) within a Bayesian framework to obtain harvest estimates and associated variance. Scenarios are named by the proportion of band deployment in each region (north, middle, south; e.g., N10 means 10% of bands were allocated to the north region). Current split was the current band distribution, even 100p was 100% of current banding totals allocated to each region, even split was equal band distribution across each region, 10k each was 10,000 bands to each region, and N11k_M10.5k_S15k was 11,000 bands allocated to the northern region, 10,500 to the middle, and 15,000 to the south.

Shifting distribution to 25% of bands in the north, 25% in the central, and 50% in the southern region resulted in mean annual bias estimates of 0.011, 0.10, and 0.11 for those regions. For all scenarios, regions, and cohorts at this scale, the mean annual bias ranged from 0.04 to 0.23, with most bias occurring in juvenile female parameter estimates and the least for adult males. Our banding recommendations for adult females and males for all scales and regions are provided (Table 7).

DISCUSSION

Vital rates of wood ducks, especially juveniles, varied by breeding latitude substantially more than longitude, raising the possibility of biased flyway-scale estimates if band deployments are not equitable across latitudinal zones or deployment geography is not weighted in the estimation process. Our results concur with Greenawalt et al. (2022), suggesting flyway-scale analysis of harvest and survival probabilities without controlling for band deployment geography masks subtle demographic differences latitudinally, which could affect harvest management decisions if deployment distribution shifts over time. Yet we found no longitudinal variation in demographic rates, suggesting consolidation of administrative boundaries across flyways is biologically viable. This further aligns with Roberts et al. (2023), which highlights the migratory connectivity of wood ducks between flyways and the need to consider if traditional flyway

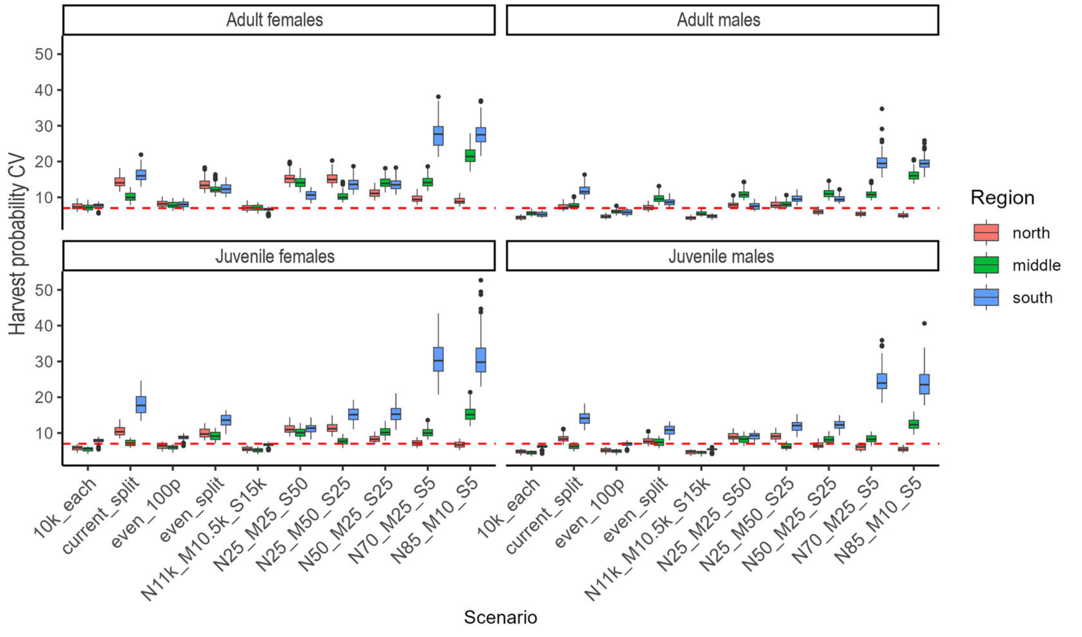

FIGURE 6 Harvest probability coefficients of variation (CVs) for each simulation scenario for 3 latitudinal regions within the Atlantic Flyway for each pre-season banded wood duck cohort (adult female, adult male, juvenile female, juvenile male). The red-dashed lines depict the set target of precision for the 5-year mean CV at 7%. We derived estimates by simulating each banding scenario 100 times for a 5-year period based on region and cohort specific estimate of demographic rates from 2000–2022. We calculated banding frequency for the simulation scenarios based on the average band deployments from 2016–2022. We then fit the simulated banding data to a dead-recovery model with Brownie parameterization (Brownie et al. 1985) within a Bayesian framework to obtain harvest estimates and associated variance. Scenarios are named by the proportion of band deployment in each region (north, middle, south; e.g., N10 means 10% of bands were allocated to the north region). Current split was the current band distribution, even 100p was 100% of current banding totals allocated to each region, even split was equal band distribution across each region, 10k each was 10,000 bands to each region, and N11k_M10.5k_S15k was 11,000 bands allocated to the northern region, 10,500 to the middle, and 15,000 to the south.

boundaries are still appropriate management delineations for all waterfowl species. Recent analysis created *ad hoc* latitudinal bins by consolidating previously described northern and southern banding regions (Kelley 1997) across flyways to calculate harvest potential and allowable harvest probabilities for management (Garrettson 2007). Delineating regions by latitude based on the most recently available data balances precision with practicality for setting banding goals and further stepping down quotas to states or smaller geographies (Yerkes 2000, Wilson et al. 2022). Specifically, using latitudinal bins addresses the observed 9% north-south difference in mean juvenile harvest probability, whereas merging states and provinces simplifies implementation (Garrettson and Howard 2023).

Our simulations highlight risks of biasing estimated demographic rates if band deployment shifts spatially, a trend that has occurred in the past and is likely to continue in the future (Raftovich et al. 2018). For example, decreased banding efforts in southern regions could inflate the effect of greater northern harvest probabilities, whereas a concentration of bands in the south could underestimate the influence of northern take. Therefore, maintaining representative sampling across breeding latitudes or using a weighted analysis by breeding region, which is likely more practical over time, is essential for unbiased estimates of demographic rates at the flyway scale (Kaminski and Gluesing 1987, Anderson and Anderson 2005).

We found the Kelley (1997) regions within flyway subdivisions exhibit slight demographic variation, which calls into question continued reliance on these boundaries for setting banding goals and quotas (Kelley 1997, Raftovich

TABLE 7 Banding recommendations to meet the ≤7% 5-year mean coefficient of variation target for pre-season banded adult female and male wood ducks for 3 latitudinal regions (across flyways) and latitudinal regions by flyway in eastern North America based on data collected in 2000–2022. Recommendations provided are a total number of deployments given the current percentage each cohort makes of band deployments.

Scale	Region	Adult female goal	Adult male goal
Three latitudinal regions	North	10,498	3,042
	Central	9,912	8,519
	South	11,999	6,534
Mississippi Flyway	North	8,993	3,655
	Central	9,090	7,124
	South	13,530	7,829
Atlantic Flyway	North	9,449	3,306
	Central	8,475	6,397
	South	9,279	6,585

et al. 2018). Meanwhile, banding efforts have significantly decreased in portions of the southeastern United States in recent years (Greenawalt et al. 2022), and ongoing funding and staffing constraints for state and federal agencies are likely to further reduce banding effort across the region (Jacobson et al. 2007). Extreme cases (e.g., when bands deployed in the southern Atlantic region represent only 5% of total bands) resulted in mean harvest probability CVs that exceeded 25% for female cohorts and failed to meet the precision threshold for all cohorts in the southern and middle regions. Given that the southern Atlantic region bands approximately 16% of the wood ducks in that flyway annually and its relative contribution has been declining, this is not an unreasonable scenario for the future. Declining spatially representative sampling amplifies the need to re-evaluate management units regularly based on the most recently available biological data.

Our recommended increased banding goals adjusted for adult females aim to rectify their historical under-representation compounded by their lower recovery rates, although we acknowledge meeting targets will be challenging (Garrettson 2021). Achieving precision targets for adult females will increase the robustness of wood duck banding programs and analyses and ensure precision targets are met for all other cohorts. Combining flyway estimates could reduce overall banding requirements compared to maintaining independent goals for each flyway (Alisauskas et al. 2009); however, flyway-level simulations demonstrate that imbalanced band deployments could still bias flyway-level rates, highlighting the need for equitable latitudinal sampling. To achieve more equitable band deployments, stepping down banding goals may be best achieved by using banding goals within the 3 latitudinal regions. These goals can then be further stepped down geographically by setting goals for each state or province based on the area of wooded wetlands (a proxy for wood duck habitat) in the state, and breeding bird survey population indices for each state (Garrettson and Howard 2023).

Our analysis provides a framework for efficient banding that balances precision and practicality. Although current banding distribution and analysis at the flyway scale are largely meeting mean harvest rate precision goals, it does not fully account for the differences in demographic rates of wood ducks breeding at northern versus southern latitudes. Regional goals based on latitude would offer a biologically relevant framework for maximizing the utility of mark-recapture data (Sofaer et al. 2019). As there are currently few alternative methods for monitoring this species across most of its breeding range (Zimmerman et al. 2015, 2017), it is critical to ensure all subsets of the population are represented in banding distributions. In addition, this approach could allow for periodic abundance estimates from bands combined with harvest survey data to produce Lincoln estimates (Lincoln 1930, Alisauskas et al. 2009), further strengthening management that is attuned to nuances in demographic rates underlying this widespread species. Banding data can also be used to link demographic rates to habitat and movement (Zhou et al. 2023), therefore ensuring unbiased banding data can improve the reliability of results and conclusions based on these data.

We acknowledge that our demographic estimates are directly influenced by the estimates of crippling loss and reporting rates we used. We chose to use a constant crippling loss of 0.2 knowing that crippling loss is variable throughout time and regions of eastern North America. Crippling loss is an extremely difficult and complex parameter to estimate (Martin and Carney 1977, Hicklin and Barrow 2004, Schulz et al. 2006); however, the constant rate of 0.2 aligns with previous wood duck research and the USFWS Adaptive Harvest Management process (Garrettson 2021, Greenawalt et al. 2022, USFWS 2023). Similarly, the reporting rate is a complex sociological parameter that likely varies by time, region, and species (Garrettson et al. 2014, Arnold et al. 2020, Greenawalt et al. 2022). We believe we have used appropriate estimates for both making our results and implications both valid and practical given the goal of our study (Garrettson 2007, 2021; Greenawalt et al. 2022).

MANAGEMENT IMPLICATIONS

Our integrated analysis provides valuable guidance for optimizing banding programs to support informed wood duck management. First, delineating regional goals by latitude offers a biologically relevant framework that captures demographic variation often missed by traditional administrative boundaries. Further, current banding distribution shortcomings, such as declining banding efforts in the Southeast, could produce biased estimates if not addressed. Maintaining balanced, representative sampling across breeding latitudes is essential to providing accurate regional and flyway-level inferences or a weighted analysis where a balanced effort cannot be maintained. Second, we recommend substantially increasing banding goals to account for under-representation of adult females that are banded during the pre-season period, excluding nest-boxes, which will increase precision of their vital rate estimates and improve their representation in banding data. Despite the increased banding goal for females, we recommend that the Atlantic and Mississippi flyways coordinate their goals, which can achieve desired precision with fewer total bands, enhancing efficiency without compromising data quality. Finally, periodic abundance estimates from banding data are needed to complement existing harvest surveys. Overall, our findings provide a framework for leveraging banding programs through efficient, representative sampling that accounts for subtle demographic variation.

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CONFLICTS OF INTEREST STATEMENT

The authors declare that there are no conflicts of interest.

ETHICS STATEMENT

This study used band recovery data provided by the United States Geological Survey Bird Banding Laboratory (BBL), which were derived from birds that were banded and later recovered through hunter harvest or found dead.

The original banding and data collection efforts were conducted by permitted individuals and agencies in accordance with United States federal regulations and guidelines for the ethical treatment of wildlife, including protocols approved under the United States Bird Banding Program. All original handling and marking of birds were carried out under valid federal banding permits and followed established animal welfare practices in effect at the time of data collection.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available in The North American Bird Banding Program Dataset at https://www.usgs.gov/labs/bird-banding-laboratory/data. Our research used publicly available band recovery data curated by the United States Geological Survey Bird Banding Laboratory; however, authors will supply the subset data upon request.

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SUPPORTING INFORMATION

Additional supporting material may be found in the online version of this article at the publisher's website.

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