USGS

science for a changing world

National Climate Adaptation Science Center

Research Priorities for Migratory Birds Under Climate Change—A Qualitative Value of Information Assessment

Circular 1472

U.S. Department of the Interior
U.S. Geological Survey

Back cover. *Calidris pusilla* (Linnaeus, 1766) (semipalmated sandpiper). Photograph by the U.S. Fish and Wildlife Service. Public domain.

Back cover. *Anas acuta* (Linnaeus, 1758) (northern pintail). Photograph by Andrea Mott, U.S. Geological Survey. Public domain.

Cover. *Anas acuta* (Linnaeus, 1758) (northern pintail). Photograph by J. Kelly, U.S. Fish and Wildlife Service. Public domain.

Research Priorities for Migratory Birds Under Climate Change—A Qualitative Value of Information Assessment

By Madeleine A. Rubenstein, Clark S. Rushing, James E. Lyons, Michael C. Runge

National Climate Adaptation Science Center

Circular 1472

U.S. Department of the Interior
U.S. Geological Survey

Sterna maxima (Boddaert, 1783) (royal tern).
Photograph by Jeff Corbett, U.S. Geological Survey.

U.S. Department of the Interior
DAVID BERNHARDT, Secretary

U.S. Geological Survey
James F. Reilly II, Director

U.S. Geological Survey, Reston, Virginia: 2020

For more information on the USGS—the Federal source for science about the Earth, its natural and living resources, natural hazards, and the environment—visit https://www.usgs.gov or call 1–888–ASK–USGS.

For an overview of USGS information products, including maps, imagery, and publications, visit https://store.usgs.gov/.

Suggested citation:
Rubenstein, M.A., Rushing, C.S., Lyons, J.E., and Runge, M.C., 2020, Research priorities for migratory birds under climate change—A qualitative value of information assessment: U.S. Geological Survey Circular 1472, 18 p., https://doi.org/10.3133/cir1472.

ISSN 2330-5703 (online)

Acknowledgments

We thank participants of two workshops for valuable contributions to the conceptual basis for this paper. In particular, we thank M. Rice, S. Covington, K. Kriese, and K. Fowler of the U.S. Fish and Wildlife Service for their insight on the process and context of land acquisition decision making.

Contents

Figures

Tables

Abbreviations

CBC	Christmas Bird Count
ProACT	Problem, Objectives, Alternatives, Consequences, and Tradeoffs
QVoI	qualitative value of information

Ardea herodias (Linnaeus, 1758) (great blue heron). Photograph by Jeff Corbett, U.S. Geological Survey.

Research Priorities for Migratory Birds Under Climate Change—A Qualitative Value of Information Assessment

By Madeleine A. Rubenstein,[1] Clark S. Rushing,[1,2] James E. Lyons,[1] Michael C. Runge[1]

Executive Summary

The mission of the U.S. Geological Survey National Climate Adaptation Science Center is to provide actionable, management-relevant research on climate change effects on ecosystems and wildlife to U.S. Department of the Interior bureaus. Providing this kind of useful scientific information requires understanding how natural-resource managers make decisions and identifying research priorities that support those decision-making processes. Migratory bird management and conservation of migratory bird habitat are central components of the U.S. Department of the Interior's mission. In particular, the U.S. Fish and Wildlife Service has an intensive, complex decision-making process for identifying high-priority parcels of land that will contribute to migratory bird conservation through permanent acquisition or easement. Climate change introduces several uncertainties into this decision-making process, and additional climate change research should help to support more informed decision making regarding habitat acquisition.

Not all climate change related uncertainties, however, will have a meaningful effect on acquisition decisions; therefore, understanding which uncertainties have the most potential to alter decision making is crucial. This document summarizes a multiyear effort to clarify the major sources of climate change uncertainty that affect migratory bird management and to articulate related research priorities. We worked with U.S. Fish and Wildlife Service staff to assess the primary ways in which climate change is likely to affect migratory birds and their habitats; to clarify uncertainties surrounding these effects; and to assess how uncertainties may affect habitat acquisition decisions. Using a modified structured decision-making approach, we assessed a set of hypotheses about how climate change will affect migratory birds and their habitats. Then, we used a qualitative value of information assessment to rank the most important topics for future research. The ranking process was built on an assessment of three primary characteristics: the magnitude of uncertainty, the topic's relevance to habitat acquisition decision making, and the feasibility of reducing the uncertainty. Based on the results of this process, high-priority topics for future research include the following:

- The effects of rising temperatures on spatial distributions of migratory birds during the breeding and nonbreeding seasons;
- Climate-driven changes to avian community composition through homogenization and loss of specialists;
- The effects of decreased precipitation on abundance in the breeding season; and
- The effects of rising temperatures on abundance in the nonbreeding season.

In addition to describing high-priority research needs, this document provides a summary of the methodology used to identify, assess, and rank uncertainties. This method was developed for a climate change related topic where a full quantitative value of information approach may not be feasible. The results and methodology described here may be useful for U.S. Geological Survey and other science-funding agencies interested in improving the applicability of their research to natural-resource management decision making.

Introduction

Natural-resource management decisions are often characterized by uncertainty, including uncertainty surrounding environmental variability and uncertainty about the efficacy of management strategies (Nichols and others, 2011). Climate change introduces additional sources of uncertainty that affect decision making in multiple ways, including through inherent uncertainties about the trajectory of climate change, the response of natural systems, and the efficacy of management interventions. Traditional approaches to natural-resource management often fail to account for the uncertainties introduced by climate change, thereby posing a challenge to current management and decision systems. Despite the risks posed by climate change, and the potential for climate change effects to render existing management approaches substantially less effective, most natural-resource decisions are made under

[1]U.S. Geological Survey.

[2]Utah State University.

assumptions that current ecological, biological, and physical processes will remain constant (in other words, stationarity; Nichols and others, 2011). Finding ways to effectively account for climate-driven uncertainty within the context of natural-resource management is therefore critical to meeting management objectives.

Migratory birds are an extensively managed resource, serving as the focus of several landmark international laws and treaties (for example, the Migratory Bird Treaty Act of 1918 [16 U.S.C. 703–712] and the Bald and Golden Eagle Protection Act [16 U.S.C. 668–668c]), executive orders (for example,, Executive Order 13186), and conservation programs (for example, North American Waterfowl Management Plan). Although multiple long-standing research programs are in place to support effective monitoring and management of migratory birds, substantial uncertainty remains about how climate change is likely to affect migratory birds and about the expected effect of management interventions in the context of climate change (Knudsen and others, 2011).

Effective management of migratory birds in the context of climate change, therefore, requires addressing and accounting for novel sources of uncertainty in a rigorous, systematic process. Multiple strategies have been developed to support decision making in the face of uncertainty, including the fields of adaptive management and structured decision making. Structured decision making is a systematic, analytical method used to break down decision making into a set of discrete components (Runge and others, 2011) and is useful for identifying priority scientific and research topics in decision making. Although the potential sources of uncertainty related to climate change and migratory birds are seemingly endless, it is important for managers and researchers in this field to focus their efforts on the particular sources of uncertainty that are most likely to improve decision outcomes and support management objectives. This focus requires considering which management actions are available to managers, assessing likely outcomes or consequences of those actions, and comparing differences in expected outcomes. In some cases, resolving uncertainty about a climate change effect may not alter decision making because a preferred management action will be favored in all scenarios; in other cases, resolving uncertainty may change which management action is favored, rendering the uncertainty more relevant to decision making. Establishing a management-relevant research program for migratory birds and climate change, therefore, requires identifying and understanding the most relevant sources of climate change uncertainty for migratory bird management.

In this document, we explore the major sources of uncertainty regarding how climate change is affecting migratory birds in an effort to create an effective, management-relevant research program within the U.S. Geological Survey. Through a series of workshops and discussions with migratory bird and habitat managers, we gathered information and conducted a semistructured expert elicitation to identify which sources of uncertainty had the greatest potential to affect management decisions, particularly those regarding land and habitat acquisition decisions. We then conducted a systematic literature review and qualitative value of information (QVoI) analysis to identify which sources of uncertainty are most significant according to three criteria: magnitude of uncertainty, relevance to land acquisition programs, and reducibility. We synthesize these findings into a description of top research priorities and review the implications of those sources of uncertainty for land acquisition decisions. In addition, we describe a methodology for identifying management-relevant research priorities that can be applied to other systems, even in the absence of data required for a formal value of information assessment. This document is intended to be useful for research program managers and for any scientist interested in understanding how their research can be as relevant as possible to natural-resource managers.

Anas acuta (Linnaeus, 1758) (northern pintail).
Photograph by Andrea Mott, U.S. Geological Survey. Public domain.

Background

Climate change is one of the most substantial drivers of ecological change facing natural-resource managers today (Weiskopf and others, 2020). Effective management of migratory birds in the face of climate change is particularly challenging because effects happen across multiple biological scales, from individuals to populations and species; multiple spatial scales, reflecting breeding, stopover, and nonbreeding grounds; and multiple dimensions, including phenological changes, distributional shifts, and demographic effects. Migratory birds are a high priority for many natural-resource managers and represent a particularly important area of focus for Federal managers within the U.S. Department of the Interior. A clear understanding of how climate change is affecting migratory birds, and what those changes mean for management decisions, is therefore critical to achieving the goals and mandates of Federal, State, and Tribal managers.

Climate Change and Migratory Birds

One of the primary effects of climate change is geographic range shifts; in other words, as species respond to spatially variable changes in temperature and precipitation, their current and future distributions may no longer align with the historical ranges they once occupied (Chen and others, 2011). These changes are not occurring evenly for all species, taxonomic groups, or regions; indeed, high variability in climate-driven range shifts has been observed even within guilds of migratory birds (La Sorte and Thompson, 2007; Tingley and others, 2012; Rushing and others, 2020). Therefore, some species may maintain historical ranges, but their optimum habitat may shift, resulting in a net loss of resources. Alternatively, they may effectively track climatic shifts faster than a predator or competitor, thereby benefiting from competitive release.

Phenological shifts are another widely recognized effect of climate change on migratory birds; for example, as temperatures have risen, multiple species have demonstrated advances in the timing of migration, arrival on breeding grounds, nesting, and egg laying (Wood and Kellermann, 2015). However, the cues driving the phases of migration and reproduction in migratory birds are complex, including exogenous signals (that is, photoperiod) that are not affected by climate change and climatic conditions experienced on wintering grounds, which may be many thousands of miles from breeding grounds. Many migratory birds, therefore, have not advanced their migration and breeding phenology sufficiently to track changes in the emergence of the plant and insect resources they rely on to nourish themselves and their offspring. This asynchrony with critical food sources may depress reproductive success or recruitment (Mayor and others, 2017), although population-level effects have been difficult to demonstrate (Miller-Rushing and others, 2008). The spatial and temporal alignment of competitors, predators, and pathogens may also similarly shift, resulting in novel interactions.

Rising temperatures and altered precipitation patterns may also have more direct effects on the abundance and population levels of migratory birds. As temperate winters become milder, winter mortality may decline for some species, resulting in increased abundance on temperate wintering grounds. Decreased precipitation, however, may decrease abundance in the breeding and nonbreeding season, particularly for species that overwinter in tropical areas.

Sources of Uncertainty

Although each of these climate change effects has received attention from the research community, numerous uncertainties remain (table 1), which have the potential to affect management decisions.

Firstly, there are significant uncertainties regarding the fundamental ecology of many migratory bird species, even without considering the potential effects of climate change. The current distribution during the breeding, nonbreeding, and migratory seasons is not known with high confidence for all species, and for many species it is not clear which season or habitat type currently limits population growth (that is, "limiting habitat;" table 1, nos. A1–A3). Because limiting factors are not known for all migratory bird species, the relationship between quantity and quality of habitat and population vital rates (for example, recruitment and survival; table 1, no. A4) is uncertain.

Climate change introduces additional uncertainties: climate change is likely to affect the spatial and temporal distribution of priority species and their habitats, but the magnitude, extent, and rate of these changes is unclear (table 1, nos. B1–B2). If the spatial or temporal distributions of limiting resources shift, it is unclear how closely migratory birds will be able to track these changes (table 1, no. B3). Climate change will also affect other important ecological relationships, including those between migratory birds and their predators, competitors, and pathogens, yet considerable uncertainties remain (table 1, no. B4).

Finally, climate change will affect social and management systems in ways that will affect migratory bird populations. Climate change is projected to affect the economic drivers that determine land-use patterns (table 1, no. C1), potentially altering the dynamics of risk facing habitat acquisition managers when they approach acquisition decisions, yet how land-use patterns will change is uncertain. Climate change highlights the substantial uncertainties facing managers about the effects of management interventions on management objectives (table 1, no. C2). The result of various management actions, such as acquisition of limiting habitat or reduction in harvest activities, may affect demographic rates or population levels, but the precise effects are often uncertain, and climate change may exacerbate these uncertainties by altering the effectiveness of previously well characterized management interventions.

Faced with these multiple sources of uncertainty, managers and researchers alike are challenged to identify which research questions should receive priority. One of the central tenants of decision analysis is that reducing uncertainty is only valuable if doing so will lead to different management decisions and the potential for better management outcomes (Runge and others, 2011). Our goal was to use the tools of decision analysis to untangle these sources of uncertainty and to identify those that have the potential to alter management decisions and that could be effectively reduced through research, thereby establishing a research program that would have high utility for natural-resource managers.

Table 1. Uncertainties characterizing migratory bird ecology and management in the context of climate change.

Questions about sources of uncertainty		
Underlying ecology	**Climate change effects to natural systems**	**Climate change effects to social and management systems**
A1. What constitutes limiting habitat for focal species? A2. What is the current distribution (spatial and temporal) of limiting habitat? A3. In which season (wintering, breeding, or stopover) does limiting habitat occur? A4. How will increased availability or conservation of limiting habitat through land acquisition affect vital rates?	B1. How will climate change affect the distribution (spatial and temporal) of focal species? B2. How will climate change affect the distribution (spatial and temporal) of limiting habitat? B3. How responsive are focal species to shifts in habitat? B4. How will climate change alter the dynamics of migratory bird predators, competitors, pathogens, and invasive species?	C1. How will climate change alter land-use patterns, and how will that affect distribution of limiting habitat? C2. How will climate change affect the effectiveness of management interventions?

Decision Context—Land Acquisition

Managers face many decisions about how to manage migratory bird populations and their habitats to reach desired outcomes, generally expressed as population objectives. From acquiring new habitat for protection to managing or restoring existing habitat, the decision landscape facing managers is complex. Yet in many ways the landscape is relatively limited because only a few key types of interventions are available to managers to achieve their goals (table 2).

These possible decisions include purchasing new land to place under permanent protection (acquisition); restoring or improving the quality of existing habitat (restoration); altering direct mortality rates (harvest and take limits); and setting priorities for future management actions (prioritization). Although we initially assessed the effects of climate change on all these decisions, we decided to focus our structured QVoI analysis on habitat acquisition decisions. This focus was partially because of the importance of habitat acquisition as a key management intervention, as well as the substantial and well-documented effects of climate change on spatial distribution of migratory birds and associated implications for long-term acquisition decisions.

Although land acquisition decisions are made by many organizations, land acquisition specifically for migratory bird populations is a central focus of the U.S. Fish and Wildlife Service. We therefore focused our analysis on major land acquisition programs used by U.S. Department of the Interior and specifically by the U.S. Fish and Wildlife Service: the Migratory Bird Conservation Fund, the Land and Water Conservation Fund, and the North American Wetlands Conservation Act (103 Stat. 1968; 16 U.S.C. 4401–4412) Grant program (table 3). Although these land acquisition programs are all different in several important ways, they each rely on a set of foundational conservation plans to define fundamental program elements, including priority species, priority regions for management and acquisition, definitions of limiting habitat and seasons, and population goals. These plans play a vital role in decision making for migratory bird management because they set boundaries around the decision context (in other words, by defining priority species and population objectives), and they provide definitions for some of the evaluation criteria (that is, priority regions and habitat types) used in land acquisition programs.

We investigated the decision criteria (that is, evaluation criteria) essential to each of these land acquisition programs as a central part of our QVoI analysis. By understanding these criteria, we were able to understand what sources of information were valuable to decision makers within the context of these decisions. We identified four core evaluation criteria that are shared by these programs to prioritize habitat for migratory bird conservation (table 4). These evaluation criteria include current distribution of a focal species, current abundance of a focal species, limiting habitat for a focal species, and risk of loss. By focusing our analysis on the sources of uncertainty relevant to these evaluation criteria, we ensured that our assessment would identify sources of uncertainty relevant to the specific acquisition context.

Table 2. Key types of migratory bird management decisions.

Management decision type	Question to consider
Habitat acquisition	Where should habitat be acquired for permanent protection?
Habitat management and restoration	Where and how should existing habitat be managed, restored, or both?
Setting harvest and take limits	What are appropriate limits for annual take, either through purposeful harvest or incidental take?
Planning and prioritization	How should species and geographies be prioritized for management intervention?

Table 3. Major Federal land acquisition programs for migratory birds.

[FWS, U.S. Fish and Wildlife Service; T&E, threatened and endangered]

Program information	Federal land acquisition program		
	Migratory Bird Conservation Fund (MBCF)	Land and Water Conservation Fund (LWCF)	North American Wetlands Conservation Act (NAWCA, 103 Stat. 1968; 16 U.S.C. 4401–4412) Grant program
Program description	Created in 1934 as part of the Migratory Bird Hunting and Conservation Stamp Act (16 U.S.C. 718–718j, 48 Stat. 452). Provides funds for the protection of migratory bird habitat. Financed primarily through the sale of Migratory Bird Hunting and Conservation Stamps ("duck stamps"). Funds are used to protect critical habitat within the FWS Refuge System for priority waterfowl.	Established in 1964 to protect public lands and waters, and financed by earnings from offshore oil and gas leasing. LWCF funds are used across U.S. Department of Interior bureaus for conservation. LWCF is used to protect migratory waterfowl habitat within the FWS Refuge System.	Established in 1989 to protect wetland habitats across North America. This program focuses primarily on migratory waterfowl, but protection of critical habitat for wetland-associated migratory birds and T&E species is also considered. Revenue from the Pittman-Robertson Act (The Federal Aid in Wildlife Restoration Act, 16 U.S.C. §§669 et seq.; an excise tax on firearms and ammunition) is the primary source of funding for NAWCA grants.
Focal species	Primary focus is waterfowl. Secondary focus is T&E species.	Primary focus is waterfowl. Secondary focus is migratory birds of conservation concern and T&E species.	Primary focus is waterfowl. Secondary focus is wetland-associated migratory birds and T&E species.
Decision maker	FWS leadership; FWS refuge and regional managers; State governments	FWS leadership; FWS refuge and regional managers	NAWCA council: FWS leadership; State representatives; National Fish and Wildlife Federation; other nongovernmental organizations
Jurisdiction	United States (Refuge System or Waterfowl Protection Area only)	United States (Refuge System only)	North America (United States, Mexico, & Canada)
Foundational plan	North American Waterfowl Management Plan (NAWMP)	NAWMP; Landbird, waterbird, & shorebird conservation plans; T&E species listings	NAWMP; Landbird, waterbird, & shorebird conservation plans; T&E species listings; State wildlife action plans
Criteria	1. Limiting factor mitigation 2. Relative abundance for priority species 3. Limiting factor and relative abundance for secondary species 4. For Waterfowl Production Areas: Risk of loss/conversion	1. Limiting factor mitigation 2. Relative abundance for priority species 3. Relative abundance for secondary species 4. Priority geography 5. T&E species recovery plan directive	1. Abundance for priority species 2. Abundance for secondary species 3. Priority geography 4. Wetland status and trend 5. Long-term conservation and climate change benefit 6. Partnerships
Climate change	Not explicitly considered.	Not explicitly considered.	Considered in evaluation of long-term benefit and whether actions are adaptive for climate change effects.

Table 4. Common evaluation criteria in Federal land acquisition programs.

[LWCF, Land and Water Conservation Fund; MBCF, Migratory Bird Conservation Fund; NAWCA; North American Wetlands Conservation Act (103 Stat. 1968; 16 U.S.C. 4401–4412)]

Evaluation criteria	Description	Example from a specific program
Current species distribution of a focal species	Is the focal species currently distributed on the parcel?	Decision tree used in evaluating parcels for LWCF asks whether a priority species (for example, Bird of Conservation Concern) is present on the land.
Current species abundance of a focal species	Is the focal species currently abundant on the parcel?	Decision tree used in evaluating parcels for MBCF acquisition asks whether the refuge in question overlaps with high abundance areas for a priority species.
Limiting habitat for a focal species	Does the parcel represent limiting habitat for the focal species? Does the parcel provide high-quality habitat for the focal species?	Evaluation criteria for LWCF program ask whether the parcel would mitigate a population-limiting factor for a priority species, as determined by subject-matter experts.
Risk of loss	Is the parcel at risk of being converted, lost, or otherwise degraded if not acquired?	Decision tree used in Waterfowl Production Area program of MBCF asks whether the parcel is at risk of being converted to agriculture if not acquired. Evaluation criteria for NAWCA grants ask whether the parcel represents a type of wetland generally in decline.

Methodology

Our QVoI analysis used a hybrid model of expert elicitation and a systematic literature review to collect information about important uncertainties constraining decision making related to migratory birds. Although we describe our methodology here, additional details are in Rushing and others (2020).

Workshops and Expert Elicitation

We held a series of workshops and in-person meetings with Federal migratory bird and habitat managers to identify major types of decisions that managers make with regards to migratory bird populations and habitats, to articulate the major mechanisms by which climate change may affect migratory birds, and to discuss major sources of uncertainty about how climate change is likely to affect migratory birds in ways that may affect management decisions.

In July 2016, we held our first workshop with scientists and migratory bird managers. Our objective was to identify the most consequential management decisions that affect migratory birds in the context of climate change by answering these questions: what decisions do migratory bird and habitat managers make? What interventions are available to them? How are these decisions and interventions potentially affected by climate change? Participants identified four key decision types (table 2) and described how each is likely to be affected by climate change. We then explored major sources of uncertainty surrounding these potential effects (table 1). Having identified the major decision types facing migratory bird and habitat managers, we were then able to advance our analysis to assess uncertainties and associated value of information.

In January 2017, we held a subsequent workshop focused exclusively on habitat acquisition and specific decisions made within the context of the three primary land acquisition programs that were the focus of our analysis (Land and Water Conservation Fund, Migratory Bird Conservation Fund, and North American Wetlands Conservation Act Grants program; table 3). This workshop was also focused on understanding how climate change introduces uncertainty into this decision-making process and on identifying which sources of uncertainty would be the most fruitful areas of research. Participants included Federal migratory bird and habitat managers, particularly those involved in decision making related to the three primary land acquisition programs. Our ultimate objective was to understand how research within the U.S. Geological Survey and other science agencies could directly inform these programs by reducing important uncertainties related to climate change. Therefore, we concentrated our efforts on understanding how uncertainties about climate change effects to migratory birds may affect habitat acquisition decision making within the context of these three specific land acquisition programs.

Problem, Objectives, Alternatives, Consequences, and Tradeoffs Framework

To identify important uncertainties associated with these acquisition programs, we adopted a modified decision analysis approach based on the Problem, Objectives, Alternatives, Consequences, and Tradeoffs (PrOACT) framework (Hammond and others, 2015). For each program, we analyzed each component of the PrOACT framework: the general decision context (problem framing), the objectives of the decision makers, the alternative potential actions to achieve these objectives, and the evaluation process used by decision makers to assess the consequences of each alternative. For the purposes of this workshop, we did not focus on the tradeoffs (optimization) component of PrOACT.

We were particularly interested in the evaluation (consequences) step of PrOACT, in which we wanted to answer this question: of the available parcels for acquisition (alternatives), how do decision makers assess which will best achieve their goals? The criteria used to evaluate parcels for acquisition reflect management objectives and underlying assumptions about the ecological system. Climate change is generally not systematically or explicitly included in these criteria (except for the North American Wetlands Conservation Act Grant program; see table 3), which poses a challenge to incorporating climate science into acquisition decision making. Participants suggested several potential additional evaluation criteria that could help to incorporate the effects of climate change into the evaluation process (table 5).

Literature Review

After the workshop, we reviewed literature to assess the state of the science surrounding major sources of uncertainty, which we expressed as a series of hypotheses. We assumed a null hypothesis (H_0) that climate change will not affect the particular ecological or demographic process of interest (for example, climate change will not affect spatial distributions) and treated each proposed hypothesis as an alternative (H_1) to the null, which assumes an ecological or demographic effect of climate change (for example, climate change will result in range shifts). Building on the uncertainties identified in the previous workshops, we were able to articulate a set of specific hypotheses that could form the basis of a management-relevant research program (table 6; see table 7 for more information on how hypotheses were evaluated). These specific hypotheses include those related to species distribution (for example, how species distributions may shift in response to climate change), abundance (for example, how demographic rates and population levels are affected by precipitation and temperature), migration and phenology (for example, how climate change will alter the spatial and temporal characteristics of migration), and community responses (for example, how climate change may affect community composition and species interactions).

Using Google Scholar and Web of Science, we searched for papers published in the academic literature using the following keywords: “migratory bird*” and “climate,” “climate change,” “temperature,” “precipitation,” or “phenology.” We also used a modified network association methodology (Lecy and Beatty, 2012), whereby we reviewed the citations within the papers located via these searches to find additional papers that the searches missed. Our review was not meant to be exhaustive; instead, we aimed to review a representative sample of published papers to draw general conclusions about the current state of knowledge regarding climate change effects on migratory birds.

Hypothesis Evaluation

Once the hypotheses were identified (table 6) and the literature compiled, we used three criteria to evaluate each hypothesis: magnitude of uncertainty, relevance to land acquisition programs, and reducibility. We established a standard rubric by which to evaluate each hypothesis on each of these criteria (table 7).

In evaluating hypotheses for the magnitude of uncertainty, we assumed that, all else equal, research and monitoring will have a larger effect on improving management outcomes when focused on hypotheses that are more uncertain (in other words, whether the null or alternate hypothesis is true is uncertain). We used the results of the literature review to score each hypothesis based on the current magnitude of uncertainty. We then evaluated hypotheses based on their relevance to decision making (that is, the relevance of resolving uncertainty to meeting fundamental management objectives). We scored each hypothesis based on the degree to which resolving uncertainty is expected to alter the outcomes of land acquisition decisions. Hypotheses in this category were scored as either 1, 2, or 3 depending on whether we judged the difference in performance to be small, moderate, or large, respectively, relative to natural variability. Finally, we assessed whether the uncertainty expressed in the hypothesis could be reduced through research and monitoring; all else equal, sources of uncertainty that can be reduced with existing data and analytical methods are easier to resolve than sources of uncertainty that will require additional long-term data collection. Although we recognize that many of these uncertainties are interrelated, we considered each source of uncertainty independently.

We, the four authors, served as an expert panel to score the hypotheses, following a formal process of expert judgment (Hanea and others, 2018). First, we each independently scored the hypotheses using the rubrics described in table 7. We then compared our scores, discussed any differences, and independently revised scores where necessary. To gather further insight, we convened a subset of U.S. Fish and Wildlife Service managers for a second in-person meeting to review our relevance scores. We discussed how the various hypotheses either were, or were not, likely to alter land acquisition decisions. After hearing those discussions, we reviewed our scores for each hypothesis. Finally, individual scores across experts were aggregated by finding a consensus score.

Table 5. Proposed climate-relevant evaluation criteria.

[—, not applicable]

Current evaluation criteria	Effect of climate change	Potential climate-focused evaluation criteria
Current species distribution	Climate change may alter current spatial and temporal distribution of focal species.	Future distribution: Is the focal species likely to be present on the parcel under future climate scenarios?
Limiting habitat	Climate change may alter the distribution and quality of limiting habitat or alter which resources or seasons are limiting.	Future limiting habitat: Is the habitat likely to remain high quality under future climate scenarios?
Risk of loss	Climate change may alter land-use patterns and practices, thereby affecting the risk of habitat loss for a given parcel.	Future risk: Is the risk of conversion or loss likely to change because of climate effects?
—	—	Landscape resilience: Would the acquisition increase overall heterogeneity of the broader landscape, increase climate resilience of the landscape, or both?
—	—	Refugia: Does the parcel incorporate characteristics of climate refugia for focal species?

Table 6. Climate change-related hypotheses and associated rankings.

[See table 7 for the scoring rubric used to determine the uncertainty, relevance, and reducibility rankings]

Hypothesis	Uncertainty	Relevance	Reducibility	Priority ranking
Species distribution				
1a. Breeding distributions will shift poleward because of warming temperatures.	2	3	3	Highest
1b. Nonbreeding distributions will shift poleward because of warming temperatures.	2	2	2	Highest
1c. Distributions will shift towards higher elevations because of warming temperatures.	3	1	2	Medium
Abundance				
2a. Warmer temperatures on temperate nonbreeding grounds will increase abundance.	4	1	1	High
2b. Decreased precipitation during the breeding season will lower abundance.	2	3	1	High
2c. Reduced precipitation on the nonbreeding grounds will decrease abundance of species that overwinter in tropical areas.	3	0	1	Low
Migration and phenology				
3a. Migration distances will shorten for short-distance migrants.	3	0	1	Low
3b. Migration distances will lengthen for long-distance migrants.	3	1	1	Low
3c. Climate-driven phenological mismatches will lower abundance of migratory birds through their effects on reproductive success.	2	1	2	Medium
Community responses				
4a. Climate change will result in a lower proportion of migratory species in temperate avian breeding communities because of increased competition with resident species.	2	1	1	Low
4b. Climate change will lead to more homogeneous bird communities that are dominated by a small number of generalist species.	2	2	3	Highest

Table 7. Hypothesis scoring rubric.

[—, not applicable]

Score	Magnitude of uncertainty	Relevance to land acquisition programs	Reducibility
0	Firm theoretical foundation and several empirical studies (>10) that support theoretical predictions	Preferred management action will be favored regardless of whether hypothesis is true.	Data necessary to reduce uncertainty does not currently exist and will be prohibitively difficult and expensive to collect given current technologies.
1	Firm theoretical foundation with robust empirical support; or several (>10) of consistent empirical studies	Reducing uncertainty is predicted to improve management outcomes, but range of outcomes will be swamped by natural variability and other uncertainties.	Data to reduce uncertainty exist but only for a limited taxonomic, geographic, or temporal scope; or cannot resolve the specific mechanisms; collection of additional data needed to discriminate among alternative mechanisms will be difficult and expensive or cannot be collected in timeframe relevant to decision.
2	Firm theoretical foundation with moderate empirical support; or Moderate number (5–10) of consistent empirical studies	Reducing uncertainty is predicted to improve management outcomes; range of outcomes will be small to moderate compared to natural variability and other uncertainties.	Data to reduce uncertainty exist but only for a limited taxonomic, geographic, or temporal scope or data only allow weak inference about mechanisms; collection of additional data needed to discriminate among alternative mechanisms is feasible given current technologies.
3	Firm theoretical foundation with no empirical support; or a few (<5) consistent empirical studies	Reducing uncertainty is predicted to improve management outcomes, and the range of outcomes will be the same order of magnitude as natural variability and other uncertainties.	Data to reduce uncertainty exist across a large taxonomic, geographic, or temporal scope; and credible inference can be made from these data.
4	Large disagreement between theory and empirical studies; or no theoretical basis and inconsistent empirical studies	—	—

Hypothesis Ranking

In conventional decision analyses, the expected value of information is the expected outcome of the optimal action after uncertainty has been reduced minus the expected outcome of the optimal action based on the current knowledge of the system (Schlaifer and Raiffa, 1961). Using our qualitative criteria, we conducted a QVoI assessment whereby the expected value of information is equivalent to the product of our uncertainty and relevance scores. Taking the product of the scores ensured that any hypothesis that scored a 0 in either of these categories automatically received a QVoI score of 0. This property is desirable because if, for example, a hypothesis was judged to be irrelevant to management decisions (score of 0 for relevance criteria), even a high degree of uncertainty would not make the hypothesis a high priority for additional research. QVoI scores therefore provide a principled method to rank hypotheses that is consistent with formal decision theory. Our additional criterion (reducibility) captures the degree to which uncertainty can be reduced through research and monitoring, which is an important consideration for prioritizing research needs. Reducibility is not directly incorporated in the QVoI analysis, and we therefore included these scores into our ranking as a second axis along which hypotheses were ranked (fig. 1). Hypotheses that rank highly for QVoI and reducibility are obvious priorities for future research, whereas hypotheses that rank poorly in both categories should not be priorities for research that aims to improve land acquisition decisions. To create our final prioritization of research topics, we placed hypotheses into four categories, according to how they ranked in terms of QVoI and reducibility (fig. 1). Highest priority hypotheses are those that rank highly in terms of QVoI and reducibility. These hypotheses are highly relevant to managers, have substantial uncertainty that needs to be reduced, and rank relatively highly in terms of reducibility. We define these as having a QVoI of greater than or equal to (≥) 4 and a reducibility of ≥2. High priority hypotheses are those that rank highly in QVoI but have low reducibility. Resolving these uncertainties would be valuable to management decision making, but the challenges associated with reducibility would render this task onerous. We define these as having a QVoI of ≥4 and a reducibility of less than (<) 2. Medium priority hypotheses have a relatively low QVoI but high reducibility. These are uncertainties that may not be of highest priority to management, or may have only a small uncertainty surrounding their likelihood of being true, but could be easily resolved. If reducibility is a high priority, these might be appealing candidate hypotheses. We define these as having a QVoI <4 and a reducibility ≥2. Low priority hypotheses have a low QVoI, indicating that they are not particularly relevant to land acquisition decision making, or have low remaining uncertainty based on the literature. In addition, they will be difficult to reduce. Therefore, these are not high priority topics. We define these as having a QVoI <4 and a reducibility <2.

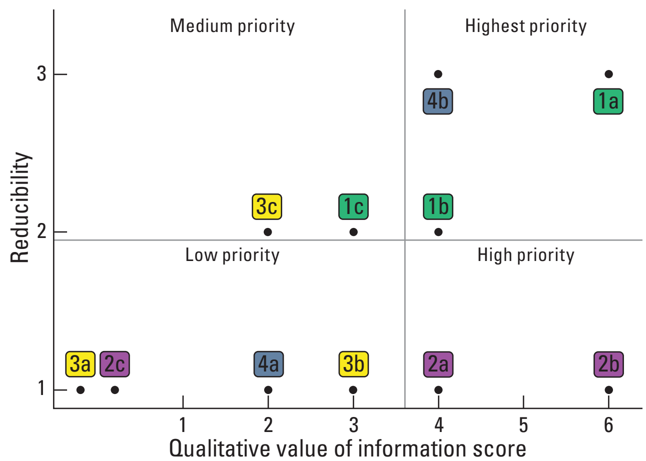

Figure 1. Eleven hypotheses about climate change effects on migratory birds plotted according to their reducibility (y axis) and their qualitative value of information score (x axis). Hypotheses in upper right quadrant are high priority because they are both highly reducible and have high value of information. Low priority hypotheses (lower left quadrant) have low value of information and low reducibility. See table 6 for hypothesis numbering and table 7 for details of scoring system. Note that a small jitter has been added to the qualitative value of information scores of hypotheses 2c and 3a to avoid overlapping points.

Results

Of the 11 hypotheses we evaluated, we identified 4 high-priority research topics, which combined moderate to high scores in magnitude of uncertainty, relevance to land acquisition programs, and reducibility (fig. 1; note that in reporting high-priority topics, we have combined hypothesis 1a and 1b because they overlap in the peer-reviewed literature) . For a complete discussion of all 11 hypotheses, see Rushing and others (2020). The four high-priority research topics represent sources of uncertainty that have substantial scientific disagreement that needs to be resolved and that are relevant to land acquisition decision making as currently practiced in Federal programs. A high reducibility score indicates that these relevant topics are top candidates for future research efforts. A low score for reducibility indicates that, although possible, reducing these uncertainties will be more difficult and potentially require additional resources.

The Effects of Rising Temperatures on Spatial Distributions of Migratory Birds During the Breeding and Nonbreeding Seasons (Hypotheses 1a and 1b)

Magnitude of Uncertainty

Breeding and nonbreeding distributions for migratory birds are widely expected to shift poleward in response to rising temperatures (Chen and others, 2011). Although a large body of research on climate-driven range shifts has developed over the past two decades, and evidence of poleward range shifts has been well documented across regions and taxa, moderate uncertainty still remains. In particular, constructing accurate projections of future range shifts at spatial scales relevant to habitat managers remains challenging. In addition, the empirical and theoretical knowledge base regarding climate-driven range shifts along southern (that is, trailing) edges of species' ranges is small. Furthermore, range shifts in nonbreeding distributions are generally less well understood; although strong theoretical evidence indicates winter temperature plays an important role in determining temperate winter distributions (Swanson and Olmstead, 1999; Canterbury, 2002), the environmental processes that limit nonbreeding distributions have received less theoretical attention than breeding season processes. Finally, variability in species' range shift responses to rising temperature is highly interspecific, and although some traits have been identified that seem to be associated with greater or lesser responses (that is, body size and dispersal capacity), considerable uncertainty remains about which species are most adaptive or vulnerable. Overall, the theoretical links between temperature and species distributions, combined with the many studies that have documented northward range shifts across many avian species, results in relatively high certainty that range limits will continue to shift northwards. But high interspecific variability, increased uncertainty about southern range edges, and lack of clarity about trait-level indicators of adaptive capacity suggest that considerable uncertainty remains.

Relevance to Land Acquisition Programs

This research priority has high relevance to managers within the context of land acquisition decision making. The presence of one or more priority species is a key criterion for land acquisition decisions, and it is clear that future range shifts are likely for many species. Parcels that are currently important because of the presence or abundance of priority species may no longer support those species in the future. Likewise, parcels that are currently uninhabited or support low-density populations may become critical to the maintenance of priority species under future climate conditions. Additional information about these projected changes could therefore fundamentally alter the outcome of management decisions if uncertainties were sufficiently reduced. Changes in breeding distribution are likely to be more relevant than changes in nonbreeding distributions, given that nonbreeding distributions occur outside the jurisdiction of Federal land acquisition programs for many priority species. In addition, shifts in nonbreeding distributions are projected to be smaller than breeding-season distributional shifts (Langham and others, 2015), resulting in less of a potential effect on acquisition decisions. Research on breeding season distributional shifts is therefore likely to have a greater relevance to managers than nonbreeding season shifts. Because the rate, direction, and magnitude of distributional shifts will vary across space, time, and species, the ability to identify parcels that will or will not support long-term management objectives before making land acquisition decisions is expected to have high value.

Reducibility

This research priority has relatively high reducibility compared to other priorities. The ability to quantify breeding distribution shifts has been facilitated by the availability of large-scale monitoring data for many species, including through the North American Breeding Bird Survey (Sauer and others, 2005) and the Audubon Christmas Bird Count (CBC; Niven and others, 2004). These structured monitoring programs are increasingly being supplemented by unstructured citizen-science initiatives (for example, eBird; Sullivan and others, 2014), which provide millions of additional observations from across the globe each year. Although observation networks for breeding distributions are more widespread than for nonbreeding distributions, several large-scale programs have been documenting the winter distribution of many bird species for decades (for examples, CBC). Augmenting these data with unstructured citizen-science initiatives like eBird, within-species distribution models will further reduce uncertainty about how winter distributions will respond to future climate change. In both seasons, recent advances in species distribution modeling have provided new methods for estimating range shifts that improve upon earlier methods by taking into account imperfect detection (Guillera-Arroita, 2017), nonequilibrium dynamics (Clement and others, 2016; Rushing and others, 2019), and spatial autocorrelation (Johnson and others, 2013). Given the quantity of existing data, the large temporal, spatial, and taxonomic scope of these data, and increasingly powerful species distribution models, reducing uncertainty about how breeding distributions will respond to future climate change should be highly feasible.

Recurvirostra americana (Gmelin, 1789) (American avocet). Photograph by Douglas Barnum, U.S. Geological Survey. Public domain.

Climate-Driven Changes to Avian Community Composition Through Homogenization and Loss of Specialists (Hypothesis 4b)

Magnitude of Uncertainty

Ecological specialization affects many processes and characteristics that relate to species' adaptive capacity in the face of climate change, including range size, dispersal dynamics, and population viability (Kisdi, 2002; Kotiaho and others, 2005; Slatyer and others, 2013). In general, specialists are thought to favor stable environments and be poor colonizers of new habitat, whereas generalists are able to thrive in disturbed and newly created habitat (Levins, 1968). As climate changes, ecological communities are predicted to become more homogeneous as generalist species flourish and specialists dwindle (McKinney and Lockwood, 1999). The relations between ecological specialization and range size, dispersal, and population viability have a strong tradition in the theoretical literature (McKinney, 1997; Büchi and Vuilleumier, 2014), providing a firm theoretical foundation for predicting how climate change will affect biotic homogenization. A growing body of empirical studies has also found evidence that avian communities have become more homogenous because of the increase of generalist species and decline of specialists (Davey and others, 2012; Le Viol and others, 2012). Although changes in community composition have coincided with changes in several climate variables, the role of climate versus land-use change has not been fully explored in the existing literature, leading to moderate uncertainty surrounding this climate change effect.

Relevance to Land Acquisition Programs

Because many of the priority species are restricted in range or low in abundance, loss of these species because of climate-driven homogenization is potentially relevant to land acquisition decisions. Reducing uncertainty about this hypothesis could allow researchers to better predict which priority species may be unable to adapt to future conditions and where these species may remain present or abundant in the face of climate disruptions. Additionally, because community homogenization is also driven by nonclimate drivers, such as urbanization and land-use change, land acquisition managers could potentially take these other drivers into account during acquisition decision making as a buffer against climate-driven homogenization.

Reducibility

The widespread availability of monitoring data from programs like the North American Breeding Bird Survey, CBC, and eBird provide ample opportunities to estimate changes in community composition of North American birds over long timescales and across multiple spatial scales. When combined with species distribution models that can account for dispersal ability (Bateman and others, 2013), these datasets may provide opportunities to predict how individual species and entire communities may be disrupted by changing patterns of abundance between generalists and specialists.

The Effects of Decreased Precipitation on Abundance in the Breeding Season (Hypothesis 2b)

Magnitude of Uncertainty

Precipitation across North America has changed in spatially variable ways; for example, precipitation has decreased in the West, Southwest, and Southeast and increased in the southern Great Plains, Midwest, and Northeast (Easterling and others, 2017). Changes in total precipitation, as well as changes in the frequency and severity of precipitation extremes, can affect the productivity of many terrestrial and aquatic habitats that are important to the survival and reproductive success of migratory birds. This importance is particularly true for the billions of waterfowl and other wetland-dependent species that rely on permanent and ephemeral wetlands for successful breeding (Johnson and others, 2005; Millett and others, 2009). The relationship between wetland productivity and recruitment and abundance of wetland-dependent migratory birds is well established from first principles (Johnson and others, 1987) and decades of long-term empirical studies (Markham, 1982; Zhao and others, 2016; Specht and Arnold, 2018). The effects of precipitation on nonwetland species is less certain, but evidence suggests that decreased precipitation can lead to lower reproductive success (Öberg and others, 2015; Conrey and others, 2016), juvenile survival (Yackel Adams and others, 2006; Vernasco and others, 2018), and adult survival (Öberg and others, 2015) in landbirds; therefore, little uncertainty remains that reduced breeding season precipitation will negatively affect these species. However, substantial uncertainty remains about spatial and temporal changes in precipitation patterns. Although most climate models agree that the frequency and severity of extreme precipitation events will increase throughout North America, models disagree substantially about regional changes in the amount and timing of precipitation (Stephens and Hu, 2010; Pierce and others, 2013; Wuebbles and others, 2017). Therefore, despite well-understood relationships between precipitation and the demography of migratory birds, the uncertainty about spatial variation in the amount, timing, and frequency of future precipitation creates substantial uncertainty regarding this hypothesis.

Relevance to Land Acquisition Programs

Given the centrality of waterfowl to many Federal land acquisition programs, future reductions in precipitation and increasing droughts have the potential to dramatically alter abundances of the priority species that drive land acquisition decisions in North America (Bethke and Nudds, 1995; Sorenson and others, 1998; Haig and others, 2019). The high spatial variability in precipitation changes makes this hypothesis particularly relevant to land acquisition decisions because understanding this spatial variation will be critical for accurately predicting which areas will provide high-quality habitat for priority species into the future.

Reducibility

The reducibility for this hypothesis is relatively low. Although the relationships between precipitation, wetland quality, and breeding success of wetland-dependent species are relatively well understood, improving management actions in the face of future precipitation changes will require improving predictions of future precipitation changes at high spatial resolutions. Although climatologists are developing a better understanding of the physical processes that affect variation in precipitation patterns (Meehl and others, 2005; Stephens and Hu, 2010; Muller and others, 2011), the predictive ability of precipitation models is still relatively low (Chen and Knutson, 2008; Wehner and others, 2010). Reducing uncertainty about this hypothesis will therefore fall heavily on the ability of climatologists to improve the predictive ability of climate models. Because of the inherent complexity of precipitation modeling, reducing uncertainty about this hypothesis will require continued long-term data collection and model development, both of which render this source of uncertainty difficult to reduce.

The Effects of Rising Temperatures on Abundance in the Nonbreeding Season (Hypothesis 2a)

Magnitude of Uncertainty

Climate conditions during the nonbreeding season can also affect abundance through survival and reproductive success of resident and migratory birds (Harrison and others, 2011). For residents and migrants that overwinter in temperate areas, adverse winter weather (for example, low temperatures and duration of frost or snow) can lower survival through direct thermoregulatory costs (Swanson and Olmstead, 1999) or food limitation (Jansson and others, 1981) and can lower subsequent reproductive success via carry-over effects on body condition or phenology (Robb and others, 2008). Increasingly mild winter temperatures in temperate areas could therefore result in higher survival and reproductive success of species that winter in these areas, potentially resulting in higher abundance if species were previously limited in the nonbreeding season. Although studies have linked improved demographic rates to warmer winter temperatures, and a few have demonstrated positive effects on overall changes in abundance, the validity of this hypothesis is conditional on winter limitation; that is, abundance of migratory bird populations will only increase in response to warming winters if winter temperature limits population growth. The degree to which populations of migratory birds are winter limited is poorly understood for most species. Collectively, the lack of theory, combined with the lack of empirical evidence regarding winter limitation and the few studies that have directly linked changes in abundance to winter temperature, leads to a large degree of uncertainty regarding this hypothesis.

Relevance to Land Acquisition Programs

The links between this hypothesis and land acquisition decision making is weaker than the links with some of our other hypotheses. If populations are currently winter limited, parcels that currently support high-abundance populations of priority species during the winter will likely remain important sites in the future regardless of whether this hypothesis is true. As a result, management decisions based on current abundance are unlikely to be detrimental under this hypothesis if winter remains the limiting season. Therefore, reducing uncertainty about this hypothesis is not likely to change which acquisition actions produce the highest benefits. However, warming temperatures may relax winter limitation enough that breeding-season processes become more limiting in the future. In this case, current means objectives used by land acquisition programs may become unreliable predictors of the parcels that are most likely to meet fundamental objectives long term. Populations are unlikely to become completely released from winter limitation, so protecting land that currently supports a high abundance of individuals is unlikely to have major downsides under future climate scenarios.

Reducibility

This hypothesis has relatively low reducibility. Measuring breeding versus winter limitation has been a central focus of avian population ecology for decades (Newton, 2004), yet researchers still lack a solid theoretical or empirical understanding of this issue because linking population processes to seasonal vital rates and environmental processes is exceedingly difficult. However, the same monitoring programs that have proven useful for modeling species distributions, including the North American Breeding Bird Survey, CBC, and eBird, provide data that can be used to quantify changes in abundance across space and time (Niven and others, 2004; Link and Sauer, 2007; Robinson and others, 2018). Combined with large-scale remote sensing data, these data can be used to model the relation between abundance and winter climate for many species (Wilson and others, 2011; Rushing and others, 2016). In cases where demographic data are also available, integrated population models could provide a powerful method to link climate variation to changes in abundance via demographic vital rates (Weegman and others, 2017), which should improve predictions about future dynamics (Zipkin and Saunders, 2018). Continued development of these data sources and analytical methods may provide important insights into this hypothesis in the future, but progress will likely be limited by the intrinsic difficulty of the questions.

Anas platyrhynchos (Linnaeus, 1758) (mallard). Photograph by Andrew Reeves, U.S. Geological Survey. Public domain.

Conclusions

An actionable science program must consider the information needs of decision makers within a particular decision context, as well as the feasibility of reducing uncertainty through scientific research. By using a modified structured decision-making approach, and a qualitative value of information analysis, we identified four high priority topics for research on migratory birds and climate change: the effects of rising temperatures on spatial distributions of migratory birds in the breeding and nonbreeding seasons, climate-driven changes to avian community composition through homogenization and loss of specialists, the effects of decreased precipitation on abundance in the breeding season, and the effects of rising temperatures on abundance in the nonbreeding season. Because we began with a thorough understanding of land acquisition programs and built our assessment on the evaluation criteria used to make acquisition decisions, our rankings are specifically tailored to the information needs of land acquisition program managers. The research priorities identified through this process are important scientifically, in that substantial uncertainty still needs to be reduced, are relevant to decision makers within the land acquisition context, and are reducible given existing methods and data.

The high-priority uncertainties we identified emphasize potential changes in spatial distribution of focal species or changes in their abundance, rather than sources of uncertainty focused on temporal changes in phenology. Although climate-driven phenological shifts remain an active area of research, we determined that this topic was not highly relevant to land acquisition decision making given the evaluation criteria currently in use. Federal land acquisition programs generally protect parcels of land in perpetuity, so climate-driven range shifts have potential to substantially alter which parcels will help meet fundamental objectives in the future. The structure of current land acquisition programs makes incorporating phenological shifts difficult, thereby reducing the management relevance of uncertainty related to phenology.

Our work focused on the specific context of habitat acquisition for migratory birds, but this approach could be used to identify important research priorities in other fields. Natural-resource managers often make decisions in complex and highly uncertain ecological systems, and available management interventions are often rare. In these situations, the qualitative value of information approach outlined here, combined with expert elicitation and a review of the existing literature, can be an important tool for improving management decisions in the face of uncertainty. By providing a replicable and transparent approach to prioritizing research efforts in cases where traditional quantitative value of information analysis is not possible, qualitative value of information is a valuable tool for prioritizing research and for improving the relevance of research products to management decisions. Results from this analysis can provide Government, academic, and nongovernmental organizations with a list of priority topics for future research and a clear rationale for allocating research efforts.

Ammodramus henslowii (Audubon, 1829) (Henslow's sparrow). Photograph by Jim Hudgins, U.S. Fish and Wildlife Service. Public domain.

References Cited

Bateman, B.L., Murphy, H.T., Reside, A.E., Mokany, K., and VanDerWal, J., 2013, Appropriateness of full-, partial-and no-dispersal scenarios in climate change impact modelling: Diversity & Distributions, v. 19, no. 10, p. 1224–1234. [Also available at https://doi.org/10.1111/ddi.12107.]

Bethke, R.W., and Nudds, T.D., 1995, Effects of climate change and land use on duck abundance in Canadian prairie-parklands: Ecological Applications, v. 5, no. 3, p. 588–600. [Also available at https://doi.org/10.2307/1941969.]

Büchi, L., and Vuilleumier, S., 2014, Coexistence of specialist and generalist species is shaped by dispersal and environmental factors: American Naturalist, v. 183, no. 5, p. 612–624. [Also available at https://doi.org/10.1086/675756.]

Canterbury, G., 2002, Metabolic adaptation and climatic constraints on winter bird distribution: Ecology, v. 83, no. 4, p. 946–957. [Also available at https://doi.org/10.1890/0012-9658(2002)083[0946:MAACCO]2.0.CO;2.]

Chen, C., and Knutson, T., 2008, On the verification and comparison of extreme rainfall indices from climate models: Journal of Climate, v. 21, no. 7, p. 1605–1621. [Also available at https://doi.org/10.1175/2007JCLI1494.1.]

Chen, I., Hill, J.K., Ohlemuller, R., Roy, D.B., and Thomas, C.D., 2011, Rapid range shifts of species associated with high levels of climate warming: Science, v. 333, no. 6045, p. 1024–1026. [Also available at https://doi.org/10.1126/science.1206432.]

Clement, M.J., Hines, J.E., Nichols, J.D., Pardieck, K.L., and Ziolkowski, D.J., 2016, Estimating indices of range shifts in birds using dynamic models when detection is imperfect: Global Change Biology, v. 22, no. 10, p. 3273–3285. [Also available at https://doi.org/10.1111/gcb.13283.]

Conrey, R.Y., Skagen, S.K., Yackel Adams, A.A., and Panjabi, A.O., 2016, Extremes of heat, drought and precipitation depress reproductive performance in shortgrass prairie passerines: The Ibis, v. 158, no. 3, p. 614–629. [Also available at https://doi.org/10.1111/ibi.12373.]

Davey, C.M., Chamberlain, D.E., Newson, S.E., Noble, D.G., and Johnston, A., 2012, Rise of the generalists—Evidence for climate driven homogenization in avian communities: Global Ecology and Biogeography, v. 21, no. 5, p. 568–578. [Also available at https://doi.org/10.1111/j.1466-8238.2011.00693.x.]

Easterling, D.R., Kunkel, K., Arnold, J., Knutson, T., LeGrande, A., Leung, L., Vose, R., Waliser, D., and Wehner, M., 2017, Precipitation change in the United States, chap. 7 *of* Wuebbles, D.J., Fahey, D.W., Hibbard, K.A., Dokken, D.J., Stewart, B., and Maycock, T., eds., Climate science special report—Fourth National Climate Assessment, volume I: Washington, D.C., U.S. Global Change Research Program, p. 207–230. [Also available at https://doi.org/10.7930/J0H993CC.]

Guillera-Arroita, G., 2017, Modelling of species distributions, range dynamics and communities under imperfect detection—Advances, challenges and opportunities: Ecography, v. 40, no. 2, p. 281–295. [Also available at https://doi.org/10.1111/ecog.02445.]

Haig, S.M., Murphy, S.P., Matthews, J.H., Arismendi, I., and Safeeq, M., 2019, Climate-altered wetlands challenge waterbird use and migratory connectivity in arid landscapes: Scientific Reports, v. 9, no. 1, p. 1–10. [Also available at https://doi.org/10.1038/s41598-019-41135-y.]

Hammond, J.S., Keeney, R.L., and Raiffa, H., 2015, Smart choices—A practical guide to making better decisions: Boston, Mass., Harvard Business Review Press, 256 p.

Hanea, A.M., Burgman, M., and Hemming, V., 2018, IDEA for uncertainty quantification, *in* Elicitation: Springer, International Series in Operations Research & Management Science, v. 261, p. 95–117. [Also available at https://doi.org/10.1007/978-3-319-65052-4_5.]

Harrison, X.A., Blount, J.D., Inger, R., Norris, D.R., and Bearhop, S., 2011, Carry-over effects as drivers of fitness differences in animals: Journal of Animal Ecology, v. 80, no. 1, p. 4–18. [Also available at https://doi.org/10.1111/j.1365-2656.2010.01740.x.]

Jansson, C., Ekman, J., and von Brömssen, A., 1981, mortality and food supply in tits Parus spp: Oikos, v. 37, no. 3, p. 313–322. [Also available at https://doi.org/10.2307/3544122.]

Johnson, D.H., Sparling, D.W., and Cowardin, L.M., 1987, A model of the productivity of the mallard duck: Ecological Modelling, v. 38, no. 3–4, p. 257–275. [Also available at https://doi.org/10.1016/0304-3800(87)90100-1.]

Johnson, D.S., Conn, P.B., Hooten, M.B., Ray, J.C., and Pond, B.A., 2013, Spatial occupancy models for large data sets: Ecology, v. 94, no. 4, p. 801–808. [Also available at https://doi.org/10.1890/12-0564.1.]

Johnson, W.C., Millett, B.V., Gilmanov, T., Voldseth, R.A., Guntenspergen, G.R., and Naugle, D.E., 2005, Vulnerability of northern prairie wetlands to climate change: Bioscience, v. 55, no. 10, p. 863–872. [Also available at https://doi.org/10.1641/0006-3568(2005)055[0863:VONPWT]2.0.CO;2.]

Kisdi, É., 2002, Dispersal—Risk spreading versus local adaptation: American Naturalist, v. 159, no. 6, p. 579–596. [Also available at https://doi.org/10.1086/339989.]

Knudsen, E., Lindén, A., Both, C., Jonzén, N., Pulido, F., Saino, N., Sutherland, W.J., Bach, L.A., Coppack, T., Ergon, T., Gienapp, P., Gill, J.A., Gordo, O., Hedenström, A., Lehikoinen, E., Marra, P.P., Møller, A.P., Nilsson, A.L.K., Péron, G., Ranta, E., Rubolini, D., Sparks, T.H., Spina, F., Studds, C.E., Sæther, S.A., Tryjanowski, P., and Stenseth, N.C., 2011, Challenging claims in the study of migratory birds and climate change: Biological Reviews of the Cambridge Philosophical Society, v. 86, no. 4, p. 928–946. [Also available at https://doi.org/10.1111/j.1469-185X.2011.00179.x.]

Kotiaho, J.S., Kaitala, V., Komonen, A., and Päivinen, J., 2005, Predicting the risk of extinction from shared ecological characteristics: Proceedings of the National Academy of Sciences of the United States of America, v. 102, no. 6, p. 1963–1967. [Also available at https://doi.org/10.1073/pnas.0406718102.]

Langham, G.M., Schuetz, J.G., Distler, T., Soykan, C.U., and Wilsey, C., 2015, Conservation status of North American birds in the face of future climate change: PLoS One, v. 10, no. 9, p. 1–16. [Also available at https://doi.org/10.1371/journal.pone.0135350.]

La Sorte, F.A., and Thompson, F.R., 2007, Poleward shifts in winter ranges of North American birds: Ecology, v. 88, no. 7, p. 1803–1812. [Also available at https://doi.org/10.1890/06-1072.1.]

Lecy, J.D., and Beatty, K.E., 2012, Representative literature reviews using constrained snowball sampling and citation network analysis: SSRN, research paper, 15 p. [Also available at https://doi.org/10.2139/ssrn.1992601.]

Le Viol, I., Jiguet, F., Brotons, L., Herrando, S., Lindström, Å., Pearce-Higgins, J.W., Reif, J., Van Turnhout, C., and Devictor, V., 2012, More and more generalists—Two decades of changes in the European avifauna: Biology Letters, v. 8, no. 5, p. 780–782. [Also available at https://doi.org/10.1098/rsbl.2012.0496.]

Levins, R., 1968, Evolution in changing environments—Some theoretical explorations: Princeton, N.J., Princeton University Press, Monographs in Population Biology, v. 2, 120 p. https://doi.org/10.1515/9780691209418.

Link, W.A., and Sauer, J.R., 2007, Seasonal components of avian population change—Joint analysis of two large-scale monitoring programs: Ecology, v. 88, no. 1, p. 49–55. [Also available at https://doi.org/10.1890/0012-9658(2007)88[49:SCOAPC]2.0.CO;2.]

Markham, B.J., 1982, Waterfowl production and water level fluctuation: Canadian Water Resources Journal, v. 7, no. 4, p. 22–36. [Also available at https://doi.org/10.4296/cwrj0704022.]

Mayor, S.J., Guralnick, R.P., Tingley, M.W., Otegui, J., Withey, J.C., Elmendorf, S.C., Andrew, M.E., Leyk, S., Pearse, I.S., and Schneider, D.C., 2017, Increasing phenological asynchrony between spring green-up and arrival of migratory birds: Scientific Reports, v. 7, no. 1, art. 1902, 10 p. [Also available at https://doi.org/10.1038/s41598-017-02045-z.]

McKinney, M.L., 1997, Extinction vulnerability and selectivity—Combining ecological and paleontological views: Annual Review of Ecology and Systematics, v. 28, no. 1, p. 495–516. [Also available at https://doi.org/10.1146/annurev.ecolsys.28.1.495.]

McKinney, M.L., and Lockwood, J.L., 1999, Biotic homogenization—A few winners replacing many losers in the next mass extinction: Trends in Ecology & Evolution, v. 14, no. 11, p. 450–453. [Also available at https://doi.org/10.1016/S0169-5347(99)01679-1.]

Meehl, G.A., Arblaster, J.M., and Tebaldi, C., 2005, Understanding future patterns of increased precipitation intensity in climate model simulations: Geophysical Research Letters, v. 32, no. 18, 4 p. [Also available at https://doi.org/10.1029/2005GL023680.]

Miller-Rushing, A.J., Lloyd-Evans, T.L., Primack, R.B., and Satzinger, P., 2008, Bird migration times, climate change, and changing population sizes: Global Change Biology, v. 14, no. 9, p. 1959–1972. [Also available at https://doi.org/10.1111/j.1365-2486.2008.01619.x.]

Millett, B., Johnson, W.C., and Guntenspergen, G., 2009, Climate trends of the North American prairie pothole region 1906–2000: Climatic Change, v. 93, no. 1–2, p. 243–267. [Also available at https://doi.org/10.1007/s10584-008-9543-5.]

Muller, C.J., O’Gorman, P.A., and Back, L.E., 2011, Intensification of precipitation extremes with warming in a cloud-resolving model: Journal of Climate, v. 24, no. 11, p. 2784–2800. [Also available at https://doi.org/10.1175/2011JCLI3876.1.]

Newton, I., 2004, Population limitation in migrants: The Ibis, v. 146, no. 2, p. 197–226. [Also available at https://doi.org/10.1111/j.1474-919X.2004.00293.x.]

Nichols, J.D., Koneff, M.D., Heglund, P.J., Knutson, M.G., Seamans, M.E., Lyons, J.E., Morton, J.M., Jones, M.T., Boomer, G.S., and Williams, B.K., 2011, Climate change, uncertainty, and natural resource management: The Journal of Wildlife Management, v. 75, no. 1, p. 6–18. [Also available at https://doi.org/10.1002/jwmg.33.]

Niven, D.K., Sauer, J.R., Butcher, G.S., and Link, W.A., 2004, Christmas Bird Count provides insights into population change in land birds that breed in the boreal forest: American Birds, v. 58, 104th Christmas Bird, p. 10–20.

Öberg, M., Arlt, D., Pärt, T., Laugen, A.T., Eggers, S., and Low, M., 2015, Rainfall during parental care reduces reproductive and survival components of fitness in a passerine bird: Ecology and Evolution, v. 5, no. 2, p. 345–356. [Also available at https://doi.org/10.1002/ece3.1345.]

Pierce, D.W., Cayan, D.R., Das, T., Maurer, E.P., Miller, N.L., Bao, Y., Kanamitsu, M., Yoshimura, K., Snyder, M.A., Sloan, L.C., Franco, G., and Tyree, M., 2013, The key role of heavy precipitation events in climate model disagreements of future annual precipitation changes in California: Journal of Climate, v. 26, no. 16, p. 5879–5896. [Also available at https://doi.org/10.1175/JCLI-D-12-00766.1.]

Robb, G.N., McDonald, R.A., Chamberlain, D.E., Reynolds, S.J., Harrison, T.J.E., and Bearhop, S., 2008, feeding of birds increases productivity in the subsequent breeding season: Biology Letters, v. 4, no. 2, p. 220–223. [Also available at https://doi.org/10.1098/rsbl.2007.0622.]

Robinson, O.J., Ruiz-Gutierrez, V., Fink, D., Meese, R.J., Holyoak, M., and Cooch, E.G., 2018, Using citizen science data in integrated population models to inform conservation decision-making: Biological Conservation, v. 227, p. 361–368. [Also available at https://doi.org/10.1016/j.biocon.2018.10.002.]

Runge, M.C., Converse, S.J., and Lyons, J.E., 2011, Which uncertainty? Using expert elicitation and expected value of information to design an adaptive program: Biological Conservation, v. 144, no. 4, p. 1214–1223. [Also available at https://doi.org/10.1016/j.biocon.2010.12.020.]

Rushing, C.S., Royle, J.A., Ziolkowski, D.J., and Pardieck, K.L., 2019, Modeling spatially and temporally complex range dynamics when detection is imperfect: Scientific Reports, v. 9, no. 1, p. 1–9. [Also available at https://doi.org/10.1038/s41598-019-48851-5.]

Rushing, C.S., Rubenstein, M.A., Lyons, J.E., and Runge, M.C., 2020, Using value of information to prioritize research needs for migratory bird management under climate change—A case study using Federal land acquisition in the United States: Biological Reviews of the Cambridge Philosophical Society, v. 95, no. 4, p. 1109–1130. [Also available at https://doi.org/10.1111/brv.12602.]

Rushing, C.S., Ryder, T.B., and Marra, P.P., 2016, Quantifying drivers of population dynamics for a migratory bird throughout the annual cycle: Proceedings of the Royal Society B: Biological Sciences, v. 283, no. 1823, 10 p. [Also available at https://doi.org/10.1098/rspb.2015.2846.]

Sauer, J.R., Link, W.A., Nichols, J.D., and Royle, J.A., 2005, Using the North American Breeding Bird Survey as a tool for conservation—A critique of Bart et al. (2004): The Journal of Wildlife Management, v. 69, no. 4, p. 1321–1326. [Also available at https://doi.org/10.2193/0022-541X(2005)69[1321:UTNABB]2.0.CO;2.]

Schlaifer, R., and Raiffa, H., 1961, Applied statistical decision theory: The American Mathematical Monthly, v. 69, no. 1, p. 72–73.

Slatyer, R.A., Hirst, M., and Sexton, J.P., 2013, Niche breadth predicts geographical range size—A general ecological pattern: Ecology Letters, v. 16, no. 8, p. 1104–1114. [Also available at https://doi.org/10.1111/ele.12140.]

Sorenson, L.G., Goldberg, R., Root, T.L., and Anderson, M.G., 1998, Potential effects of global warming on waterfowl populations breeding in the northern Great Plains: Climatic Change, v. 40, no. 2, p. 343–369. [Also available at https://doi.org/10.1023/A:1005441608819.]

Specht, H.M., and Arnold, T.W., 2018, Banding age ratios reveal prairie waterfowl fecundity is affected by climate, density dependence and predator-prey dynamics: Journal of Applied Ecology, v. 55, no. 6, p. 2854–2864. [Also available at https://doi.org/10.1111/1365-2664.13186.]

Stephens, G.L., and Hu, Y., 2010, Are climate-related changes to the character of global-mean precipitation predictable?: Environmental Research Letters, v. 5, no. 2, 7 p. [Also available at https://doi.org/10.1088/1748-9326/5/2/025209.]

Sullivan, B.L., Aycrigg, J.L., Barry, J.H., Bonney, R.E., Bruns, N., Cooper, C.B., Damoulas, T., Dhondt, A.A., Dietterich, T., Farnsworth, A., Fink, D., Fitzpatrick, J.W., Fredericks, T., Gerbracht, J., Gomes, C., Hochachka, W.M., Iliff, M.J., Lagoze, C., La Sorte, F.A., Merrifield, M., Morris, W., Phillips, T.B., Reynolds, M., Rodewald, A.D., Rosenberg, K.V., Trautmann, N.M., Wiggins, A., Winkler, D.W., Wong, W.-K., Wood, C.L., Yu, J., and Kelling, S., 2014, The eBird enterprise—An integrated approach to development and application of citizen science: Biological Conservation, v. 169, p. 31–40. [Also available at https://doi.org/10.1016/j.biocon.2013.11.003.]

Swanson, D.L., and Olmstead, K.L., 1999, Evidence for a proximate influence of winter temperature on metabolism in passerine birds: Physiological and Biochemical Zoology, v. 72, no. 5, p. 566–575. [Also available at https://doi.org/10.1086/316696.]

Tingley, M.W., Koo, M.S., Moritz, C., and Rush, A.C., 2012, The push and pull of climate change causes heterogeneous shifts in avian elevational ranges: Global Change Biology, v. 18, no. 11, p. 3279–3290. [Also available at https://doi.org/10.1111/j.1365-2486.2012.02784.x.]

Vernasco, B.J., Sillett, T.S., Marra, P.P., and Ryder, T.B., 2018, Environmental predictors of nestling condition, postfledging movement, and postfledging survival in a migratory songbird, the wood thrush (*Hylocichla mustelina*): The Auk, v. 135, no. 1, p. 15–24. [Also available at https://doi.org/10.1642/AUK-17-105.1.]

Weegman, M.D., Arnold, T.W., Dawson, R.D., Winkler, D.W., and Clark, R.G., 2017, Integrated population models reveal local weather conditions are the key drivers of population dynamics in an aerial insectivore: Oecologia, v. 185, no. 1, p. 119–130. [Also available at https://doi.org/10.1007/s00442-017-3890-8.]

Wehner, M.F., Smith, R.L., Bala, G., and Duffy, P., 2010, The effect of horizontal resolution on simulation of very extreme US precipitation events in a global atmosphere model: Climate Dynamics, v. 34, no. 2–3, p. 241–247. [Also available at https://doi.org/10.1007/s00382-009-0656-y.]

Weiskopf, S.R., Rubenstein, M.A., Crozier, L.G., Gaichas, S., Griffis, R., Halofsky, J.E., Hyde, K.J.W., Morelli, T.L., Morisette, J.T., Muñoz, R.C., Pershing, A.J., Peterson, D.L., Poudel, R., Staudinger, M.D., Sutton-Grier, A.E., Thompson, L., Vose, J., Weltzin, J.F., and Whyte, K.P., 2020, Climate change effects on biodiversity, ecosystems, ecosystem services, and natural resource management in the United States: Science of the Total Environment, v. 733, 18 p. [Also available at https://doi.org/10.1016/j.scitotenv.2020.137782.]

Wilson, S., LaDeau, S.L., Tøttrup, A.P., and Marra, P.P., 2011, Range-wide effects of breeding-and nonbreeding-season climate on the abundance of a Neotropical migrant songbird: Ecology, v. 92, no. 9, p. 1789–1798. [Also available at https://doi.org/10.1890/10-1757.1.]

Wood, E.M., and Kellermann, J.L., eds., 2015, Phenological synchrony and bird migration—Changing climate and seasonal resources in North America: Boca Raton, Fla., CRC Press, Cooper Ornithological Society Studies in Avian Biology, v. 47, 246 p. [Also available at https://doi.org/10.1201/b18011.]

Wuebbles, D.J., Fahey, D.W., Hibbard, K.A., Dokken, D.J., Stewart, B.C., and Maycock, T.K., eds., 2017, Climate science special report—Fourth national climate assessment v. I: Washington, D.C., U.S. Global Change Research Program, 470 p. [Also available at https://doi.org/10.7930/J0J964J6.]

Yackel Adams, A.A., Skagen, S.K., and Savidge, J.A., 2006, Modeling post-fledging survival of lark buntings in response to ecological and biological factors: Ecology, v. 87, no. 1, p. 178–188. [Also available at https://doi.org/10.1890/04-1922.]

Zhao, Q., Silverman, E., Fleming, K., and Boomer, G.S., 2016, Forecasting waterfowl population dynamics under climate change—Does the spatial variation of density dependence and environmental effects matter?: Biological Conservation, v. 194, p. 80–88. [Also available at https://doi.org/10.1016/j.biocon.2015.12.006.]

Zipkin, E.F., and Saunders, S.P., 2018, Synthesizing multiple data types for biological conservation using integrated population models: Biological Conservation, v. 217, p. 240–250. [Also available at https://doi.org/10.1016/j.biocon.2017.10.017.]

Phalacrocorax auritus (Lesson, 1831) (double-crested cormorant). Photograph by Jeff Corbett, U.S. Geological Survey.

For more information about this publication, contact:
USGS National Climate Adaptation Science Center
12201 Sunrise Valley Drive, MS 516
Reston, VA 20192
703–648–5801

For additional information, visit: https://www.usgs.gov/ecosystems/climate-adaptation-science-centers

Publishing support provided by the Reston and Rolla Publishing Service Centers

USGS

Rubenstein and others—**Research Priorities for Migratory Birds Under Climate Change—A QVoI Assessment**—CIR 1472

ISSN 2330-5703 (online)
https://doi.org/10.3133/cir1472