PHENOLOGICAL SHIFTS IN VEGETATION GREENUP AND SPRING ARRIVAL OF MIGRATORY SONGBIRDS OF CONSERVATION CONCERN IN ALASKA

by

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ABSTRACT

Phenological shifts in vegetation greenup and spring arrival of migratory songbirds of conservation concern in Alaska

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Migratory birds across the globe are experiencing impacts to their demography at an alarming rate. With 30% of bird species lost since the 1970's (3 billion birds), researchers are working to unravel what may be contributing to these losses. Particularly in northern latitudes where climate change is accelerating, pinpointing what is impacting these shifts is critical. The complexity of these losses may be linked to impacts as a result of climatic shifts, greenup timing, and environmental impacts such as precipitation, temperature fluctuation, and arthropod emergence. Estimates of spring arrival were calculated for 61 species of songbirds in Alaska; 37 of these had sufficient years of estimates (across at least one of 11 distinct locations) to calculate trends over time in spring arrival, as well as trends in asynchrony (the difference in days between spring arrival and greenup). Most species in most locations did not show any particular trend. For spring arrival, 7 species/location combinations trended towards earlier arrival, 19 trended towards later arrival, and 135 had nonsignificant trends. With asynchrony, 10 species/location combinations had decreasing asynchrony, 14 had trends of increasing asynchrony, and 136 had nonsignificant trends. To look for any evidence of species tracking year-to-year changes in greenup, correlations of spring arrival anomalies with greenup anomalies were also calculated. For this test, 31 species/location combinations had a positive correlation (i.e. some evidence of tracking), 133 correlations were nonsignificant, and 2 species had a negative correlation. Particularly with insectivorous migratory species that are experiencing significant declines across the globe, determining which species are experiencing shifts in migration timing is crucial.

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INTRODUCTION:

Phenology (or the timing of life events) is strongly influenced by climate, and species across a wide array of taxa are experiencing phenological shifts in response to climate change (Cohen et al. 2018, Prather et al 2023). With species showing delays and/or advancements in phenology, many researchers predict that climate change will lead to significant and wide-ranging negative consequences to species and the communities they are part of or depend on (Kharouba et al. 2018). It remains unknown which are the most important climatic variables that drive phenological shifts (Cohen et al. 2018). One of the major signals of current climate change is change in both temperature and precipitation, which are also important drivers of the timing of avian migration (Prather et al 2023).

Studies of the seasonal migration of passerines has gained widespread interest to better assess their responses to climate change, in particular relating spring arrival (of migratory birds on their breeding grounds) to estimates of 'spring greenup.' Greenup is a temperature-driven event based on the timing of foliage production in spring (Neupane et al. 2022). With temperature being a large driver of greenup, the timing of seasonal events such as budburst, flowering, hatching, and migration could be altered (Hurlbert & Liang, 2012). When birds migrate, they time their migration with a multitude of environmental cues and how they decide to time their migration could potentially have negative consequences to that individual's fitness (Burnside et al. 2021).

Over the past few decades, large-scale warming has increased the average surface air temperature on earth by approximately 0.74°C, causing many wildlife species to shift distributions and alter timing of arrival and departure (Hurlbert & Liang, 2012). These sensitivities to changes in greenup timing, coupled with how a species can respond to these shifts, could result in a “phenological mismatch” where the timing of resource need and the timing of resource availability are not aligned (Robertson et al., 2024). This decoupling can create a sensitivity to change with negative effects on reproductive success and demography of migratory birds (Shipley et al. 2020). While some species may be able to keep up with these shifts in greenup, some species may be more vulnerable to climate change impacts resulting in possible further decline of many migratory birds.

Northern latitudes are experiencing an acceleration in climate change at an alarming rate leading to concerns about the cascading effects of temperature changes impacting plant communities, arthropod abundance, and bird migration timing. Northern latitudes have been preferred by many migratory birds for breeding and nest site selection. With many different ecoregions, Alaska provides a diversity of habitats that migratory birds depend on for breeding and nest site selection. During their migration, many birds travel to Alaska to achieve the necessary requirements for a successful breeding season. In some regions of Alaska, the arctic and boreal ecobiomes provide crucial breeding grounds and food sources for more than half of North America’s migratory birds (*USGS Fact Sheet 2013–3054 n.d.*).

This thesis examines the research question, “Is the amount of phenological asynchrony (the difference between spring arrival and greenup) changing for migratory birds in Alaska?”. Remote-sensing data available from USGS was used to measure vegetation greenness throughout each year and provided different greenup metrics. eBird data collected from 2001-2022 was used to estimate spring arrival to determine if there is any phenological asynchrony of migratory bird timing and greenup.

This study looked into both bird arrival timing and greenup for every year for distinct locations (adjacent hexagons) in both Alaska and parts of Yukon, Canada to measure asynchrony and look for changes over time. Spring arrival estimates were generated for all bird species for as many years as possible for each location. Phenological asynchrony for each species was calculated to identify species with the most dramatic phenological asynchronies. To see how far from the long-term average the values were for each species, anomalies were calculated for both mid-greenup and spring arrival.

LITERATURE REVIEW

INTRODUCTION:

The timing of greenup (vegetation emergence) is critical to the function of ecosystems and wildlife survival and provides a proxy for food availability for birds (Both et al. 2009). As it becomes warmer in the spring and vegetation begins to leaf out, arthropods emerge to feed on the new leaves (Tulp et al. 2008). Arthropods are a crucial food source for many bird species that depend on them for fuel for migration and to provide for their young once they start breeding. When birds migrate and arrive too early to a location before peak resources are available, this can result in freezing due to colder temperatures and hatching chicks too soon with not enough food resources (Mayor et al. 2017). Those that arrive too late risk fewer nest site selection, competition for mate selection, and less resource availability later in the season. With temperature changes occurring in northern latitudes with possible shifts in greenup timing of plant emergence, it is important to study and understand how migratory birds are responding to these shifts especially when considering possible future declines in breeding productivity and demography.

This literature review will first discuss population dynamics and abundance of migratory bird populations in Alaska. This review will focus on studies that investigate migration routes and stopover sites, reproduction and fitness outcomes, regional effects, and how climate change is impacting their demography. The second section will examine greenup timing and resource availability and how this impacts insect resources. The next section will cover habitat availability, optimal habitat for nest site selection and brood success, ecoregions, and trends in phenological intervals. Remote sensing technology (EVI and MODIS) will also be discussed on how it can be used to gain visuals of the onset of greenness. It will then cover asynchrony and phenological shifts in response to weather and temperature fluctuations. The final section will discuss the various modeling from past studies which include logistic generalized additive models (GAMs) to derive estimates of bird arrival and will examine how these models provide estimates to determine any shifts in spring arrival by identifying species or populations with the most extreme phenological asynchronies.

MIGRATORY BIRDS**:**

Pursuing resources, many birds follow seasonal migration routes to reach habitats for both breeding and nonbreeding seasons (La Sorte et al., 2014). The ecological productivity of an environment is important for birds, in order to provide optimal conditions for finding food sources, breeding and nest site selection, ideal climate, and raising their young. Every spring and autumn, millions of bird species endure a complex journey flying from their seasonal breeding grounds to where they will stay during winter. Along the way, multiple stopover sites are essential for the survival of migratory birds ensuring adequate refueling for long distance travel. Many species fly thousands of kilometers and can fly multiple days at a time before stopping (Newton et al. 2008; "*Bird migration,"* 2021). Understanding the relationships between migratory birds and shifts in climate change is important in understanding the current state of bird populations (Wood et al. 2015).

ALASKA AS A MIGRATION DESTINATION:

During migration, a lot of migratory birds travel to northern latitudes to achieve the necessary requirements for successful breeding. At over 1.7 million square kilometers, large mountain ranges, glaciers, and expansive coastlines and tundra, provide abundant resources that many birds flock to. The diverse ecoregions of Alaska contain many distinct habitat types (shrubland, boreal forests, arctic and alpine tundra, temperate rainforests, riverine environments, freshwater, and coastal) which provide habitats to a large variety of songbirds. Over five billion birds travel to Alaska during spring migration following various flyways to reach their destinations (*"Audubon Alaska," 2022).* Favoring the ideal conditions that Alaska provides during breeding season, more than 250 migratory bird species will visit during a season. With the long journey to reach Alaska, energy demands are high when reaching their breeding grounds to regain enough energy reserves to sustain themselves during the breeding season.

THREATS TO MIGRATORY BIRDS:

Migratory bird populations are vulnerable to climate change impacts as they travel long distances through many different climates (La Sorte et al., 2014). Some passerines such as insectivorous migratory birds have experienced some of the most severe declines across North America. In Canada, insectivorous species such as swifts, nightjars, and swallows have experienced the steepest decline of any avian group making it one of the most severe declines in North America (Michel et al. 2021, Rosenberg et al. 2019). Across the avifauna, these declines are not restricted to just threatened species, with a majority of the declines linked to common and widespread species such as sparrows, warblers, blackbirds, and finches (Rosenberg et al. 2019). At almost 3 billion birds lost (30% since 1970) in North America, more research is needed to investigate what drivers are contributing to that decline (Rosenberg et al. 2019).

Although the reasons for the decline in insectivorous birds are still not fully understood, changes in prey abundance (particularly arthropods), land-use changes on breeding grounds, and shifts in climate indices are likely culprits (Michel et al. 2021). Across North America, migratory birds have faced many complications on their long arduous migration flyways, including being subject to wildfires and smoke. Birds that must fly through smoke or fly around smoke can get disoriented, fly off-route, increasing flight altitudes to crossover smoke plumes, and exhaust resource stores resulting in lost weight needed for migration, and doubling migration timing which can greatly impact a bird’s survival (Overton et al. 2022).

Migration depends on having habitat connectivity, and with habitat fragmentation and land-use, these linkages can pose problems for birds that depend on them (Welling et al., n.d.). Corridors are important for wildlife populations to increase reliable food availability and to provide necessary habitat cover. With increased fragmentation, these broken linkages could become problematic for wildlife survival. These large-scale disruptions such as wildfires, logging, and oil-spills have created barriers to bird migration, navigation, and sustenance, and have resulted in mass die-offs of migratory birds.

These threats are increasing for migratory birds in Alaska due to logging, oil development, habitat loss, wildfires, insect outbreaks, and climate change (Alaska Department of Fish and Game 2015). Sea ice decline, ocean acidification, temperature fluctuations, permafrost melting, and vegetation changes are some of the many variables as a result of climate change. For avian populations, one of the more recent concerns are impacts to their phenological timing and if they are able to adapt to these shifts in climate. These threats have raised concerns about the state of the biodiversity of many species. With concerns raised, the Alaska Department of Fish Game (2015) developed the Alaska Wildlife Action Plan that is geared towards proactively addressing the conservation needs of wildlife. This plan was developed in 2006 and revised again in 2015 and is guided by input both from conservation partners and the public to work towards preventing species from becoming threatened or endangered. Of the 326 species in the plan, 192 are birds.

GREENUP AND RESOURCE AVAILABILITY:

Ecosystem processes deeply rely on the yearly cycles of vegetation greenness and are crucial in maintaining a healthy ecosystem (Neupane et al. 2022). To meet their needs for food sources, habitat, and nesting, birds follow peak vegetation greenness. Energy demands are high when completing the long migration journey with birds requiring fuel for both the flight and for sufficient energy in finding a breeding territory upon arrival (La Sorte et al., 2014). Migration is thought to begin when birds experience different environmental and endogenous circannual rhythms (an internal process) that initiates birds to begin heading to their breeding grounds from their wintering grounds as well as prompting molt and rapid fat accumulation (Hurlbert & Liang, 2012; La Sorte et al., 2014). Environmental cues such as precipitation, temperature, and greenness also prompt birds to begin migrating. These endogenous circannual rhythms are thought to have a greater influence on long-distance migratory birds compared to short-distance migrants with a potential inability for long-distance migrants to adapt to local weather signals on their migration routes that short-distance migrants may be more attuned to (Hurlbert & Liang, 2012).

Following resources, many hypothesize that migratory birds follow what is considered the “green wave”, the progression of greenup along their migration route where birds follow the wave of new plant growth to forage the abundance of insects (La Sorte & Graham, 2021). This green wave was originally contemplated as a process only done by mammals such as ungulates that follow the pulse of fresh vegetation for the most optimal and nutritious plant growth (Fagan & Gurarie, 2020). This process is done by following vegetation across latitudes or through different elevations. Many are considering that migratory birds may follow the same process in following peak resources. It is feared that the timing of the green wave may change with amplified climatic shifts, environmental impacts such as shifting snowmelt timing, air temperature variation, and precipitation changes (O'Leary et al., 2020). In northern latitudes, earlier snow-melt and increased temperatures may pose problems resulting in greenup occurring too early, prompting migratory birds to potentially miss the pulse of the green wave resulting in fewer resources to survive.

With green up variation and climate change influences, there may be cascading effects resulting in shifts in plant communities and arthropod emergence which has raised concerns on if birds are able to track these changes in greenup. Arthropods depend on specific temperatures to time when to be active and lay eggs, and when to emerge to feed. During the summer, arthropods lay their eggs and after winter, climate drives the emergence of arthropods with the onset of temperature rise and snowmelt (Tulp et al. 2008). Since arthropod lifespans are relatively brief, there are often short burst events of adult arthropod abundance. With climate change, these freeze-thaw cycles that occur may impact the winter survival of arthropods and seasonal patterns of resource availability. (Tulp et al. 2008).

RESOURCE ABUNDANCE AND TROPHIC RELATIONSHIPS:

Arthropods are a favored food source for a multitude of bird species and provide high energy fuel for flight. Not only are arthropods important for migration but they are also a crucial food source for nestlings (Tulp et al. 2008). With arthropod emergence depending on temperature, climate change impacts can affect the abundance of insects. By the time spring and summer arrive, arthropod emergence may not be at the level that birds require for survival. There have also been concerns about cascading effects with the recent shifts in plant communities in Alaska (McDermott et al. 2021). Arctic tundra, for example, is seeing an increase in tall woody shrubs in areas that are primarily tundra due to warmer and longer summers which can potentially change the composition of the food web structure (McDermott et al. 2021). With increased temperatures and increased abundance of insects, studies have indicated that this combination could increase the risk of insect outbreaks on important plant communities (McDermott et al. 2021 and Logan et al. 2003). An overabundance of insect outbreaks can be detrimental and destroy the habitats that migratory birds thrive in.

CLIMATE CHANGE, WEATHER, AND TEMPERATURE FLUCTUATIONS:

In the arctic, annual average temperatures have been warming at almost double the global mean (Overland et al. 2019). In Alaska, tundra environments are typically snow-free 2-4 weeks earlier in the coastal southwest than environments in the north providing breeding sites sooner than that of the north (Conklin et al. 2010). Southwest Alaska consists of subarctic tundra while central and southeast Alaska are primarily boreal forests. These arctic and boreal ecobiomes provide vital breeding grounds for more than half of North America's migratory birds (*USGS Fact Sheet 2013–3054 n.d.*). Climate change, however, has begun to alter these once abundant habitats with rapid changes such as reduction of tundra that is slowly turning into forest, insect outbreaks and wildfires, and changes to wetland habitat (*USGS Fact Sheet 2013–3054 n.d.*).

Plant productivity success depends on many variables and one that can impact plant growth is climate variability. There are many different climate indices such as El Niño Southern Oscillation, North Atlantic Oscillation, and Atlantic Multidecadal Oscillation (Michel et al. 2021). These indices calculate different weather patterns and conditions that vary each year. Weather and temperature are one of the main drivers that influence when arthropods become abundant and available as food sources to migratory birds. When fluctuations in climate occur such as windspeeds and hurricanes, these resources can be negatively affected.

REMOTELY SENSED VEGETATION COVER:

Remotely sensed vegetation data has gained recent use in examining vegetation productivity to help in the study of bird population fluctuation. It is a useful tool in looking at vegetation dynamics, biodiversity, animal movement, and population dynamics (Cole et al. 2015). When looking at spring temperature changes and the resulting greenup variation, remotely sensed satellite imagery can help assess the changes of greenup over time in a given area. One example of a remotely sensed satellite is MODIS (Moderate Resolution Imaging Spectroradiometer). MODIS is a satellite-based sensor that is used for both earth and climate measurements.

From MODIS, a tool called EVI (Enhanced Vegetation Index) is used to measure the health and density of vegetation. MODIS is the most widely used measurement to evaluate vegetation condition with remotely sensed imagery (Zhang et al. 2022). For studying ecological environments, remote sensing satellite imagery is an important research tool for studying greenup. It can measure vegetation productivity and can also be used to study the spatial and temporal aspects of vegetation development (Cole et al 2015).

PHENOLOGICAL SHIFTS, ASYNCHRONY, AND MISMATCH:

How birds respond to shifts in climate change is crucial especially when considering possible future declines in breeding productivity and demography. When birds migrate to fulfill their breeding requirements and arrive too early before enough peak resources are available, they risk the possibility of freezing due to colder temperatures and potentially hatching chicks too early without reliable food resources. Those that arrive too late risk fewer nest site selection, competition for mate selection, and less resource availability later in the season. Measuring changes in arrival, greenup, and asynchrony over time is essential as it can tell us if a species arrival timing is increasing, decreasing, or varying. Depending on the context these changes may have fitness consequences for species e.g. through breeding success in Alaska.

NEGATIVE FITNESS CONSEQUENCES AND BIODIVERSITY LOSS:

There can be negative impacts to their fitness if birds migrate before or after peak resources are available. This may result in decreases in breeding productivity and risk on survival. In aerial insectivores for example, temperature is crucial when it comes to hatch success. With inclement weather or unpredictable cold snaps, exposure to colder than normal temperatures can impact both the hatching and survival of nestlings. Tree Swallows in particular have shown negative fitness consequences as a result of temperature shifts. One study found that on average, fewer Tree Swallow individuals survive to fledgling when exposed to temperatures that descend through a range of 15.5 to 18.5 celsius range and that the number of fledglings produced per nest dropped rapidly from 3.3 to 1.4 chicks. (Shipley et al. 2020).

It has been found that some species may experience long-term changes in timing of arrival with some birds advancing their migration and some birds delaying their migration. This may vary for birds migrating on different flyways and that some species may be expanding their usual breeding ranges to adapt to possible changes on their route (Barton et al. 2018). By advancing arrival time earlier, these species risk advancing their reproduction during potentially colder times of the year and could have widespread impacts on their reproductive success. With aerial insectivores experiencing one of the most dramatic declines of any other avian taxonomic group, concerns arise on if they can keep up with climate change.

ESTIMATING SPRING ARRIVAL AND GREENUP:

Studying phenological intervals requires methodology that can observe the timing of recurring biological events. Using survey data, migration can then be quantified using different statistical models. In recent literature, phenological intervals were able to be computed using logistic generalized additive models (GAMs) and Bayesian spatial autoregressive models (Youngflesh et al. 2021). These studies also used Normalized Difference Vegetation Index (NDVI) and Moderate Resolution Imaging Spectroradiometer (MODIS) to use remotely sensed land cover data to show onset of greenness. There are multiple indices of remotely sensed resources such as NDVI and EVI (Enhanced Vegetation Index). This remotely sensed satellite data is important in that it can provide valuable indicator of vegetation condition as well as provide geographic trends in studying phenological intervals between spring greenup and migratory bird arrival using mid-greenup metrics (Mayor et al. 2017, Youngflesh et al. 2021).

Recent studies have been using eBird data and utilized different approaches to estimate spring arrival (Hurlbert, Mayor et al., Youngflesh et al. 2021, Robertson et al. 2024). Authors have typically compared the mean onset of greenup with the mean onset of arrival timing to see if there is any asynchrony of birds and greenup changing over time (Youngflesh et al. 2021, Mayor et al. 2017). These estimates can help determine any possible shifts in spring arrival by identifying species or populations with the most extreme changes in arrival and/or phenological asynchrony.

CONCLUSION:

As climate continues to change globally, how these changes will impact migratory birds is still being investigated. With possible impacts to food resource availability and habitat and mate selection, the timing of green up may have detrimental consequences to migratory birds. By using eBird data to derive spring arrival estimates using logistic generalized additive models (GAMs), valuable data can be contributed towards the ongoing research for migratory birds of greatest conservation need.

METHODS:

DATA EXTRACTION AND PROCESSING:

Checklist data was obtained from the eBird platform (ebird.org), a citizen science program that provides valuable biodiversity data resources which can be useful in studying bird abundance and distribution. 61 migratory passerine species were selected from those listed within the Alaska Wildlife Action Plan for species indicated as greatest conservation need (Alaska Department of Fish and Game 2015). For these species eBird data was obtained for 2001 through 2022 (based on the starting year used by Mayor et al. 2017) for the state of Alaska (USA) and the provinces of Yukon and British Columbia (Canada).

The R package *auk* was used for data extraction and processing (Strimas-Mackey et al. 2023). This package provides functions to filter out the eBird data down to selected species, which can be used to create individual species .csv files with presence/absence data based on individual checklists that detected, or did not detect, a given species. A total of 1.5 million checklists were used for the species in this study.

For each species, final ranking scores, dietary guilds, and habitat niches were included in the data. For final ranking scores, status scores are indicated by high or low and has a color category of red, orange, blue, and yellow based on vulnerability and high action need. Alaska ranking scores were gathered through NatureServe Explorer for a local range data for species of conservation need based on a numerical ranking score from 1 (critically imperiled) to 5 (secure), at both global (G rank) and subnational (S rank) scales based on biological vulnerability and rarity. G1 indicates critical imperilment/risk of extinction on a global basis and S1 indicates critical imperilment within a particular state (*"Definitions of NatureServe,"* (n.d.), Gotthardt et al. 2012).

Table 1

Status and Biological Scores

Numerical Category	Color Category	Status Score	Biological Score	Action Score		Description
I	Red	High	High	and	High	High status, biological vulnerability, and action need
II	Red	High	High	or	High	High status and either high biological vulnerability or high action need.
III	Orange	High	Low	and	Low	High status and low biological vulnerability and action need.
IV	Orange	Unknown	High	and	High	Unknown status and high biological vulnerability and action need.
V	Orange	Unknown	High	or	High	Unknown status and either high biological vulnerability or high action need.
VI	Blue	Unknown	Low	and	Low	Unknown status and low biological vulnerability and action need.
VII	Yellow	Low	High	and	High	Low status and high biological vulnerability and action need.
VIII	Yellow	Low	High	or	High	Low status and either high biological vulnerability or high action need.
IX	Blue	Low	Low	and	Low	Low status and low biological vulnerability and action need.

Note. A table generated by the Alaska Natural Heritage Program, University of Alaska Anchorage (Gotthardt et al. 2012) that shows the numerical and color categories used to show the status and the biological and/or action qualitative scores for species.

Table 2.

Final Ranking Scores of Species

Final Rank	**Common Name**	**Scientific Name**	**Feeding Guild**
II Red	Alder Flycatcher	*Empidonax alnorum*	Invertivore
II Red	American Pipit	*Anthus rubescens*	Invertivore
II Red	Bank Swallow	*Riparia riparia*	Invertivore
II Red	Barn Swallow	*Hirundo rustica*	Invertivore
II Red	Olive-sided Flycatcher	*Contopus cooperi*	Invertivore
II Red	Rufous Hummingbird	*Selasphorus rufus*	Nectarivore, Invertivore
II Red	Tree Swallow	*Tachycineta bicolor*	Invertivore
II Red	Western Wood-Pewee	*Contopus sordidulus*	Invertivore
II Red	White-crowned Sparrow	*Zonotrichia leucophrys*	Invertivore, Granivore
III Orange	Blackpoll Warbler	*Setophaga striata*	Invertivore
III Orange	Savannah Sparrow	*Passerculus sandwichensis*	Granivore, Invertivore
IV Orange	American Redstart	*Setophaga ruticilla*	Invertivore
IV Orange	MacGillivary’s Warbler	*Geothlypis tolmiei*	Invertivore
V Orange	American Tree Sparrow	*Spizella arborea*	Invertivore, Granivore
V Orange	Arctic Warbler	*Phylloscopus borealis*	Invertivore
V Orange	Golden-crowned Sparrow	*Zonotrichia atricapilla*	Frugivore, Granivore, Invertivore
V Orange	Lapland Longspur	*Calcarius lapponicus*	Granivore, Invertivore
V Orange	Orange-crowned Warbler	*Oreothlypis celata*	Frugivore, Invertivore
V Orange	Red-winged Blackbird	*Agelaius phoeniceus*	Invertivore, Granivore
V Orange	Wilson's Warbler	*Cardellina pusilla*	Invertivore
VII Yellow	Belted Kingfisher	*Megaceryle alcyon*	Piscivore
VII Yellow	Chipping Sparrow	*Spizella passerina*	Granivore, Invertivore
VII Yellow	Common Yellowthroat	*Geothlypis trichas*	Invertivore
VII Yellow	Fox Sparrow	*Passerella iliaca*	Granivore, Frugivore
VII Yellow	Lincoln's Sparrow	*Melospiza lincolnii*	Granivore, Invertivore
VII Yellow	Northern Flicker	*Colaptes auratus*	Invertivore, Herbivore
VII Yellow	Ruby-crowned Kinglet	*Regulus calendula*	Invertivore
VII Yellow	Rusty Blackbird	*Euphagus carolinus*	Invertivore, Frugivore, Granivore
VII Yellow	Townsend’s Warbler	*Setophaga townsendi*	Invertivore
VII Yellow	Varied Thrush	*Ixoreus naevius*	Granivore, Invertivore, Frugivore
IX Blue	Dark-eyed Junco	*Junco hyemalis*	Invertivore, Granivore
IX Blue	Hermit Thrush	*Catharus guttatus*	Invertivore, Frugivore
IX Blue	Pacific-slope Flycatcher	*Empidonax difficilis*	Invertivore
IX Blue	Red-breasted Sapsucker	*Sphyrapicus ruber*	Invertivore
IX Blue	Song Sparrow	*Melospiza melodia*	Invertivore, Granivore
IX Blue	Swainson's Thrush	*Catharus ustulatus*	Invertivore, Frugivore
IX Blue	Yellow Warbler	*Setophaga petechia*	Invertivore

Note. List of species with dietary guilds listed and biological vulnerability scores.

HEXAGON SPATIAL UNITS (LOCATIONS)

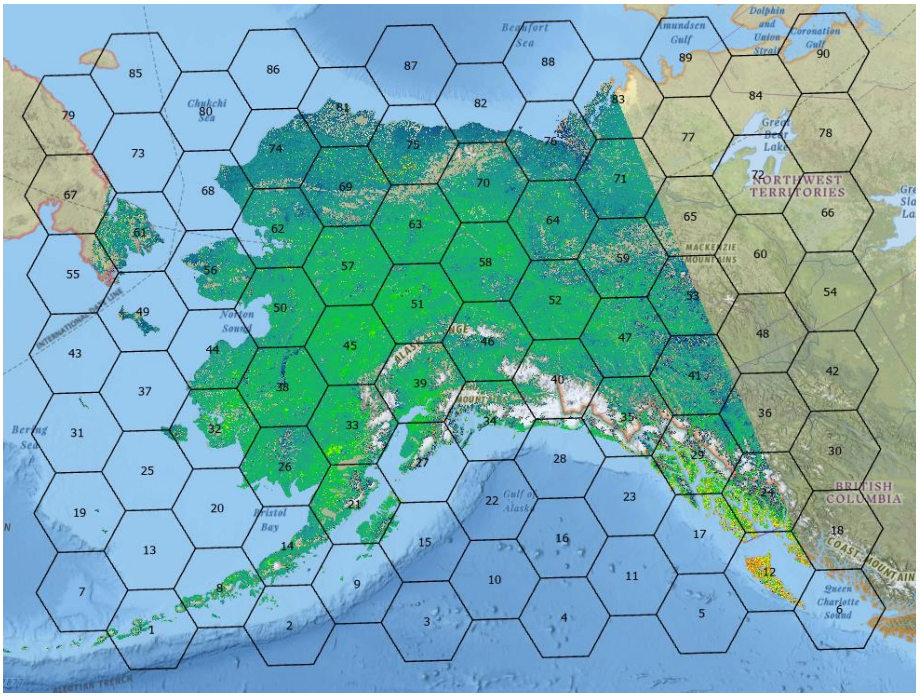
Within R and ArcGIS Pro, uniform hexagons were generated in Alaska and parts of the Yukon (Canada) to use as spatial units for greenup data and estimates of spring arrival (Fig. 1). The cities with the most detections within the data from 2001-2022 were selected as names for each chosen hexagon, and referred to in this thesis as the name of each different hexagon or 'location.' For Southeast Alaska, these included Ketchikan (hex 24), Juneau (hex 29), and Haines (hex 35). For Southcentral Alaska, these were Kodiak (hex 21), Homer (hex 27), Valdez (hex 34), and Anchorage (hex 39). For Interior Alaska, Tok (hex 46) and Fairbanks (51) were selected. For Canada, in the Yukon territory these were Teslin (41) and Carmacks (hex 47). Each hexagon was 285 km across (distance between opposite edge lengths), which was used to have hexagons of ~70K km^2.

LOGISTIC GENERALIZED ADDITIVE MODELS (GAMS):

Once individual species data was filtered, we calculated estimates of spring arrival, for each species/location/year combination with sufficient data, in R. Using the approach by Youngflesh et al. (2021), logistic Generalized Additive Models (GAMs) were used in a Bayesian framework, to obtain species-specific spring arrival estimates for a given year and location (hexagon). The package *rstanarm* was used to fit the GAM models (Goodrich et al. 2023). To maintain consistency, a set timeframe was selected for Julian day following the Julian day calendar. Ensuring that species that arrive after spring migration were not included, Julian day 211 (late July) was selected as the cutoff date for data to be included. There was also a cutoff for ensuring species were not included that were too early in migration, where Julian day 60 (early March) was selected as the beginning date to except data. To run the logistic GAM, a minimum set of detections were selected. There had to be at least 20 checklists with detections and at least 20 with non-detections with 10 unique days with detections. Data were filtered in R. For all 61 species, half-maximum estimates (or estimate of arrival time) were calculated for the hexagon/year combinations with sufficient data (Fig. 2).

Figure 1

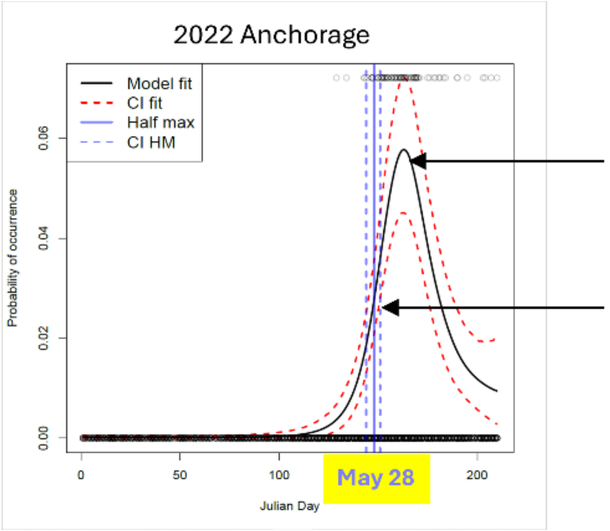
Hexagon Locations with 2022 Mean Mid-Greenup



Note. Hexagons covering the span of Alaska and parts of Yukon, Canada and British Columbia. Mid-greenup layer included showing greenup timing for 2022 (MODIS Land Cover Dynamics MCD12Q2).

Figure 2

Spring Arrival Estimate



maximum occurrence

‘half max’ is the date with half of the max probability of occurrence

Note. Example of GAM model output for Olive-sided Flycatcher (OSFL) from 2022 in the Anchorage hexagon. Individual dots along the bottom are checklists without OSFL detections, by Julian Day. Individual dots along the top are checklists with detections of OSFL. The y axis is the modeled probability of occurrence based on the GAM predictions. The peak of the model fit (black curve) is the maximum occurrence/greatest probability of OSFL detection. The “half max” (blue vertical line) is the point on the curve with half of the maximum probability of occurrence. It corresponds to a specific day of the year, with a 90% credible interval (dotted blue lines), used as our estimate of spring arrival for that species in that year and location. The mean date of spring arrival for OSFL in 2022 in the Anchorage area was Julian Day 148 (May 28th).

REMOTE-SENSING LAND COVER DATA (MODIS):

To estimate greenup for each year in each location, the MODIS Land Cover Dynamics MCD12Q2 data product, which used Enhanced Vegetation Index (EVI) to show onset of greenness, was used (Friedl et al. 2022). This layer provided mid-greenup data from 2001-2022 for the study area. It provides science data sets (SDSs) that map global land surface phenology metrics. These are measured at 500-meter spatial resolution and annual time step.

Once the EarthData layer was extracted, it was input into ArcGIS Pro within the hexagons. ArcGIS Pro generated mid-greenup zonal statistics for each hexagon for each year.

Following the example of Youngflesh et al. (2022), a ‘forest land cover’ mask was created to limit our mid-greenup calculation to forested areas. The USGS EarthData land cover layer MCD12Q1.061 was uploaded into ArcGIS Pro to provide high quality MODIS land cover types at yearly intervals. Different land cover variables were selected using the FAO-Land Cover Classification System Land cover (LCCS1) where Evergreen Needleleaf Forests, Evergreen Broadleaf Forests, Deciduous Needleleaf Forests, Deciduous Broadleaf Forests, Mixed Broadleaf/Needleleaf Forests, Mixed Broadleaf Evergreen/Deciduous Forests, Open Forests, and Sparse Forests were selected and filtered through extracting by attribute and masking in GIS. Zonal statistics were generated in ArcGIS Pro for each year (2001-2022) and for each hexagon. From the mid-greenup zonal statistics file generated, the mean mid-greenup values for each hexagon and year were calculated to use with asynchrony calculations.

DETERMINING PHENOLOGICAL ASYNCHRONY:

Asynchrony is simply the difference in time between two measurable phenological events. For this study, in a given year and location it is the difference between our estimate of mid-greenup and our estimate of spring arrival. We used “spring arrival – mid-greenup” so asynchrony has a positive value when arrival is after greenup, and a negative value when spring arrival is before greenup. The difference, in days, is the amount of asynchrony for that species, in a given year, in that location.

TRENDS IN MID-GREENUP, SPRING ARRIVAL, AND ASYNCHRONY

Simple linear regression of mean mid-greenup in a hexagon as predicted by year, was conducted for 11 hexagons. In addition, linear regression of 1) spring arrival date as predicted by year, and 2) asynchrony as predicted by year, was conducted for species/location combinations with a minimum of 5 years of arrival estimates. The original dataset included 61 landbird species but was reduced to 37 to eliminate any resident species as well as those that did not have sufficient data. Significant regression coefficients (using an alpha of 0.10) are reported, but it is important to note that a correction for multiple comparisons using the false discovery rate method (Benjamini & Hochberg 1995) resulted in 0 statistically significant trends in mean mid-greenup over time in individual hexagons, 0 in spring arrival trends over time, and 0 statistically significant trends in asynchrony over time for individual species/location combinations.

CORRELATION OF ANOMALIES

Spring arrival and mid-greenup anomalies were also calculated, in order to test for correlations (using Pearson's r) of anomalies for each species/location combinations with at least 5 years of arrival estimates. Mid-greenup anomalies for each year and hexagon were calculated as the difference from the 21-year average (2001-2022) mid-greenup date. A positive anomaly indicates a later greenup than the mean and a negative anomaly refers to an earlier greenup than the mean. Spring arrival anomalies were then calculated for each species, in a given hexagon (with at least 5 years spring arrival estimates), based on the difference between a given year's spring arrival estimate and the overall average (for that species in that hexagon). Pearson's r values are reported, using both uncorrected p-values (using an alpha of 0.10), and with a correction for multiple comparisons using the false discovery rate method (only one correlation of anomalies remained statistically significant; Benjamini & Hochberg 1995). Species results were sorted taxonomically using the eBird/Clements Checklists of Birds of the World through Cornell (Clements et al. 2023).

RESULTS:

In the 11 locations with sufficient spring arrival estimates to use for further analyses, most linear regression trends were not significant (Table 3). Juneau and Kodiak NWR both showed significant trends towards earlier mid green-up (-0.5 days/year in Juneau and -0.46 days/year for Kodiak NWR; Fig. 3) but with relatively low R^2 values (Table 3). The other 9 locations showed non-significant trends for mid-greenup.

Table 3.

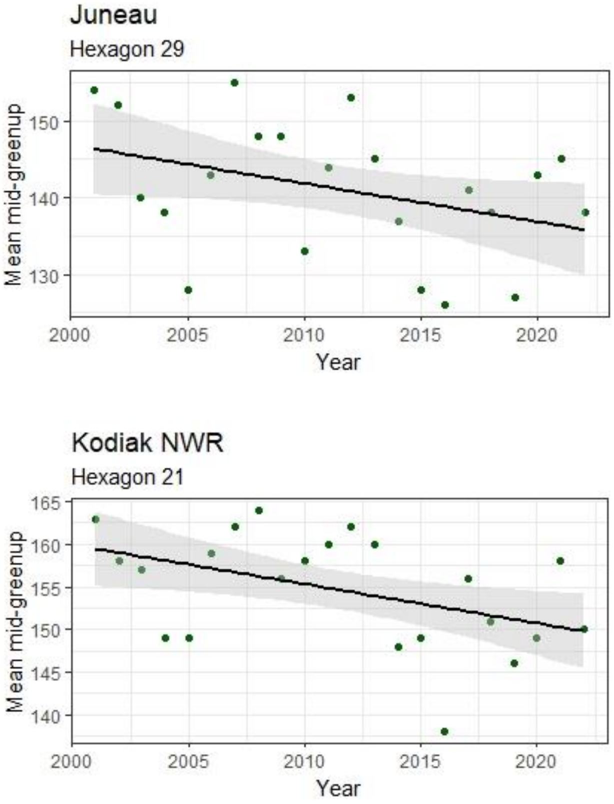
Linear Trends of Mean Mid-Greenup in Each Location Over Time

Location	hexagon	$F_{(1,20)}$	year coefficient	se	p-value	adj R^2
Ketchikan	24	2.554	-0.526	0.329	0.126	0.069
Juneau	29	3.117	-0.500	0.283	**0.093**	0.092
Haines	35	2.224	-0.319	0.214	0.152	0.055
Teslin (Yukon, Canada)	41	1.296	-0.219	0.192	0.268	0.013
Carmacks (Yukon, Canada)	47	0.102	-0.055	0.171	0.753	-0.045
Kodiak NWR (Alaska)	21	4.949	-0.460	0.207	**0.038**	0.158
Homer	27	2.318	-0.293	0.192	0.144	0.059
Valdez	34	1.080	-0.241	0.232	0.311	0.004
Anchorage	39	1.431	-0.200	0.167	0.246	0.020
Tok	46	0.503	-0.112	0.158	0.487	-0.024
Fairbanks	51	0.567	-0.114	0.151	0.460	-0.021

Note. F test statistics (and p-values), year coefficients with standard errors, and adjusted R^2 values for each linear regression. Significant ($p < 0.10$) negative regression coefficients represent trends towards earlier greenup, however none of these trends were significant when correcting for multiple comparisons using the false discovery rate method.

Figure 3

Mid-greenup Trends Over Time



Note. Shown are the two significant linear regression trends for mean mid-greenup in specific locations (2001-2022) from Table 3. Regression line plotted with 90% CI (shaded).

SPRING ARRIVAL TRENDS

For spring arrival estimates, most species/hexagon combinations (with at least 5 years of arrival estimates) had non-significant trends (Table 4). Of the species and hexagon combinations, 7 resulted in trends of earlier arrival, 135 had non-significant trends of arrival, and 19 had trends towards later arrival. Rufous Hummingbird *(Selasphorus rufus)* showed a significant negative trend towards an earlier arrival with a significant regression coefficient of -1.4. Swainson’s Thrush resulted in a positive trend towards earlier arrival with a significant regression coefficient of 0.8.

Table 4

Linear Trends of Spring Arrival Over Time

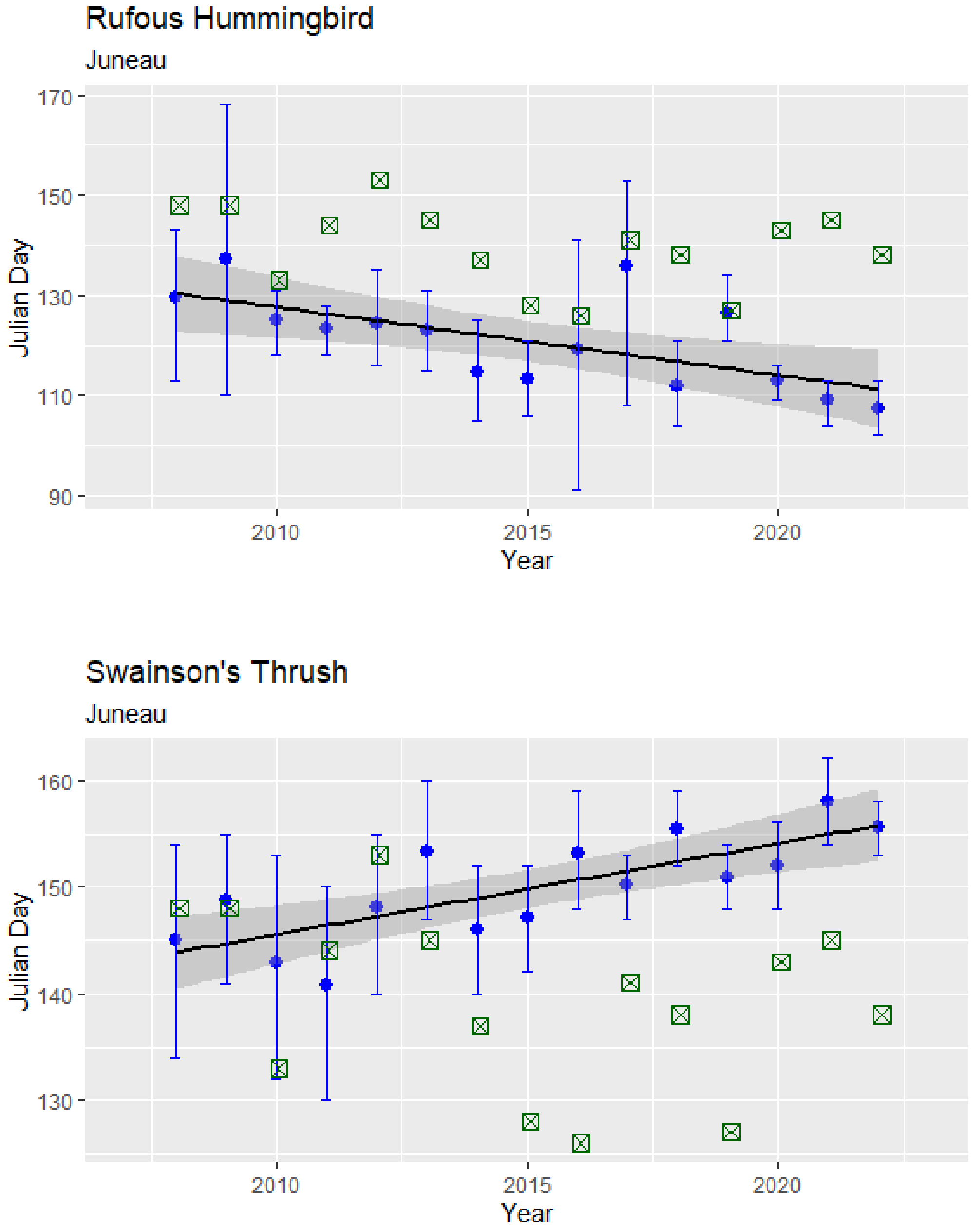
	Southeast Alaska			**Yukon, Canada**		**Southcentral Alaska**				**Interior Alaska**	
	Ketchikan	**Juneau**	**Haines**	**Teslin**	**Carmacks**	**Kodiak**	**Homer**	**Valdez**	**Anchorage**	**Tok**	**Fairbanks**
Common Name	**24**	**29**	**35**	**41**	**47**	**21**	**27**	**34**	**39**	**46**	**51**
Rufous Hummingbird	NS	**-1.4***					**2.4**	NS			
Belted Kingfisher			3.0						NS		
Red-breasted Sapsucker		NS									
Northern Flicker			**1.6**		NS				NS		1.1
Olive-sided Flycatcher							NS		NS		
Western Wood-Pewee			NS		NS				0.92		
Alder Flycatcher		NS					NS		NS		**0.8**
Pacific-slope Flycatcher	NS	NS									
Bank Swallow		NS	NS		NS		NS		NS		NS
Tree Swallow	NS	**-0.5**			NS	NS	NS	NS	NS		0.8
Barn Swallow	NS	NS									
Arctic Warbler										NS	
Ruby-crowned Kinglet	NS	NS	NS	NS	NS		NS	**2.8***	NS		NS
Varied Thrush			NS				NS		NS		NS
Swainson's Thrush	NS	**0.8***	NS		NS		NS		NS		NS
Hermit Thrush	NS	**-0.7**	NS		NS	NS	NS	NS	NS		NS
American Pipit	NS	NS	NS		NS		NS		**2.4**		**5.3**
Lapland Longspur		NS					NS		**2.0**		NS
Chipping Sparrow			NS	NS	**1.6**						
American Tree Sparrow											NS
Fox Sparrow		NS	NS		NS		**-4.3**	NS	NS		NS
Dark-eyed Junco					NS						NS
White-crowned Sparrow			NS		NS	NS			NS		NS
Golden-crowned Sparrow	-1.1	NS							NS		NS
Savannah Sparrow	NS	NS	NS		NS		NS	NS			
Song Sparrow									NS		
Lincoln's Sparrow	NS	NS	NS		NS		NS	NS	NS		NS
Red-winged Blackbird		NS	NS		NS						
Rusty Blackbird			NS						NS		NS

(cont.) Common Name	**24**	**29**	**35**	**41**	**47**	**21**	**27**	**34**	**39**	**46**	**51**
Orange-crowned Warbler	NS	NS	NS			NS	NS	NS	NS		0.4
MacGillivary's Warbler	NS										
Common Yellowthroat	NS	NS	1.2		**1.0**						
American Redstart		NS									
Yellow Warbler	NS	NS	NS		NS		NS	NS	**0.4**	NS	NS
Blackpoll Warbler			NS						**0.8**	NS	NS
Townsend's Warbler	NS	**-0.6**					NS		NS		**3.5***
Wilson's Warbler	NS	NS	NS		NS		NS	NS	NS		**-1.1***

Note. Linear trends in Julian day estimates of spring arrival for species/location combinations with at least 5 years of arrival estimates. Blank cells reflect <5 years of arrival estimates, NS reflect a non-significant linear trend, and a number represents a significant regression coefficient (in days/year) for 'year' (negative values reflect a trend of earlier arrival, positive values a trend of later arrival) with $p < 0.01$(bold with asterisk), $p < 0.05$ (in bold) or $0.05 < p < 0.10$ (plain text). However, none of these trends were significant when correcting for multiple comparisons using the false discovery rate method. Species are listed in taxonomic order.

Figure 4

Arrival Estimates and Trend Over Time of Rufous Hummingbird and Swainson's Thrush



Note. Arrival estimate plots of Rufous Hummingbird and Swainson's Thrush with trends over time. The blue points represent estimates of spring arrival from the GAMs with a 90% credible interval in blue error bars. The green points (boxes with x) are the mean mid-greenup for that location/year. For Rufous Hummingbird, b = -1.4 (p = 0.008) and for Swainson's Thrush, b = 0.8 (p < 0.001).

ASYNCHRONY TRENDS

Similar to the analysis of trends in spring arrival, most species in most locations had non-significant trends in asynchrony (Table 5). Of the species and hexagon combinations, 10 results had trends towards decreasing asynchrony, 136 had non-significant trends of asynchrony, and 14 had trends towards increasing asynchrony. Rufous Hummingbird has a trend of increasing asynchrony of 3.0 days/year in the Homer, Alaska area (hex 27). American Pipit has a value of 2.6 days/year for Anchorage (hex 39) indicating increasing asynchrony while White-crowned Sparrow has a negative value of -2.5 for Carmacks (hex 47) indicating decreasing asynchrony. Both are level II Red on the final rank score for greatest conservation need. Northern Flicker, Lapland Longspur, Rusty Blackbird, Orange-crowned Warbler, Blackpoll Warbler and Swainson’s Trush also had results that had significant trends of increasing asynchrony.

Table 5.

Linear Trends of Asynchrony Over Time

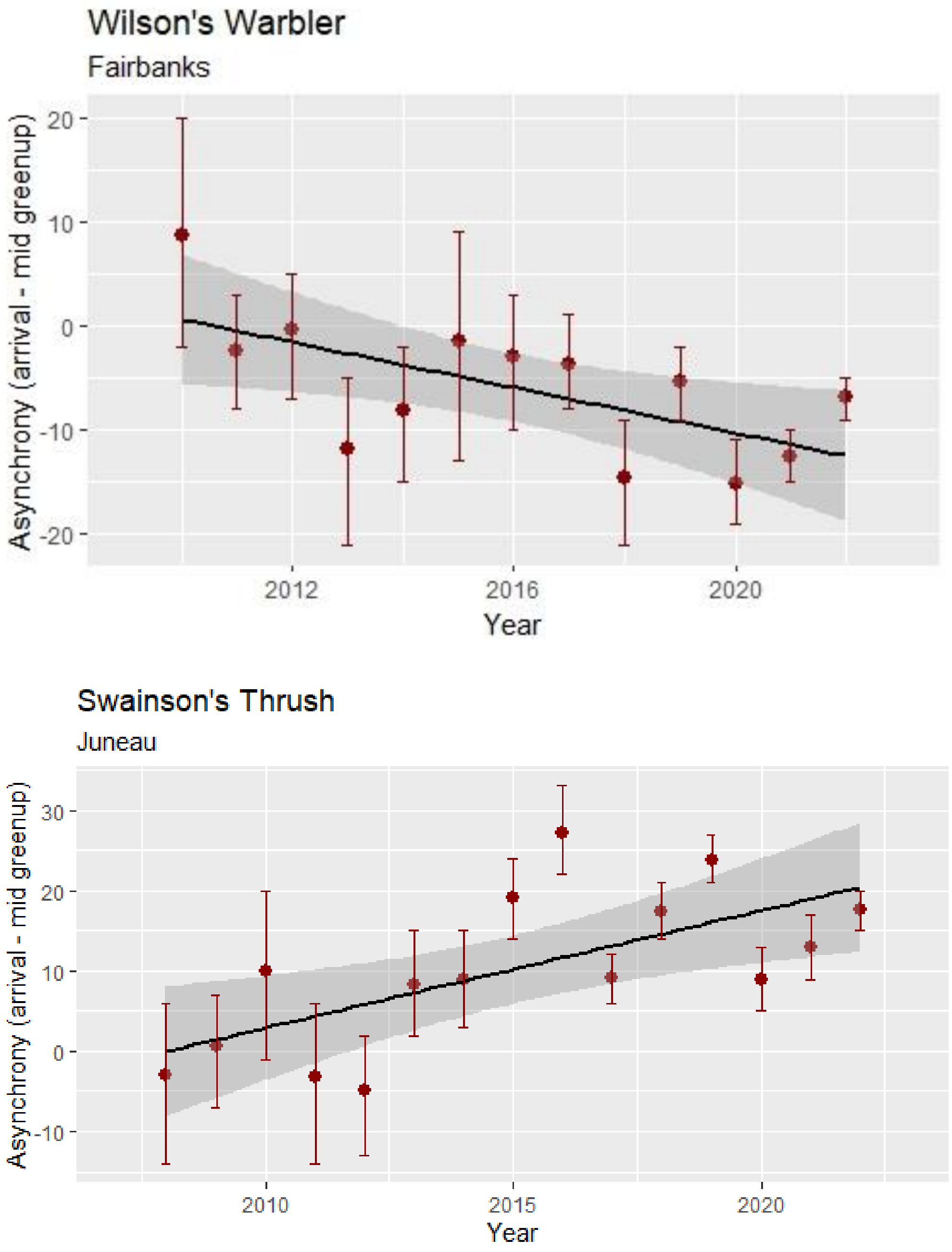
	Southeast Alaska			**Yukon, Canada**		**Southcentral Alaska**				**Interior Alaska**	
	Ketchikan	**Juneau**	**Haines**	**Teslin**	**Carmacks**	**Kodiak**	**Homer**	**Valdez**	**Anchorag**	**Tok**	**Fairbanks**
Common Name	**24**	**29**	**35**	**41**	**47**	**21**	**27**	**34**	**39**	**46**	**51**
Rufous Hummingbird	NS	NS					**3.0***	NS			
Belted Kingfisher			NS						NS		
Red-breasted Sapsucker		NS									
Northern Flicker			NS		-1.3				NS		**1.1**
Olive-sided Flycatcher							NS		NS		
Western Wood-Pewee			NS		NS				NS		
Alder Flycatcher		NS					NS		NS		NS
Pacific-slope Flycatcher	NS	NS									
Bank Swallow		NS	NS		NS		NS		NS		NS
Tree Swallow	NS	NS			NS	NS	NS	NS	NS		NS

(cont.) Common Name	**24**	**29**	**35**	**41**	**47**	**21**	**27**	**34**	**39**	**46**	**51**
Barn Swallow	1.8	NS									
Arctic Warbler										NS	
Ruby-crowned Kinglet	NS	NS	NS	NS	NS		NS	3.0	NS		NS
Varied Thrush			NS				NS		NS		NS
Swainson's Thrush	NS	**1.4***	**-1.8**		-2.0		NS		NS		NS
Hermit Thrush	1.0		NS		-3.7	NS	NS	NS	NS		NS
American Pipit	2.1	NS	NS		NS		NS		**2.6**		4.7
Lapland Longspur		NS					NS		**2.0**		NS
Chipping Sparrow			NS	NS							
American Tree Sparrow											NS
Fox Sparrow		NS	NS		NS		-3.7	NS	NS		NS
Dark-eyed Junco					NS						NS
White-crowned Sparrow			NS		**-2.5**	NS			NS		NS
Golden-crowned Sparrow	NS	NS							NS		NS
Savannah Sparrow	NS	NS	NS		-3.6		NS	NS			
Song Sparrow									NS		
Lincoln's Sparrow	NS	NS	NS		NS		NS	NS	NS		NS
Red-winged Blackbird		NS	NS		NS						
Rusty Blackbird			NS						**0.8**		NS
Orange-crowned Warbler	**0.8**	NS	NS			NS	NS	NS	NS		NS
MacGillivary's Warbler	NS										
Common Yellowthroat	NS	NS	NS		NS						
American Redstart		NS									
Yellow Warbler	NS	NS	NS		-1.4		NS	NS	NS	-1.7	NS
Blackpoll Warbler			NS						**1.1**	NS	NS
Townsend's Warbler	NS	NS					NS		NS		2.9
Wilson's Warbler	NS	NS	NS		NS		NS	NS	NS		**-1.1**

Note. Linear trends over time in estimates of asynchrony (mid-greenup minus spring arrival, in days) for species/location combinations with at least 5 years of arrival estimates. Blank cells reflect <5 years of asynchrony estimates, NS reflect a non-significant linear trend, negative values reflect a trend of decreasing asynchrony, positive values reflect a trend of increasing asynchrony with $p<0.01$(bold with asterisk), $p< 0.05$ (in bold) or $0.05 < p < 0.10$ (plain text). However, none of these trends were significant when correcting for multiple comparisons using the false discovery rate method. Species are listed in taxonomic order.

Figure 5

Trend Over Time in Asynchrony of Wilson's Warbler and Swainson's Thrush



Note. Variation in asynchrony between two of the significant species that showed high levels of increasing or decreasing asynchrony. Points are estimates of asynchrony based on (arrival - mid-greenup), with 90% credible intervals. For Wilson's Warbler, b = -1.1 (p = 0.02) and for Swainson's Thrush, b = 1.4 (p = 0.007).

CORRELATION OF ANOMALIES:

Most species/location combinations did not have significant correlations of mid-greenup anomalies with spring arrival anomalies (Table 6). However, when a correlation was significant it tended to be positive (31 species/location combinations had significant positive correlations and only 2 species/location combinations had a negative correlation). 15 of the 37 species had at least one location with a positive correlation, including the Orange-crowned Warbler (*Oreothlypis celata*) in Anchorage (r = 0.84, uncorrected p < 0.001, fdr corrected p = 0.015, Fig. 6). A positive correlation can be considered as some evidence that a species is tracking year-to-year changes in greenup. Bank Swallows *(Riparia riparia)* in Anchorage, and Golden-crowned Sparrows *(Zonotrichia atricapilla)* in Fairbanks, had a negative correlation of anomalies which is the opposite of what is expected if a species is tracking changes in greenup. These positive and negative correlations are summarized in Figure 7.

Table 6.

Pearson's r values for Correlation of Anomalies

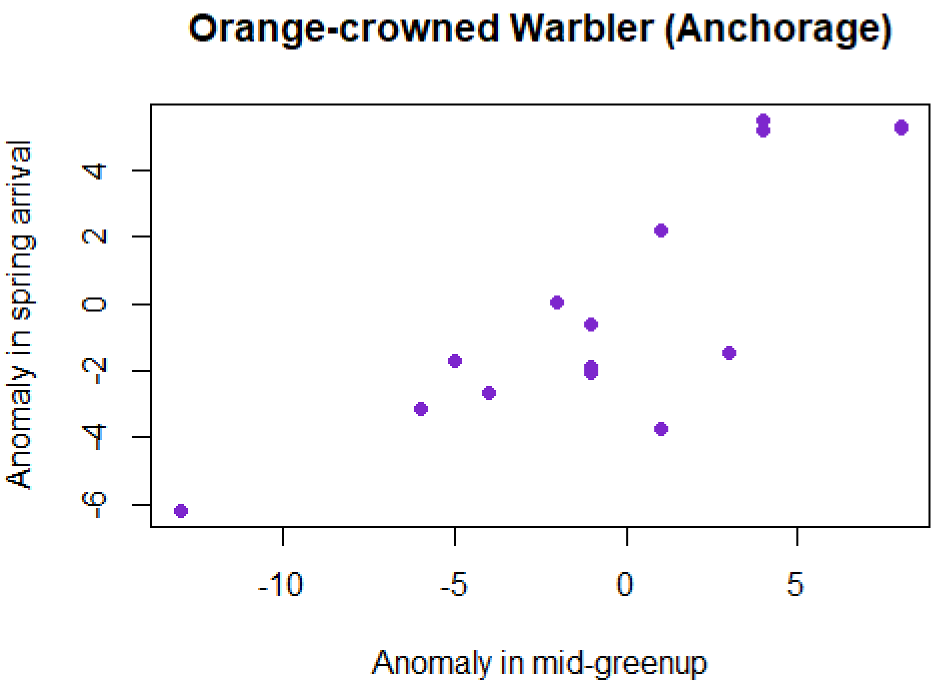
	Southeast Alaska			Yukon, Canada		Southcentral Alaska				Interior Alaska	
	Ketchikan	**Juneau**	**Haines**	**Teslin**	**Carmacks**	**Kodiak**	**Homer**	**Valdez**	**Anchorage**	**Tok**	**Fairbanks**
Common Name	**24**	**29**	**35**	**41**	**47**	**21**	**27**	**34**	**39**	**46**	**51**
Rufous Hummingbird	0.49	0.26			-0.01	-0.69		0.49		0.26	
Belted Kingfisher			0.22						-0.24		
Red-breasted Sapsucker		0.39									
Northern Flicker			***0.75***		0.66				0.37		***0.64***
Olive-sided Flycatcher							0.29		0.12		
Western Wood-Pewee			-0.27		-0.50				0.41		
Alder Flycatcher		-0.49					0.20		-0.25		-0.35
Pacific-slope Flycatcher	**0.52**	**0.52**									
Bank Swallow		-0.30	-0.19		-0.65		-0.52		**-0.49**		0.50
Tree Swallow	-0.22	0.31	-0.29		0.49	-0.26	-0.08	-0.07	-0.03		-0.07
Barn Swallow	0.37	0.10									
Arctic Warbler										0.01	
Ruby-crowned Kinglet	***0.71***	**0.62**	0.32	-0.14	-0.07		0.44	-0.15	***0.72***		0.34
Varied Thrush			***0.71***				0.48		0.40		0.37
Swainson's Thrush	-0.07	-0.06	0.01		-0.01		0.33		0.28		0.01
Hermit Thrush	0.13	**0.54**	**0.68**		-0.46	-0.10	***0.59***	-0.43	0.30		0.45
American Pipit	0.25	-0.28	-0.54		0.11		0.10		-0.13		0.09
Lapland Longspur		-0.56					-0.22		0.17		0.69
Chipping Sparrow			0.17	0.45	0.60						
American Tree Sparrow											-0.02
Fox Sparrow		0.44	0.08		0.33		0.44	-0.56	0.40		0.03
Dark-eyed Junco					-0.08						**0.67**
White-crowned Sparrow			-0.23		0.00	0.20			-0.38		0.52
Golden-crowned Sparrow	0.05	0.24							-0.08		**-0.82**
Savannah Sparrow	0.28	***0.52***	-0.12		-0.22		-0.06	-0.55		**0.46**	**0.55**
Song Sparrow									***0.42***		
Lincoln's Sparrow	-0.08	***0.78***	-0.13		0.63		0.55	0.00	***0.64***		0.28

(cont.) Common Name	**24**	**29**	**35**	**41**	**47**	**21**	**27**	**34**	**39**	**46**	**51**
Red-winged Blackbird		0.08	0.21		0.34						
Rusty Blackbird			0.29						**0.50**		0.14
Orange-crowned Warbler	***0.58***	***0.70***	**0.56**			-0.01	**0.49**	-0.42	$\boxed{\textbf{\textit{0.84}}}$		0.11
MacGillivray's Warbler	0.37										
Common Yellowthroat	0.13	0.25	0.43		0.44						
American Redstart		-0.22									
Yellow Warbler	-0.34	***0.55***	0.45		0.39		0.46	-0.20	0.11	0.34	0.11
Blackpoll Warbler			-0.19						0.09	-0.21	0.38
Townsend's Warbler	***0.66***	***0.70***					**0.50**		0.16		0.23
Wilson's Warbler	**0.69**	0.39	0.32		***0.99***		**0.58**	0.34	0.37		0.15

Note. Pearson's *r* values of spring arrival anomalies with mid-greenup anomalies for species/location combinations with at least 5 years of arrival estimates. Blank cells reflect <5 years of arrival estimates. Using uncorrected p-values, regular type reflects a non-significant correlation, ***bold and italics*** indicate significance at $p < 0.05$ and **bold values** indicate significance at $0.05 < p < 0.10$. Using the false discovery rate method, only the correlation for Orange-crowned Warbler in Anchorage (39) was statistically significant (shown with a □). Species are listed in taxonomic order.

Figure 6

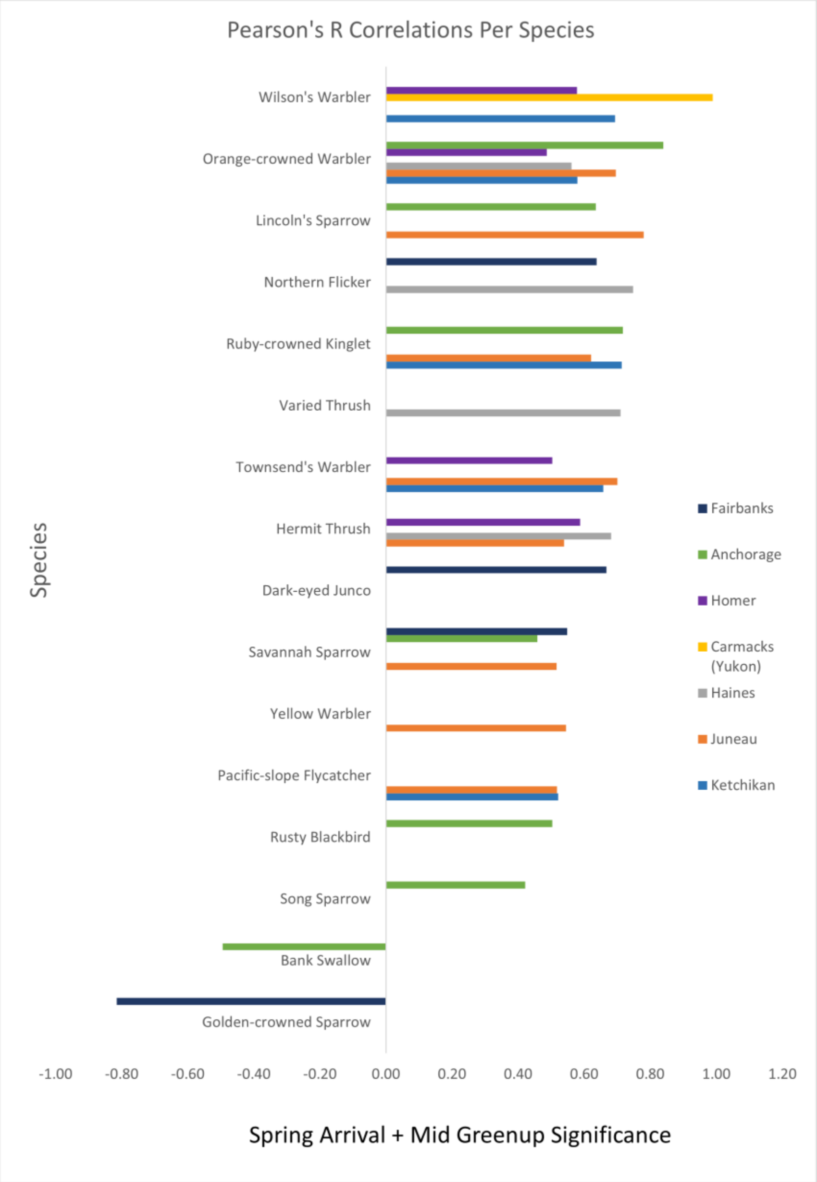
Correlation of Spring Arrival/Mid-Greenup Anomalies of Orange-crowned Warbler in Anchorage



Note: Anomaly in spring arrival: for a given year, species, and location, that year's spring arrival estimate minus the mean across all of the years of spring arrival estimates. Anomaly in mid-greenup: for a given year and location (hexagon), that year's mean mid-greenup minus the mean across all of the years of mid-greenup (in that location). In this plot, the positive correlation (*r* = 0.84, fdr corrected p = 0.015) reflects that in years with earlier-than-average mid-greenup (in Anchorage), Orange-crowned Warblers tended to also have an earlier-than-average estimate of spring arrival.

Figure 7

Significant Pearson's r Correlation Values for Species/Locations



Note. A bar chart showing species and locations with significant* correlations of spring arrival anomalies with mid-greenup anomalies. Not represented are 21 species that did not have a significant correlation in any location (Table 6). *without correcting for multiple comparisons.

DISCUSSION:

This study asked whether bird species of conservation concern in different parts of Alaska are 1) experiencing shifts in spring arrival (earlier or later) over time, 2) increasing or decreasing asynchrony (the difference between spring arrival and vegetation greenup) over time, and/or 3) potentially 'tracking' year-to-year variation in vegetation greenup, i.e. arriving earlier when greenup is earlier and arriving later when greenup is later. Particularly with insectivorous migratory species that are experiencing significant declines across the globe, determining whether species are experiencing shifts in migration timing is critical (Rosenberg et al. 2019).

Of the 37 species in 11 locations (hexagons) with sufficient years of spring arrival estimates to analyze, most trends over time of the date of spring arrival were not significant (Table 5). Exceptions to this included seven species with a trend towards an earlier spring arrival in at least one location, and six species with later arrival in at least on location (although as noted in Tables, these results were not significant when accounting for multiple comparisons). Swainson's Thrush *(Catharus ustulatus)* had a trend of later arrival (0.8 days/year, $p < 0.001$, Fig. 4) in Juneau and is listed as a IX Blue in conservation level. Alder Flycatcher *(Empidonax alnorum)*, a II Red in conservation, also arrived later, in the Fairbanks area (0.8 days/year, $p = 0.02$). Rufous Hummingbird *(Selasphorus rufus)* had a trend of earlier arrival (-1.4 days/year, $p = 0.008$, Fig. 4) in Juneau and is listed as a II Red in conservation level. Other research has shown that Rufous Hummingbirds may be migrating faster than in previous time periods (Courter, 2017). As a long-distance migrant, Rufous Hummingbirds migrate to higher latitudes than any other hummingbird species (Courter, 2017). Courter found that while they arrived 8-11 days later in Oregon, they in turn arrived 7-17 days earlier in northern areas in Washington and British Columbia.

With asynchrony (the difference between spring arrival and mid-greenup, in days), similarly the majority of species/location combinations had nonsignificant trends (136 total, Table 6), with 10 species/location combinations showing decreasing asynchrony over time, and 14 species/location combinations with trends of increasing asynchrony. Rufous Hummingbird *(Selasphorus rufus)* showed a trend of increasing asynchrony (3.0 days/year, p = 0.007) in Homer while Wilson's Warbler *(Cardellina pusilla)* showed a trend of decreasing asynchrony (-1.1 days/year, p = 0.02) in Fairbanks. Both are listed as a level II Red in the final rank score for greatest conservation need. It has been hypothesized that changing temperatures may be the culprit for variation in phenological advancement as it can result in a decrease in insect availability. This decoupling can also expose nestlings to inclement weather conditions and higher rates of chick mortality (Shipley et al. 2020).

Looking at correlations of anomalies, there was a bit more of a potential 'signal' in terms of evidence suggesting that some species might be tracking year-to-year changes in mid green-up. With the caveat that all but one Pearson's *r* value would not be considered significant when correcting for multiple comparisons, there were many more species/location combinations with a positive correlation (31) compared to just 2 with a negative correlation (Fig. 7). In particular, Orange-crowned Warbler (*Oreothlypis celata*) had a positive correlation in five locations, representing Southeast (Ketchikan, Juneau, and Haines) and Southcentral Alaska (Homer and Anchorage; Fig. 6). Ruby-crowned Kinglet (*Regulus calendula*) also had a positive correlation in Ketchikan and Anchorage. Another species with a positive correlation was Wilson's Warbler (*Cardellina pusilla*) in Carmacks, Yukon: again, some evidence that species may be tracking changes in greenup in these locations.

With the green-wave hypothesis, a changing climate could be disrupting the food availability needs of migratory birds (La Sorte et al. 2014). This may result in birds having difficulty keeping track with changes in greenup. Bank Swallow (*Riparia riparia*) had a negative correlation of anomalies in Anchorage (*r* = -0.49) and Golden-crowned Sparrow *(Zonotrichia atricapilla)* had a negative correlation in Fairbanks (*r* = -0.82) indicating that these species may be experiencing difficulty in tracking changes in greenup. Bank Swallow (*Riparia riparia*) is also listed as a II Red (high status and either high biological vulnerability and action need) on the final rank score of species of greatest conservation need and Golden-crowned Sparrow *(Zonotrichia atricapilla)* is listed as V Orange (within the second tier of conservation need, indicating unknown status and either high biological vulnerability and action need).

Of the swallow species, Bank Swallows have shown one of the steepest declines in population sizes. An estimated 89% has been lost in North America since 1970, and a staggering 98% decline has been estimated in Canada making it a rapidly declining species (*Bank Swallow*, n.d.). As an aerial insectivore, the dependency on reliable arthropod availability is high. Impacts to breeding phenology and climate change may be resulting in these declines. In Canada, a 57-year study focusing on four swallow species found that while Barn Swallow *(Hirundo rustica)* and Tree Swallow *(Tachycineta bicolor)* had advancement in clutch initiatian dates, Cliff Swallow *(Petrochelidon pyrrhonota)* had unchanged performance and Bank Swallow *(Riparia riparia)* had poorer breeding performance with similar clutch initiation dates from previous years along with a decrease in 0.5 egg/clutch over time (Imlay et al., 2018). All four species showed a decrease in hatching success than earlier years, highlighting the declines seen across many aerial insectivores. The importance of consistent snowpacks for overwinter survival success of arthropods is crucial and with many regions experiencing warmer weather conditions earlier in the season, the future outlook on breeding phenology and success of these species still remains unknown.

Analysis of mid-greenup on its own showed no widespread trends over the duration of the study (2001-2022). This was somewhat surprising as, particularly in Alaska, it has been found that arctic regions are warming rapidly with changes in spring temperatures and precipitation (Boelman et al., 2017). However, the variation in mid-greenup from year to year (e.g. in Juneau and Kodiak NWR, Fig. 3) appears to mask any ‘signal’ of earlier greenup over time (Table 3).

There was considerable uncertainty in the estimates of spring arrival, with many species/location/year combinations showing wide credible intervals (Fig. 4). Due to the wide credible intervals for the spring arrival estimates, many estimates of asynchrony also had wide credible intervals (Fig. 5). Although there was uncertainty, linear regression on the point estimates was used to detect possible trends, however most trends over time in the species/location combinations were not significant for either spring arrival or asynchrony (Tables 5 and 6). Those that could be considered significant, ended up not having a significant p-value when correcting for multiple comparisons indicating that there was not much evidence for generalizable trends in earlier/later spring arrival or increasing/decreasing asynchrony.

For future analysis, data could be analyzed using a spatially autoregressive model by combining hexagon-specific spring arrival estimates following the approach of Youngflesh et al. (2021) to generate region-wide estimates of arrival time. Especially with the large quantities of nonsignificant results, it may be beneficial to expand to adjacent hexagons. Based on the limitations of eBird data collection across the state, modeling could potentially be improved with more checklists added in the future for each location. Since its launch in 2002, eBird has provided a valuable data-source for exploring long-term changes in avian populations across the globe. For future analysis, to increase spring arrival detection data, it may be useful to include historic banding data collected at banding stations across the state to aid in increasing more species detections that eBird may not be able to provide in a given area.

CONCLUSION:

By using logistic Generalized Additive Models (GAMS) to generate species-specific arrival estimates for all species from 2001-2022, arrival estimates were able to be generated to pinpoint which species may be experiencing phenological asynchronies. The spring arrival anomalies generated for each location and species provided an insight into which species are able to potentially track changes in greenup. This research aimed to identify which species are experiencing the most dramatic phenological asynchronies to pinpoint those that may be candidates in need of further research. Studying the seasonal changes of bird migration and greenup overtime is critical during a rapidly changing climate, particularly with northern latitudes where many migratory birds migrate to and depend on. With the risk of possible fitness consequences for species (both in breeding and nest success) in Alaska, this research can help inform wildlife conservation management in investing more research in migratory bird conservation, especially for species of greatest conservation need.

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