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Supplementary material

Appendix 1.

Additional information about assigning species characteristics from Birds of North America Online accounts

We characterized species' migration type (complete or partial), migration distance, overlap of breeding and wintering range, average wintering latitude, diet (herbivore, insectivore, carnivore), circadian migration patterns, conspecific group size during migration, habitat specialization, territoriality, and presence of protandry using species accounts on Birds of North America Online (BNA, Rodewald 2015). For the species included, year of last account updates ranged from 1995 to 2018. We recognize that this is an imperfect system for characterizing species, but BNA account records are largely based off of peer-reviewed publications, rather than the personal observations of a single or a few authors, so we felt that this was the best option to gather data for many species. We assigned traits missing from a species' Birds of North America record as 'no data' for that species.

In general, we used the first paragraph under each relevant heading (Diet and foraging; distribution, migration, and habitat; etc) when possible, and continued into more specific subheadings until we found the information of interest. For several variables, we characterized first into more specific groupings with more levels and combined groupings into less specific groupings with fewer levels if there was a low number of species in a level, and where applicable, constructed and compared models using the different grouping schemes to ensure grouping method did not affect results.

Migration type, distance, and range characteristics

We used the “Distribution, Migration, and Habitat” heading and the species distribution map to characterize migration and distribution variables. Migration type and distance variables were characterized using the “Nature of Migration” subheading. We defined ‘partially migratory’ species as those species in which some but not all individuals or populations migrate, and considered a species partially migratory if any populations in some portion of its range were reported as being partially migratory or if some populations were migratory and others were resident. We classified migration distance according to what the BNA entry authors considered the migration distance, and also visually inspected the species distribution map to ensure that these classifications were relevant across our included species. We combined ‘short’ and ‘mid’ from migration Dist1 into ‘short’ for migration Dist2 and ‘long’ and ‘trans-equatorial’ into ‘long’ for migration Dist2.

We characterized wintering location as primarily in the United States, Central America, or South America using the “Winter Range” subheading and the species distribution map to characterize wintering location. For species whose wintering ranges spanned multiple categories, we originally allowed wintering latitude characteristics to encompass entire wintering range and include multiple levels (Wint1), but this approach led to many levels and very uneven group sizes between levels, so we recharacterized this variable to only include the category that describes location of the majority of the wintering range, or for very large ranges, the average latitude of the wintering range (Wint2). We used only Wint2 in analysis.

We identified species with overlapping breeding and wintering ranges using the species distribution maps, characterizing species with ‘year-round’ areas between breeding and wintering as having overlapping distributions (we did not attempt to specify if these year-round areas were due to leap-frog migrants or year-round residents).

We classified spring migration time of day and group size using the “Migratory Behavior” subheading, which made explicit mention of these traits in most cases. We allowed species to be classified as diurnal, nocturnal, or both, and designated a single group size for each species based off of the most common migratory group observed when multiple modes have been observed.

We identified the presence of protandry using the “Nature of Migration” subheading. We classified species as displaying protandry (differential arrival timing on the breeding grounds) if the BNA entry noted males arriving earlier on the breeding grounds either by migrating earlier or faster than females (there were no instances of females arriving first), or males wintering farther north than females. We did not consider differential migration between juveniles and adults. We did not distinguish between ‘no data/unknown’ and no protandry because no entries stated a demonstrated absence of differential migration.

Diet

We used the “Diet and Foraging” heading for each species to characterize primary diet. We used the “Major Food Items” subheading and selected the first food source listed or the food source identified as the primary food source in the entry as primary diet type. We originally distinguished between granivores and nectarivores/frugivores but combine these into “herbivores” because of low sample size.

Habitat specialization & territoriality variables

We used the “Habitat in breeding range” heading to classify habitat specialization in species, and characterized species as habitat specialists if the entry explicitly stated the species was a specialist, or if the entry described a narrow habitat type (e.g. specific tree species, single successional stages, etc). We used the “Spacing” subheading under the “Behavior” heading to classify territoriality in species, and characterized species as territorial if the entry states that males defend a territory during the breeding season, regardless of territory size.

Table A1. Life history characteristics and corresponding variable levels used to hypotheses about the relationship between life history and distribution shifts. Species were assigned to levels of variables using Birds of North America entries.

Variable	Levels
Migration type	Complete; partial
Migration distance 1 (Dist1)	Short; mid; long; Trans-equatorial/long
Migration distance 2 (Dist2)	Short; long
Wintering location 1 (Wint1)	United States (U.S); Central America (C.A.); South America (S.A.); U.S./C.A.; C./S.A.; all
Wintering location II (Wint2)	U.S.; C.A.; S.A.
Overlapping breeding & wintering ranges	Yes; no
Migration time of day	Day; night; both
Migratory group size	Individual group; conspecific group; mixed flock
Presence of differential migration across sexes	Yes (timing or distance); no
Primary diet	Insectivore; herbivore; carnivore
Habitat specialist	Yes; no
Territorial	Yes; no

Table A2. Species and life history traits used to examine shifts in breeding distribution centroid from 1994-2017. “Region” is the region(s) in which each species was analyzed, and “Family” is taxonomic family for each species. Life history traits were classified using Birds of North America (Rodewald 2015) and details of classification and the levels of each trait are described above.

Common Name	Scientific Name	Region	Family	Primary Diet	Migration Strategy	Migratory Distance1	Migratory Distance2	Migration Time of Day	Migrant Group Size	Differential Migration by Sex	Habitat Specialist	Territorial	Wintering Latitude1	Wintering Latitude2	Overlapping Ranges
Osprey	*Pandion haliaetus*	East, West	Pandionidae	Vertebrate	Complete	Long	Long	Day and Night	Individual	No	No	No	CA	Central America	No
Red-tailed Hawk	*Buteo jamaicensis*	East, Central, West	Accipitridae	Vertebrate	Partial	Short	Short	Day	no data	No	No	Territorial	US and CA	United States	Yes
Golden Eagle	*Aquila chrysaetos*	Central, West	Accipitridae	Vertebrate	Partial	Short	Short	Day	Individual	No	No	Territorial	US	United States	Yes
Northern Harrier	*Circus hudsonius*	East, Central, West	Accipitridae	Vertebrate	Partial	Long	Long	Day	no data	No	No	No	US and CA	United States	Yes
Swainson's Hawk	*Buteo swainsoni*	Central, West	Accipitridae	Vertebrate	Complete	Very long	Long	Day	Conspecific group	No	No	Territorial	SA	South America	No
Sharp-shinned Hawk	*Accipiter striatus*	East, Central, West	Accipitridae	Vertebrate	Partial	Mid	Short	Day	Individual	No	No	Territorial	US and CA	United States	Yes
Killdeer	*Charadrius vociferus*	East, Central, West	Charadriidae	Invertebrate	Partial	Mid	Short	Day and Night	Conspecific group	No	No	Territorial	US and CA	United States	Yes
Long-billed Curlew	*Numenius americanus*	Central, West	Scolopacidae	Invertebrate	Complete	Mid	Short	no data	Conspecific group	No	Yes	Territorial	CA	Central America	No
Chimney Swift	*Chaetura pelagica*	East, Central	Apodidae	Invertebrate	Complete	Very long	Long	Day	Conspecific group	No	No	No	SA	South America	No
Vaux's Swift	*Chaetura vauxi*	West	Apodidae	Invertebrate	Complete	Very long	Long	Day	Conspecific group	No	Yes	No	CA and SA	South America	No
Ruby-throated Hummingbird	*Archilochus colubris*	East, Central	Trochilidae	Plant	Complete	Long	Long	no data	no data	Yes	No	Territorial	CA	Central America	No
Northern Flicker (Yellow-shafted)	*Colaptes auratus auratus*	East, Central	Picidae	Invertebrate	Partial	Mid	Short	Day and Night	Conspecific group	Yes	No	Territorial	US	United States	Yes
Northern Flicker (Red-shafted)	*Colaptes auratus cafer*	Central, West	Picidae	Invertebrate	Partial	Mid	Short	Day and Night	no data	No	No	Territorial	US	United States	Yes
Northern Flicker (unid. subspp)	*Colaptes auratus*	Central	Picidae	Invertebrate	Partial	Mid	Short	Day and Night	no data	No	No	Territorial	US	United States	Yes
American Kestrel	*Falco sparverius*	East, Central, West	Falconidae	Invertebrate	Partial	Short	Short	Day	Individual	No	No	Territorial	US and CA	United States	Yes
Prairie Falcon	*Falco mexicanus*	Central, West	Falconidae	Vertebrate	no data	no data	no data	Day	no data	No	Yes	Territorial	US	United States	Yes
Acadian Flycatcher	*Empidonax virescens*	East	Tyrannidae	Invertebrate	Complete	Mid	Short	no data	no data	Yes	No	Territorial	CA	Central America	No
Least Flycatcher	*Empidonax minimus*	East, Central	Tyrannidae	Invertebrate	Complete	Mid	Short	no data	no data	Yes	No	Territorial	CA	Central America	No
Dusky Flycatcher	*Empidonax oberholseri*	West	Tyrannidae	Invertebrate	Complete	Short	Short	Night	no data	Yes	No	Territorial	CA	Central America	No
Gray Flycatcher	*Empidonax wrightii*	West	Tyrannidae	Invertebrate	Complete	Short	Short	Night	no data	Yes	Yes	Territorial	CA	Central America	No
Western Wood-Pewee	*Contopus sordidulus*	Central, West	Tyrannidae	Invertebrate	Complete	Very long	Long	no data	no data	No	No	Territorial	SA	South America	No
Say's Phoebe	*Sayornis saya*	Central, West	Tyrannidae	Invertebrate	no data	Short	Short	Day	Individual	Yes	No	no data	All	United States	Yes
Eastern Phoebe	*Sayornis phoebe*	East, Central	Tyrannidae	Invertebrate	Partial	Long	Long	Day	no data	No	No	Territorial	US and CA	United States	Yes
Eastern Kingbird	*Tyrannus tyrannus*	East, Central, West	Tyrannidae	Invertebrate	Complete	Very long	Long	Day	Conspecific group	Yes	No	Territorial	SA	South America	No
Loggerhead Shrike	*Lanius ludovicianus*	East, Central, West	Laniidae	Invertebrate	Partial	Short	Short	Day	no data	No	No	Territorial	US and CA	United States	Yes
Red-eyed Vireo	*Vireo olivaceus*	East, Central, West	Vireonidae	Invertebrate	Complete	Very long	Long	Night	no data	No	No	Territorial	SA	South America	No
White-eyed Vireo	*Vireo griseus*	East	Vireonidae	Invertebrate	Partial	Mid	Short	Night	no data	No	No	Territorial	US and CA	United States	Yes
Yellow-throated Vireo	*Vireo flavifrons*	East, Central	Vireonidae	Invertebrate	Complete	Long	Long	Night	no data	No	Yes	No	CA and SA	United States	No
Warbling Vireo	*Vireo gilvus*	East, Central, West	Vireonidae	Invertebrate	Partial	Mid	Short	Night	Mixed flock	No	No	Territorial	CA	Central America	Yes
Bell's Vireo	*Vireo bellii*	East, Central	Vireonidae	Invertebrate	Complete	Short	Short	Night	no data	No	No	Territorial	CA	Central America	No
Purple Martin	*Progne subis*	East, Central, West	Hirundinidae	Invertebrate	Complete	Very long	Long	Day	Conspecific group	No	No	Territorial	SA	South America	No
Barn Swallow	*Hirundo rustica*	East, Central, West	Hirundinidae	Invertebrate	Complete	Very long	Long	Day	Mixed flock	No	No	Territorial	CA and SA	United States	Yes
Tree Swallow	*Tachycineta bicolor*	East, Central, West	Hirundinidae	Invertebrate	Complete	no data	no data	Day	Conspecific group	No	No	Territorial	CA	Central America	No
Red-breasted Nuthatch	*Sitta canadensis*	East, West	Sittidae	Invertebrate	Partial	no data	no data	Day and Night	Mixed flock	No	No	Territorial	US	United States	Yes
Sedge Wren	*Cistothorus platensis*	East, Central	Troglodytidae	Invertebrate	Partial	Short	Short	Night	Conspecific group	No	Yes	Territorial	US	United States	No
Marsh Wren	*Cistothorus palustris*	East, Central, West	Troglodytidae	Invertebrate	Partial	no data	no data	Night	no data	No	No	Territorial	CA	Central America	Yes
House Wren	*Troglodytes aedon*	East, Central, West	Troglodytidae	Invertebrate	Partial	Mid	Short	Night	no data	No	No	Territorial	CA	Central America	No
Blue-gray Gnatcatcher	*Polioptila caerulea*	East, Central, West	Polioptilidae	Invertebrate	Partial	no data	no data	no data	no data	No	No	Territorial	CA	Central America	Yes
Ruby-crowned Kinglet	*Regulus calendula*	East, West	Regulidae	Invertebrate	Partial	Short	Short	no data	no data	Yes	No	Territorial	US and CA	United States	Yes
Western Bluebird	*Sialia mexicana*	West	Turdidae	Invertebrate	Partial	Mid	Short	Day	Mixed flock	No	Yes	Territorial	US	United States	Yes
Mountain Bluebird	*Sialia currucoides*	Central, West	Turdidae	Invertebrate	Complete	Short	Short	no data	Mixed flock	Yes	No	Territorial	US	United States	Yes
Eastern Bluebird	*Sialia sialis*	East, Central	Turdidae	Invertebrate	Partial	Short	Short	Day	Conspecific group	No	No	Territorial	US	United States	Yes
Wood Thrush	*Hylocichla mustelina*	East	Turdidae	Invertebrate	Complete	Mid	Short	Night	no data	No	No	Territorial	CA	Central America	No
American Robin	*Turdus migratorius*	East, Central, West	Turdidae	Invertebrate	Partial	Short	Short	Day	Conspecific group	No	No	Territorial	US	United States	Yes
Sage Thrasher	*Oreoscoptes montanus*	West	Mimidae	Invertebrate	Complete	Short	Short	no data	no data	Yes	Yes	Territorial	US	United States	No
Cedar Waxwing	*Bombycilla cedrorum*	East, Central, West	Bombycillidae	Invertebrate	no data	no data	no data	Day and Night	no data	No	No	No	US and CA	United States	Yes
Chestnut-collared Longspur	*Calcarius ornatus*	Central	Calcariidae	Invertebrate	Complete	Mid	Short	no data	Individual	Yes	Yes	Territorial	US	United States	No
Pine Warbler	*Setophaga pinus*	East	Parulidae	Invertebrate	Partial	Short	Short	Night	Mixed flock	No	Yes	Territorial	US	United States	Yes
Yellow Warbler	*Setophaga petechia*	East, Central, West	Parulidae	Invertebrate	Complete	Long	Long	Night	Conspecific group	Yes	No	Territorial	CA and SA	United States	No
Common Yellowthroat	*Geothlypis trichas*	East, Central, West	Parulidae	Invertebrate	Partial	no data	no data	Night	no data	Yes	No	Territorial	US and CA	United States	Yes
Kentucky Warbler	*Geothlypis formosa*	East	Parulidae	Invertebrate	Complete	Mid	Short	Night	Individual	No	No	no data	CA	Central America	No
Yellow-throated Warbler	*Setophaga dominica*	East	Parulidae	Invertebrate	Partial	Mid	Short	Night	no data	No	No	Territorial	CA	Central America	Yes
Black-and-white Warbler	*Mniotilta varia*	East	Parulidae	Invertebrate	Complete	Long	Long	Night	Mixed flock	Yes	No	Territorial	CA	Central America	No
Chestnut-sided Warbler	*Setophaga pensylvanica*	East	Parulidae	Invertebrate	Complete	Mid	Short	Night	no data	No	Yes	Territorial	CA	Central America	No
Worm-eating Warbler	*Helmitheros vermivorum*	East	Parulidae	Invertebrate	Complete	Mid	Short	Night	no data	No	Yes	Territorial	CA	Central America	No
Hooded Warbler	*Setophaga citrina*	East	Parulidae	Invertebrate	Complete	Mid	Short	Night	no data	No	No	Territorial	CA	Central America	No
Prairie Warbler	*Setophaga discolor*	East	Parulidae	Invertebrate	Partial	Mid	Short	Day and Night	Conspecific group	Yes	No	Territorial	US and CA	Central America	No
American Redstart	*Setophaga ruticilla*	East, Central	Parulidae	Invertebrate	Complete	Mid	Short	Night	Mixed flock	No	No	Territorial	CA	Central America	No
Black-throated Blue Warbler	*Setophaga caerulescens*	East	Parulidae	Invertebrate	Complete	Mid	Short	no data	no data	Yes	No	Territorial	CA	Central America	No
Canada Warbler	*Cardellina canadensis*	East	Parulidae	Invertebrate	Complete	Long	Long	Night	Mixed flock	Yes	No	Territorial	CA	South America	No
Nashville Warbler	*Oreothlypis ruficapilla*	East, West	Parulidae	Invertebrate	Complete	Mid	Short	Night	Mixed flock	Yes	No	Territorial	CA	Central America	No
Black-throated Gray Warbler	*Setophaga nigrescens*	West	Parulidae	Invertebrate	Complete	Short	Short	Night	Mixed flock	No	No	no data	CA	Central America	No
Yellow-breasted Chat	*Icteria virens*	East, Central, West	Icteriidae	Invertebrate	Complete	Mid	Short	Night	Individual	Yes	No	Territorial	CA	Central America	No
Henslow's Sparrow	*Ammodramus henslowii*	East	Passerellidae	Invertebrate	Complete	Short	Short	no data	no data	No	Yes	No	US	United States	No
Song Sparrow	*Melospiza melodia*	East, Central, West	Passerellidae	Invertebrate	Partial	Mid	Short	Night	no data	Yes	No	Territorial	US	United States	Yes
Dark-eyed Junco (Slate-colored)	*Junco hyemalis hyemalis*	East	Emberizidae	Invertebrate	Partial	Short	Short	Night	no data	Yes	No	Territorial	US	United States	Yes
Dark-eyed Junco (Oregon)	*Junco hyemalis oreganus*	West	Emberizidae	Invertebrate	Partial	Short	Short	Night	no data	Yes	No	Territorial	US	United States	Yes
Dark-eyed Junco (Gray-headed)	*Junco hyemalis caniceps*	West	Emberizidae	Invertebrate	Partial	Short	Short	Night	no data	Yes	No	Territorial	US	United States	Yes
Bobolink	*Dolichonyx oryzivorus*	East, Central	Icteridae	Invertebrate	Partial	Very long	Long	Night	Conspecific group	Yes	No	Territorial	SA	South America	No
Baltimore Oriole	*Icterus galbula*	East, Central	Icteridae	Plant	Complete	Long	Long	Day and Night	Conspecific group	Yes	No	Territorial	CA	Central America	No
Purple Finch	*Haemorhous purpureus*	East, West	Fringillidae	Plant	no data	no data	no data	Night	no data	Yes	No	no data	US	United States	Yes
American Goldfinch	*Spinus tristis*	East, Central, West	Fringillidae	Plant	Partial	Mid	Short	Day	Conspecific group	Yes	No	no data	US	United States	Yes
Cassin's Finch	*Haemorhous cassinii*	West	Fringillidae	Plant	Partial	Short	Short	no data	no data	No	Yes	Territorial	US and CA	United States	Yes

Life history hypotheses and predictions

We hypothesized that changes to seasonality in the temperate region (Peñuelas and Filella 2001, Richardson et al. 2013, Vitasse et al. 2018, Zohner and Renner 2019) associated with climate change may change the costs and benefits of migration, leading to decreased migration and a southward shift in breeding distributions (Austin and Rehfisch 2005). With this hypothesis, we predicted that partial migrants, short-distance migrants, species with overlapping ranges, and species with wintering locations at higher latitudes would have breeding distribution centroids that shifted south, because these species are likely to be facultative migrants and adjust migratory programs in response to environmental factors (Ramenofsky et al. 2012). Conversely, we expected that complete migrants, long-distance migrants, species with disjunct ranges, and species that winter at low latitudes or in the southern hemisphere would exhibit northward shifts in breeding centroid because they would be more constrained by 'hard-wired' migratory schedules (Ramenofsky et al 2012). We used migration type, migration distance, overlap of breeding and wintering range, and average wintering latitude as covariates to explain distribution centroid shifts to test this hypothesis.

We hypothesized that climate change may cause changes to supplemental cues that influence migratory timing, cessation, and the onset of reproductive readiness (Gwinner 1977, Wingfield et al. 1992), leading to changes to migration and shifts in breeding distribution centroid. Here, we predicted that species that use different cues to assess resources, and that are exposed to different cues during migration would respond differently. We used diet, circadian migration patterns, and conspecific group size during migration to explain centroid shifts to test this hypothesis. Specifically, we predicted that herbivores, diurnal migrants, or species migrating in conspecific groups would have southward shifts in breeding distribution centroid relative to carnivores, nocturnal migrants, or species that do not migrate with conspecifics because green up is likely an important cue for food availability for herbivores and is advancing rapidly (Visser and Both 2005), diurnal migrants may receive more visual cues about resources and conditions during migration (Ward and Raim 2011), and social information can mediate responses to supplemental cues (Helm et al. 2006, Teitelbaum et al. 2016).

Finally, we hypothesized that mismatch between the availability of prey resources and the arrival and breeding of migratory birds (Visser and Both 2005, Saino et al. 2011) may result in a latitudinal selection gradient resulting in distribution centroid shifts. We used habitat specialization, territoriality, and presence of protandry (i.e. if males tend to arrive earlier on the breeding grounds) as covariates to examine if phenological mismatch has created a gradient. We predicted that specialists, territorial species, and protandrous species would exhibit southward shifts in breeding distribution centroids because they would be more likely to experience negative consequences of mismatch (Julliard et al. 2003, Helm et al. 2006, Jonzén et al. 2007, Day and Kokko 2015, Pearce-Higgins et al. 2015) than generalists, non-territorial species, and non-protandrous species, which we expected to would have northward shifts in centroid.

Model selection for life history trait analysis

We organized life history traits into three groups corresponding to our three hypotheses to explain centroid shifts: (1) migration type (complete or partial), migration distance, overlap of breeding and wintering range, and average wintering latitude to examine whether climate-driven changes in seasonality explained southward shifts in centroids; (2) diet (herbivore, insectivore, carnivore), circadian migration patterns, and conspecific group size during migration to examine the role of supplementary cues; and (3) habitat specialization, territoriality, and presence of protandry to examine whether phenological mismatch in northern breeding areas influenced shifts. For each of these three sets of covariates, we ran linear mixed models with all single covariates and possible combinations of covariates and a random effect of family. We ran all combinations and interactions in each region unless a covariate was limited by insufficient sample size or covariates were correlated within a region. We selected the best model from each hypothesis in each region using a combination of LOO-CV and Bayesian model stacking, and then created a final model set of the best models from each hypothesis and combinations of these models.

We used efficient leave-one-out cross validation (LOO-CV) via the R package loo (Vehtari et al. 2018) for model selection, and verified that LOO-CV model selection was not biased by small group sample sizes by comparing LOO-CV results with Bayesian model stacking model weights (Yao et al. 2018), because using LOO-CV to select a single best model from a set of many models can sometimes cause overfitting with small sample sizes (Piironen and Vehtari 2017). If the most-supported model by LOO-CV was not also the most-supported model by model stacking weights, we used the weights of the individual covariates to assess if interactions between covariates were causing overfitting of interaction levels with few observations. We did not use model weights of the full set of models on their own to determine the most-supported model because model stacking weights penalize covariates that appear across many models by splitting their weights across all models, so using the single covariate weights was the best way to assess if covariates were overfit.

Model Selection Results

Eastern Region

Table A3–A5. Model selection results for model set including **(A3)** migration type (Mig), migration distance (Dist1 with levels short, mid, long, very long; or Dist2 with levels short, long), whether breeding and wintering distributions overlap (Overlap), and wintering latitude (Wint); **(A4)** primary diet type (Diet), migration time (Time), and migratory group size (Group); and **(A5)** habitat specialization (Hab), whether species are territorial (Terr), and presence of differential migration by sex (Sex) in the eastern region, from leave-one-out cross validation and Bayesian model stacking (BMS) weights. All models include a random effect of taxonomic family. Models are in ordered most-supported to least-supported based on Expected Log Pointwise Posterior Density (ELPD) from LOO-CV. The models used to determine the most-supported model across the three hypotheses is indicated in bold.

Table A3 Eastern Region

MODEL	ELPD DIFF	ELPD LOO	SE ELPD	Eff Pars LOO	SE Eff Pars	LOO IC	SE LOO IC	BMS Weight
Intercept	**0**	**-131.7**	**6.5**	**16.2**	**3.5**	**263.5**	**13.0**	**0.461**
Dist2	**-0.8**	**-132.6**	**6.3**	**18**	**3.4**	**265.1**	**12.6**	**0.271**
Wint	-0.8	-132.6	6.8	19.4	3.9	265.2	13.7	0.267
Overlap	-1.5	-133.2	6.3	16.9	3.3	266.4	12.6	0
Mig	-2.1	-133.8	6.3	16.9	3.3	267.7	12.6	0
Dist1	-4.7	-136.5	6.6	19.2	3.8	273	13.2	0

Table A4 Eastern Region

MODEL	ELPD DIFF	ELPD LOO	SE ELPD	Eff Pars LOO	SE Eff Pars	LOO IC	SE LOO IC	BMS Weight
Diet	**0**	**-127.9**	**6.2**	**10.7**	**2.7**	**255.8**	**12.5**	**0.516**
Diet + Time	-0.8	-128.7	6.4	11.9	3	257.3	12.7	0.369
Diet + Group	-2.7	-130.6	6	11.9	2.7	261.1	12.0	0
Diet ×Time	-3.3	-131.2	6.3	13.5	3.3	262.3	12.7	0
Intercept	-3.8	-131.7	6.5	16.2	3.5	263.5	13.0	0.041
Diet + Time + Group	-4.5	-132.4	6.4	15.1	3.4	264.7	12.9	0
Time	-6.4	-134.3	6.4	18.8	3.6	268.6	12.9	0
Group	-7.8	-135.7	7	17.4	3.8	271.3	14.0	0.073
Time + Group	-9.9	-137.8	6.9	19.5	3.8	275.5	13.8	0

Table A5 Eastern Region

MODEL	ELPD DIFF	ELPD LOO	SE ELPD	Eff Pars LOO	SE Eff Pars	LOO IC	SE LOO IC	BMS Weight
Sex	**0**	**-131.4**	**7**	**17.2**	**3.7**	**262.7**	**13.9**	**0.553**
Intercept	-0.4	-131.7	6.5	16.2	3.5	263.5	13	0.157
Sex + Terr	-1	-132.3	6.1	17.9	3.4	264.6	12.2	0.290
Sex + Hab	-1.4	-132.7	6.8	17.8	3.6	265.4	13.6	0
Hab	-1.8	-133.1	6.5	16.9	3.4	266.3	13	0
Terr	-2.3	-133.6	5.8	17.1	3.3	267.3	11.5	0
Sex + Hab + Terr	-2.8	-134.1	6.3	19.1	3.5	268.3	12.6	0
Hab + Terr	-3.3	-134.7	6	18.3	3.4	269.4	11.9	0

Eastern Region

Table A6. Bayesian model stacking weights for single covariates in the eastern region, for each set of covariates corresponding to the three hypotheses: **(1)** migration type (Mig), migration distance (Dist1 with levels short, mid, long, very long; or Dist2 with levels short, long), whether breeding and wintering distributions overlap (Overlap), and wintering latitude (Wint); **(2)** primary diet type (Diet), migration time (Time), and migratory group size (Group); and **(3)** habitat specialization (Hab), whether species are territorial (Terr), and presence of differential migration by sex (Sex).

Hypothesis 1		**Hypothesis 2**		**Hypothesis 3**	
Covariate	BMS Weight	Covariate	BMS Weight	Covariate	BMS Weight
Intercept	0.461	Diet	0.861	Sex	0.828
Dist2	0.271	Group	0.082	Terr	0.171
Wint	0.267	Intercept	0.057	Intercept	0.001
Type	0	Time	0	Hab	0
Overlap	0				

Eastern Region

Table A7. Model selection results for model set including covariates from most-supported model from each single-hypothesis model set (Table A3-A5) and combinations of these covariates in the eastern region, from leave-one-out cross validation and Bayesian model stacking (BMS) weights. All models include a random effect of taxonomic family. Models are in ordered most-supported to least-supported based on Expected Log Pointwise Posterior Density (ELPD) from LOO-CV, although model weights were also considered to determine most-supported model because LOO-CV can cause overfitting with small sample sizes. The most-supported model used for inference is indicated in bold.

MODEL	ELPD DIFF	ELPD LOO	SE ELPD	Eff Pars LOO	SE Eff Pars	LOO IC	SE LOO IC	BMS Weight
Diet + Sex	**0**	**-126.4**	**6.2**	**10.5**	**2.4**	**252.7**	**12.5**	**0.732**
Diet	-1.5	-127.9	6.2	10.7	2.7	255.8	12.5	0.016
Diet + Dist2	-3.2	-129.6	5.8	12.4	2.7	259.1	11.7	0
Diet + Sex + Dist2	-3.3	-129.7	6.5	13.9	3.3	259.3	13.1	0
Diet × Dist2	-4.7	-131	5.4	17.1	3.4	262	10.8	0.170
Sex	-5	-131.4	7	17.2	3.7	262.7	13.9	0.005
Intercept	-5.4	-131.7	6.5	16.2	3.5	263.5	13	0

Dist2	-6.2	-132.6	6.3	18	3.4	265.1	12.6	0.076

Western Region

Table A8–A10. Model selection results for model set including **(A8)** migration type (Mig), migration distance (Dist1 with levels short, mid, long, very long; or Dist2 with levels short, long), whether breeding and wintering distributions overlap (Overlap), and wintering latitude (Wint); **(A9)** primary diet type (Diet), migration time (Time), and migratory group size (Group); and **(A10)** habitat specialization (Hab), whether species are territorial (Terr), and presence of differential migration by sex (Sex) in the western region, from leave-one-out cross validation and Bayesian model stacking (BMS) weights. All models include a random effect of taxonomic family. Models are in ordered most-supported to least-supported based on Expected Log Pointwise Posterior Density (ELPD) from LOO-CV, although model weights were also considered to determine most-supported model because LOO-CV can cause overfitting with small sample sizes. The models used to determine the most-supported model across the three hypotheses is indicated in bold.

Table A8 Western Region

MODEL	ELPD DIFF	ELPD LOO	SE ELPD	Eff Pars LOO	SE Eff Pars	LOO IC	SE LOO IC	BMS Weight
Intercept	**0**	**-119.3**	**8.9**	**6**	**2.5**	**238.7**	**17.8**	**0.956**
Overlap	-0.8	-120.1	8.8	6.6	2.6	240.2	17.5	0
Mig	-0.8	-120.2	8.5	6.7	2.5	240.3	17	0
Wint	-2	-121.3	8.9	8.3	3.3	242.7	17.8	0
Dist2	-2.8	-122.1	8.8	9.1	3.5	244.3	17.7	0
Dist1	-3.8	-123.1	9.6	10.6	4.5	246.3	19.2	0.044

Table A9 Western Region

MODEL	ELPD DIFF	ELPD LOO	SE ELPD	Eff Pars LOO	SE Eff Pars	LOO IC	SE LOO IC	BMS Weight
Diet	**0**	**-118.9**	**8.2**	**6.5**	**2.5**	**237.8**	**16.4**	**0.681**
Intercept	-0.4	-119.3	8.9	6	2.5	238.7	17.8	0.319
Diet + Time	-2	-120.9	8	8	2.7	241.8	15.9	0
Time	-2.1	-121	8.4	7.3	2.6	241.9	16.8	0
Group	-3.4	-122.3	8.8	9.3	3.5	244.6	17.7	0
Diet + Group	-3.6	-122.5	8.8	10.1	3.7	245	17.6	0
Diet × Time	-4	-122.9	7.5	9	2.6	245.7	15	0
Time + Group	-5.8	-124.7	9.3	11.4	4.3	249.4	18.5	0
Diet + Time + Group	-6	-124.9	8.5	11.7	3.9	249.7	17.1	0

Table A10 Western Region

MODEL	ELPD DIFF	ELPD LOO	SE ELPD	Eff Pars LOO	SE Eff Pars	LOO IC	SE LOO IC	BMS Weight
Sex	**0**	**-119.1**	**8.6**	**6**	**2.3**	**238.2**	**17.2**	**0.620**
Intercept	-0.2	-119.3	8.9	6	2.5	238.7	17.8	0.380
Sex + Hab	-0.9	-120	8.4	6.5	2.4	240.1	16.9	0
Hab	-1	-120.1	8.8	6.4	2.6	240.2	17.5	0
Terr	-1.1	-120.2	8.3	6.4	2.3	240.4	16.6	0
Sex + Terr	-1.5	-120.6	8.3	7.1	2.4	241.1	16.7	0
Sex + Hab + Terr	-1.7	-120.8	8	6.9	2.2	241.7	16	0
Hab + Terr	-2	-121.1	8.3	6.9	2.4	242.1	16.5	0

Western Region

Table A11. Bayesian model stacking weights for single covariates in the western region, for each set of covariates corresponding to the three hypotheses: **(1)** migration type (Mig), migration distance (Dist1 with levels short, mid, long, very long; or Dist2 with levels short, long), whether breeding and wintering distributions overlap (Overlap), and wintering latitude (Wint); **(2)** primary diet type (Diet), migration time (Time), and migratory group size (Group); and **(3)** habitat specialization (Hab), whether species are territorial (Terr), and presence of differential migration by sex (Sex).

Hypothesis 1		**Hypothesis 2**		**Hypothesis 3**	
Covariate	BMS Weight	Covariate	BMS Weight	Covariate	BMS Weight
Intercept	0.956	Diet	0.672	Sex	0.694
Dist1	0.044	Intercept	0.328	Intercept	0.306
Overlap	0	Time	0	Hab	0
Mig	0	Group	0	Terr	0
Wint	0				

Western Region

Table A12. Model selection results for model set including covariates from most-supported model from each single-hypothesis model set (Table A8–A10) and combinations of these covariates in the western region, from leave-one-out cross validation and Bayesian model stacking (BMS) weights. All models include a random effect of taxonomic family. Models are in ordered most-supported to least-supported based on Expected Log Pointwise Posterior Density (ELPD) from LOO-CV, although model weights were also considered to determine most-supported model because LOO-CV can cause overfitting with small sample sizes. The most-supported model used for inference is indicated in bold.

MODEL	ELPD DIFF	ELPD LOO	SE ELPD	Eff Pars LOO	SE Eff Pars	LOO IC	SE LOO IC	BMS Weight
Diet	**0**	**-118.9**	**8.2**	**6.5**	**2.5**	**237.8**	**16.4**	**0.552**
Sex	-0.2	-119.1	8.6	6	2.3	238.2	17.2	0.448
Intercept	-0.4	-119.3	8.9	6	2.5	238.7	17.8	0
Diet + Sex	-0.5	-119.4	8.1	6.9	2.5	238.7	16.3	0
Diet × Sex	-1.1	-120	7.9	7.3	2.4	240.1	15.8	0

Central Region

Table A13–A15. Model selection results for model set including **(A13)** migration type (Mig), migration distance (Dist1 with levels short, mid, long, very long; or Dist2 with levels short, long), whether breeding and wintering distributions overlap (Overlap), and wintering latitude (Wint); **(A14)** primary diet type (Diet), migration time (Time), and migratory group size (Group); and **(A15)** whether species are territorial (Terr) and presence of differential migration by sex (Sex) in the central region, from leave-one-out cross validation and Bayesian model stacking (BMS) weights. Some covariates included in other regions were not included in models for the central region because there was not adequate sample size in this region. All models include a random effect of taxonomic family. Models are in ordered most-supported to least-supported based on Expected Log Pointwise Posterior Density (ELPD) from LOO-CV, although model weights were also considered to determine most-supported model because LOO-CV can cause overfitting with small sample sizes.

Table A13 Central Region

MODEL	ELPD DIFF	ELPD LOO	SE ELPD	Eff Pars LOO	SE Eff Pars	LOO IC	SE LOO IC	BMS Weight
Mig	**0**	**-127.8**	**10.6**	**8.2**	**4.2**	**255.6**	**21.1**	**0.711**
Overlap	-0.9	-128.7	10.9	8.5	4.5	257.5	21.9	0
Intercept	-1.2	-129.0	11.6	8.5	4.7	258.0	23.1	0
Wint	-1.2	-129.0	11.6	9.3	5.0	258.0	23.2	0.289
Dist1	-2.3	-130.1	10.8	12.4	5.4	260.1	21.7	0
Dist2	-2.8	-130.6	11.3	11.1	5.3	261.2	22.6	0

Table A14 Central Region

MODEL	ELPD DIFF	ELPD LOO	SE ELPD	Eff Pars LOO	SE Eff Pars	LOO IC	SE LOO IC	BMS Weight
Diet	**0**	**-128.9**	**10.8**	**9.6**	**5.2**	**257.9**	**21.6**	**0.534**
Intercept	-0.1	-129	11.6	8.5	4.7	258	23.1	0.466
Diet + Time	-1	-130	10.3	10.7	5	259.9	20.6	0
Time	-1.2	-130.1	10.5	9.5	4.4	260.2	21	0
Diet × Time	-1.4	-130.3	10	10.5	4.8	260.7	20	0
Diet + Group	-2.7	-131.7	10.8	13.3	6.1	263.3	21.6	0
Group	-2.9	-131.8	11.5	13.2	6.3	263.7	23.1	0
Group + Time	-4	-133	10.3	13.8	5.7	265.9	20.6	0.001
Diet + Group + Time	-4.1	-133	10.2	14.3	5.8	266	20.3	0

Table A15 Central Region

MODEL	ELPD DIFF	ELPD LOO	SE ELPD	Eff Pars LOO	SE Eff Pars	LOO IC	SE LOO IC	BMS Weight
Sex	**0**	**-128.9**	**11.1**	**8.6**	**4.6**	**257.8**	**22.1**	**0.574**
Intercept	-0.1	-129.0	11.6	8.5	4.7	258.0	23.1	0.427
Sex + Terr	-1.5	-130.4	10.9	10.6	4.8	260.9	21.8	0
Terr	-1.9	-130.8	11.1	10.7	4.8	261.7	22.2	0

Central Region

Table A16. Bayesian model stacking weights for single covariates in the central region, for each set of covariates corresponding to the three hypotheses: **(1)** migration type (Mig), migration distance (Dist1), whether breeding and wintering distributions overlap (Overlap), and wintering latitude (Wint); **(2)** primary diet type (Diet), migration time (Time), and migratory group size (Group); and **(3)** whether species are territorial (Terr) and presence of differential migration by sex (Sex).

Hypothesis 1		**Hypothesis 2**		**Hypothesis 3**	
Covariate	BMS Weight	Covariate	BMS Weight	Covariate	BMS Weight
Mig	0.712	Diet	0.519	Sex	0.586
Wint	0.288	Intercept	0.481	Intercept	0.414
Intercept	0	Time	0	Terr	0
Dist1	0	Group	0		
Overlap	0				

***Habitat specialist was not included in this region because of insufficient sample size**

<u>Central Region</u>

Table A17. Model selection results for model set including covariates from most-supported model from each single-hypothesis model set (Table A13–A15) and combinations of these covariates in the central region, from leave-one-out cross validation and Bayesian model stacking (BMS) weights. All models include a random effect of taxonomic family. Models are in ordered most-supported to least-supported based on Expected Log Pointwise Posterior Density (ELPD) from LOO-CV, although model weights were also considered to determine most-supported model because LOO-CV can cause overfitting with small sample sizes. The most-supported model used for inference is indicated in bold.

MODEL	ELPD DIFF	ELPD LOO	SE ELPD	Eff Pars LOO	SE Eff Pars	LOO IC	SE LOO IC	BMS Weight
Mig	**0**	**-127.8**	**10.6**	**8.2**	**4.2**	**255.6**	**21.1**	**0.333**
Mig + Diet	-0.2	-128	9.8	9.9	4.7	256	19.5	0.438
Mig + Sex	-0.7	-128.5	10.5	8.9	4.3	256.9	20.9	0
Sex	-1.1	-128.9	11.1	8.6	4.6	257.8	22.1	0
Diet	-1.1	-128.9	10.8	9.6	5.2	257.9	21.6	0.002
Intercept	-1.2	-129	11.6	8.5	4.7	258	23.1	0.228
Mig + Diet + Sex	-1.2	-129	9.9	10.4	4.9	258	19.8	0
Diet + Sex	-1.3	-129.1	10.2	9.5	4.8	258.2	20.4	0

Mig × Sex	-1.5	-129.4	10.6	9.7	4.6	258.7	21.2	0
Diet × Sex	-1.7	-129.5	10.3	9.7	4.9	258.9	20.6	0
Mig × Diet	-1.8	-129.6	9	12.1	4.7	259.3	18.0	0

References

Austin, G.E. and M.M. Rehfisch. 2005. Shifting nonbreeding distributions of migratory fauna in relation to climatic change. *Global Change Biol.* 11: 31-38.

Day, E. and H. Kokko. 2015. Relaxed selection when you least expect it: why declining bird populations might fail to respond to phenological mismatch. *Oikos* 124: 62-68.

Gwinner, E. 1977. Circannual rhythms in bird migration. *Annu. Rev. Ecol. Syst.* 8: 381-405.

Helm, B., T. Piersma, and H. van der Jeugd. 2006. Sociable schedules: interplay between avian seasonal behavior and social behavior. *Anim. Behav.* 72: 245-262.

Jonzén, N., A. Hedenström, and P. Lundberg. 2007. Climate change and the optimal arrival time of migratory birds. *Proc. R. Soc. B.* 274: 269-274.

Julliard, R., F. Jiguet, and D. Couvet. 2003. Common birds facing global changes: what makes a species at risk? *Global Change Biol.* 10: 148-154.

Pearce-Higgins, J.W., S.M. Eglington, B. Martay, and D.E. Chamberlain. 2015. Drivers of climate change impacts on bird communities. *J. Anim Ecol.* 84: 943-954.

Peñuelas, J. and I. Filella. 2001. Responses to a warming world. *Science* 294: 793-795.

Piironen, J. and A. Vehtari. 2017. Comparison of Bayesian predictive methods for model selection. *Statistics and Computing* 27: 711-735.

Ramenofsky, M., J.M. Cornelius, and B. Helm. 2012. Physiological and behavioral responses of migrants to environmental cues. *J. Ornithol.* 153: 181-191.

Richardson, A.D., T.F. Keenan, M. Migliavacca, Y. Ryu, O. Sonnentag, and M. Toomey. 2013. Climate change, phenology, and phenological control of vegetation feedbacks to the climate system. *Agricultural and Forest Meteorology* 169: 156-173.

Rodewald, P. (Editor). 2015. The Birds of North America: https://birdsna.org. Cornell Laboratory of Ornithology, Ithaca, NY.

Saino, N., R. Ambrosini, D. Rubolini, J. von Hardenberg, A. Provenzale, K. Hüppop, O. Hüppop, A. Lehikoinen, E. Lehikoinen, K. Rainio, M. Romano, and L. Sokolov. 2010. Climate warming, ecological mismatch at arrival and population decline in migratory birds. *Proc. R. Soc. B* 278: 20101778.

Teitelbaum, C.S., S.J. Converse, W.F. Fagan, K. Böhning-Gaese, R.B. O'Hara, A.E. Lacy, and T. Mueller. Experience drives innovation of new migration patterns of whooping cranes in response to global change. *Nature Communications* 7: 12793.

Visser, M.E., and C. Both. 2005. Shifts in phenology due to global climate change: the need for a yardstick. *Proc. R. Soc. B* 272: 2561-2569.

Vitasse, Y., C. Signarbieux, and Y.H. Fu. 2018. Global warming leads to more uniform spring phenology across elevations. *Proc. Natl. Acad. Sci. USA* 115: 1004-1008.

Ward, M.P. and A. Raim. 2011. The fly-and-social foraging hypothesis for diurnal migration: why American crows migrate during the day. *Behav. Ecol. and Sociobiol.* 65: 1411-1418.

Wingfield, J.C., T.P. Hahn, R. Levin, and P. Honey. 1992. Environmental predictability and control of gonadal cycles in birds. *J. Exp. Zool.* 261: 214-231.

Yao, Y., A. Vehtari, D. Simpson, and A. Gelman. 2018. Using stacking to average Bayesian predictive distributions (with discussion). *Bayesian Analysis* 13: 917-1007.

Zohner, C.M. and S.S. Renner. 2019. Ongoing seasonally uneven climate warming leads to earlier autumn growth cessation in deciduous trees. *Oecologia* 189: 549-561.