FUTURE INVESTIGATORS IN NASA EARTH AND SPACE SCIENCE AND TECHNOLOGY

Linking emerging threats to wildlife and human health to climate change effects on boreal forest ecosystems

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BACKGROUND

Emergent disease outbreaks in human and wildlife populations are a well-established threat of ongoing climate change and habitat degradation[1,2]. As a result, research initiatives to better integrate knowledge from across disciplines are increasingly being employed as a means to protect the health of human and wildlife populations[3–5]. At the center of this research are zoonoses – pathogens transmitted between animals and humans – which account for over 60% of all infectious diseases[6]. Zoonotic diseases can pose both novel threats – such as the emergence of new coronaviruses and influenza strains – or chronic threats like Lyme disease and West Nile virus[7,8]. Because zoonotic diseases originate in wildlife populations, the distribution, abundance, and movement of these populations is critical in understanding risks to human populations and society.

Both climate change and land conversion practices are altering the ranges and abundance of vertebrate species[9] and their associated diseases[10]. Range expansion of disease-carrying organisms, such as ticks and mosquitos, have caused an increase in the number of tropical diseases appearing in the American South, while warming conditions in the Northeast and Midwest has seen a rise in tick populations and their associated diseases[11,12].

Many of these impactful emerging and chronic infectious pathogens in the United States are found in migratory bird populations, including Avian Influenza, West Nile virus, Lyme disease, and Salmonellosis[13]. Migratory birds are unique in their role in disease systems in two distinct ways. The first is the ability of birds to fly long distances over short periods, during which they transport a variety of living organisms, including parasites and pathogens, over geographical barriers and across continents[11,13]. As a result, pathogens infecting birds during migratory periods have the potential to disperse rapidly into new ecosystems[11]. The second trait that sets birds apart is the rapid shift in community composition over the annual cycle that characterizes avian communities, with hundreds of bird species migrating across continents twice a year[14]. Because bird species vary widely in their ability to contract and transmit certain diseases[15–17], changing community composition across the annual cycle may facilitate or dampen disease transmission in certain areas during certain seasons[18]. For example, an influx of individuals of a highly susceptible species in a specific area can facilitate the conditions needed for a regional epidemic to emerge[18]. In addition, birds are particularly susceptible to infection during migration as their immune systems are depressed due to the taxing nature of making consecutive long-distance flights[19]. In all, migratory birds have the potential to radically alter the disease landscape of particular regions and spread pathogens that drive epidemics of zoonotic diseases across continental scales.

Climate and land use change is rapidly altering the distribution, abundance, and species composition of avian communities at a global scale[9,20]. Although early efforts to predict the facilitation of disease by birds has been undertaken[19], the consequences of changes to avian distributions to wildlife and human health are largely unknown. One compelling and under-researched avian disease vector is the Pine Siskin (*Spinus pinus*), a species often present in Salmonellosis outbreaks in the United States and Canada[21]. The Pine Siskin is a seed-eating boreal songbird found across North America that exhibits dramatic "irruptive" migratory behaviors, during which millions of birds are found at abnormal concentrations beyond their normal range[22]. The irruptions of Pine Siskins take two principal forms: an east-west irruption, with birds moving across Canada, and north-south irruptions, with birds moving as far south as the southern United States[23] (Fig. 2). These irruptions are the product of "boom-bust" cycles of food availability in the boreal forests brought on by 2–3 year conifer reproductive cycles (masting cycles)[23,24]. Masting cycles in boreal forests are driven by climatic factors, with dry, warm summers leading to greater cone production[25]. Irruptions are in turn affected by climatic variables through these dynamics on masting behavior[26]. Further increasing the strength of southerly irruptions are harsh winter temperature conditions, during which irruptions become more intense and force birds further south[26].

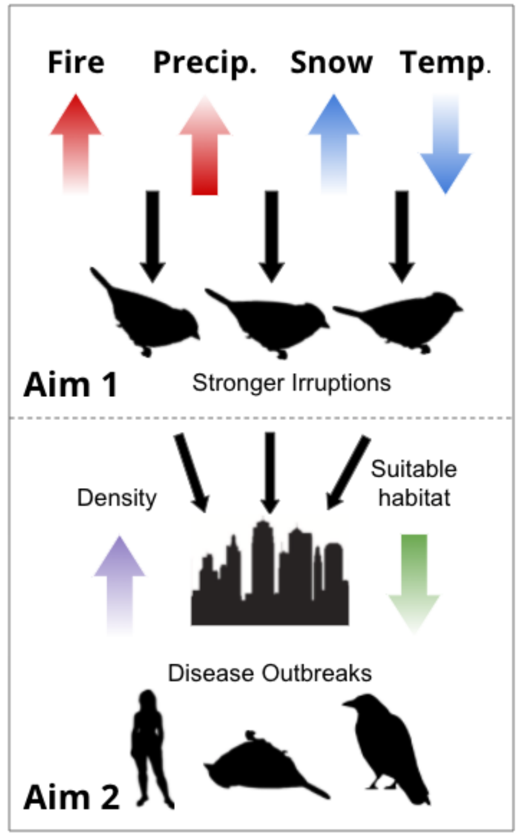

Figure 1: Conceptual overview of the proposal. Aim 1 will test the hypothesis that increased fire, summer precipitation, winter snow cover, and colder winters will lead to stronger and more frequent irruptions. Aim 2 will test whether stronger irruptions lead to increased density, expanded habitat use, and greater incursion into urban areas - therefore increasing the probability of Salmonellosis outbreaks.

Periodic irruptions can lead to large differences in the density of siskins at locations depending on the year[22,27], and therefore change the composition of the avian community at those sites. Due to their susceptibility to *Salmonella* and associations with large-scale outbreaks[21], these changes to community composition may lead to increased rates of disease transmission both within siskin populations and among avian communities more broadly. Dense siskin populations in a given area likely act as a source of *Salmonella* that then spills over into populations of suseptible species[21]. Salmonellosis outbreaks caused by *Salmonella typhimurium* infection are a growing threat to both avian and human populations, having become increasingly commonplace in the United States over the last 40 years, leading to increased avian illness and mortality and spillover events into human populations[17]. Presently, the linkage between climatic factors, migratory dynamics and subsequent disease outbreaks is unknown.

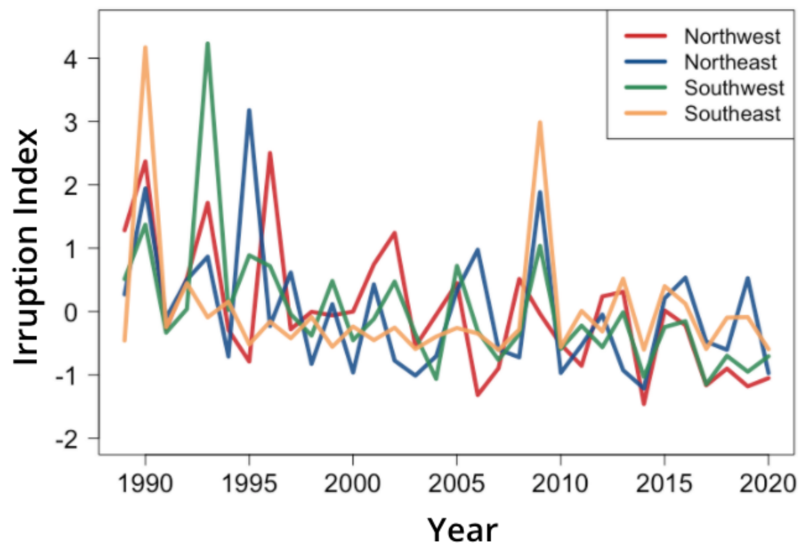

Figure 2: Prototype model of the normalized regional irruption indices for the incursion of the Pine Siskin. Large values represent years where large incursions of Pine Siskins were recorded at backyard bird feeders, as reported by Project Feederwatch.

Here, I propose a two-tiered approach using NASA-enabled remote sensing data to investigate the nature of a climate-driven source of increased disease risk to wildlife and human populations (Fig. 1). I plan to 1) create a working model to predict the frequency and strength of irruptions of the Pine Siskin from MODIS-derived climate and fire products, and 2) use land cover maps to analyze how the strength of irruptions modulates disease risk across habitat types.

PROPOSED WORK

Aim 1: Determine how fire regimes, precipitation, snow cover, and temperature (MODIS/Terra data) interact to modulate the strength and frequency of boreal songbird irruptions.

Hypothesis 1: Increasing intensity and frequency of large wildfires, decreased summer precipitation, increased snow cover and increasing frequency of severe winter temperature events lead to more frequent and intense irruptions of Pine Siskins and other boreal songbirds into the US. I predict that conditions that lead to less productive masting booms (increased fire, decreased precipitation) and harsher winters (increased snow cover, low winter temperature) lead to more frequent and stronger irruptions (Fig. 1). Regionally, I predict that poor conditions in Eastern or Western Canada will lead to stronger irruptions in the American East and West, respectively.

Methods 1: I will use a combination of remote sensing data products (MODIS/Terra, Table 1), including precipitation, snow cover, fire and land surface temperature maps in conjunction with ecological big-data products (eBird, Project Feederwatch, Table 1). From these products, I will develop U.S.-based regional indices (Northwest, Northeast, Southwest, Southeast) of irruptions and for fire, precipitation temperature and snow for Eastern and Western Canada (see Fig 2 for prototype). To conduct the analysis, I will use a hierarchical Bayesian analytical approach, where the strength and likelihood of irruptions is informed by abiotic factors.

Aim 2: Analyze land cover data (CONUS/Landsat) to determine how the strength of Pine Siskin irruptions modulate habitat use and correspond with outbreaks of Salmonellosis.

Hypothesis 2a: Increased strength of irruptions leads Pine Siskins to utilize a wider variety of land cover types with increased frequency due to stronger intraspecific competition for food resources. Specifically, stronger irruptions lead to greater incursion into human-dominated urban, suburban, and agricultural landscapes. I predict that as the strength of irruptions increases regionally, the average habitat quality utilized by siskins decreases. Separately, I will specifically compare the strength of siskin irruptions to abundance in urban and suburban areas. I predict that the stronger regional irruptions will lead to a higher proportion of birds occupying a larger number of urban sites.

Methods 2a: I will use land cover data (CONUS/Landsat) to characterize habitat favorability for the Pine Siskin in metropolitan areas within the contiguous United States by comparing habitat types to citizen science data detailing the presence of the species (eBird, Project Feederwatch). Habitats that support a greater number of siskins will be considered highly favorable habitats, while land-use types supporting lower numbers of siskins will be considered poor habitats. Once the favorability of habitats is established, I will compare previously constructed yearly regional irruption strength indices (Fig. 2) to the proportion of sighting records across habitat suitability and abundance in human-associated areas using a Bayesian hierarchical linear model.

Hypothesis 2b: Strong irruptions leading to incursion of Pine Siskins into urban areas will be associated with a greater probability of detection of Salmonellosis among Pine Siskins, as well as urban-associated conspecifics. I predict that Salmonellosis outbreaks around major metropolitan areas will be more likely in strong irruption years.

Methods 2b: I will use federally reported disease data (WHISPers) in conjunction with regional irruption indices (Aim 1) and urban incursion metrics (Aim 2) to investigate the role of the strength of regional irruptions on the probability of disease outbreaks in avian populations around cities in the Northern United States. I will model the likelihood of detecting an outbreak for each metropolitan area in each year as a function of irruption strength with a Bayesian hierarchical logistic model.

ALIGNMENT WITH NASA OBJECTIVES

The emergent risks to human health are increasingly being recognized as the result of the downstream effects of anthropogenic changes to the Earth system as a whole[28]. This project fits into NASA's goals to understand earth as a system, specifically in that it focuses on detecting and predicting changes to earth's ecosystems and biodiversity (NASA Strategic Objectives 1.1). Climatic conditions in boreal forests shift the avian community composition at a continental scale, and this proposal will further discern how human-driven climate change will modulate these dynamics. This proposal will broadly address how global ecosystems are changing (Earth Science Research Program 2.1 - Carbon Cycles and Ecosystems), as we will consider a >20 year time period stretching back to 2000. The incursion of millions of boreal songbirds into virtually every ecoregion in the United States represents a major shift in the communities within those ecosystems.

Furthermore, this proposal addresses the Earth Science Directorate's goals to understand how land cover and land use change lead to consequences to human societies and ecosystem sustainability (Earth Science Research Program 2.1 - Carbon Cycles and Ecosystems). This project will serve the dual purpose of identifying how land use change puts pressures on local ecosystems by forcing more disease-susceptible individuals into sub-optimal habitat, and to investigate how this may be leading to spillover events into local human and wildlife populations. The results of this project will lead to a better understanding of human health risks, and thus advance NASA's goals of safeguarding and improving life on earth (NASA Strategic Objectives 1.1).

Type	**Data**	**Source**	**Organization(s)**	**Data Availability**
Climate	Fire	MODIS/Terra	NASA	2000 - Present
	Precipitation	MODIS/Terra	NASA	2000 - Present
	Temperature	MODIS/Terra	NASA	2000 - Present
	Snow	MODIS/Terra	NASA	2000 - Present
Land use	Land cover	CONUS/Landsat	MRLC/NASA	2001 - 2019
Avian	eBird	Citizen Science	Cornell Lab of Ornithology	2003 - Present
	Project Feederwatch	Citizen Science	Cornell Lab of Ornithology	1989 - Present
Disease	WHISPers	USGS compiled	USGS	1988 - Present

Table 1. Information on datasets to be used for the outlined project.

PROPOSED TIMELINE

Fall 2022
- Start Fellowship

Winter 2023
- Develop yearly indices of fire, summer precipitation, snow cover and temperature data using NASA products.
- Develop indices of songbird irruptions strength and frequency from previous prototype for five target species.

Spring - Summer 2023
- Analysis: Determine relevant climatic factors on irruption frequency and strength using Bayesian statistical methods.

Fall 2023 - Winter 2024
- Prepare manuscript: *Climate change effects in boreal forests driving increased frequency and strength of songbird irruptions.* Target Journal: PNAS. Target publication date: February 2024

Winter - Summer 2024
- Develop pipeline for analyzing land use maps, grade maps for habitat suitability.
- Process and integrate songbird disease data from WHISPers into spatial model

Fall 2024 - Winter 2025
- Analysis: Determine the relationship between irruption strength, land-use changes, and disease outbreaks among avian communities using Bayesian statistical methods.

Spring - Summer 2025
- Prepare manuscript: *Cumulative effect of landscape and climate change on habitat use: effects on distribution of the disease vector Spinus pinus.* Target Journal: Global Change Biology. Target publication date: August 2025
- Complete proposal
- Defend dissertation

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