SECTION 1. ADMINISTRATIVE INFORMATION

Project title: Managing waterfowl harvest under climate change

Investigator: Michael C. Runge[1]

Cooperators and Partners: Patrick K. Devers[2], G. Scott Boomer[2], James E. Lyons[1], Anna M. Tucker[1,3], Qing Zhao[4], Jamie Ashander[1]

Institutions: 1. U.S. Geological Survey, Eastern Ecological Science Center at Patuxent Research Refuge, Laurel, MD. 2. Branch of Assessment and Decision Support, U.S. Fish and Wildlife Service, Division of Migratory Bird Management, Laurel, MD, 3. U.S. Geological Survey, Iowa Cooperative Fish and Wildlife Research Unit, Ames, IA, 4. Bird Conservancy of the Rockies, Fort Collins, CO.

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Reporting period: June 4, 2020 – June 3, 2023

Actual total cost: $345,904

SECTION 2. PLAIN LANGUAGE PUBLIC SUMMARY:

Our ability to effectively manage wildlife in North America is founded in an understanding of how our actions and the environment influence wildlife populations. Current practices use population monitoring data from the past to determine key ecological relationships and make predictions about future population status. In most cases, including the regulation of waterfowl hunting in North America, these forecasts assume that the environmental conditions observed in the past will remain the same in the future. However, climate change is influencing wildlife populations in many dynamic and uncertain ways, leading to a situation in which our observations of the past are poor predictors of the future. If we continue to use the existing framework to set waterfowl hunting regulations without accounting for climate change, there is the potential for under- or over-harvesting which would negatively affect waterfowl populations and hunters across North America.

This project laid the theoretical groundwork for incorporating climate change projections into the current adaptive harvest management frameworks used to set U.S. hunting regulations for North American waterfowl. We developed an optimization tool that allowed us to evaluate the potential costs of continuing to use existing models to inform hunting regulations despite evidence of climate change effects on populations. We are finalizing an analysis of the properties of a policy that accounts for climate change, which will determine the net benefits of implementing such a policy. Once this analysis is complete, we will produce a guidance document that summarizes our current knowledge about the effects of climate change on waterfowl populations, and the steps needed to implement a policy. This work directly supports the U.S. Fish and Wildlife Service in their role setting hunting regulations, ensuring sustainable harvest opportunities of these public trust species.

SECTION 3. PROJECT SUMMARY:

With the current project, we aimed to advance our understanding of natural resource management under non-stationarity, particularly within the context of waterfowl hunting regulations. There are many forms of ecological non-stationarity, but in this context we focus mainly on changes in demographic rates from their historical averages due to shifts in the environment due to climate change. We developed theoretical and applied analyses of optimal time-dependent management of waterfowl harvest in a changing system. We addressed this problem by first developing optimization methods for time-dependent problems, and studying the behavior of time-dependent optimal management. Next, we turned to the applied problem of adaptive harvest management of mallard duck (*Anas platyrhynchos*) under climate change. We developed several projected futures for duck breeding habitat in the Canadian Prairie Pothole Region (PPR) under climate change and employed these in an analysis of the value of climate information for waterfowl harvest. We found that in theory, optimal time-dependent management can be anticipatory and applying such management can provide benefits in a rapidly changing system. We also found that breeding pond habitat sensitivity to climate is a key driver of habitat futures in the Canadian PPR. Our analysis of the value of climate information is ongoing. Throughout, we communicated plans, co-developed methods, and shared findings with our management partners at U.S. Fish and Wildlife Service (USFWS) and to the broader harvest management community. We conclude by recommending further study of the properties of time-dependent management for species with varying demography and management systems with lower monitoring and updating frequencies than the yearly updates used in mallard adaptive harvest management (AHM).

SECTION 4. REPORT BODY:

Purpose and Objectives:

We aimed to further understanding of natural resource management under non-stationarity, particularly within the context of waterfowl hunting regulations established by the United States Fish and Wildlife Service (FWS) under the Migratory Bird Treaty Act of 1918 (16 U.S.C. § 703-712). The project had three objectives: (1) develop a prototype optimization tool that incorporates non-stationarity, (2) use this approach to evaluate the properties of time-dependent harvest strategies explicitly derived under system change, (3) work closely with FWS and other partners to address policy issues relevant to longstanding stakeholder concerns that are critical to current decision frameworks.

During the project, we accomplished the following: (1) established a theoretical framework for informing dynamic decisions in the face of climate change, (2) used the framework to evaluate strategies for decision making in the face of global change, and (3) communicated to USFWS, the Migratory Bird Program Administrative Flyway Councils, and the Harvest Management Working Group[1] about the applicability of our work to their management concerns.

This project is an initial step in a long process of accounting for non-stationarity in management decisions. This effort is deeply relevant to our current moment but still largely lacking from current applications in natural resource management.

Organization and Approach:

Developing understanding of nonstationary dynamics in a harvested population

We began the first phase of the project by studying time-dependent optimal management in a theoretical harvest model. The demography of the harvest population was structured as a discrete-logistic growth model, with parameters chosen to roughly approximate mallard duck (*Anas platyrhynchos*) demography.

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[1] A working group composed of representatives from USFWS, USGS, the Canadian Wildlife Service, and the Flyway Councils that was established in 1992 to review the science and practice of managing waterfowl harvests in the U.S. and Canada.

We specified scenarios for system change in the parameters for growth rate *r* and carrying capacity *K*. To produce optimal time-dependent policies we used a backward-iteration stochastic dynamic program (SDP) with specified discount rate, over a 50-year period of change in demographic parameters. To solve the full SDP, we specified values for the population size at year 50 using a value iteration into the future from year 50 onward, at a discount rate consistent with that used during the transient SDP. For a variety of scenarios of system change, we then computed optimal policies and used replicate forward simulations to examine the effects on the cost of applying a stationary harvest policy to the non-stationary system. Also using forward simulations, we projected the population size in the final year of system change and compared it with the optimal population size (to achieve maximum sustained yield).

A framework to understand the value of climate information given uncertainty

We began the second phase of the project by developing a framework to compute the value of adopting a time-dependent management strategy. The methods developed in this first phase of the project (Tucker & Runge 2021) produce optimal time-dependent management strategies and simulations to directly evaluate the cost of being wrong in the units of the management objective (here, number of ducks harvested). This work set the stage to develop a framework for computing the value of climate information for harvest management.

The value of climate information is an application of value of information (VoI) analysis. Value of information is a well-established tool, used in resource management to assess whether additional data can improve management outcomes (Runge *et al.* 2011; Canessa *et al.* 2015). An important component of VoI analyses is assessing the expected value of perfect information (EVPI), which involves analyzing which actions would be best if perfect information was available to inform questions about whether additional information is useful for management goals. We developed code to compute the value of climate information by finding the optimal time-dependent harvest policy under several different climate change scenarios.

In our framework, a decision-maker acts according to their believed scenario of system change (action a) in a world where the true system change (the state of world s) produces the outcome ($U_{a,s}$ the utility) of the management action. For this decision-maker facing a choice among many potential models s ∈ S (s is for state of the world, S is the set of all possible states considered in the analysis), the EVPI is calculated as the difference between outcomes for a utility-maximizing decision-maker acting with certainty versus acting under uncertainty,

$$EVPI = \mathbb{E}_{s \in S} \max_{a \in A} U_{a,s} - \max_{a \in A} E_{s \in S} U_{a,s},$$

where $U_{a,s}$ is the utility or outcome of taking action a given state of world s (Runge *et al.* 2011). In practice, we compute optimal time-dependent strategies for each scenario of system change (s ∈ S) and examine the outcomes using forward simulations for situations where the actions (a ∈ A) may differ from or match the true state of the world. In other words, we calculate the value, in terms of number of ducks harvested, of knowing the climate future with certainty. We use the forward simulations to estimate the cost of incorrectly assuming that the system is not changing.

As we built this framework, we used it in two ways. First, we focused on the choice of whether to apply a stationary management model or apply a time dependent model. This work shed light on the properties of time-dependent harvest policy in a theoretical context (Tucker & Runge 2021). We examined the *cost of being wrong* in a changing system. Within the context of theoretical models of system change, we simulated outcomes of forward projections in which either the optimal policy or a stationary policy is applied. We examined how these outcomes varied with the nature and degree of system change (Tucker & Runge 2021). We also computed a related quantity, the *benefits of being correct* and using these two inputs quantified the *net benefits of adopting a time-dependent policy* as a function of the nature and degree of theoretical system change.

Second, we focused on the value of information on system change within the context of time-dependent harvest policy. We computed the EVPI for information on system change, which elucidates the value of reducing uncertainty about the system change scenario. EVPI also requires calculating the optimal time-dependent policy with uncertainty ($\max_{a \in A} E_{s \in S} U_{a,s}$). This quantity also allows us to calculate the *expected regret* for adopting a policy other than the optimal time-dependent strategy with uncertainty, including the regret from maintaining status quo stationary management.

This quantity is subtly different than the cost of being wrong calculated previously—it is an expectation rather than a point estimate based on the nature and degree of system change.

Application to North American Waterfowl Management

In the third phase of the project, we proceeded to develop applications of time-dependent management to waterfowl harvest management in North America. These efforts were conducted with the goal of aiding the FWS in evaluating whether adopting a time-dependent strategy for North American waterfowl would be effective in achieving program goals. To achieve this, we devoted major effort to analyzing the potential value of time-dependent management to adaptive harvest management (AHM) of mid-continent mallards (*Anas platyrhynchos*). We also devoted some effort to Atlantic Population (AP) Canada goose (*Branta canadensis*) (U.S. Fish and Wildlife Service 2007), a population where time dependent management might be relevant, but which currently is not managed using AHM.

Adaptive Harvest Management (AHM) of mid-continent mallard

We began with application to mid-continent mallard AHM due to its national importance. As the longest running AHM program (Johnson et al. 1997), this stock set FWS harvest regulations in the Central and Mississippi Flyways[2].

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[2] The Central Flyway consists of the states of Montana, Wyoming, Colorado, New Mexico, Texas, Oklahoma, Kansas, Nebraska, South Dakota, and North Dakota, and the Canadian provinces of Alberta, Saskatchewan, and the Northwest Territories. The Mississippi Flyway consists of the states of Alabama, Arkansas, Indiana, Illinois, Iowa, Kentucky, Louisiana, Michigan, Minnesota, Mississippi, Missouri, Ohio, Tennessee, and Wisconsin, and the Canadian provinces of Saskatchewan, Manitoba, and Ontario.

The overall goal of our application to mid-continent mallard AHM was to use our framework to answer the applied question for waterfowl harvest: Under current climate forecasts, how much do we expect to gain from switching to a time-dependent management protocol? The answer to this question arises from applying value of information analysis to mid-continent mallard (MCM).

Developing a time-dependent AHM decision process

We developed a time-dependent version of the current decision model underlying MCM AHM.

As a starting point, we used the current AHM process (U.S. Fish and Wildlife Service 2021b). This decision model includes two state variables (U.S. Fish and Wildlife Service 2021b): mallard breeding population (BPOP) and breeding ponds for the Canadian portion of the Prairie Pothole region (PPR). Both state variables are monitored annually during the Waterfowl Breeding Population and Habitat Survey (WBPHS) conducted by the FWS. Currently, AHM for MCM uses an auto-regressive, stationary model for pond dynamics. AHM also uses several candidate models for duck demography, with different weights assigned to each and annual model weight updating.

Building on the Tucker & Runge (2021) approach, we developed a time-dependent version of AHM. Instead of directly changing growth rate and carrying capacity, as in the theoretical work, we used a more mechanistic approach to model system change. Future change to the Prairie Pothole region in which mallards breed will involve changes in pond dynamics (Zhao *et al.* 2016, 2018, 2019b). Because AHM uses ponds as a state variable, which influences duck reproductive rate, changes in pond dynamics are conceptually similar to the changes to vital rates contemplated in Tucker & Runge (2021). Like the current AHM model, our approach specifies an optimal policy as a choice of regulatory package (closed, restrictive, moderate, liberal) that depends on ponds and breeding population. Unlike the current AHM, the optimal policy also depends on the year.

For our time-dependent implementation, we developed decision optimization code in R to implement the existing decision optimization underlying AHM (U.S. Fish and Wildlife Service 2021b) but that accommodates a non-stationary pond model that depends on climate conditions. We then incorporated this code into the Tucker & Runge (2021) framework for time-dependent optimization, which accommodates a period of future non-stationarity by computing the value of system states at the end of this period, and then using backward iteration to find optimal time-dependent decisions from present day to the end of the period of non-stationarity. As described below, climate projections cover the future to 2100 so we evaluated optimal time-dependent policies up to 2100.Our approach allows specifying a discount rate, by which the value of future harvest is discounted both during the time-dependent phase and into the future after 2100.

Projections of habitat futures in the Prairie Pothole Region

Applying the time-dependent AHM process required developing projections of future ponds in the Canadian prairies. We built on previous work by collaborator (Q. Zhao) that linked climate projections to demographics of MCM (Zhao *et al.* 2016, 2018, 2019b), by developing state-space models of pond number dynamics as influenced by a set of environmental covariates.

We used two gridded datasets to derive data on historical climate observations and climate projections, for the Canadian PPR. We assembled historical data on climate observations in the Canadian PPR, using a gridded dataset of meteorological observations (Livneh *et al.* 2015). These observations were selected because they serve as the training dataset for the localized constructed analogs (LOCA) downscaling of climate projections (Pierce *et al.* 2014) for coupled model intercomparison project 5 (CMIP5) (Pierce *et al.* 2014). We selected this product because it was the only established peer reviewed downscaled product that was available in 2021 with spatial coverage that overlapped the Canadian PPR.

We obtained data on May breeding ponds from the WBPHS for the survey strata corresponding to the Canadian PPR. Pond data prior to 1961 were omitted due to data reliability issues and changes in survey procedures in the Canadian PPR (U.S. Fish and Wildlife Service 2021b).

We built a predictive model for May breeding ponds based on climate and past year ponds as a predictor variable. To do so, we built a state-space model that predicts ponds in the next year based on current ponds and covariates that reflect recent precipitation, temperature, and regional dryness. We included covariates for the mean maximum Spring temperature (March to May), cumulative precipitation (January to April), and a drought index reflecting multi-year water balance. The temperature and cumulative precipitation covariates were selected based on a brief model selection exercise and were in line previous work that linked climate projections to demographics of MCM via breeding pond habitat (Zhao *et al.* 2016, 2018, 2019b) as well as prior research on the regional climate (Ballard *et al.* 2013; Sofaer *et al.* 2016). As a drought index, we used the May 18-month Standardized Precipitation Evapotranspiration Index (SPEI (Vicente-Serrano *et al.* 2010). At 18-month scale, SPEI characterizes as similar degree of multi-year drought to the Palmer Drought Severity Index (PDSI) (Vicente-Serrano *et al.* 2010). Previously, PDSI has been used as an effective predictor of pond dynamics in the PPR (Ballard *et al.* 2013).

Applying value of climate information framework to mallard AHM

We considered three sources of uncertainty related to future change in this system (Fig. 1): 1) potential changes in the effects of precipitation and temperature variables on the number of breeding ponds (habitat response), 2) predictions of future climate conditions under different emissions scenarios, and 3) the emission scenario most likely to be realized (climate futures). We applied our value of climate information framework to mid-continent mallard AHM in two steps. In the first step, we combined uncertainty in climate futures with uncertainty in habitat response to generate four possible habitat futures for the Canadian PPR (Fig. 1). Uncertainty in climate future was included by using two emissions scenarios, Representative Concentration Pathways (RCPs) 4.5 and 8.5 from CMIP5. To characterize uncertainty in pond response to climate we used the posterior of our fitted model for pond futures to generate two scenarios that bracket the pond response: *max_sensitivity*, where climate covariates have a strong influence on ponds, and *min_sensitivity*, where climate covariates have a weak influence on ponds.

The combination of two emission scenarios with two bracketing pond response models yielded four habitat futures. For each of these we produced ensemble mean projections of the number of breeding ponds in the Canadian PPR for in each year to 2100, which accounted for uncertainty in realized climate conditions.

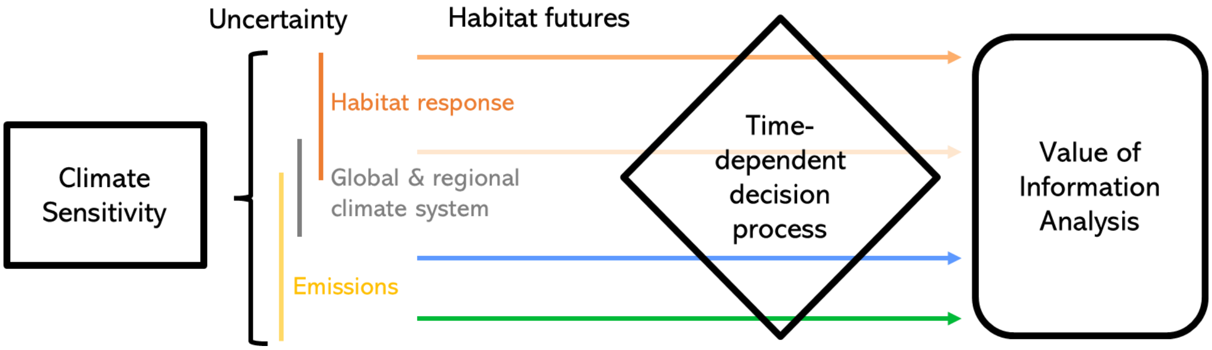

Fig. 1 *Framework for value of climate information analysis for this study. Uncertainty in emissions, global and regional climate system response to emissions, and habitat response to climate is combined to generate habitat futures. These are fed into a time-dependent decision process optimization to derive optimal time-dependent policies. Using simulations under varying assumptions about the true state of the world combined with optimal time-dependent policies, the value of climate information is quantified. Our analysis of mid-continent mallard (*Anas platyrhynchos*) adaptive harvest management generated four habitat futures based on emissions scenarios from the Coupled Model Intercomparison Project 5 (CMIP5) for Representative Concentration Pathways (RCPs 4.5 or 8.5) and two potential habitat responses to climate (maximum habitat sensitivity or minimum habitat sensitivity). Uncertainty in the global and regional climate system response was integrated via use of ensemble mean climate projections under each emissions scenario.*

In the second step, we used our time-dependent AHM decision model to derive the optimal time-dependent policy for each habitat future. For each of these policies, we assume that both the effect of climate on ponds and the emissions scenarios are known with certainty, and the key source of uncertainty is due to ensemble model predictions of precipitation and temperature. For each habitat future, we then used replicate forward simulations (*n=50*) to examine outcomes for management (a) according to the optimal policy generated by time-dependent AHM for the given habitat future (i.e, applying the time-dependent policy that matches the true system state), (b) according to time-dependent policies for other futures (i.e, applying time-dependent policies derived for the other three habitat futures), and (c) according to status quo, stationary management (time-independent). We performed this exercise for a variety of discount rates, in response to management partner and stakeholder interest in the effect of discounting in this system. Our focal outcome was the net present value of cumulative future harvest in perpetuity. We also examined other outcomes of the simulated policies. These included outcomes relating to duck harvest and population size: average total annual harvest, and the average breeding population from present to 2100. We also examined policy outcomes of interest to key stakeholders, which included: the frequency of regulatory changes between years from present to 2100, and the frequency with which various regulatory packages (i.e., closed, restrictive, moderate, liberal) would be recommended from present to 2100.

Based on projections of outcomes we calculated a variety of quantities related to the value of climate information. These included the EVPI for using climate information in time-dependent management, as well as the expected regret from maintain status quo management in a non-stationary system. We calculated each of these quantities for the main program objective, net present value of cumulative future harvest and as a function of several assumed discount rates.

Atlantic Population Canada Goose

During the project, we also began to explore the prospects of time-dependent management for Atlantic Population (AP) Canada Goose. AP geese are a stock of Canada goose that winter in Eastern North America and breed in the Ungava Peninsula (60.405286, -73.959433) , Quebec, Canada (Hauser *et al.* 2007). AP geese are not currently managed in an AHM process, in part because their population age-structure and delayed maturity which may result in "population momentum", raising a challenge for AHM (U.S. Fish and Wildlife Service 2007). However, these same factors mean that AP geese may potentially benefit from time-dependent management approaches. Exploring this possibility is important because breeding success of AP geese appears to be highly sensitivity to environmental conditions, namely snow and ice, on the breeding grounds in Ungava Peninsula (Sheaffer & Malecki 1996). These conditions will likely change over the near term with climate change, but the nature of future change is uncertain (Mudryk *et al.* 2020). We engaged with FWS (J. Dooley, Goose Specialist) to evaluate prospects for applying time-dependent management models to AP geese. We outlined a model to evaluate the general question of whether anticipatory, time-dependent management could benefit AP geese, or other age-structured populations.

Engagement with management partners and stakeholders

Throughout the project, we engaged with partners at the FWS and with stakeholders through the Harvest Management Working Group (HMWG). This working group is composed of representatives from USFWS, USGS, the Canadian Wildlife Service, and the Flyway Councils, and was established in 1992 to review the science and practice of managing waterfowl harvests in the U.S. and Canada (U.S. Fish and Wildlife Service 2021a). These interactions included sharing plans, describing theoretical results, sharing preliminary results from applications to North American waterfowl AHM and discussing next steps. This coproduction work has been crucial for the development of this project. Interactions with partners and stakeholders are described in detail below in the “Stakeholder Engagement” section.

Project Results, Analysis, and Findings:

Theory results

We found the *net benefits of adopting a time-dependent policy* were highest with strong change in growth rate (r) or carrying capacity (K) (Fig. 2; also see Figure 3 of Tucker & Runge (2021)) as a function of the nature and degree of theoretical system change. We also found that the system state in final year was closer to optimal population size at maximum sustained yield (MSY; Fig. 3).

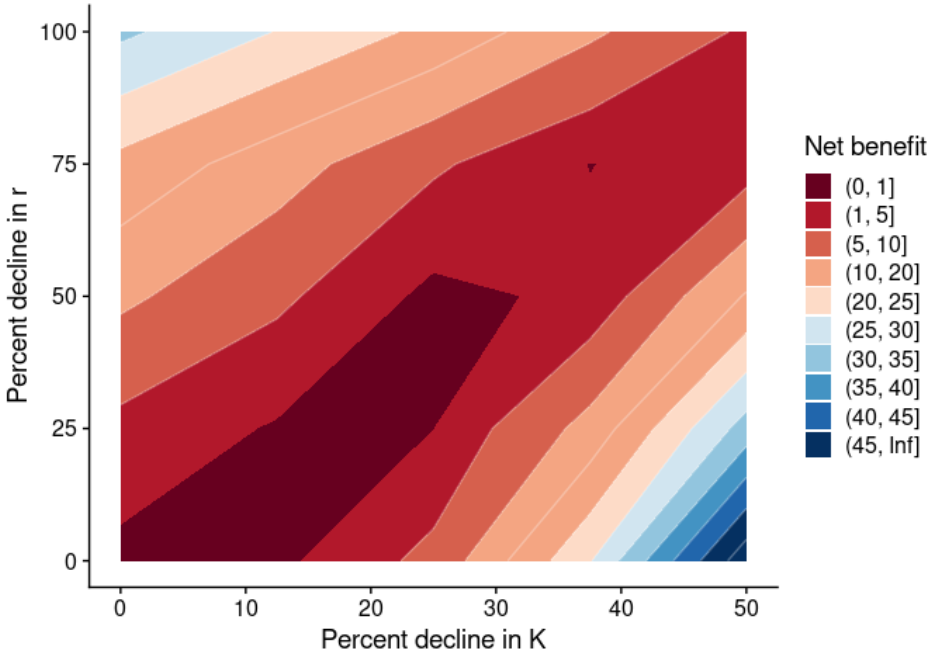

Fig. 2 *Effects of changes in growth rate* (r) *and carrying capacity* (K) *on the net benefit of applying time-dependent management vs stationary management to a changing system based on this report. Compare with Figure 3 of* Tucker & Runge (2021) *which separates the cost during the transient period and in terms of the (undiscounted) final value after the 50-year period of system change.*

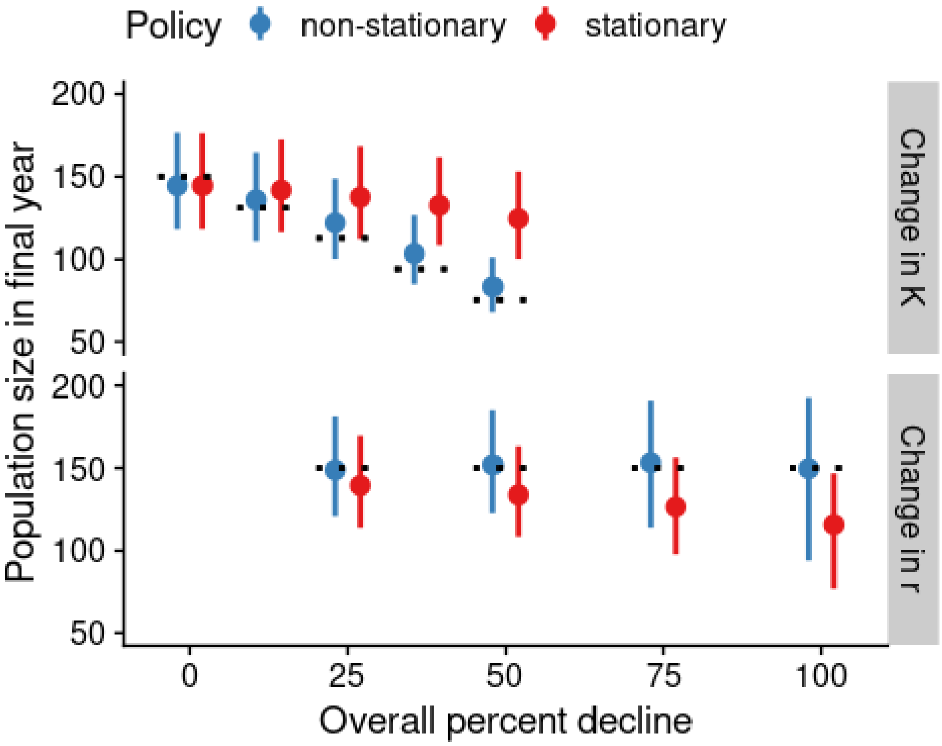

Fig. 3 *Final population sizes from forward simulations under non-stationary system dynamics with either time-dependent optimal policy (blue), computed with knowledge of non-stationary dynamics or stationary policy (red), which assumes incorrect stationary dynamics. Dotted line is N*= K/2 the optimal population size at equilibrium under MSY. Adapted from Figure 4 of* Tucker & Runge (2021) .

Pond futures in the Canadian PPR

We produced high temporal resolution projections of future climate for the Canadian PPR (Fig. 4), for the covariates of interest in our pond model. For these projections, climate model hindcasts match past covariates. As Sofaer *et al.* (2017) point out, because downscaled models are bias corrected but not for the particular statistics we examine here (which include, e.g., areal averages of summed variables) differences between past observations and hindcasts can be large. Comparing the hindcasts to observations (Fig. 4) suggests that the ensemble of CMIP5 general circulation models (GCMs) fits these historical covariate patterns in the Canadian PPR rather well. We additionally examined bivariate plots showing the correlation between each of our covariates, which also confirmed a reasonable fit of the hindcast to the observations (not shown).

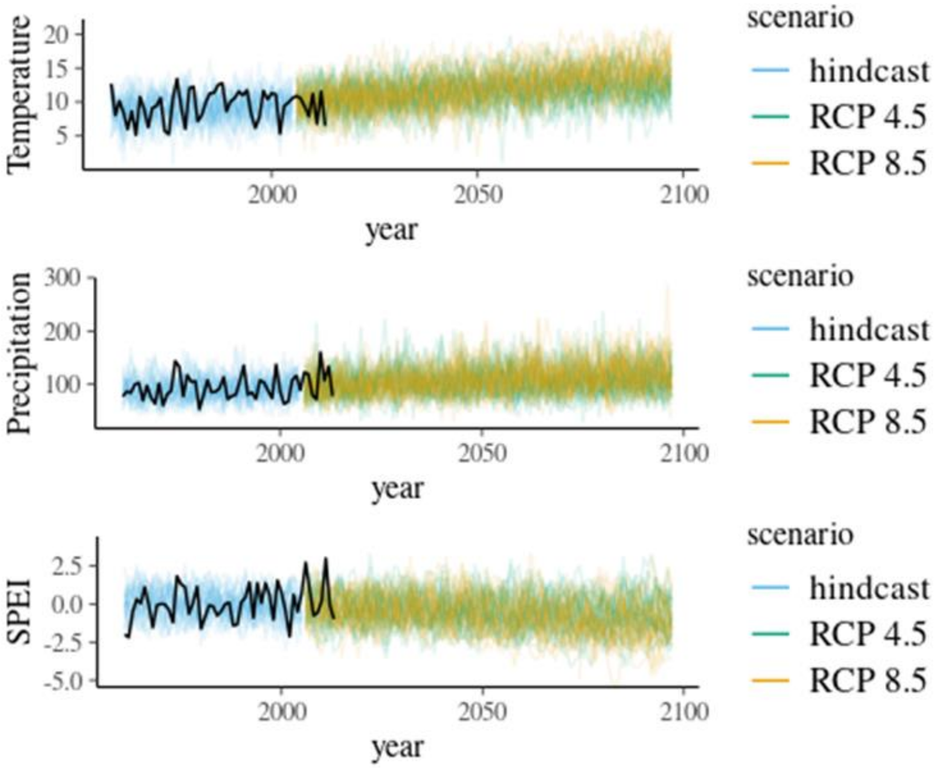

Fig. 4 *Environmental covariates included in our pond model for the Canadian Prairie Pothole Region (PPR). Covariates included are the mean daily maximum temperature for March to May, the cumulative precipitation for January to April, and the 18-month Standardized Precipitation Evapotranspiration Index (SPEI). Plots include observations (thick black line) from* (Livneh *et al.* 2015)*. Also shown are hindcasts or projections for Representative Concentration Pathways (RCPs) 4.5 or 8.5 from Coupled Model Intercomparison Project 5 (CMIP5). Each thin colored line corresponds to an individual general circulation model (GCM) included in CMIP5 (thin colored lines).*

Our projections of habitat futures for the Canadian PPR (Fig. 5) illustrate that potential futures for the region vary widely within the envelope of climate and pond response uncertainty. When using the ensemble mean projection from the GCMs included in CMIP5 to project climate covariates, the major driver of future habitat is the pond response to climate (i.e., the choice of *max_sensitivity* vs *min_sensitivity* pond model).

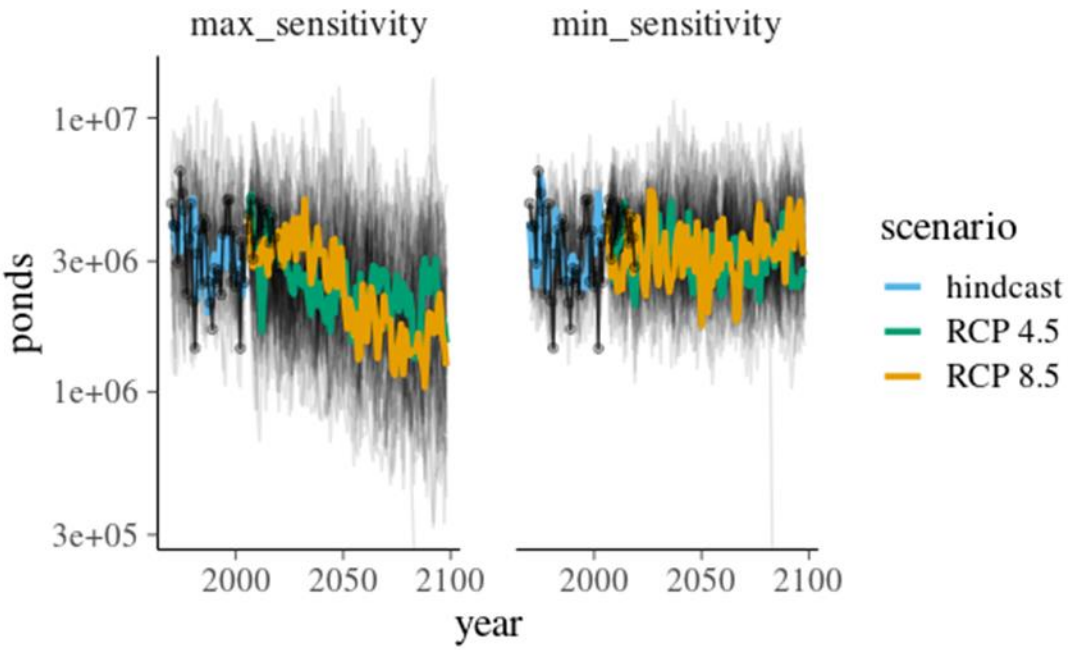

Fig. 5 *Trajectories of pond counts per year under observed data (dots), predicted ponds from fit to observed data (thick solid black line), and projections using our pond model from general circulation model (GCM) hindcasts or projections under Coupled Model Intercomparison Project 5 (CMIP5) for Representative Concentration Pathways (RCPs) 4.5 or 8.5 (colored lines) for two scenarios of pond response to climate (*max_sensitivity *and* min_sensitivity). *Thin black lines show projections and hindcasts for individual GCMs included in CMIP5.*

Value of climate information for waterfowl harvest management

During the project we developed preliminary results for the value of climate information for waterfowl management and shared these with partners and stakeholders. However, the information we shared was preliminary and is subject to revision. It was provided to meet the need for timely best science. The information was provided on the condition that neither the U.S. Geological Survey nor the U.S. Government shall be held liable for any damages resulting from the authorized or unauthorized use of the information. Given the conditions under which preliminary results were shared it is inappropriate to include results here. Work is ongoing to finalize these results, and share them in due course through publication in a peer-reviewed journal.

Conclusions:

This project addressed questions of how to optimally manage natural resource under system change. This addresses priority needs of the FWS (U.S. Fish and Wildlife Service 2021a), reflecting a recognition that natural resource management policies that assume stationarity are sub-optimal at best and detrimental at worst (Milly *et al.* 2008; Nichols *et al.* 2011). The findings of this project have already advanced the state of knowledge nationally, regarding methods for time-dependent optimal harvest and behavior of such policies (Tucker & Runge 2021).

During this project we developed theoretical work showing that time-dependent policies can account for and, indeed, anticipate, changes in underlying demographic parameters of a harvested population. We used those results to characterize the cost of managing under the status quo assumption of stationarity in a non-stationary system—we examined how that cost varied as a function of the nature and degree of system change. This work demonstrated that greatest benefits to adopting time dependent harvest policies occur in strongly changing systems (i.e., systems that will experience strong declines in growth rate or carrying capacity in the future). We also examined the value of climate information for the objectives for mallard harvest management, focusing on AHM of mid-continent mallard.

Findings from our project are relevant across the nation. For example, in the Atlantic Flyway[3], regulations are set based on a suite of species for which demographic models do not currently exist. The theoretical simulation work conducted in this project provides a basis to develop guidance for the best practices to address non-stationarity in the absence of mechanistic models explicitly linking demographics to climate change.

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[3] The Atlantic Flyway consists of the states of Connecticut, Delaware, Florida, Georgia, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, North Carolina, Pennsylvania, Rhode Island, South Carolina, Vermont, Virginia, and West Virginia; the Canadian territory of Nunavut and provinces of Newfoundland, New Brunswick, Nova Scotia, Ontario, Prince Edward Island, and Quebec; plus the U.S. territories of Puerto Rico and U.S. Virgin Islands.

Developing such guidance is the natural next step of this project once the value of climate information analysis is completed. Such a guidance document will lay out the costs and benefits of incorporating time dependent policies into current AHM framework. It can also include guidance for further work needed, including steps for implementing time-dependent management if it is deemed cost-effective.

Two additional future directions arose in the project. First is the role of monitoring and policy updates. For example, an infrequently observed system or one with infrequent policy updates would behave much differently under time-dependent management than that studied here (Tucker & Runge 2021). It is very likely that the frequency of policy updates and monitoring play an important role in resolving uncertainty and responding to it.

Second is the effects for time-dependent management on varying life-history, demography and other potential drivers of differential species response to system change. A first step here is represented by our ongoing investigations to understand if time-dependent, anticipatory policy are advantageous for AP geese, or other age-structured populations. However, a great deal more research in this area is needed.

Finally, some tasks will not be completed as part of this project. The proposal originally envisioned work to develop an active adaptive management strategy, including a belief state, for time-dependent management to evaluate the interplay between learning, uncertainty, time horizons, and the discounting of future rewards. The project work certainly sets the stage for this task, which is theoretically interesting. However, because such a strategy may not be useful if the value of climate information is low, we did not prioritize developing one before we could finalize the value of information analysis for the applied setting of waterfowl AHM that is a key priority of our management partners.

Outreach and Products:

Through this project we have conducted major outreach to the scientific and management community to describe the need for management tools that address non-stationarity and highlight our work to address this gap. We led organization of a USGS Powell Center Working Group with participants from two countries, two universities, and three USGS Science Centers (including two USGS Climate Adaptation Science Centers). We also led organization of a symposium, accepted at the 2023 The Wildlife Society (TWS) Annual Meeting and sponsored by the Biometrics Working Group of TWS.

This project has produced two main scientific products. First a program written in R that allows users to input different values (e.g., types of non-stationarity, discount rate, time horizon) and evaluate optimal harvest strategies under projections of future change, with forward projections to understand effects on management outcomes. Second, a manuscript that employed this program code to examine time-dependent management of a harvested population under system change to describe the properties of optimal policies under certainty and characterize the cost of incorrectly assuming stationarity in a non-stationary system. These products are accessible to the management community: the program is published as USGS Software Release (Tucker & Runge 2023), the paper is published in The Wildlife Society's flagship journal *Journal of Wildlife Management* (Tucker & Runge 2021). This is a subscription journal, but access is included with membership in TWS, the largest society of wildlife management professionals in North America.

Three more products are in preparation. First, a synthetic paper describing time-dependent management for non-stationary systems for a general resource management audience and synthesizing methods and considerations in decision-making for non-stationary systems. Second, an applied paper framing current climate projections and waterfowl demographic models in the context of the simulation models to describe the costs of continuing to use a stationary policy and potential benefits to be gained from adopting a time-dependent strategy. Third, we are preparing an analysis of time-dependent management for AP Canada goose, an age-structured population.

Scientific Products

Published

- Tucker, A.M. & Runge, M.C. (2023) Optimal harvest of a theoretical population under climate change. USGS Software Release. https://doi.org/10.5066/P9GCJAVB.
- Tucker, A.M. & Runge, M.C. (2021). Optimal Strategies for Managing Wildlife Harvest Under System Change. *The Journal of Wildlife Management*, 85, 847–854.

In preparation

- Tucker, A. M., J. Ashander, R. E. W. Berl, J. Reimer, M. Runge, *et al.* Natural resource management under global change: Time-dependent decisions for non-stationary systems. *Manuscript in revision after review at* Nature Sustainability.
- Ashander. J., R. E. W. Berl, G. S. Boomer, P. Devers, J. E. Lyons, T. L. Morelli, M. C. Runge. A. Terando, A. M. Tucker, Q. Zhao. Managing Waterfowl Harvest Under Climate Change: Assessing the Value of Information About Future Climate for Time-dependent Optimal Management.
- Ashander, J., A. M. Tucker, J. L. Dooley, P. K. Devers, M. C. Runge. Optimal management of wildlife harvest under climate change: The influence of age-structure.

Scientific Presentations

- Tucker, A.M. and M.C. Runge. 2021. Optimal strategies for managing wildlife harvest under system change. The Wildlife Society Annual Conference. Virtual.
- Tucker, A.M., M.C. Runge, and J.D. Ashander. October 2021. Dynamic management strategies for non-stationary systems. Northeast CASC Climate Adaptation Science Symposium, Linking Science and Management Workshop. Virtual.
- Runge, M.C., A.M. Tucker, and J. Ashander. Managing waterfowl harvest under climate change: Time-dependent optimal policies to address non-stationary dynamics. Northeast and Southeast Climate Adaptation Science Centers Webinar, Dec. 1, 2021. Virtual.
- Ashander. J., M. C. Runge. A. M. Tucker. Managing an integrated socio-environmental system under non-stationary environmental change: Assessing the value of forecasts for time-dependent optimal policy. Ecological Forecasting Initiative Virtual Conference, May 23-25, 2022, Virtual.
- Ashander. J., R. E. W. Berl, G. S. Boomer, P. Devers, J. E. Lyons, T. L. Morelli, M. C. Runge. A. Terando, A. M. Tucker, Q. Zhao. Managing Waterfowl Harvest Under Climate Change: Assessing the Value of Information About Future Climate for Time-dependent Optimal Management. Accepted by The Wildlife Society Annual Meeting, November 6-10, 2022. Spokane, WA

Accepted

- Ashander. J., R. E. W. Berl, G. S. Boomer, P. Devers, J. E. Lyons, T. L. Morelli, M. C. Runge. A. Terando, A. M. Tucker, Q. Zhao. Future climate change and management of waterfowl harvest in North America. Accepted by The Wildlife Society Annual Meeting, November 2023. Louisville, KY.
- Devers et al Communicating the challenges and tools for addressing natural resource conservation in the face of system change. Accepted by The Wildlife Society Annual Meeting, November 2023. Louisville, KY.
- Berl, R. E.W., Patrick K. Devers, G. Scott Boomer, Jaime Ashander, Anna M. Tucker, Michael C. Runge Implications of social non-stationarity and changing hunter behaviors for waterfowl harvest. Accepted by The Wildlife Society Annual Meeting, November 2023. Louisville, KY.

- Tucker, A. M., J. Ashander, R. E. W. Berl, J. Reimer, M. Runge, *et al.* Time-dependent wildlife management for a non-stationary world. Accepted by The Wildlife Society Annual Meeting, November 2023, Lousville, KY.

Other Outreach

Postdoc (A.M. Tucker) the Investigator (M. Runge) and Collaborators (P.K. Devers, G.S. Boomer; FWS) (J.E. Lyons, USGS) led a successful proposal to the USGS Powell Center for a Working Group, "Markov decision processes in non-autonomous socio-ecological systems" which began in 2020. Postdoc co-led the group including regular group-wide updates, meeting organization and facilitation, and logistics for travel and meeting timing with the Powell Center. Starting in Fall 2021 postdoc (J. Ashander) joined the project and co-led Powell Center Working Group as well. Group activities included:

- October 2020: Virtual Powell Center introductory call and member lightning talks: 10/19/20 - 12/4/20
- February 2021: Virtual Powell Center four-day workshop, 2/8/21 - 2/11/21
- September 2021: Virtual Powell Center four-day workshop, 09-13 to 09-16
- February 2022: Virtual Powell Center four-day workshop, 02-07 to 02-10
- September 2022: In-person Powell Center five-day workshop, 09-26 to 09-30
- June 2023: Virtual Powell Center four-day workshop, 06-12 to 06-15
- April 2024: Upcoming in-person Powell Center five-day workshop, 04-08 to 04-12.

Postdocs (J. Ashander; A.M. Tucker) led organization of accepted symposium for 2023 TWS meeting, "Time-dependent wildlife management for a non-stationary world". Invited panelists represent multiple perspectives (DOI science agencies, DOI management agencies, the cooperative research unit of the USGS which works with state agencies) as well as two speakers describing academic work conducted in partnership with state agencies (Washington DFW) or local NGOs (community land trusts). Speakers include project partners (P.K. Devers, FWS).

Stakeholder Engagement:

This project was tailored to address priority needs of the FWS, which has identified “time-dependent optimal solutions to address system change” as a very important long-range priority (U.S. Fish and Wildlife Service 2021a). The project was developed in collaboration with the FWS Division of Migratory Bird Management to directly address their questions and concerns about climate change effects on waterfowl harvest. Key persons in the development and implementation of the AHM plan (P. Devers and G.S. Boomer) were collaborators on this project. We included them from the inception of the research project to ensure early and constant feedback with the Flyways and Harvest Management Working Group about the applicability of our work to their management concerns.

Because the project planning and execution directly involved decision-makers at the US FWS (G. S. Boomer, P. K. Devers), the project included frequent, at least monthly communications with these partners throughout the project. For further feedback and review we engaged with the Harvest Management Working Group. We also engaged with the Goose Technical Committee of the Atlantic Flyway.

FWS and the Harvest Management Working Group

The two key partners in this project were the USGS Eastern Ecological Science Center (EESC) and the USFWS Division of Migratory Bird Management. This project built upon 25 years of applied research in support of adaptive management decision frameworks that have informed U.S. waterfowl harvest regulations while accumulating knowledge about and increasing our understanding of North American waterfowl population dynamics (Nichols *et al.* 2019).

Due to the relevance to existing AHM decision frameworks, we relied on the Harvest Management Working Group to review and provide feedback on model development and resulting decision analysis. The Harvest Management Working Group (HMWG) provides technical guidance to the FWS and Flyway Councils related to the development and implementation of waterfowl harvest strategies. Due to its mission and make up, the HMWG was well positioned to provide important guidance and feedback on each of element of this project.

Throughout the project, we invited input from key stakeholders via presentations to the HMWG at their annual December meetings. The first presentation detailed our initial thoughts and described a “proof of concept” model to demonstrate the effects of non-stationarity on harvest management, work which was later published (Tucker & Runge 2021). The second presentation explored how existing demographic models of waterfowl population dynamics could be used to link climate projections to population projections and will also address the potential costs of failing to adopt a time-dependent management policy. Sharing and discussing this work early in the development process was crucial for identifying whether additional more complex applications of the optimization envisioned in the proposal would be useful or not.

After a final report is delivered to the FWS providing guidance on implementation of a time-dependent strategy for North American waterfowl, we will continue to communicate with the Harvest Management Working Group to provide support and address further questions that arise.

Atlantic Flyway

To evaluate partner and stakeholder interest in the question of whether time-dependent, anticipatory policy are advantageous for Atlantic population (AP) geese, we engaged with the AP goose management community. We gave a presentation in February 2022 to the Goose Technical Committee of the Atlantic Flyway during the annual Flyway meeting. Subsequently, we engaged with FWS (J. Dooley, Goose Specialist) to evaluate prospects for applying time-dependent management models to AP geese. We presented an outline for an analysis of whether anticipatory, time-dependent management could benefit AP geese, or other age-structured populations to the Goose Technical Committee at the Atlantic Flyway meeting in February 2023 and received positive feedback.

Stakeholder engagement and communication

- Ashander, J., A. M. Tucker, P. Devers, J. L. Dooley, M. C. Runge. Climate Change and Managing Atlantic Population Canada Geese. Presentation to the CAGO Committee. Atlantic Flyway Meeting. Jekyll Island, GA (virtual presentation). February 29, 2023.
- Ashander, J., A.M. Tucker, M.C. Runge. Time-dependent optimal solutions to address system change. Harvest Management Working Group Annual Meeting. Pt. Aransas, Texas (virtual presentation). December 12, 2022.
- 2022-02-22: Ashander, J., A. M. Tucker, P. Devers, M. C. Runge. Climate Change and Managing Harvest of AP Geese. Presentation to the CAGO Committee. Atlantic Flyway Meeting. Newport, RI (virtual).
- 2021-12-07: Ashander, J., A.M. Tucker, M.C. Runge. Time-dependent optimal solutions to address system change. Harvest Management Working Group Annual Meeting (virtual).
- Runge, M. C., A. M. Tucker, J. Ashander. Managing Waterfowl Harvest under Climate Change: Time-Dependent Policies to Address Non-Stationary Dynamics. Northeast Climate Adaptation Science Center Webinar Series Co-sponsored by Southeast Climate Adaptation Science Center. Online 2021-12-01.

REFERENCES

Ballard, T., Seager, R., Smerdon, J.E., Cook, B.I., Ray, A.J., Rajagopalan, B., *et al.* (2013). Hydroclimate Variability and Change in the Prairie Pothole Region, the “Duck Factory” of North America. *Earth Interactions*, 18, 1–28.

Canessa, S., Guillera-Arroita, G., Lahoz-Monfort, J.J., Southwell, D.M., Armstrong, D.P., Chadès, I., *et al.* (2015). When do we need more data? A primer on calculating the value of information for applied ecologists. *Methods in Ecology and Evolution*, 6, 1219–1228.

Hauser, C.E., Runge, M.C., Cooch, E.G., Johnson, F.A. & Harvey, W.F. (2007). Optimal control of Atlantic population Canada geese. *Ecological Modelling*, 201, 27–36.

Livneh, B., Bohn, T.J., Pierce, D.W., Munoz-Arriola, F., Nijssen, B., Vose, R., *et al.* (2015). A spatially comprehensive, hydrometeorological data set for Mexico, the U.S., and Southern Canada 1950–2013. *Sci Data*, 2, 150042.

Milly, P.C.D., Betancourt, J., Falkenmark, M., Hirsch, R.M., Kundzewicz, Z.W., Lettenmaier, D.P., *et al.* (2008). Stationarity Is Dead: Whither Water Management? *Science*, 319, 573–574.

Mudryk, L., Santolaria-Otín, M., Krinner, G., Ménégoz, M., Derksen, C., Brutel-Vuilmet, C., *et al.* (2020). Historical Northern Hemisphere snow cover trends and projected changes in the CMIP6 multi-model ensemble. *The Cryosphere*, 14, 2495–2514.

Nichols, J.D., Kendall, W.L. & Boomer, G.S. (2019). Accumulating evidence in ecology: Once is not enough. *Ecology and Evolution*, 9, 13991–14004.

Nichols, J.D., Koneff, M.D., Heglund, P.J., Knutson, M.G., Seamans, M.E., Lyons, J.E., *et al.* (2011). Climate change, uncertainty, and natural resource management: Climate Change and Natural Resource Management. *The Journal of Wildlife Management*, 75, 6–18.

Pierce, D.W., Cayan, D.R. & Thrasher, B.L. (2014). Statistical Downscaling Using Localized Constructed Analogs (LOCA). *Journal of Hydrometeorology*, 15, 2558–2585.

Runge, M.C., Converse, S.J. & Lyons, J.E. (2011). Which uncertainty? Using expert elicitation and expected value of information to design an adaptive program. *Biological Conservation*, Adaptive management for biodiversity conservation in an uncertain world, 144, 1214–1223.

Sheaffer, S.E. & Malecki, R.A. (1996). Predicting Breeding Success of Atlantic Population Canada Geese from Meteorological Variables. *The Journal of Wildlife Management*, 60, 882–890.

Sofaer, H.R., Barsugli, J.J., Jarnevich, C.S., Abatzoglou, J.T., Talbert, M.K., Miller, B.W., *et al.* (2017). Designing ecological climate change impact assessments to reflect key climatic drivers. *Glob Change Biol*, 23, 2537–2553.

Sofaer, H.R., Skagen, S.K., Barsugli, J.J., Rashford, B.S., Reese, G.C., Hoeting, J.A., *et al.* (2016). Projected wetland densities under climate change: habitat loss but little geographic shift in conservation strategy. *Ecological Applications*, 26, 1677–1692.

Tucker, A.M. & Runge, M.C. (2021). Optimal Strategies for Managing Wildlife Harvest Under System Change. *The Journal of Wildlife Management*, 85, 847–854.

Tucker, A.M. & Runge, M.C. (2023). Optimal harvest of a theoretical population under climate change. USGS Software Release. https://doi.org/10.5066/P9GCJAVB

U.S. Fish and Wildlife Service. (2007). *Adaptive Harvest Management: 2008 Hunting Season*. U.S. Department of Interior, Washington, D.C.

U.S. Fish and Wildlife Service. (2021a). *2020 Harvest Management Working Group Meeting Report*. U.S. Department of Interior, Washington, D.C.

U.S. Fish and Wildlife Service. (2021b). *Adaptive Harvest Management 2022 Hunting Season*. U.S. Department of Interior, Washington, D.C.

Vicente-Serrano, S.M., Beguería, S. & López-Moreno, J.I. (2010). A Multiscalar Drought Index Sensitive to Global Warming: The Standardized Precipitation Evapotranspiration Index. *Journal of Climate*, 23, 1696–1718.