

Long-term trends and drought:
spatiotemporal variation in juvenile sex ratios of North American ducks

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1 Abstract

2 Sex ratios affect population dynamics and individual fitness, and changing sex ratios can
3 be indicative of shifts in sex-specific survival at different life stages. While climate- and
4 landscape-change alter sex ratios of wild bird populations, long-term, landscape scale assess-
5 ments of sex ratios are rare. Further, little work has been done to understand changes in
6 sex ratios in avian communities. In this manuscript, we analyse long-term (1961-2015) data
7 on five species of ducks across five broad climatic regions of the United States to estimate
8 the effects of drought and long-term trends on the proportion of juvenile females captured
9 at banding. As waterfowl have a 1:1 sex ratio at hatch, we interpret changes in sex ra-
10 tios of captured juveniles as changes in sex-specific survival rates during early life. Seven
11 of twelve species-region pairs exhibited evidence for long-term trends in the proportion of
12 juvenile females at banding. The proportion of juvenile females at banding increased for
13 duck populations in the western United States and typically declined for duck populations
14 in the eastern United States. We only observed evidence for an effect of drought in two
15 of the twelve species-region pairs, where the proportion of females declined during drought.
16 As changes to North American landscapes and climate continue and intensify, we expect
17 continued changes in sex-specific juvenile survival rates. More broadly, we encourage further
18 research examining the mechanisms underlying long-term trends in juvenile sex ratios in
19 avian communities.

20 **Key words:** Bayesian, climate change, drought, hierarchical model, population sex ratio,
21 sex-specific survival, waterfowl

1 Introduction

Sex ratios are a key component of population structure, but are often assumed to be constant due to the difficulty of estimating sex ratios in wild populations (Lee et al., 2011). However, sex ratios often vary temporally and spatially in populations of wild organisms (Lemons et al., 2012; Alisauskas et al., 2014; Frew et al., 2018; Fox and Cristensen, 2018). This variation can influence population dynamics and may indicate changes in ecological processes that influence sex ratios either pre- or post-nascence. Further, population sex ratios and mating systems are important drivers of effective population size, demographic stochasticity, and extinction risk (Nunney, 1993; Bessa-Gomes et al., 2004; Lee et al., 2011). Thus, understanding population sex ratios is critical for ecological theory and successful applied conservation efforts (Mayr, 1939; Donald, 2007).

Reviews of sex ratios in birds (Mayr, 1939; Donald, 2007) have repeatedly demonstrated that for the majority of bird populations, sex ratios differ from equilibrium and are male-biased. Researchers have identified three primary drivers behind skewed sex ratios. First, skewed sex ratios can arise due to unequal sex ratios at fertilization or conception. For instance, climatic variation has been linked to a skewed sex ratio in juvenile red-winged blackbirds (*Agelaius phoeniceus*), where longer nesting seasons lead to maternal adjustment of offspring sex ratio favoring juvenile females (Weatherhead, 2005). Similarly, Seychelles warblers (*Acrocephalus sechellensis*) facultatively adjust the sex ratio of eggs before laying based on the quality of habitat, with higher quality habitat favoring female-biased sex ratios (Komdeur, 1996; Komdeur et al., 1997). Second, differing sex ratios at birth might cause skewed sex ratios in a population, potentially due to sex-specific hatching probability in birds. Third, variation in sex-specific mortality rates could lead to skewed sex ratios in juveniles and adults (Veran and Beissinger, 2009; Eberhart-Phillips et al., 2018; Gownaris and Boersma, 2019). For instance, a number of studies have shown that variation in resource requirements of different sexes can lead to variation in juvenile mortality rates (Weatherhead

48 and Montgomerie, 1995; Cooch et al., 1997; Lemons et al., 2012). However, despite this body
49 of research, few studies have examined variation in juvenile sex ratios of avian communities
50 at continental or even regional scales (but see Fox and Cristensen 2018).

51 North American waterfowl banding data provide a rich opportunity to examine ecologi-
52 cal questions at broad spatiotemporal scales (e.g., Ross et al. 2015; Specht and Arnold 2018;
53 Zhao et al. 2019). As early as 1933, Aldo Leopold commented that the sex ratio of ducks
54 was ‘seriously deranged’ (Leopold, 1933) while reviewing data generated by Lincoln (1932)
55 that indicated duck populations have exceedingly male-biased adult sex ratios (Mayr, 1939;
56 Bellrose et al., 1961). Puzzlingly, there is substantial evidence that waterfowl have an even
57 sex ratio at hatch (Bellrose et al., 1961; Clutton-Brock, 1986; Blums and Mednis, 1996; Hepp
58 et al., 1989; Lehikoinen et al., 2008; Swennen et al., 1979; Cooch et al., 1997; Lemons et al.,
59 2012). In ducks, skewed adult sex ratio is driven by increased mortality risk for adult females
60 during the breeding season. While males invest energy in plumage (Promislow et al., 1994)
61 and mating attempts, females must produce, lay, and incubate eggs, and then brood and
62 defend ducklings for several weeks. This energetic expenditure towards reproduction and
63 increased predation risk (Sargeant et al., 1984) leads to reduced survival of breeding females
64 relative to males (Arnold et al., 2016), and skews adult sex ratios. However, the potential
65 for sex-biased survival during early life remains under-examined for ducks and other wildlife
66 species, particularly at broad spatiotemporal scales. Sex-biased survival during early life
67 can have important implications. For example, biased offspring sex ratios due to sex-specific
68 juvenile survival rates in common eiders (*Somateria mollissima*), snowy plovers (*Charadrius*
69 *nivosus*), and Magellanic penguins (*Spheniscus magellanicus*) lead to biased adult sex ra-
70 tios in these species (Lehikoinen et al., 2008; Eberhart-Phillips et al., 2018; Gownaris and
71 Boersma, 2019). Given a dramatic increase in adult male to female ratios in North Ameri-
72 can duck populations (Alisauskas et al., 2014) and the potential for variation in sex-specific
73 juvenile mortality to affect adult sex ratios, we sought to examine long-term trends in sex
74 ratios of juvenile ducks in North America.

75 We formulated two research questions regarding the sex ratio of juvenile ducks in North
76 America: (1) Is the decline in the proportion of juvenile female ducks at banding in North
77 America similar to declines observed in Europe (Fox and Cristensen, 2018), and do these
78 declines vary spatially? (2) Given projected changes in precipitation and the strong link-
79 age between hydrologic conditions and waterfowl populations (Sorenson et al., 1998), does
80 drought play a role in affecting the sex ratio of juvenile ducks? We addressed these ques-
81 tions by modeling the effects of regional Palmer-Hydrological Drought Index (PHDI) and
82 long-term trends on the proportion of juveniles captured at banding that were female for
83 five duck species in five climatic regions defined by the National Center for Environmental
84 Information (Figure 1; Karl and Koss, 1984) from 1961-2015.

85 2 Methods

86 We downloaded capture-release data for five different species of ducks that occur in
87 North America: mallards (*Anas platyrhynchos*), northern pintails (*Anas acuta*), blue-winged
88 teal (*Anas discors*), American black ducks (*Anas rubripes*), and wood ducks (*Aix sponsa*)
89 from the U.S. Geological Survey GameBirds CD (Patuxent, MD, USA; USGS Bird Banding
90 Laboratory 2017) for the years 1961-2015. We restricted release data to birds that were
91 marked as hatch-year (i.e., flighted juvenile) from July-September. We obtained Palmer
92 Hydrological Drought Index values from the National Oceanic and Atmospheric Adminis-
93 tration’s Climate at a Glance: Regional Time Series from January 1961 - December 2015
94 (NOAA, 2020), and used the mean PHDI value from May-June as a measure of drought
95 during the breeding season. We chose the Upper Midwest, Northeast, Northwest, West,
96 and Northern Rockies and Plains climatic regions as study areas as these are the primary
97 breeding areas for ducks in the contiguous United States (Figure 1; Karl and Koss, 1984).

98 We partitioned the release data into these five climate regions. Total releases for each

99 species in each region are provided in Table 1, and sample sizes through time per region,
100 species, and sex can be found in the supplemental material (S1). We only included species
101 and regions in analyses when greater than 27,500 individuals (500 individuals/year) had been
102 released over the course of the study in a region. Since not all species were well represented
103 in all regions across time, bold values in Table 1 represent the species-region pairs that we
104 analyzed in this manuscript.

105 We developed a Bayesian hierarchical model that we describe using the appellation of
106 Berliner (1996). We first created a data model which links our data, total captures of juvenile
107 females and males per year in each region, to our proposed ecological process model for the
108 probability of each juvenile being a female. Probability density or mass functions of our
109 variables are noted using square brackets, so that $[a|b]$ represents the probability distribution
110 of random variable a conditional on b . We used the same model for each species-region pair.

111 For each species-region pair, we estimated the probability of a juvenile being female
112 during each year (π_t) as a function of the number of captured juvenile females (y_t) and the
113 total number of captured juveniles (η_t) using a binomial distribution,

$$y_t \sim \text{Binomial}(\eta_t, \pi_t) \tag{1}$$

114 We modeled the log odds of the probability of a juvenile being female using a normal distri-
115 bution with a time-varying mean (μ_t) with uncertainty (σ^2) on the logit scale. We modeled
116 the time-varying mean as a function of an intercept (α), the Palmer Hydrological Drought
117 Index (PHDI) specific to each climate region during each year, and a long-term trend.

$$\text{logit}(\pi_t) \sim \text{normal}(\mu_t, \sigma^2), \tag{2}$$

$$\mu_t = \alpha + \beta_{\text{PHDI}} * \text{PHDI}_t + \beta_t * t.$$

118 We assumed PHDI was measured without error. Negative PHDI values indicate drought,

119 while positive values indicate wet years. Thus, when interpreting β_{PHDI} values, a positive
 120 value indicates that the proportion of juvenile females at banding decreases during drought,
 121 and a negative value indicates that the proportion of juvenile females at banding increases
 122 during drought. Each parameter included in the data and process model above required a
 123 prior distribution. We chose vague priors for each parameter,

$$\begin{aligned}\sigma &\sim \text{gamma}(1, 1), \\ \alpha &\sim \mathcal{N}(0, 2.25), \\ \boldsymbol{\beta} &\sim \mathcal{N}(0, 10).\end{aligned}\tag{3}$$

124 The joint posterior distribution can be expressed as,

$$\begin{aligned}[\boldsymbol{\alpha}, \boldsymbol{\beta}, \sigma, \boldsymbol{\pi} | \mathbf{y}, \boldsymbol{\eta}] &\propto \prod_{t=1}^T [y_t | \pi_t, \eta_t] [\pi_t | \boldsymbol{\alpha}, \boldsymbol{\beta}, \sigma] \\ &\times [\boldsymbol{\alpha}] [\boldsymbol{\beta}] [\sigma].\end{aligned}\tag{4}$$

125 We used the package `rjags` (Plummer, 2019) in R version 3.6.2 (R Core Team, 2019)
 126 for our analysis. We sampled three chains for 1,000,000 iterations, with a burn-in of 500,000
 127 iterations. We retained every fiftieth iteration. We visually assessed convergence of param-
 128 eters using trace plots, and all parameters had $\hat{R} < 1.01$ for all models. We used posterior
 129 predictive checks to calculate Bayesian p-values for model-checking, using the deviance dis-
 130 crepancy function as described in Conn et al. (2018). Bayesian p-values were between 0.1-0.9
 131 for all models. Thus, our model-checking shows no evidence for lack of fit (Table 2).

3 Results

Greater than 1.5 million hatch-year ducks were captured at 2,291 unique sites (Figure 1) across five different U.S. climate regions from 1961-2015 (Table 1). We found support for long-term changes in juvenile sex ratios for seven of twelve species-region pairs (Figure 2), but only observed drought effects in two species-region pairs. The direction of temporal trends varied among species and regions, but seemed to generally vary along a longitudinal gradient (Figure 3), where sex ratios became more female-biased in western regions, and more male-biased in eastern regions. Mallard populations experienced long-term increases in the proportion of juvenile females at banding in the Northwest ($\beta_t = 0.081$, $f = 1$) and West ($\beta_t = 0.141$, $f = 1$) climate regions. In the Northern Rockies and Plains climate region, the proportion of juvenile females at banding increased for northern pintail ($\beta_t = 0.051$, $f = 0.98$), was stable for mallard, and declined for blue-winged teal ($\beta_t = -0.037$, $f = 0.99$). In the Upper Midwest climate region, the proportion of juvenile females at banding declined for wood duck ($\beta_t = -0.031$, $f = 1$), but was stable for mallard and blue-winged teal (Table 3). Finally, the proportion of juvenile females at banding declined for mallard ($\beta_t = -0.049$, $f = 1$) and wood duck ($\beta_t = -0.017$, $f = 0.99$) in the Northeast climate region, but was stable for blue-winged teal and American black duck. Drought generally did not impact sex ratios of juvenile waterfowl (Table 3), where there was little support for variation in the proportion of females at banding as a function of Palmer Hydrological Drought Index (Figure 4) for most species-region pairs. However, there was evidence that drought led to lower proportions of juvenile females at banding for American black duck in the Northeast climate region ($\beta_t = 0.009$, $f = 0.92$), and mallards in the Upper Midwest climate region ($\beta_t = 0.009$, $f = 0.93$).

154 4 Discussion

155 We observed substantial evidence for long-term changes in the proportion of juvenile
156 females at banding relative to juvenile males in seven of the twelve study populations. Strik-
157 ingly, this effect appears to change across longitudinal gradients, where the proportion of
158 juvenile females at banding increased in western populations, and declined in eastern popu-
159 lations, similar to declines observed in Europe (Fox and Cristensen, 2018). Drought effects
160 on sex ratios were rarely observed (two of 12 study populations), but consistently led to
161 a lower proportion of juvenile females at banding during drought years when effects were
162 significant. Numerous studies have documented 50:50 waterfowl sex ratios at hatch (e.g.,
163 Blums and Mednis 1996; Lemons et al. 2012). Thus, we interpret shifts in the proportion
164 of juvenile females at banding as evidence for sex-specific variation in survival during early
165 life, but cannot confirm any driving force.

166 We observed inter-regional variation in long-term changes in the proportion of juve-
167 nile females at banding. There are numerous hypotheses that might explain species- and
168 region-specific variation in long-term trends in the proportion of juvenile females at banding.
169 Lesser snow goose (*Anser caerulescens caerulescens*) juvenile sex ratios at banding became
170 more female-biased over time as habitat degraded because of an overabundance of geese
171 in breeding areas (Cooch et al., 1997). Cooch et al. (1997) attributed this shift to higher
172 juvenile male mortality due to resource reduction, and the increased energetic requirements
173 of structurally larger male goslings. Lemons et al. (2012) drew similar conclusions for a
174 female-biased juvenile sex ratio due to differential early-life mortality in black brant (*Branta*
175 *bernicla nigricans*). Thus, one hypothesis is that perhaps these long-term changes in the
176 proportion of females at banding may be due to long-term shifts in habitat quality that vary
177 longitudinally.

178 The species-region pairs with strong evidence for drought effects had lower proportions

179 of juvenile females at banding during drier years, and lower proportions of juvenile males at
180 banding during wetter years. This is in direct contrast to the resource limitation hypothe-
181 sis; drought conditions reduce available forage, leading to decreased early-life survival rates
182 for larger-bodied individuals (i.e., males) relative to females. Of note, none of the species
183 modeled in the Northern Rockies and Plains (i.e., Prairie Pothole Region) had support for
184 drought affecting the proportion of juvenile females at banding, despite large sample sizes and
185 clear evidence of drought affecting other duck demographic rates (Dufour and Clark, 2002).
186 Future research should examine differential relationships between environmental conditions
187 and sex-specific duckling survival at finer scales.

188 While our results provide insights into long-term changes at landscape scales, there may
189 also be substantial heterogeneity within the climatic regions examined in this study. For
190 example, within the Prairie Pothole Region, located in the Northern Rockies and Plains,
191 western portions are becoming drier with less wetland availability while eastern portions
192 become wetter with more wetland availability (Millett et al., 2009; Niemuth et al., 2014).
193 Substantial heterogeneity in fecundity also occurs at finer scales within the broad climatic
194 regions we used as study areas (Specht and Arnold, 2018). Thus, perhaps our analyses
195 did not adequately capture the effects of climate by using PHDI at large regional scales.
196 We note that sampling effort, intensity, and location might also affect our results. For
197 instance, during drought years field biologists trap ducks in extant wetlands that may have
198 different habitat quality and conditions than nearby ephemeral or semi-permanent wetlands.
199 Density-dependent mechanisms may also impact sex-specific juvenile duckling survival, and
200 the duration and extent of existing abundance surveys did not allow us to incorporate the
201 effects of density-dependence across all regions. These density-dependent mechanisms may
202 vary spatially (Zhao et al., 2016; Specht and Arnold, 2018), and may act interactively with
203 climate change to affect future waterfowl demographic rates (Zhao et al., 2018).

204 We might expect continued long-term changes in juvenile duck sex ratios as climate and

205 anthropogenic actions continue to impact these broad regions. As population demographers
206 move away from including sex ratio as a constant in population estimates, small changes
207 in sex ratio may influence projections from population models and associated management
208 actions. It will be of paramount importance to continue banding efforts to monitor long-term
209 changes in sex ratio and other demographic rates. While we have briefly discussed potential
210 explanations for long-term trends, the underlying mechanistic reasons for the observed pat-
211 terns in the data were not tested in our analyses, and should be examined further. Given
212 the rarity at which researchers have examined changes in juvenile sex ratios at broad scales
213 (Fox and Cristensen, 2018) in avian communities, we encourage continued research to both
214 estimate baseline juvenile sex ratios in avian communities, and examine the mechanisms
215 underlying long-term trends and short-term variation in response to climatic anomalies.

216 **Author Contributions**

217 SLE, TVR, and JSS conceived the manuscript, SLE led the analysis, with important contri-
218 butions from TVR, MGL, and PJW. SLE and TVR led the writing of the manuscript. All
219 authors contributed to manuscript revisions.

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226 **Data Accessibility**

227 Data and code for analyzing the data will be archived at the Dryad Digital Repository.
228 Data used in this study are also compiled by and publicly available through the USGS Bird
229 Banding Laboratory.

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Tables

Table 1. Total hatch-year (i.e., flighted juvenile) captures of American black duck (ABDU), blue-winged teal (BWTE), mallard (MALL), northern pintail (NOPI), and wood duck (WODU) in each NOAA U.S. Climate Region (Karl and Koss, 1984) from July-September, 1961-2015. Capture and release data are from the U.S. Geological Service Bird Banding Laboratory GameBirds CD (Patuxent, MD, USA). Bold values indicate the specific species and regions used in the analysis.

Region	Species Codes				
	ABDU	BWTE	MALL	NOPI	WODU
Northeast	70962	28529	201496	1833	122183
Upper Midwest	8498	59545	338093	5126	182944
Northern Rockies and Plains	23	173925	145877	45814	2408
Northwest	0	748	116309	10219	8978
West	0	13	91289	15002	1964

Table 2. Bayesian p -values of models estimating the proportion of hatch year (i.e., flighted juvenile) ducks that are females for American black duck (ABDU), blue-winged teal (BWTE), mallard (MALL), northern pintail (NOPI), and wood duck (WODU) in five NOAA U.S. Climate Regions (Karl and Koss, 1984) from 1961-2015.

Region	Species Codes				
	ABDU	BWTE	MALL	NOPI	WODU
Northeast	0.72	0.42	0.53	-	0.63
Upper Midwest	-	0.88	0.52	-	0.49
Northern Rockies and Plains	-	0.80	0.58	0.72	-
Northwest	-	-	0.54	-	-
West	-	-	0.59	-	-

Table 3. Means (μ), standard deviations (σ), and f-values (f; the proportion of the marginal posterior distribution on the same side of zero as the mean) of regression parameter posterior distributions for the effects of a long-term trend (Time) and Palmer Hydrological Drought Index (PHDI) from models of juvenile sex ratio of American black duck (ABDU), blue-winged teal (BWTE), mallard (MALL), northern pintail (NOPI), and wood duck (WODU) marked in five NOAA U.S. Climate Regions (NE = Northeast, UM = Upper Midwest, RP = Northern Rockies and Plains, NW = Northwest, and WE = West; Karl and Koss 1984) from 1961-2015.

Species_Region	Time			PHDI		
	μ	σ	f	μ	σ	f
ABDU_NE	-0.007	0.014	0.71	0.009	0.006	0.92
BWTE_UM	-0.002	0.018	0.54	-0.006	0.010	0.73
BWTE_RP	-0.037	0.016	0.99	0.006	0.006	0.82
BWTE_NE	-0.007	0.025	0.61	0.002	0.012	0.58
MALL_NE	-0.049	0.011	1	-0.006	0.006	0.83
MALL_UM	0.007	0.011	0.76	0.009	0.006	0.93
MALL_RP	0.008	0.020	0.65	-0.004	0.007	0.70
MALL_NW	0.081	0.023	1	0.005	0.012	0.65
MALL_WE	0.141	0.029	1	-0.007	0.010	0.76
NOPI_RP	0.051	0.024	0.98	0.003	0.009	0.63
WODU_NE	-0.017	0.007	0.99	-0.001	0.004	0.62
WODU_UM	-0.031	0.007	1	0.002	0.004	0.69

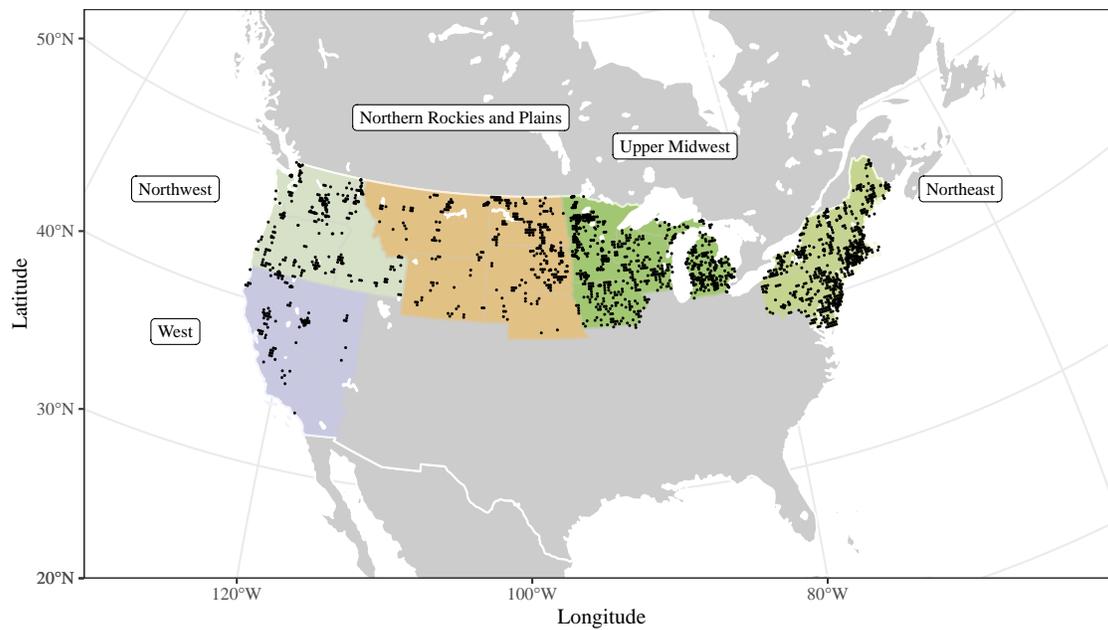


Figure 1. Release locations ($n = 2,291$) of 1,578,169 hatch-year ducks of five species marked in the West, Northwest, Northern Rockies and Plains, Upper Midwest, and Northeast U.S. Climate Regions (Karl and Koss, 1984) from 1961-2015.

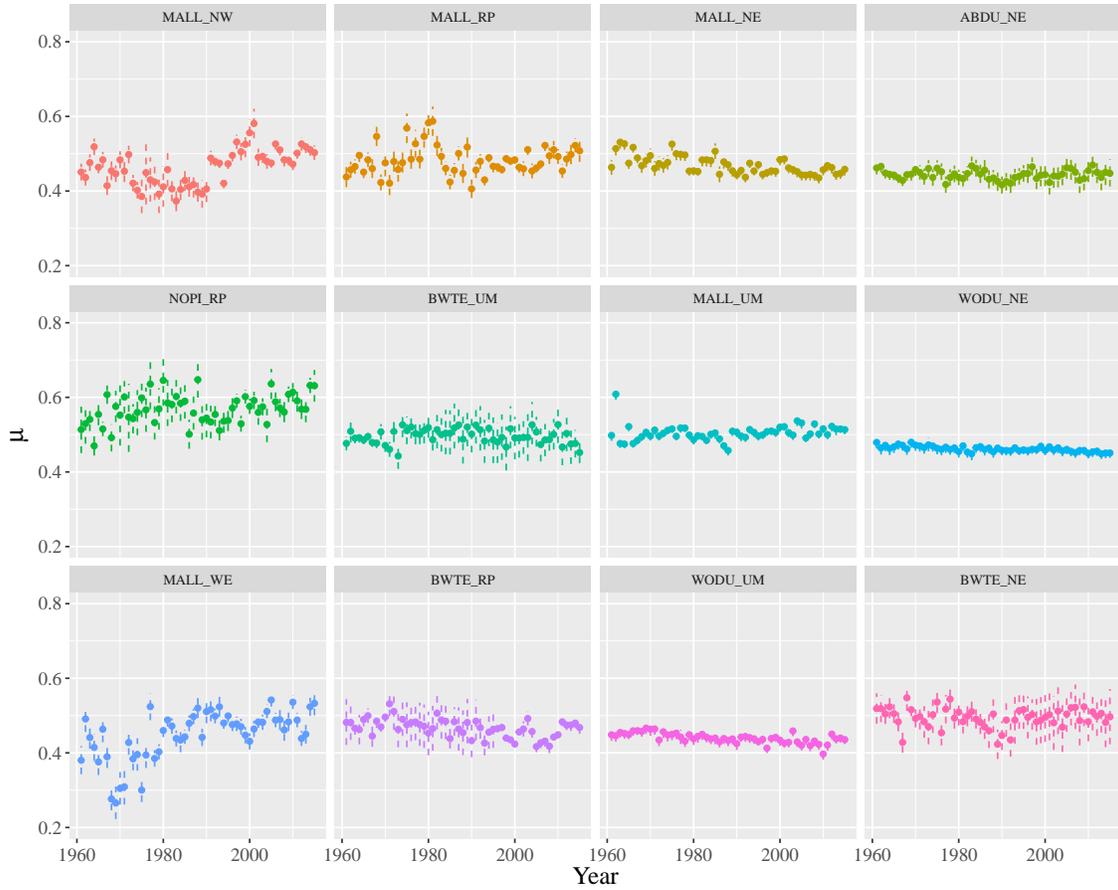


Figure 2. Means (points) and 95% credible intervals (dashed lines) of posterior distributions for estimates of the proportion of females for American black duck (ABDU), blue-winged teal (BWTE), mallard (MALL), northern pintail (NOPI), and wood duck populations in the Northeast (NE), Northern Rockies and Plains (RP), Upper Midwest (UM), Northwest (NW), and West (WE) U.S. Climate Regions (Karl and Koss, 1984)

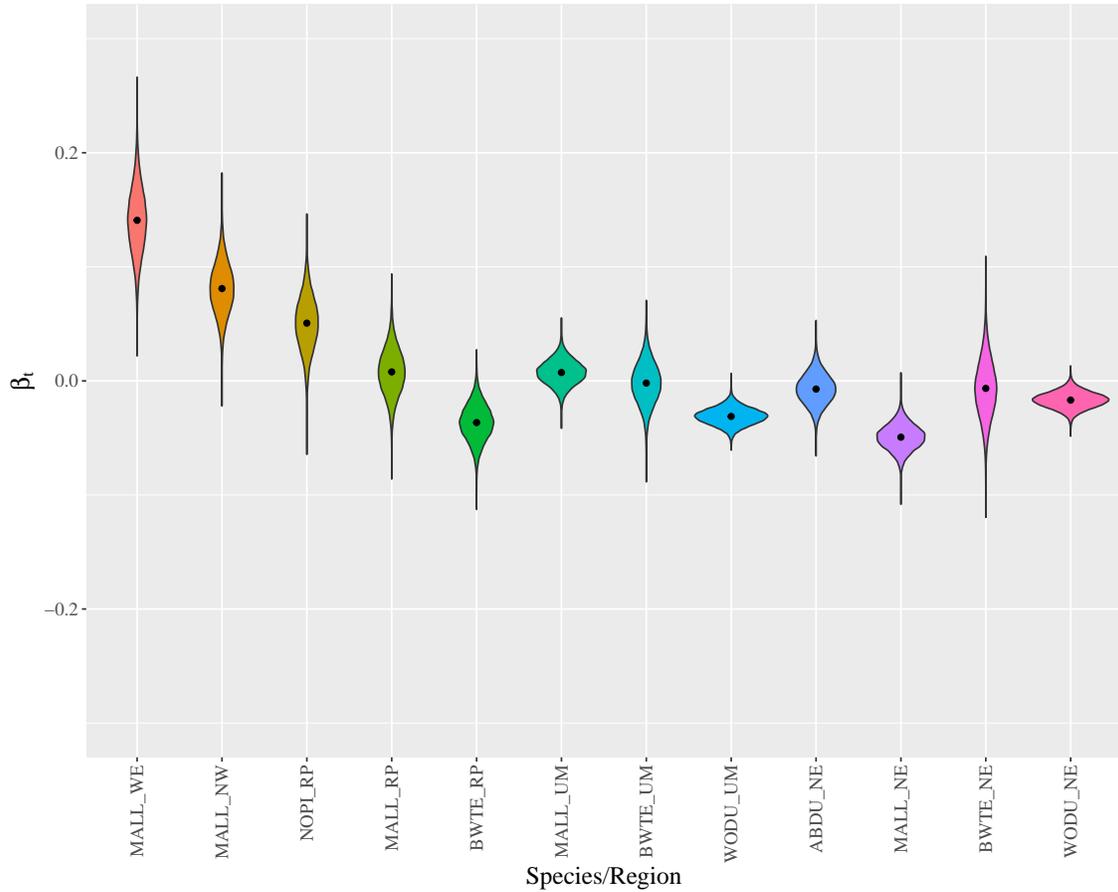


Figure 3. Violin plots of marginal posterior distributions and means (points) of the effect of long-term trends on the proportion of juvenile females for American black ducks (ABDU), blue-winged teal (BWTE), mallards (MALL), northern pintails (NOPI), and wood ducks (WODU) in the Northeast (NE), Northern Rockies and Plains (RP), Upper Midwest (UM), Northwest (NW), and West (WE) U.S. Climate Regions (Karl and Koss, 1984).

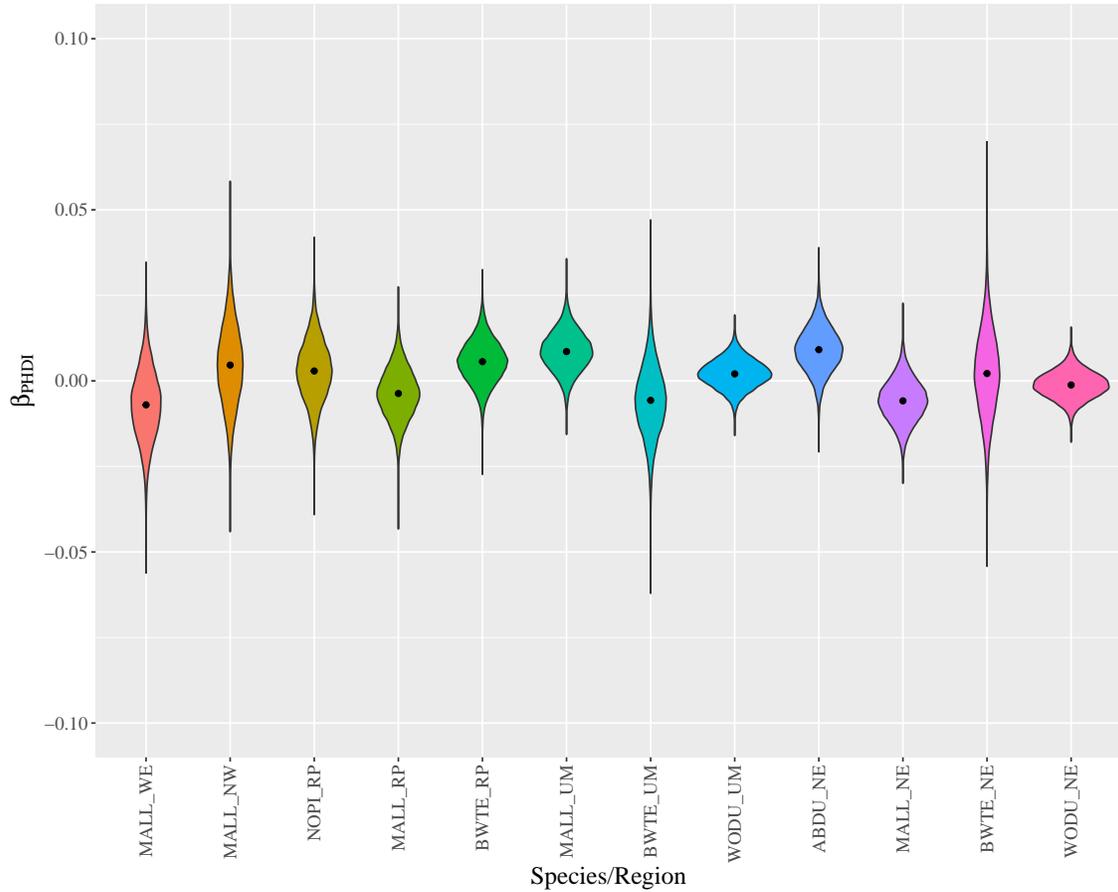


Figure 4. Violin plots of marginal posterior distributions and means (points) of the effect of Palmer Hydrological Drought Index (PHDI) on the proportion of juvenile females for American black ducks (ABDU), blue-winged teal (BWTE), mallards (MALL), northern pintails (NOPI), and wood ducks (WODU) in the Northeast (NE), Northern Rockies and Plains (RP), Upper Midwest (UM), Northwest (NW), and West (WE) U.S. Climate Regions (Karl and Koss, 1984).