USGS
science for a changing world

Ecological Forecasting—21st Century Science for 21st Century Management

Open-File Report 2020–1073

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

Ecological Forecasting—21st Century Science for 21st Century Management

By John B. Bradford, Jake F. Weltzin, Molly McCormick, Jill Baron, Zack Bowen, Sky Bristol, Daren Carlisle, Theresa Crimmins, Paul Cross, Joe DeVivo, Mike Dietze, Mary Freeman, Jason Goldberg, Mevin Hooten, Leslie Hsu, Karen Jenni, Jennifer Keisman, Jonathan Kennen, Kathy Lee, David Lesmes, Keith Loftin, Brian W. Miller, Peter Murdoch, Jana Newman, Karen L. Prentice, Imtiaz Rangwala, Jordan Read, Jennifer Sieracki, Helen Sofaer, Steve Thur, Gordon Toevs, Francisco Werner, C. LeAnn White, Timothy White, and Mark Wiltermuth

Open-File Report 2020–1073

U.S. Department of the Interior
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:
Bradford, J.B., Weltzin, J.F., McCormick, M., Baron, J., Bowen, Z., Bristol, S., Carlisle, D., Crimmins, T., Cross, P., DeVivo, J., Dietze, M., Freeman, M., Goldberg, J., Hooten, M., Hsu, L., Jenni, K., Keisman, J., Kennen, J., Lee, K., Lesmes, D., Loftin, K., Miller, B.W., Murdoch, P., Newman, J., Prentice, K.L., Rangwala, I., Read, J., Sieracki, J., Sofaer, H., Thur, S., Toevs, G., Werner, F., White, C.L., White, T., and Wiltermuth, M., 2020, Ecological forecasting—21st century science for 21st century management: U.S. Geological Survey Open-File Report 2020–1073, 54 p., https://doi.org/10.3133/ofr20201073.

ISSN 2331-1258 (online)

Acknowledgments

This workshop was enabled by financial support from the USGS Ecosystems Mission Area and logistical support from the USGS John Wesley Powell Center for Analysis and Synthesis. In addition, we appreciate the engagement, enthusiasm, and participant support provided by our partner agencies and the USGS Executive Leadership Team. The findings and conclusions in this report are those of the author(s) and do not necessarily represent the views of the U.S. Fish and Wildlife Service.

Contents

Tables

Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
yard (yd)	0.9144	meter (m)

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
meter (m)	1.094	yard (yd)

Abbreviations

AIM	assessment, inventory, and monitoring
BISON	Biodiversity Information Serving Our Nation
BLM	Bureau of Land Management
BOEM	Bureau of Ocean Energy Management
BOR	Bureau of Reclamation
COAWST	Coupled Ocean Atmosphere–Wave–Sediment Transport model
CSS	Core Science Systems (USGS)
CWD	Chronic Wasting Disease
DOI	Department of the Interior
EDDMapS	Early Detection and Distribution Mapping System
EDRR	Early Detection and Rapid Response
EF	ecological forecasting
ELT	Executive Leadership Team (USGS)
EPA	U.S. Environmental Protection Agency
FIA	Forest Inventory and Analysis Program
FS	U.S. Department of Agriculture Forest Service
FTE	full-time employee
FWS	U.S. Fish and Wildlife Service
FY	fiscal year
GS	General Schedule
INHABIT	Invasive Species Habitat Tool
IWP	Integrated Water Prediction Program
LiDAR	light detection and ranging
NASA	National Aeronautics and Space Administration
NGO	nongovernmental organization
NISIMS	National Invasive Species Information Management System
NMFS	National Marine Fisheries Service
NOAA	National Oceanic and Atmospheric Administration
NPFMC	North Pacific Fishery Management Council
NPS	National Park Service
NRCS	National Resources Conservation Service (USDA)
NWHC	National Wildlife Health Center (USGS)
NYC DEP	New York City Department of Environmental Protection
PBT	parentage-based tagging
PFMC	Pacific Fishery Management Council
PIT	passive integrated transponder
QA/QC	quality assurance and quality control
RLGIS	Refuge Lands Geographic Information System
ROMS	Regional Ocean Modeling System
SAV	submerged aquatic vegetation

Abbreviations—Continued

TNC	The Nature Conservancy
UC	University of California
USACE	U.S. Army Corps of Engineers
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey

Ecological Forecasting—21st Century Science for 21st Century Management

By John B. Bradford,[1] Jake F. Weltzin,[2] Molly McCormick,[1] Jill Baron,[3] Zack Bowen,[2] Sky Bristol,[4] Daren Carlisle,[5] Theresa Crimmins,[6] Paul Cross,[7] Joe DeVivo,[8] Mike Dietze,[9] Mary Freeman,[10] Jason Goldberg,[11] Mevin Hooten,[12] Leslie Hsu,[13] Karen Jenni,[14] Jennifer Keisman,[15] Jonathan Kennen,[16] Kathy Lee,[17] David Lesmes,[18] Keith Loftin,[19] Brian W. Miller,[20] Peter Murdoch,[21] Jana Newman,[22] Karen L. Prentice,[23] Imtiaz Rangwala,[24] Jordan Read,[25] Jennifer Sieracki,[26] Helen Sofaer,[27] Steve Thur,[28] Gordon Toevs,[23] Francisco Werner,[29] C. LeAnn White,[30] Timothy White,[31] and Mark Wiltermuth[32]

Abstract

Natural resource managers are coping with rapid changes in both environmental conditions and ecosystems. Enabled by recent advances in data collection and assimilation, short-term ecological forecasting may be a powerful tool to help resource managers anticipate impending near-term changes in ecosystem conditions or dynamics. Managers may use the information in forecasts to minimize the adverse effects of ecological stressors and optimize the effectiveness of management actions. To explore the potential for ecological forecasting to enhance natural resource management, the U.S. Geological Survey (USGS) convened a workshop titled "Building Capacity for Applied Short-Term Ecological Forecasting" on May 29–31, 2019, with participants from several Federal agencies, including the Bureau of Land Management, the U.S. Fish and Wildlife Service, the National Park Service, and the National Oceanic and Atmospheric Administration as well as all mission areas within the USGS.

Participants broadly agreed that short-term ecological forecasting—on the order of days to years into the future—has tremendous potential to improve the quality and timeliness of information available to guide resource management decisions. Participants considered how ecological forecasting could directly affect their agency missions and specified numerous critical tools for addressing natural resource management concerns in the 21st century that could be enhanced by ecological forecasting. Given this breadth of possible applications for forecast products, participants developed a repeatable framework for evaluating the potential value of a forecast product for enhancing resource management. Applying that process to a large list of forecast ideas that were developed in a brainstorming session, participants identified a small set of promising forecast products that illustrate the value of ecological forecasting for informing resource management. Workshop outcomes also include insights about important likely obstacles and next steps. In particular, reliable production and delivery of operational ecological forecasts will require a sustained commitment by research agencies, in partnership with resource management agencies, to maintain and improve forecasting tools and capabilities.

[1]U.S. Geological Survey, Southwest Biological Science Center, Flagstaff, AZ
[2]U.S. Geological Survey, Ecosystems Mission Area, Fort Collins, CO
[3]U.S. Geological Survey, Fort Collins Science Center, Fort Collins, CO
[4]U.S. Geological Survey Core Science Systems, Science Analytics and Synthesis, Denver, CO
[5]U.S. Geological Survey, Earth System Processes Division, Lawrence, KS
[6]USA National Phenology Network, University of Arizona, Tucson, AZ
[7]U.S. Geological Survey, Northern Rocky Mountain Science Center, Bozeman, MT
[8]National Park Service, Fort Collins, CO
[9]Department of Earth & Environment, Boston University, Boston, MA
[10]U.S. Geological Survey, Patuxent Wildlife Research Center, Athens, GA
[11]U.S. Fish and Wildlife Service
[12]U.S. Geological Survey, Colorado Cooperative Fish and Wildlife Research Unit, Fort Collins, CO
[13]U.S. Geological Survey, Science Analytics and Synthesis, Lakewood, CO
[14]U.S. Geological Survey, Energy and Minerals Mission Area, Denver, CO
[15]U.S. Geological Survey, Maryland Water Science Center
[16]U.S. Geological Survey, New Jersey Water Science Center, Lawrenceville, NJ
[17]U.S. Geological Survey, Environmental Health Mission Area, Grand Rapids, MN
[18]U.S. Geological Survey, Water Mission Area, Reston, VA
[19]U.S. Geological Survey, Kansas Water Science Center, Lawrence, KS
[20]U.S. Geological Survey, North Central Climate Adaptation Science Center, Fort Collins, CO
[21]U.S. Geological Survey, Northwest Region
[22]U.S. Fish and Wildlife Service, Fort Collins, CO
[23]Bureau of Land Management, Washington, D.C.
[24]North Central Climate Adaptation Science Center & Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, CO
[25]U.S. Geological Survey, Water Mission Data Science Branch, Middleton, WI
[26]National Park Service
[27]U.S. Geological Survey, Pacific Island Ecosystems Research Center, Volcano HI
[28]National Oceanic and Atmospheric Administration, National Centers for Coastal Ocean Science, Silver Spring, MD
[29]National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Silver Spring, MD
[30]U.S. Geological Survey, National Wildlife Health Center, Madison, WI
[31]Bureau of Ocean Energy Management, Environmental Studies Program, Sterling, VA
[32]U.S. Geological Survey, Upper Midwest Environmental Sciences Center, La Crosse, WI

Background and Motivation for the Workshop

Changing environmental conditions are altering ecosystems, and the pace of change is projected to accelerate throughout this century (Mahlstein and others, 2013). Reliable predictions about how ecosystems will be impacted by both short- and long-term environmental fluctuations can improve current decision making regarding natural, municipal, agricultural, economic, and public health issues and challenges. Natural resource managers (hereafter managers) need the best available science to anticipate these changes in environmental and ecological conditions and to promote ecosystems with structures and compositions that will be suited to future conditions (Bradford and others, 2018). For example, managers require information, including uncertainty estimates, about how the natural resources they manage may respond to external drivers or stressors. Some ecological processes with forecast potential that would have direct relevance to resource management include biological invasions, contaminant exposure, disease risk, climatic trajectories that alter temperature or hydrologic regimes, extreme weather events, and changing regimes of hazards, such as fires, floods, or drought (table 1). Managers need specific insights about how alternative management strategies could be used to mitigate adverse effects of these external drivers. In addition, ecological forecasts can help managers recognize situations where they may need to define new expectations for ecosystem services provided by their resources. Some specific examples and related management activities and decisions are shown in table 1.

Ecological forecasting (EF) seeks to anticipate future ecological states and dynamics (Bradford and others, 2018) and includes both predictions and projections. Ecological forecast predictions are probabilistic estimates of ecosystem states or events based on the status quo of current conditions, whereas ecological forecast projections are probabilistic statements about how ecosystem states or events will respond to defined scenarios of boundary conditions (MacCracken, 2001; Luo and others, 2011; Dietze, 2017). For example, short-term (multimonth) ecological forecasts of a fish population may include predictions for the next year based on estimates of current population dynamics, and the forecasts may include projections of how the population dynamics might respond to alternative management scenarios. Predictions are typically generated for relatively short-time future horizons (weeks to months), whereas projections can be generated for short time periods but are often used to consider outcomes over long time periods (for example, many years to decades). Mortality of trees in dry forests assessed in the short term could be projected to increase dramatically if temperatures rise in coming decades (longer term). Although predictions and projections are distinct approaches to anticipating future ecological dynamics, knowledge gained from short-term prediction models can be applied to improve long-term projection models.

The process of EF for any given species, process, or system requires (1) information about initial conditions, (2) models that describe relationships between endogenous

Table 1. Examples of ecological processes and relevant resource management activities and decisions that may benefit from short-term, iterative forecasts.

[Information in this table was derived from discussions at the workshop and from Dietze and others (2018)]

Topic area	Ecological process examples	Relevant management activities and decisions
Hydrology	Freshwater flows and temperatures, reservoir levels, sea levels	Flood mitigation, fisheries management, hydropower production, environmental flow and water quality management, protected species management
Vegetation	Plant community composition, vegetation structure	Siting and rehabilitation of energy development activities, ecological restoration, livestock grazing timing and intensity, timber harvest permitting, recreation permitting and management
Fish and wildlife	Population dynamics, migrations, distributions	Management of wildlife populations, including threatened and endangered species conservation; regulation and permitting for hunting, sport fishing, commercial fishing, wildlife viewing; planning and permitting for resource extraction; environmental flow management
Biological threats	Toxins, diseases, insect and invasive species spread	Planning for threat eradication efforts; early detection and rapid response; design of surveillance, prevention, and control; livestock management
Extreme events	Wildfires, drought-driven mortality	Fire suppression; restoration and rehabilitation planning; landslide and erosion risk

and exogenous processes and drivers, and (3) data that can be assimilated and used to validate and iteratively improve forecasts (Clark and others, 2001; Dietze 2017). Iterative EF—wherein predictions are improved gradually by assimilating data in near realtime—relies on a repeating cycle of updating forecasts and associated uncertainties in light of new evidence and analysis, and using this information to refine and improve models. This iterative process in EF is critical for accumulating knowledge about how an ecological system functions—knowledge that, over time, improves both forecasts and projections. EF at the subseasonal to seasonal temporal scale is particularly well suited to iterative EF because the short-term forecasts allow for rapid iteration and model improvement. Subseasonal to seasonal EF is an approach to anticipating future ecological dynamics that has particular relevance to natural resource management (Luo and others, 2011; Dietze and others, 2018; Vitart and Brown, 2019).

The practice of short-term iterative EF is an exciting new field of particular relevance for applied science organizations like the USGS because it offers potentially dramatic benefits to both natural resource management and scientific research (Clark and others, 2001). A focus on EF enables scientists to produce societally relevant forecasts of the natural world—including those involving aeroallergens, disease vectors, contaminant and toxin effects, invasive species, land treatment effectiveness, and bird migrations—that policymakers and resource managers can use to make management decisions. At the same time, building iterative, short-term ecological forecast models helps scientists better understand patterns, processes, and drivers in the shared human and natural environment.

EF also resonates with many resource managers because it is consistent with adaptive management techniques already used by many resource management agencies and organizations (Dietze 2017). Iterative forecasting creates an opportunity to dynamically incorporate real-time data, which drives improvements and innovations in data collection; information management; modeling structure; and data processing, analysis, delivery, and visualization in support of translational science translational science that links research results to decision making. EF has the potential to bring together multiple agencies across jurisdictional and ecological boundaries (for example, integrating watershed management with coastal environment research and management), and these partnerships will help researchers prioritize their work efforts to most directly meet management needs.

EF creates many opportunities for engagement between researchers and practitioners on the front lines of natural resource management and decision making (Enquist and others, 2017). This engagement can benefit research efforts by ensuring that research products are targeted at management needs. It can benefit resource management by ensuring that managers are aware of the most current information, tools, and technologies.

Managers are a key stakeholder audience for EF, and the relevance of forecasts can be strengthened by ensuring that the spatial and temporal scales of operational EF and long-term environmental projections are intentionally matched to the scales of resource management decisions that the forecasts are designed to inform. Participation in EF can encourage managers to stay engaged and actively involved in forecast development and iterative improvement, thereby increasing the value and relevance of forecasts for management decisions, promoting participation in coproduction of actionable science, and fostering partnerships with other agencies or States that need EF.

Knowledge gained through iterative, short-term EF can also be used to enhance understanding of longer term processes (for example, carbon sequestration in wetlands under different management scenarios, managing habitats for migratory animals, selecting seed sources for landscape reclamation, and guiding permitting for energy development). Operational EF also requires an investment in human infrastructure, including the crucial requirement for two-way communications with stakeholders and, almost certainly, science coproduction (Wall and others, 2017).To be useful for resource management and be able to affect management actions, ecological forecasts must leverage technologies and interactive tools that deliver data products and forecasts to the right person, at the right place and time, on the right device (Dietze and others, 2018).

Improving capacity for EF can help the USGS meet several strategic objectives. EF is directly relevant to recent USGS initiatives related to “integrated predictive science capacity” that are designed to focus USGS research and capacity on the development and delivery of, in the words of then-USGS Acting Director Bill Werkheiser, “powerful new products and services that provide: (1) vulnerability detection and assessment, (2) prediction and forecasting, (3) early warning, and (4) decision support at the scale of decisions” (Langseth, 2017). Ecological forecasting can advance the recently launched USGS initiative, provisionally called “EarthMAP,” which is designed to support a vision for USGS contributions to 21st century science in which, in the words of USGS Director Jim Reilly, “the USGS will deliver well-integrated observations and predictions of the future state of natural systems—water, ecosystems, energy, minerals, hazards—at regional and national scales, working primarily with Federal, State, and academic partners to develop and operate the capability” (Langseth, 2019).

In addition, a focus on EF also supports the USGS’s proposed “Integrated Decision Support System,” which envisions integration of research and development, observations and monitoring, modeling, synthesis, analysis and delivery—including communications of higher level, nationally recognized products, several of which rely on forecasting. For example, improvements in EF can help us understand and predict terrestrial, freshwater, and marine invasive species, which is a DOI priority and a growth area for the USGS Ecosystems Mission Area. Increased capacity in EF will also contribute directly to emerging USGS initiatives, including the Landscape Science Strategy, the Biosurveillance and Early Detection/Rapid Response network, the Science for Infrastructure Strategy, Smart Energy, and the Integrated Drought Science Plan (Ostroff and others, 2017), and an emerging focus on harmful algal blooms. Finally, improved capacity for EF creates opportunities for the USGS to contribute to interagency efforts that are increasingly focused on Earth system prediction, such as the National Earth System Prediction Capability group (earthsystemprediction.gov), and the USGS's initiative to strengthen collaborations between USGS and NOAA scientists, who are already delivering ecological forecasts of harmful algal blooms and hypoxia. The value of developing and applying predictions to improve natural resource management has also been recognized by the White House's Fiscal Year 2021 Administration Research and Development Budget Priorities, which explicitly identifies Earth system prediction as a priority (Executive Office of the President, 2019).

Workshop Goals and Structure

To explore the potential for EF to improve applied research and natural resource management capabilities within the USGS and its partners, the USGS Ecosystems Mission Area convened a workshop on May 29–31, 2019, in Fort Collins, Colorado (appendix 1). Participants included about 45 natural resource management agency representatives and science researchers from across the Nation and a variety of agencies and academic organizations. Participants included resource managers and administrators from the Bureau of Land Management (BLM), Bureau of Reclamation (BOR), Bureau of Ocean Energy Management (BOEM), National Oceanic and Atmospheric Administration (NOAA), National Park Service (NPS), and U.S. Fish and Wildlife Service (FWS). About one-half of the workshop participants were USGS scientists from all USGS mission areas. Participants included academic scientists with particular expertise in EF (Boston University), climate science (University of Colorado) and the operationalization of ecological forecasts (University of Arizona). In addition to exploring potential applications of EF to 21st century science and 21st century natural resource management (see the workshop goals outlined in the box below), the workshop had the benefit of raising awareness among participants about EF.

The workshop was designed both to inform participants and to actively engage them in thinking about EF (appendix 1). Day 1 included the sharing of background information about EF, and participant presentations about their perspectives on the potential for EF to advance their agency's mission. Day 1 ended with the participants brainstorming about ideas for promising ecological forecast products and identifying approaches for critically evaluating the value of potential ecological forecasts for enhancing resource management.

On Day 2, a breakout group of participants from management agencies identified obstacles to implementing ecological forecasts within their organizations, and a separate breakout group of science researchers explored opportunities for applying new scientific tools and techniques to develop forecasts. Using the outcomes of these two breakout groups, the entire group refined the process for evaluating the value of a forecast for resource management into a defined, repeatable framework (table 2). Working in groups organized around topical expertise, participants applied the evaluation framework to rank the list of potential products the group developed on Day 1 and to identify the most promising forecast products.

On Day 3, participants worked in small groups to provide more detailed information, based on a standardized rubric for requirements (appendix 2), about each of the most promising forecast products listed in table 3 (appendix 3). The workshop concluded with a plenary discussion in which all participants provided feedback about the workshop itself and shared their broader thoughts about advancing EF within their agencies. This included recognition that iterative EF has potential to enhance long-term projections of ecological processes with recognized value for management. One of the most challenging long-term changes where near-term EF can improve models is long-term vegetation dynamics under global change scenarios.

Workshop goals

- Identify and describe some promising potential ecological forecasting products.
- Support the development of predictive capacity in support of science and society—across a wide range of temporal and spatial scales—within the U.S. Geological Survey (USGS).
- Promote a culture of coproduction between the USGS and key U.S. Department of Interior (DOI) Bureau partners charged with managing DOI trust species, habitats, and natural resources.
- Improve communication, coordination, and collaboration between the USGS and the National Oceanic and Atmospheric Administration in support of high-level interest in building joint capacity among agencies.
- Strengthen relationships between the USGS Ecosystems, Water, and Environmental Health Mission Areas, among others.
- Raise awareness of ecological forecasting potential and build a forecast culture among the USGS and its stakeholders.

Workshop Results

Result 1—Criteria for Evaluating the Value of Potential Forecast Products

Natural resource managers make a wide variety of decisions, from site-level decisions that influence management over short time periods and small areas to national-scale decisions with decadal or longer term implications. Because EF may inform many of these decisions, the set of potentially useful forecast products is large. Identifying and prioritizing forecast products that are needed and that could feasibly be produced (those that are "most promising") was determined by the workshop participants to be an important first step in developing useful forecast products. The participants quickly recognized the need for an objective and repeatable framework for evaluating and prioritizing potential EF products. During the first and second days of the workshop, participants helped develop such a process by determining criteria by which forecast products could be critically evaluated and by enumerating the specific attributes of forecast products that could be described to enable evaluation and prioritization.

Participants agreed upon five overarching criteria for evaluating forecast products. These and their attributes are outlined in table 2. First and foremost, demonstrated **demand and relevance** to specific resource management decisions was identified as an essential characteristic of forecast products worth pursuing.

Table 2. Five criteria to be applied when assessing the value of a potential ecological forecasting product.

Criteria	Attributes
Demand and relevance (essential)	Who will use the forecast and what decisions will the forecast influence?
	How will management decisions be improved by production of and access to the forecast?
	What existing or potential partnerships can advance forecast development and use, and could partnerships leverage resources?
	How does the forecast relate to agency, Bureau, Department, and Administration priorities and missions? Does the U.S. Geological Survey and (or) partners have statutory authority to deliver the forecast?
State of the science	How well understood is the ecological process being forecasted? Are the driving variables, functional forms, and parameters known?
	How is the forecasted process represented in existing system models that could accelerate forecast development and also potentially improve the system models themselves?
	Are rapid improvements in forecast skill anticipated? (Can the uncertainty be measured and can the uncertainty be expected to be reduced by iterative model improvement and additional investment?)
	Are historical data available for synthesis to inform model structure, and will monitoring data be available in the future to validate forecasts and improve the model?
Operational implementation	What is the expected cost, in money and time, to operationalize forecast delivery?
	Is the latency of the data streams needed to drive forecast models short enough to produce timely forecasts useful to management decisions?
	How will the spatial and temporal scales of the forecast be aligned with scales appropriate for resource management?
	What is needed to deliver the forecast products in a format and structure needed by resource managers?
	Are nongovernmental entities or other third parties potentially interested in adding value and (or) disseminating the forecast?
	Are there litigation risks related to disseminating and using the forecasts for producers and consumers, respectively?
Value for improving decision-support	What is the potential magnitude of improvement in resource management decisions as a result of using the forecast versus using alternative data sources?
	How will the forecast help manager-researcher partnerships apply adaptive management?
	Would forecast producers and consumers commit to working together to develop and use the forecast? (co-production)
Management-Research integration and long-term adaptive management	How can the format and structure of the forecast product be structured to integrate into the decision processes of resource managers?
	How will the forecast be delivered to targeted stakeholders and (or) made available to a broad array of users?
	What is the relevance of the forecast to the culture of the organizations producing and consuming the forecast?

Participants also noted that forecast products should be evaluated based on the maturity, or **state of the science** that supports the ability to forecast an ecological process, as well as on the feasibility of producing, delivering, and using the forecast within the context of an agency's **operational implementation**. Operational implementation refers to the structures that an agency must have in place to deliver a continued stream of ecological forecasts to managers. Participants noted that clear communication between managers and researchers would be required to efficiently and effectively develop and use new forecast approaches and products. As such, they emphasized that products should be evaluated based on their **value for improving decision support** and researcher-manager communication and relationships. During the in-workshop evaluations described below, participants noted that potential forecasts should also be assessed in terms of their value in promoting **management-research integration and long-term adaptive management relationships.** They noted that this value could be enhanced by designing forecasts to match the frequency, resolution, and latency needed to inform management decisions. Because this point was recognized later in the workshop, that criterion is shown in table 2, but the examples in the appendixes do not include it explicitly. Although participants embraced and used these five overarching criteria (the "rubric") for evaluating proposed forecast products that emerged from the workshop, they also recognized that these five are only a starting point, and that the rubric should be refined and enhanced as the experience in setting forecast priorities and developing and applying ecological forecasts progresses.

Result 2—Identification of Example Promising Forecast Products

Considering and evaluating opportunities for potentially useful forecast products was a major component of the workshop. Although some participants arrived at the workshop with ideas for forecasts, many additional opportunities were identified during brainstorming discussions on the first day of the workshop (appendix 4). To narrow the list, the group categorized all product suggestions by biome (that is, terrestrial, freshwater, marine, or cross-biome) and by the management challenge being addressed (that is, disease, toxins, and invasives; resource use and development—migration; status and trends—hazards; see appendix 5). Breakout groups with topical expertise within each biome considered all proposed forecast products relevant to their biome and rated products based on the forecast evaluation criteria in table 2 to identify potentially useful forecast products that could improve resource management within a given biome. Outcomes from the small group ratings were then discussed by the whole group, and participants developed a consensus list of the promising forecast products discussed (table 3). Appendix 3 contains additional details about each ecological forecasting product.

Participants emphasized that the set of forecast products identified in table 3 is not comprehensive and that the value of the list of products was constrained by (1) the breadth of the topic versus the assembled expertise at the workshop, (2) the need for additional and intensive discussion and vetting of forecast products with resource managers on the ground,

Table 3. Promising potential ecological forecasting products identified at the workshop.

[CWD, Chronic Wasting Disease; NGO, nongovernmental organization. Abbreviations of specific organizations: BLM, Bureau of Land Management; BOEM, Bureau of Ocean Energy Management; BOR, Bureau of Reclamation; EPA, U.S. Environmental Protection Agency; FS, U.S. Forest Service; FWS, U.S. Fish and Wildlife Service; NASA, National Aeronautics and Space Administration; NOAA, National Oceanic and Atmospheric Administration; NPS, National Park Service; USGS National Wildlife Health Center; NYC DEP, New York City Department of Environmental Protection; TNC, The Nature Conservancy; USACE, U.S. Army Corps of Engineers; USDA NRCS, U.S Department of Agriculture National Resources Conservation Service; USGS, U.S. Geological Survey. Abbreviations of States: AK, Alaska; CA, California; OR, Oregon; WA, Washington]

Topic	Management need	Forecast description	Partners and collaborators	Stakeholders
Freshwater cyanobacterial blooms	High temporal resolution forecasts of toxin exposure can improve management of drinking water, agricultural irrigation, livestock, fish and wildlife populations	Daily forecasts of cyanobacterial blooms for inland freshwater lakes (near term); daily toxin and health effects forecasts	EPA, NASA, and NOAA	States, Tribal Nations, drinking water utilities, and BLM, BOR, NPS, FWS, and USACE
Chronic Wasting Disease	State and Federal agencies need spatially explicit, seasonal forecasts of CWD prevalence to establish harvest levels for game populations affected by CWD and to prioritize monitoring	Annual forecasts of CWD prevalence and resulting population-level effects	USGS science centers, State wildlife agencies, FWS, NPS, and BLM	Hunters and the general public

Table 3. Promising potential ecological forecasting products identified at the workshop.—Continued

Topic	Management need	Forecast description	Partners and collaborators	Stakeholders
Early detection of invasive species	Seasonal and spatially explicit forecasts of biological invasions can increase efficiency of monitoring and eradication treatments, thus reducing ecological, economic, and public health impacts	Spatially explicit predictions of invasive species distribution and spread to inform treatment, containment, and eradication efforts	NPS, BLM, FWS	Invasive species managers, State and local partners, Cooperative Weed Management Areas, and policymakers
Coastal marsh erosion	Forecasting vegetation and habitat change resulting from sea-level rise and storm surge can inform siting of living shorelines and anticipate impacts to wildfowl populations	Short-term forecasts of coastal ecosystem vulnerability (resilience) potential	NOAA, EPA, coastal communities, FWS refuges, NPS, EPA, State agencies, NGOs, coastal commercial operations	Governments and residents of coastal zones
Phenology and migration hotspot forecasting	Advance warning of seasonal events in plants and animals, including migrations in seabirds and marine mammals, can inform and improve a wide range of resource management activities and treatments	Management-relevant seasonal events in plants and animals, at the extent, resolution, and format to support management	NOAA, BOEM, NPS, FWS, universities	USGS and partners, FWS, NPS, BLM, FS, NOAA, BOEM, State extension agents, Tribal Nations, private industry, and the public
Vegetation dynamics	Projecting how and when plant communities will change can improve the climate viability of species selected for restoration, inform the evaluation of land treatment suitability, and strengthen long-term planning for resource use and extraction	Forecasts of vegetation composition that are validated and calibrated on an annual basis with the use of vegetation-monitoring data to improve long-term projections	Land management agencies (State and Federal—for example, BLM, FWS, NPS, Tribal Nations), USGS, university scientists, USDA NRCS	Federal and State land management agencies, Tribal Nations, and private property owners and managers interested in habitats and migration corridors
Dryland restoration	Dryland restoration and reclamation projects are highly weather dependent, so managers need forecasts of the probability of success to maximize the efficiency of investments and enable widespread effective restoration and reclamation	Seasonal forecasts of the probability of establishment and persistence of seeded species relevant to post-disturbance recovery and restoration success	Initial partners include USGS and BLM, but can be expanded upon proof of concept	BLM, NPS, FWS, FS, Tribal Nations, State agencies, private ranchers, and conservation NGOs
Reservoir thermal bank	Reservoir temperature forecasts can inform management of downstream regulated river reaches with species of concern and improve management of fish habitat conditions to increase fish populations	Monthly to season ahead forecast of reservoir thermal bank for water release planning	Delaware River Master's office, NOAA, NYC DEP, others	Dam managers and other water managers (for example, USACE, local, FWS, TNC)
Disease outbreaks in waterfowl	Forecasts of waterfowl disease can enable proactive water level management to reduce outbreaks of avian botulism and reduce overall negative impacts to waterfowl populations	A web-based forecast of avian botulism that will help water managers proactively manage refuge units to prevent an outbreak of avian botulism based on abiotic conditions	FWS, USGS	FWS, State agencies, NGOs, and other Federal agencies

Table 3. Promising potential ecological forecasting products identified at the workshop.—Continued

Topic	Management need	Forecast description	Partners and collaborators	Stakeholders
Salmon population dynamics	Forecasting salmon population abundance and distribution in response to environmental changes can inform water management and increase understanding of dam management and (or) removal impacts	Salmon population dynamics that integrate existing biological, ecological, water, ocean, and management forecasting tools	NOAA, USGS, BOR, State agencies (CA, OR, WA, AK), Tribal Nations, NGOs, academics, and so forth	Partners plus the Fishery Management Councils, dam operators, and State water and fish management agencies

(3) the need for additional documentation, prioritization, and conversation with agency leadership, and (4) the need for extensive considerations of the research to operations continuum, particularly in a time of flat budgets. Participants noted that the list could help increase awareness of potential applications for EF and that comprehensive scoping, evaluation, and prioritization of forecast products would require time and expertise beyond that available at the workshop, as well as additional vetting and discussion with managers working in the field.

The set of ecological forecasts that the workshop participants considered the most promising (table 3; appendix 3) are relevant to a broad range of contemporary natural resource management challenges. Suggested forecasts for informing management of freshwater and marine systems included cyanobacterial blooms, coastal marsh erosion, and reservoir thermal bank dynamics. Other suggested products focus on providing information for wildlife management, including waterfowl disease outbreaks, migration hotspots, Chronic Wasting Disease forecasts, and salmon population dynamics. Similarly, products with high value for informing the management of terrestrial vegetation included forecasts of vegetation dynamics in response to disturbance, drought, and climate, as well as dryland restoration, and plant phenology (see box below). Although these forecast products have clear potential for improving natural resource management as well as a defined set of partners, collaborators, and stakeholders, developing and delivering any of these forecasts would require further scoping, communication with managers working in the field, and a sustained programmatic investment.

Example ecological forecasting of phenology

The timing of seasonal events in plants and animals—including migration, seed ripening, egg hatch, and green-up—is relevant to a wide range of management decisions. Anticipating when various life-cycle events will occur can improve planning for such activities as burning, thinning, or chemical control—ensuring that they are conducted when they will be most effective—and allow for scheduling of normal human and industry operations to minimize human-wildlife conflicts. Monitoring activities may also be timed to coincide with particular life-cycle stages. With phenological information available, hunting and fishing seasons and closures can be scheduled to be most effective and minimize negative impacts.

Spatially explicit ecological forecasts can be particularly relevant to resource management. For example, advance warning of where and when birds will migrate could inform when to turn off wind turbines temporarily to minimize collisions with birds and bats while minimizing losses in energy generation. A knowledge of when ground-nesting birds are nesting can narrow the window of beach closures. Forecasts of marine mammal migrations can improve shipping lane designations and fishing restrictions. The additional information provided in forecasts has the potential to minimize negative impacts to managed resources, improve efficiencies, and save money.

Approaches for generating forecasts of phenological events range from simple, deterministic models to dynamic, iterative Bayesian approaches. Benefits of simplistic approaches include ease of operationalizing and relatively low implementation costs; however, tradeoffs include a lack of accounting for uncertainty and potentially overstating confidence in the prediction. In contrast, probabilistic, iterative, and dynamic methods may be more costly and time-consuming to develop, implement, and maintain, but may offer the benefits of greater accuracy and a more explicit accounting of uncertainty, which improve the value of the forecast.

The approach selected to generate a forecast should match the risk associated with the consequences of a particular resource management decision. Situations where the accuracy and precision of a forecast must be high, such as in the case of closing public beaches to minimize disruption of ground-nesting birds, may call for intensive methods. In contrast, situations requiring less accurate forecasts may rely on simpler and less costly approaches. One example is the 6-day forecasts of spring season onset provided by the USA National Phenology Network. These forecasts are derived from a simple heat accumulation threshold model (www.usanpn.org/news/spring), and are used by industry for such activities as turfgrass management and landscape care that require basic information about spring onset with a short lead time.

Result 3—Insights About Next Steps for Advancing Ecological Forecasting

Participants were enthusiastic about the future of EF, and closing comments in the workshop included widespread expressions of hope that this workshop is only the beginning of a long-term investment in EF. The list of promising forecast products illustrates the breadth and diversity of natural resource management decisions that could be informed by EF. The authors recognize that the list would need to be further evaluated and refined, particularly in cooperation with the relevant agencies and other forecast end users, to ensure that investments in developing forecasts would have beneficial effects on management decisions.

All participants concurred that successful application of EF would require a sustained commitment on the part of both producers and end users of forecasts to build and sustain coproduction teams (Wall and others, 2017). Developing ecological forecasts and integrating them into resource management decisions is a substantial challenge that is achievable only if agency roles are properly identified and partnerships are leveraged or new ones created. Making forecast delivery timely and efficient will almost certainly require new or enhanced capacity in such areas as computer infrastructure and human workforce capabilities. Likewise, the potential for iterative improvement in forecast skill is a major strength of short-term EF that will be realized only if appropriate monitoring data continue to be collected and integrated into forecast models.

Representatives from natural resource management agencies were particularly enthusiastic about building teams focused on coproduction of forecast products but cautioned that fully integrating forecasts into their agency workflows may in some cases require a paradigm shift in both management and science agencies. At some management agencies, the agency's scientific capacity might need to be increased.

Case studies that demonstrate the strategic value of EF products could help advance research-management partnerships and foster long-term commitments. Such case studies should be able to show that forecast skill can improve with iteration. The dramatic improvement in weather forecast skill over the past several decades is an example of how this iterative process can work (Bauer and others, 2015). Iterative improvement in ecological models may be facilitated by modern computational capability, which can facilitate direct integration of observations and ecological models (Luo and others, 2011; Dietze and others, 2018).

Result 4—Recommendations for Supporting Long-Term Management-Research Partnerships

Because of the inherently short timeframe and limited participant breadth in a workshop format, the forecast products listed in table 3 should be viewed mainly as examples that illustrate how EF may be used to improve resource management. These examples are not a final, vetted list of the objectively "best" forecast products to be pursued in the future. Participants from resource management agencies were especially clear that the forecast products that are expected to be the most useful will likely emerge from long-term coproduction efforts involving partnerships between science and management agencies. Such coproduction can ensure that products are focused on the appropriate temporal and spatial scales for the forecast and that they are delivered in a format that can be integrated into management agency decision-making operations.

Sustained research-management partnerships can help improve the EF models as well as foster understanding of the value of a particular ecological forecast. "Buy-in" and involvement by all parties for a sustained period of time helps them recognize that, although forecasts may have limited applications initially, they can be expected to improve with each successive iteration and, over time, will increasingly provide valuable information for informing decisions for both the short-term and long-term. Building and sustaining coproduction partnerships represents both a challenge and an opportunity that participants universally agreed would be essential for optimizing the use of 21st century science to inform 21st century resource management.

Implications for USGS Research and Operations

Although participants arrived with a broad range of perspectives about EF, a clear outcome of the workshop was a shared recognition that science-based ecological forecasts have tremendous potential to improve the quality and timeliness of information available to guide resource management decisions. Participants expressed enthusiasm about the opportunity for developing iterative EF, which involves combining forecast models with regular observations that test and improve the model. As previously noted, weather forecasts are a well-recognized example of iterative forecasting, and the feedbacks between observations and models have resulted in incremental but remarkable improvements in weather forecast skill over the past several decades (Bauer and others, 2015). Similar iterative frameworks for ecological forecasts can be constructed to leverage observations from remote sensing platforms and (or) systematic environmental monitoring data (Luo and others, 2011).

Although the promising potential of iterative forecasts was widely embraced by workshop participants, they expressed the need to communicate that the skill of forecast products may initially be low but can be expected to increase over time with successive iterations. Participants expressed that near-term skill limitations should not prevent the development of potential products with high demand, strong scientific basis, and potential for improvement. Based on lessons learned from NOAA's experience, participants also recognized that developing and delivering ecological forecasts takes substantial time and inherently involves some risk that the forecasts may not be sufficiently skillful to inform management. Hence, quantifying and conveying forecast uncertainty is essential, and setting appropriate expectations among forecast users would be crucial for sustaining engagement and support.

Although the workshop focused primarily on exploring the potential of short-term, iterative EF, participants also identified long-term (for example, decadal and longer) projections of ecosystem dynamics and states as crucial natural resource management tools for assessing the potential impact of global change. In the context of changing climate, changing disturbance regimes, and shifting human resource use, long-term ecological projections can be built upon process-based ecological models forced by scenarios representing alternative future conditions (Bonan and Doney, 2018).

Although iterative improvements in these long-term models will be slower than with short-term forecast models, the projections provide valuable insights about potential future resource conditions that can inform strategic management decisions. Even models that can produce long-term projections may be strengthened by repeated data integration and iterative improvement. For example, integrating periodically collected vegetation and plant community data from ongoing monitoring programs (for example, Bureau of Land Management and the Forest Service monitoring programs) with dynamic vegetation models can help ensure that those models appropriately represent observed dynamics, strengthening confidence in the models' ability to appropriately forecast multidecadal vegetation shifts in response to 21st century climate change. Based on the agency representation at the workshop, both short-term forecasts and long-term projections have substantial potential for dynamic, real-time, and forward-looking natural resource management.

Workshop participants identified an array of existing forecast applications, providing perhaps the most powerful evidence that EF can improve resource management. Across the "research to operations" continuum, several agencies are developing, and in some cases using, ecological forecasts. At present, the most advanced operational ecological forecasts are produced by NOAA, and include forecasts of fishery stocks (National Oceanic and Atmospheric Administration, 2020b), harmful algal blooms, hypoxia, pathogens, and aquatic habitat (National Oceanic and Atmospheric Administration, 2020a). In building and delivering these forecasts, NOAA scientists have learned several lessons that can inform new forecast development—notably, the need for long-term investment and sustained multiparty engagement from researchers, operational staff, and forecast users in multidisciplinary teams.

The USGS, which has research and operational components that include (1) large-scale, long-term monitoring activities, (2) extensive modeling and analysis capacity, (3) high-quality and contemporary information technology infrastructure, and (4) extensive scientific expertise in all environmental sciences, is well-suited to produce ecological forecast products. Within the USGS, ongoing forecasting efforts presently include streamflow forecasts from the Integrated Water Prediction (IWP) Program and the USA National Phenology Network's phenological forecasts. Forecasting abilities for natural hazards, such as volcanic eruptions, tsunamis, and earthquakes, are also moving forward with the aid of the John Wesley Powell Center (for example, Field and others, 2017). Scientists working on current efforts can provide critical insights about developing and delivering operational ecological forecasts.

Workshop participants universally agreed that fostering a community of practice around EF will accelerate both new forecast development and improvements in existing forecasts. Particularly useful would be opportunities to share information about techniques for "formalizing" ecological forecasts into iterative frameworks designed to improve over time. Successful forecasts are likely to be built upon solid ecological knowledge, effective local-scale management-research partnerships, and operational capacity with national scope. The USGS may be uniquely structured to satisfy these diverse requirements because it has both programs with national-scale capacity and a network of local partnerships and research activities.

Successful production of useful ecological forecasts at USGS will depend on both researchers and resource managers having a strong awareness of—and a willingness to embrace, both conceptually and organizationally—the "research to operations" continuum. The USGS would need to work with scientific partners to conduct research that develops new understanding and new data and information products, and it would need to commit to support operationalizing the delivery of interpreted, management-relevant data and information products. To date, the USGS has excelled at the research end of the continuum. In the future, the USGS could consider a strategic approach to strengthen the operations end of the continuum, which would require a commitment to develop, maintain, improve, and deliver operational forecast products. Supporting long-term operational forecast development and delivery would augment the current practice of third-party entities using USGS data and data products for forecasting purposes.

Conclusions

This workshop suggested that EF has potential for improving resource management, but it also identified several substantial obstacles to realizing that potential. By including a diverse group of researchers and managers from within the USGS and its partners, this workshop encompassed a broad suite of perspectives, including researchers who can contribute to forecast development, program directors who can enable forecast delivery, and resource managers who can integrate forecasts into management operations. The list of promising EF products provides a specific illustration of how ecological forecasts may be developed and delivered to inform resource management decisions. Participants also identified several crucial implications for USGS research and operations to make effective EF possible, including the critical need to build and sustain management-research partnerships.

References Cited

Bauer, P., Thorpe, A., and Brunet, G., 2015, The quiet revolution of numerical weather prediction: Nature, v. 525, no. 7567, p. 47–55, accessed June 10, 2020, at https://doi.org/10.1038/nature14956.

Bonan, G.B., and Doney, S.C., 2018, Climate, ecosystems, and planetary futures—The challenge to predict life in Earth system models: Science, v. 359, no. 6375, p. eaam8328, accessed June 10, 2020, at https://doi.org/10.1126/science.aam8328.

Bradford, J.B., Betancourt, J.L., Butterfield, B.J., Munson, S.M., and Wood, T.E., 2018, Anticipatory natural resource science and management for a changing future: Frontiers in Ecology and the Environment, v. 16, no. 5, p. 295–303, accessed June 10, 2020, at https://doi.org/10.1002/fee.1806.

Clark, J.S., Carpenter, S.R., Barber, M., Collins, S., Dobson, A., Foley, J.A., Lodge, D.M., Pascual, M., Pielke, R., Pizer, W., Pringle, C., Reid, W.V., Rose, K.A., Sala, O., Schlesinger, W.H., Wall, D.H., and Wear, D., 2001, Ecological forecasts—An emerging imperative: Science, v. 293, no. 5530, p. 657–660, accessed June 10, 2020, at https://doi.org/10.1126/science.293.5530.657.

Dietze, M.C., 2017, Ecological Forecasting: Princeton, New Jersey, Princeton University Press, 270 p.

Dietze, M.C., Fox, A., Beck-Johnson, L.M., Betancourt, J.L., Hooten, M.B., Jarnevich, C.S., Keitt, T.H., Kenney, M.A., Laney, C.M., Larsen, L.G., Loescher, H.W., Lunch, C.K., Pijanowski, B.C., Randerson, J.T., Read, E.K., Tredennick, A.T., Vargas, R., Weathers, K.C., and White, E.P., 2018, Iterative near-term ecological forecasting—Needs, opportunities, and challenges: Proceedings of the National Academy of Sciences of the United States of America, v. 115, no. 7, p. 1424–1432, accessed June 10, 2020, at https://doi.org/10.1073/pnas.1710231115.

Enquist, C.A., Jackson, S.T., Garfin, G.M., Davis, F.W., Gerber, L.R., Littell, J.A., Tank, J.L., Terando, A.J., Wall, T.U., Halpern, B., Hiers, J.K., Morelli, T.L., McNie, E., Stephenson, N.L., Williamson, M.A., Woodhouse, C.A., Yung, L., Brunson, M.W., Hall, K.R., Hallett, L.M., Lawson, D.M., Moritz, M.A., Nydick, K., Pairis, A., Ray, A.J., Regan, C., Safford, H.D., Schwartz, M.W., and Shaw, M.R., 2017, Foundations of translational ecology: Frontiers in Ecology and the Environment, v. 15, no. 10, p. 541–550, accessed June 10, 2020, at https://doi.org/10.1002/fee.1733.

Executive Office of the President, 2019, Fiscal Year 2020 Administration research and development budget priorities: Executive Office of the President Memorandum for the Heads of Executive Departments and Agencies M-19-25, 9 p., accessed June 2, 2020, at https://www.whitehouse.gov/wp-content/uploads/2019/08/FY-21-RD-Budget-Priorities.pdf.

Field, E.H., Milner, K.R., Hardebeck, J.L., Page, M.T., van der Elst, N., Jordan, T.H., Michael, A.J., Shaw, B.E., and Werner, M.J., 2017, A spatiotemporal clustering model for the third uniform California earthquake rupture forecast (UCERF3-ETAS)—Toward an operational earthquake forecast: Bulletin of the Seismological Society of America, v. 107, no. 3, p. 1049–1081.

Langseth, M.L., 2017, Bureau priorities and an integrated predictive science capacity: U.S. Geological Survey web page, accessed June 2, 2020, at https://my.usgs.gov/confluence/display/cdi/Bureau+Priorities+and+an+Integrated+Predictive+Science+Capacity.

Langseth, M.L., 2019, USGS Director's science planning strategy (EarthMap!)—Being a part of preparing for the future: U.S. Geological Survey web page, accessed June 2, 2020, at https://my.usgs.gov/confluence/pages/viewpage.action?pageId=635125463#space-menu-link-content.

Luo, Y., Ogle, K., Tucker, C., Fei, S., Gao, C., LaDeau, S., Clark, J.S., and Schimel, D.S., 2011, Ecological forecasting and data assimilation in a data-rich era: Ecological Applications, v. 21, no. 5, p. 1429–1442, accessed June 10, 2020, at https://doi.org/10.1890/09-1275.1.

MacCracken, M., 2001, Prediction versus projection—Forecast versus possibility: WeatherZine, v. 26, p. 1–29, accessed June 10, 2020,at https://sciencepolicy.colorado.edu/zine/archives/1-29/26/guest.html.

Mahlstein, I., Daniel, J.S., and Solomon, S., 2013, Pace of shifts in climate regions increases with global temperature: Nature Climate Change, v. 3, no. 8, p. 739–743, accessed June 10, 2020, at https://doi.org/10.1038/nclimate1876.

National Oceanic and Atmospheric Administration, [2020]a, NOAA ecological forecasting: National Oceanic and Atmospheric Administration web page, accessed June 2, 2020, at https://oceanservice.noaa.gov/ecoforecasting/.

National Oceanic and Atmospheric Administration, [2020]b, Population assessments—Fish stocks: National Oceanic and Atmospheric Administration web page, accessed June 2, 2020, at https://www.fisheries.noaa.gov/topic/population-assessments#fish-stocks.

Ostroff, A.C., Muhlfeld, C.C., Lambert, P.M., Booth, N.L., Carter, S.L., Stoker, J.M., and Focazio, M.J., 2017, USGS integrated drought science: U.S. Geological Survey Circular 1430, 24 p., accessed June 10, 2020, at https://doi.org/10.3133/cir1430.

Vitart, F., and Brown, A., 2019, S2S forecasting—Towards seamless prediction: World Meteorological Organization Bulletin, v. 68, no. 1, accessed May 28, 2020, at https://public.wmo.int/en/resources/bulletin/s2s-forecasting-towards-seamless-prediction.

Wall, T.U., McNie, E., and Garfin, G., 2017, Use-inspired science—Making science usable by and useful to decision makers: Frontiers in Ecology and the Environment, v. 15, no. 10, p. 551–559, accessed June 10, 2020, at https://doi.org/10.1002/fee.1735.

Appendixes 1 through 5

The agenda and the responses from the working groups contained in these appendixes are reproduced as submitted by the workshop participants, with only minor editorial changes for clarity and consistency. The abbreviations used are defined in the Abbreviations list in the front of the report.

Appendix 1. Workshop Agenda

	Day 1: Wednesday, May 29
8:30	Open (Jake Weltzin); Welcome to Fort Collins Science Center (Sharon Taylor) and to the Powell Center (Jill Baron); Logistics (Leah Colasuonno)
8:50	Workshop goals and structure (Jake)—ELT aspirational charge (Anne Kinsinger)
9:05	Group Introductions and brief comments about ecological forecasting (John Bradford)
10:00	Overview of workshop agenda (John)
10:45	Basics of iterative, short-term ecological forecasting: 45 minutes, with discussion (Mike Dietze)
1:00	Review afternoon objectives (John)
1:10	Participant presentations—Perspectives on forecasting by forecast consumers and producers (Jill)
3:30	Developing, describing and evaluating potential forecast products—Criteria and attributes (John)
4:30	Brainstorming potential forecast products and ideas (Jake)
5:30	Wrap-up (Jake)
	Day 2: Thursday, May 30
8:30	Open Day 2, reflect on yesterday, and review agenda and goals for the day (Jake)
8:45	Small groups—Identify opportunities and obstacles (Jake)
9:30	Small group reports
10:15	Revisit criteria and attributes (John)
10:45	Discuss and populate distillation framework to identify ecological forecasting projects (John)
11:30	Define work groups to work on ecological forecasting products and setting the task (John and Jill)
12:30	Small groups populate cells with potential forecast products and rate (H,M,L) relative to criteria
2:45	Report out and identify top 2 to 4 products per group (10 minutes + 5 minutes for questions and answers) (Jake)
3:30	Plenary discussion of top products to determine products for which to develop prospectuses (Jill)
4:00	Discussion of purpose and structure of prospectus template (Jake)
4:30	Identify writing teams for prospectuses and define group activities for tomorrow (Jake)
4:45	Summary of day (Jake)
	Day 3: Friday, May 31
8:30	Review today's objectives—Confirm report structure and write product descriptions
8:40	Consider outline for report (John)
9:00	Writing teams draft descriptions of forecast products and (or) organize matrix for small groups
11:15	Closing and round robin final comments (Jake)
12:00	Adjourn

Appendix 2. Standardized Rubric for Describing a Forecast Product

The successful development of any potential forecast product requires an understanding of the proposed application for the product as well as additional information to facilitate prioritization and production of the forecast. The categories of information listed below were developed by the workshop participants and later used by small ad hoc teams of workshop participants to prepare more detailed descriptions of each of the most promising (as determined by the workshop participants) potential forecast products. Those detailed descriptions are included in appendix 3 and summarized in table 3.

- Forecasting product name
- Desired future state
- Expected outcome
- Expected partners and (or) collaborators
- Expected stakeholders
- Product description
- Evaluation against standardized criteria (from table 2 of report)
    - Demand and relevance
    - State of the science
    - Operational implementation
    - Value for improving decision support
- Modeling requirements
- Data requirements
- Cyberinfrastructure requirements
- Human infrastructure requirements
- Opportunities for emergent advanced technologies
- Summary of resource requirements
- Timeline with milestones
- Examples of existing forecasts and relevant sources of information

Appendix 3. Descriptions of the Most Promising Forecast Products Considered at the Workshop

During and after the workshop, small teams provided descriptions of each potential forecast product listed in table 2 using the requirements rubric in appendix 2. Given the time constraints, participants were asked to document only the "Evaluation against standardized criteria" portion of the rubric, but some teams completed the entire rubric. Thus, the completeness of the teams' descriptions varies among the potential products, which are listed below and followed by more detailed descriptions of each. This is not an exhaustive list of all potential forecast products; rather the list reflects the workshop participants' particular knowledge and areas of expertise.

- Freshwater Cyanobacterial Blooms and Toxins
- Chronic Wasting Disease
- Early Detection of Invasive Species
- Coastal Marsh Erosion
- Phenology and Migration Hotspot Forecasting
- Vegetation Dynamics
- Dryland Restoration
- Reservoir Thermal Bank
- Disease Outbreaks in Waterfowl
- Salmon Population Dynamics

Freshwater Cyanobacterial Blooms and Toxins

Forecasting Product Name

Short-term forecasts of cyanobacterial blooms and toxins in freshwater lakes

Desired Future State

Daily forecasts of cyanobacterial blooms for inland freshwater lakes (near term); daily toxin forecasts and potential assessments of long-term cumulative health effects to inform actionable natural resource management decisions made outside of the USGS.

Expected Outcome

Successful forecast results of harmful algal blooms in publicly accessible mobile and web-based applications will provide decision makers the ability to make more timely decisions supported by the best available science. With these forecasting tools in hand, they will be able to balance the fullest resource use with health protection (of humans, wildlife, livestock, companion animals) and socioeconomic effects resulting from harmful algal bloom toxin exposure. For example, department of health and municipal water managers may send out an advisory not to swim in or have livestock drink from these water sources. Timescale-dependent outcomes (near-term, mid-term, long range) are limited by future satellite characteristics, such as pixel resolution, flyover frequency, optical or thermal infrared bands relevant to algal pigments, and continued research to understand bloom dynamics, toxin production, and health effects. Iterative approaches will regularly continuously improve our ability to produce more accurate forecasts with increasingly higher resolution as technology develops and our understanding of algal physiology, toxin production, and health effects improve with continued research in the next 5 to 10 years.

Expected Partners and (or) Collaborators

Current partners in our collaborative development of tools that use remotely sensed data to measure algal abundance in freshwaters include the EPA, NASA, and NOAA, and numerous research teams in academia. These same partners are expected to be collaborators on a forecasting tool moving forward. Selected stakeholders would be involved in iterative beta testing of forecasting tools, such as States, Tribes, and drinking water utilities as well as other Federal agencies, such as the BLM, BOR, NPS, FWS, and USACE, to ensure that improvements are relevant for the Nation's lakes and reservoirs.

Expected Stakeholders

FWS refuges for management of migratory bird, fisheries, and other Trust species obligations; USACE and BOR for management of resource access for recreation (tourism); the NPS for human and ecological health protection (wildlife and recreation, especially backcountry drinking water access); the BLM for management of grazing and irrigation to protect agricultural products; the public (drinking water, dermal contact), recreationists (fishing, swimming, hiking), pet owners (dogs), agriculture (irrigation, livestock); the EPA, States, and Tribes for Clean Water Act and Safe Drinking Water Act compliance and human health protection; the NOAA for fish and shellfish advisories in coastal waters

Product Description

Mobile application that forecasts algal blooms at scalable pixel resolution from 300 to 900 meters, dependent on water body size. The output is a visual map with concentration of bloom and threshold exceedance. Locations can be selected by entering the coordinates or visual selection of waterbody on a map. It includes a trend display. Longer range goals include the following: In 5 to 10 years, being able to forecast toxin within the application (subject of ongoing research). Thresholds would be based upon known health outcomes versus suspected health outcomes (a subject of ongoing research), ideally.

Evaluation Against Standardized Criteria

Demand and relevance.—Real-time access to algal bloom abundance above a set threshold of concern can improve the timeliness and effectiveness of decisions produced by natural resource and public health managers. Decisions to balance water use and health protection will result in improved advisories for water use for drinking water, agricultural irrigation, and recreation. These forecasts are additionally useful for understanding potential toxin exposure for fish and other wildlife, and pets.

Development of forecasts of harmful algal blooms by USGS fits within our priorities to provide information on environmental health and protecting natural resources. Forecasting methods are currently in development in a partnership with the NOAA, EPA, and NASA. Further engagement with water managers is needed in order to better establish links into decision-making processes. Economy of scale is obtained from transferring success in one particular geography to a national scale. Forecasts will be scalable from individual water bodies with increasing efficiency of scale to the entire Nation.

State of the science.—The state of the science is currently fairly well understood for the detection of cyanobacterial blooms (cell abundance) using remote sensing. There is a significant body of knowledge on the limitation and applicability of remotely sensed data for these measurements (https://www.epa.gov/water-research/cyanobacteria-assessment-network-cyan). These well-established methodologies can be used for forecasting and over time (as technology allows) can be improved so that it is possible to forecast toxin occurrence and health effects. The Algal Toxins and Harmful Algal Bloom Science Team (https://www.usgs.gov/mission-areas/environmental-health/science/toxins-and-harmful-algal-blooms-science-team?qt-science_center_objects=0#qt-science_center_objects) in the USGS Environmental Health Mission Area is currently focused on toxin effects research and toxin production and control. This information is needed to extend the current capacity to include toxin and health-outcome forecasting.

The forecast process is represented in an existing, well-established EPA–NOAA–NASA–USGS model that can be adapted and improved and thus could accelerate forecast tool development. Model improvement is expected as advances of needed technology become available. The ability to forecast toxins and health effects (desired improvements) will be provided through current and planned research in the Algal Toxins and Harmful Algal Bloom Science Team.

We can anticipate iterative improvements in forecast skill and reduction in uncertainty as new data are collected and incorporated into the forecasting model. There are historical data available to synthesize and inform model structure and ongoing data collection that can improve the model.

Operational implementation.—The expected cost to operationalize forecast delivery includes approximately 5 to 10 FTEs of various expertise over a 5- to 10-year period. Cost to end user for instrumentation is about $10,000 to $20,000. The agreement for satellite imagery is currently covered.

The latency of the data streams needed to drive forecast models is appropriate to produce timely forecasts useful to management decisions.

Some nongovernmental entities, such as public drinking water suppliers, are potentially interested in adding value and disseminating forecasts. With appropriate disclaimers on the limitations of the science and the ongoing model, calibration, validation, and litigation risks could be minimized.

Value for improving decision support.—Coproduction of this model with forecast consumers will benefit from detailed considerations of mutual commitments.

Accurate and precise forecasts will enable managers to be proactive in communication of resource users, water delivery, movement, and containment. Forecasts provide information to managers so they make informed decisions and can be proactive, if needed, in closing recreational areas for human and domestic animal health protection. An accurate and precise forecast would correspondingly increase the ease of managing resources. The greatest improvement would be realized after achieving the ability to forecast toxin production and anticipate health effects given exposure.

Chronic Wasting Disease

Forecasting Product Name

Forecasting Chronic Wasting Disease (CWD) prevalence and resulting population-level effects to support harvest management and adaptive monitoring decisions

Desired Future State

Managers in State and Federal agencies will use this forecasting tool on an annual basis both to help establish harvest levels for game populations affected by CWD and to prioritize monitoring and data collection activities that will increase fundamental understanding of CWD and its effects.

Expected Outcome

As current beta-testing level models (see “product description” below) and forecasts are improved through close collaboration with State game managers, they will allow managers in State and Federal agencies to:

- Explore the implications of alternative harvest strategies on hunting revenues, ungulate populations, and CWD prevalence in affected areas and populations, and ultimately to use the results to help establish harvest levels, and
- Identify and execute cost-effective monitoring and data collection activities to improve understanding and reduce uncertainties in CWD prevalence and effects.

Model outcomes will include quantitative projections and predictions of the efficacy of future management actions and the sampling intensities required to document change in CWD dynamics. The tool will provide information to support the evaluation of alternative allocations of resources on data collection and adaptive monitoring approaches to reduce uncertainty in the model predictions through the explicit inclusion of cost estimates on different datastreams as well as management actions.

Expected Partners and (or) Collaborators

Multiple USGS science centers will contribute to modeling efforts (for example, USGS Cooperative Research Units, USGS Northern Rocky Mountain Science Center, NWHC). Model use and refinement will be codeveloped with State wildlife agencies, FWS, NPS, and BLM.

Expected Stakeholders

Hunters and the general public.

Product Description

Demographic and disease modeling have a long history of development and use (Bernoulli, 1760; Ross, 1911; Kermack and McKendrick, 1927; Leslie, 1945). Advances in statistical methodology and computing power allow for the incremental improvement of these model predictions over time and the incorporation of multiple datastreams. Recent and current developments in these modeling approaches include incorporating spatial components and optimal adaptive management (Garlick and others, 2014; Williams and Hooten, 2016; Hefley and others, 2017).

Demographic and disease models for CWD have been developed as an R package (Cross and Almberg, 2019) and are currently in beta testing for web deployment. As described at the link, the models are an early version of one potential formulation of a decision-support tool for natural resource managers interested in investigating different scenarios associated with CWD. In this version, a user specifies all the relevant parameters for deer and elk vital rates, hunting mortality, and disease transmission; then the model calculates and plots the total number of individuals, prevalence, age and sex distribution, and how many deaths were natural, were from hunting, or were CWD-related.

Further development of this model in close consultation with one or more decision-making partners could include the following phases:

Phase A.—Engage partners and tailor the models to best meet stakeholder needs and interests. Work with interested State fish and game managers to demonstrate the beta-testing model and engage in discussion about how they might use such forecasts and how the beta version could be modified to better suit their needs. For example, illustrate multiple scenario planning projections of the impacts of hunting regulations and predation on CWD dynamics over 5- to 10-year time horizons; work with State agencies to understand how harvest decisions and disease prevalence affect hunting revenues and hunter satisfaction, and incorporate those outcomes in the predictive model.

Phase B.—Update models using population-specific data and updated understanding of disease dynamics and illustrate decision recommendations. Work with interested State fish and game managers to integrate their State-level and sub-population-specific data into the model, enabling a shift from simulated scenarios with hypothetical populations to iterative predictions based on annually updated data under different scenarios. Use initial model runs to illustrate to the stakeholders how the forecast can be used to support harvest decisions, to identify the most important uncertainties, and to develop adaptive monitoring decisions.

Phase C.—Extend the forecasting models to include spatially explicit components, incorporating movement data. This will expand the potential uses of the model to enable assessment of the impacts of reducing artificial aggregations (resulting from irrigation, baiting, mineral licks) and how management actions in one region may affect another.

Evaluation Against Standardized Criteria

Demand and relevance.—The demand for and relevance of this forecast is rated as **high**. There is currently high interest from DOI and the Federal administration in CWD and in supporting State-level management of the disease. State wildlife agencies are likely to be the dominant users.

State of the science.—The state of the science to support this forecast is rated as **medium**. Modeling frameworks are well known and have been implemented in several systems. Population modeling parameters associated with deer and elk are also well known—counts and density information are collected, but sometimes with high uncertainty. Disease parameters, such as routes and rates of transmission, effects of host aggregation, environmental reservoir dynamics, in contrast, are not well estimated and are areas for future improvement. Forecasting skill may not improve rapidly owing to the slow temporal dynamics of the disease; however, additional environmental testing tools may improve modeling of the environmental reservoir. Historic and future data are and will continue to be collected to improve the model, although there are sometimes issues with the sharing of information across jurisdictions.

Operational implementation.—The ability to implement this forecast and make it operational is rated as **high**. As discussed above, demographic and disease modeling are well-established for wildlife populations, and beta-level models already exist for CWD. The vision of an annually updated model makes data latency and modeling effort of minimal concern. Historic and future data are and will continue to be collected to improve the model, and annual updates based on data will align well with management changes to hunting regulations.

Operational and implementation challenges do exist: sometimes policy barriers limit the sharing of information across jurisdictions, and there are past and current lawsuits against State and Federal agencies over the disease management in ungulates. For example, FWS is currently in litigation over the supplemental feeding of elk and the potential CWD impacts. Supplemental feeding also occurs on FS properties.

If these forecasts are applied in an adaptive management context, including implementation and monitoring of alternative management actions, it will accelerate learning, and the more refined models may evolve relatively quickly.

Value for improving decision support.—The value of this forecast to improve decision support is rated as **medium**. USGS is currently working with several State and Federal partners on CWD projects. These forecasting tools are likely to expand these partnerships into other regions where the USGS does not currently have active partnerships. The forecast can help structure the sampling necessary to evaluate management efficacy and provide a tool to facilitate an adaptive management conversation. This medium rating is based principally on the reality that State fish and wildlife agencies operate under many different pressures that may make it challenging for them to incorporate CWD forecasts fully into their planning processes. The practical, on-the-ground impact of these forecasts will be proven out over time.

Modeling Requirements

Phase A could be made more useful with the inclusion of economic considerations associated with the sampling regime. Phase B is currently in development in a few systems but may require more software development to make the models portable to other systems. Phase C may require additional science development in migratory systems where diffusion models may not be appropriate. Recent technical advances allow for faster statistical estimation of spatio-temporal diffusion models, but implementing these models in an interactive way may be challenging.

Data Requirements

Collected annually by State and Federal agencies:

- Deer and elk population counts
- Deer and elk movements
- Hunting levels
- CWD testing
- Economic costs of different datastreams

Some potential partners may prefer to develop their own approaches if they have the resources to build these models and analyze them internally.

Cyberinfrastructure Requirements

The models currently in beta testing are hosted internally on cloud hosting solutions; however, the security and maintenance costs of the application are currently borne at the science center level where there is limited support, expertise, and capacity. Future web applications are likely to need dedicated server capabilities within the USGS or there must be resources to pay for cloud computing.

Human Infrastructure Requirements

Capabilities are already present within the USGS but staff may be occupied with other activities. Enhanced liaison activities (1 FTE) would greatly expand the impact and reach of the forecasting tools.

Opportunities for Emergent Advanced Technologies

Similar to weather models, demographic and disease models have a long history of development and use. However, there is opportunity for incremental improvement of these models through the inclusion of additional covariates, accounting for regional difference, reduced parameter uncertainty, and the ability to incorporate ensemble modeling techniques. The backbone of these models could have application to many other systems, including migratory birds, T&E species, and species of management concern.

References Cited

Bernoulli, D., 1760, Reflexions sur les avantages de l'inoculation: Mercure de France (Paris), p. 173–190, accessed May 12, 2020, at http://cerebro.xu.edu/math/Sources/DanBernoulli/1760_reflections_inoculation.pdf. [Reprinted in L.P. Bouckaert, B.L. van der Waerden (eds.), Die Werke von Daniel Bernoulli, Bd. 2 Analysis und Wahrscheinlichkeitsrechnung, Birkhauser, Basel, 1982, p. 268)].

Cross, P.C., and Almberg, E.S., 2019, CWDsims—An R package for simulating chronic wasting disease scenarios: U.S. Geological Survey data application accessed May 13, 2020, at https://doi.org/10.5066/P9QZTTLY.

Garlick, M.J., Powell, J.A., Hooten, M.B., and MacFarlane, L.R., 2014, Homogenization, sex, and differential motility predict spread of chronic wasting disease in mule deer in southern Utah: Journal of Mathematical Biology, v. 69, no. 2, p. 369–399, accessed June 10, 2020, at https://doi.org/10.1007/s00285-013-0709-z.

Hefley, T.J., Hooten, M.B., Russell, R.E., Walsh, D.P., and Powell, J.A., 2017, When mechanism matters—Bayesian forecasting using models of ecological diffusion: Ecology Letters, v. 20, no. 5, p. 640–650, accessed June 10, 2020, at https://doi.org/10.1111/ele.12763.

Kermack, W.O., and McKendrick, A.G., 1927, Contributions to the mathematical theory of epidemics—I: Proceedings of the Royal Society of Edinburgh, v. 115A, p. 700–721, accessed June 8, 2020, at https://www.sciencedirect.com/science/article/abs/pii/S0092824005800400.

Leslie, P.H., 1945, The use of matrices in certain population mathematics: Biometrika, v. 33, no. 3, p. 183–212, accessed June 10, 2020, at https://doi.org/10.1093/biomet/33.3.183.

Ross, R., 1911, Some quantitative studies in epidemiology: Nature, v. 87, no. 2188, p. 466–467, accessed June 10, 2020, at https://doi.org/10.1038/087466a0.

Williams, P.J., and Hooten, M.B., 2016, Combining statistical inference and decisions in ecology: Ecological Applications, v. 26, no. 6, p. 1930–1942, accessed June 10, 2020, at https://doi.org/10.1890/15-1593.1.

Early Detection of Invasive Species

Forecasting Product Name

Forecasting invasive species suitability and spread to support Early Detection and Rapid Response (EDRR)

Desired Future State

Management agencies use spatially explicit forecasts of invasive species distribution and spread to inform treatment, containment, and eradication efforts.

Expected Outcome

Ecological forecasts will improve the cost-effectiveness of invasion management and reduce the ecological, economic, and public health impacts of invasive species.

Expected Partners and (or) Collaborators

National Park Service, Bureau of Land Management, U.S. Fish and Wildlife Service

Expected Stakeholders

Invasive species managers, natural resource managers, State and local partners, including Cooperative Weed Management Areas, policymakers

Product Description

Early Detection and Rapid Response (EDRR) to invasive species provides cost-effective mechanisms to protect biological resources. At local, regional, and national scales, managers must prioritize surveillance and management actions to reduce the long-term costs of harmful invaders. Although the ability to eradicate and contain invasive species is greatest early in the invasion process, managers lack tools to anticipate where a problematic invader is likely to spread. Models that integrate environmental conditions with pathways of natural and human-mediated spread can guide risk assessments and decisions about where to direct monitoring efforts. The USGS is currently investing in habitat-focused tools to deliver model outputs to DOI agency partners. Extending such tools to better incorporate spread mechanisms and provide iterative predictions that account for spread over time would enable rapid and systematic management responses. Delivering spatial information on invasion risk in a user-friendly and consistent format across taxa would be relevant for local targeting of management responses and regional and national planning. These forecasts effectively build on existing USGS expertise and investments, as well as on established management partnerships.

Evaluation Against Standardized Criteria

Demand and relevance.—Resource managers oversee large areas with multiple mandates; it is universal that the capacity to monitor conditions across an entire landscape is unrealistic. Invasive species can therefore get a toehold in a given region or management unit, and practitioners may not become aware of the infestation until the invasion is well underway. This problem is faced by all Federal land management agencies, as well as by State and local partners, and applies to terrestrial, freshwater, and marine systems.

Predictive models have been effectively used to target local survey efforts for invasive species, but these have three common limitations. First, models have been developed for a relatively narrow set of invasive organisms, including Dreissinid (zebra) mussels (*Dreissena polymorpha* [Pallas, 1771]), forest pests, and plants. It is the success of several of these models that underlies the demand for information for a broader set of taxa from management partners. Second, models are rarely embedded in user-friendly decision support tools. This has limited their utility to a subset of savvy and highly engaged partners, whereas there exists a much broader management community whose decisions could be informed by predictive knowledge. Finally, models are often one-off products, which quickly become outdated in the face of dynamic invasions.

The iterative nature of ecological forecasting (EF) aligns with the need for consistently updated predictions that incorporate recent patterns of invader spread, as well as ongoing changes to human land use and invasion pathways. Ecological forecasting of invasive species spread would inform decisions at multiple scales, from surveillance efforts within management units to risk assessments at regional and national scales. This information could guide the allocation of scarce resources to improve management effectiveness and efficiency.

USGS is well poised to support EF of invasive species spread. The Department of the Interior has identified EDRR as a critical priority and has developed an implementation framework (U.S. Department of the Interior, 2016). The USGS Invasive Species Program supports a network of USGS scientists with expertise across a breadth of invasive taxa and with established partnerships with management partners relevant to those taxa. The operational capacity for developing iterative ecological forecasts can be effectively supported by USGS Core Science Systems (CSS). Examples of collaborative efforts across USGS mission areas focused on invasive species prediction already exist. For example, USGS scientists are actively collaborating with NPS, BLM, and FWS partners on the development of the INHABIT (Invasive Species Habitat Tool) model delivery and communication tool, leveraging support from both the USGS Ecosystems Mission Area and CSS. This tool is being designed to deliver iterative predictions within a user-friendly online interface, and currently focuses on invasive plants. Extending USGS science support capacity for invasive species to a wider array of taxa, such as additional plant species and insects, could inform a broader array of partners. Model development could also include more mechanistic incorporation of spread pathways where information is available. Where available, information on invader abundance could also enhance predictions of spread by accounting for propagule pressure and could underlie inferences regarding patterns of an invader's impact.

State of the science.—Modeling suitability and spread of invasive species is well developed and there exists considerable expertise within Federal agencies, including the USGS and the USDA. Modeling approaches also can have much in common with those used in epidemiology—an area with substantial investment and success. Model development occurs along a continuum from species-specific mechanistic models of spread rates and patterns to simple correlative approaches that estimate habitat suitability across space. This continuum reflects variation in the level of information available for each invasive species; for example, mechanisms of spread are well known for some taxa and poorly known for others. Pathways of spread also differ in their predictability. Predicting where a species is likely to spread is often achievable and readily improvable through iteration, whereas predicting the precise rate of spread and timing of arrival to a specific locality may be less reliable and more subject to circumstance.

There is potential for operational and delivery tools to incorporate outputs from across the continuum of information availability and model complexity. For example, a common interface for communication and use could be developed and leveraged by different projects focusing on different species but producing outputs in a standardized format. The frequency of forecast iterations can be varied among species to reflect differences in spread rates and the timelines of management planning. Model development can leverage existing databases within the USGS (for example, Biodiversity Information Serving Our Nation [BISON]), partner Federal agencies (for example, National Invasive Species Information Management System [NISIMS], Assessment, Inventory, and Monitoring [AIM], Refuge Lands Geographic Information System [RLGIS]), non-Federal partner organizations and citizen science efforts (for example, Early Detection and Distribution Mapping System [EDDMapS], iNaturalist, iMapInvasives). The INHABIT tool provides an example of how these databases can underlie an iterative and automatable workflow that feeds into a codeveloped website for dissemination of model outputs.

Developing predictions beyond a species' existing range boundaries, and under new environmental conditions, can be challenging and is inherently difficult to validate. However, the field of invasion biology has had important successes even under these conditions, and quantitative and spatially explicit predictions provide information to move decision making beyond ad hoc approaches. Coproduction of models and model delivery platforms between scientists and managers is critical for establishing the partner engagement that will lead to model validation with locally collected data, which provides a basis for iterative model improvement. The taxonomic scope of an invasion-focused EF initiative by the USGS is potentially wide, with relevance for problematic invasive species across terrestrial, freshwater, and marine biomes.

Operational implementation.—Operationalizing forecast delivery for predicting invasive species spread is attainable in relatively short timeframes. Scientists can draw from established modeling approaches, existing spatiotemporal datasets on environmental conditions, and established digital databases of species records. Invasive species are a priority issue for many managers, and management agencies have established partnerships both among agencies—for example, the Federal Interagency Committee for the Management of Noxious and Exotic Weeds—and with local partners with which to share new tools and approaches. The dynamic nature of species invasions and the huge ecological and economic costs they impose means that decisions regarding surveillance and treatment are frequently revisited (for example, on an annual basis). There is an eagerness among managers and planners to work as codevelopers by providing regularly updated information on spatial distributions and other attributes of invasions, and to work to iteratively improve model delivery interfaces, as well as the underlying predictive information.

The INHABIT project illustrates the feasibility of forecasting the distribution and spread of invasive species; this project developed species distribution models and an online model delivery platform in less than 1 year for a number of plant species, using programming and data science infrastructure to allow for iterative model updates. INHABIT is being codeveloped by managers from the USGS, NPS, FWS, and BLM, with management agencies outlining project goals and deliverables, providing feedback on the usability of the online tool, and testing the tool in field applications. Managers are actively engaged in promoting the tool through their established networks.

Value for improving decision support.—Invasive species managers frequently cite the need for better EDRR tools as a priority. Land management agencies do not have the capacity to survey all resources that fall within their jurisdictions. Forecasting tools help them to target their efforts towards those locations where new incursions are most likely to occur. The willingness to both develop and use such tools has been expressed in the past, as evidenced by the increasing number of invasive species mapping and risk assessment tools that continue to be made available (for example, EDDMapS and the USDA Forest Service 'Alien Forest Pest Explorer' tool). In fact, USGS, NPS, FWS, and BLM managers have all played an active role in codeveloping and testing the INHABIT tool. Stakeholders have expressed interest in using

INHABIT to help them manage invasive species infestations more effectively, and they continue to provide input to help improve it. Further, codevelopers and stakeholders have requested that additional species be modeled for inclusion in the INHABIT tool.

Not only would invasive species suitability and spread forecasting improve the effectiveness of control efforts, but it would also improve the abilities for researchers and managers to apply adaptive management. The forecast would allow for regular input of new species occurrences and updating of habitat conditions. Additionally, models could be updated as better data and new technologies become available. This iterative process will help managers adjust their control and monitoring efforts as new data becomes available and conditions change on the ground. Further, the forecast would be able to identify changes more quickly than managers are capable of doing on the ground for all lands under their jurisdiction.

Modeling Requirements

The USGS has the capability to develop models for predicting species distributions and spread. Modeling requirements will depend on the type of model, the spatial resolution, and the amount of available data. Natural history knowledge and data availability are generally more limiting than the modeling requirements. Established open-source resources are available for model development; particularly, those in R. Stan and TensorFlow are examples of other software for Bayesian statistics and deep learning, respectively, for which there are R interfaces. The USGS has developed the Software for Assisted Habitat Modeling (Morisette and others, 2013), which provides a graphical user interface to species distribution modeling tools in R. Other such interfaces are also available (for example, Kass and others, 2018).

Data Requirements

Forecasts for each species will require, at a minimum, occurrence information and data on conditions underlying habitat suitability, such as climate, weather, land cover, and disturbance history. Occurrence data exists for many species and is maintained in a number of readily accessible databases, including EDDMapS, iMapInvasives, BISON, NISIMS, and RLGIS. Spatial data layers representing ecological conditions known or hypothesized to limit species distributions are used as predictors in suitability models. Meteorological data are widely available, and efforts have been made to represent attributes of climate and weather that are physiologically relevant to study organisms (for example, metrics of water balance). Land cover data are of reasonable quality and resolution across the United States and continue to improve with advances in remote sensing. Soil data are generally poorer in quality. It is important to use species' natural history to guide selection of predictor variables, both for suitability and for spread.

Data availability for modeling pathways of spread may be more limiting than for modeling suitability, and estimates of species dispersal capability are generally poorly known. Long-distance dispersal of problematic invaders is often human-mediated, and there are opportunities to develop credible predictions based on human activity patterns. It may be necessary to compile datasets to support such predictions, such as a nationwide database of trails. Iterative modeling provides an opportunity to improve our knowledge of vectors of spread.

Cyberinfrastructure Requirements

Collaboration between the USGS Ecosystems Mission Area and the Core Science Systems Mission Area would enable a forecasting initiative to leverage existing USGS resources. Computing resources and website development and hosting are two important areas for collaboration. The INHABIT project provides an example of one such collaboration. This project used a Shiny app, created using the R software system, to deliver model outputs. A streamlined process for USGS hosting of Shiny apps is likely to be important to multiple EF applications, and would also facilitate communication of USGS research more broadly.

Human Infrastructure Requirements

Dedicated personnel will be necessary for the success of any EF initiative. For example, forecasts based on simple or existing ecological models might require one or more full-time mid-level data scientists (for example, GS–9 or higher), whereas a forecast based on more complex methods may require both a data scientist and a PhD-level researcher (for example, a postdoctoral fellow), in addition to investments of time by USGS principal investigators. Social scientists and project facilitators would benefit any major initiatives. Note that these staffing levels are just examples; complex projects may require more resources. Commitment to staffing development and support positions for multiple years will be necessary to achieve the benefits of iterative forecasting. Attention should be given to the long-term maintenance of forecasting workflows.

Opportunities for Emergent Advanced Technologies

Forecasts to inform EDRR efforts are likely to draw from advanced statistical methods, such as machine learning and Bayesian statistics. Opportunities exist to integrate deep learning and other advances in computer science and statistics. Input data may also draw from advanced technologies, for example by using environmental DNA (deoxyribonucleic acid) to survey for focal taxa, or through the use of advanced remote sensing to derive predictor layers.

Summary of Resource Requirements

Expertise in data science will be critical for efficient and automated forecasting. Most USGS researchers do not have the expertise to develop forecasting workflows, nor the time. It will be important to hire dedicated programmers and to learn from forecasting initiatives outside the agency.

Timeline With Milestones

Timeline will vary with goals, resources, and study systems.

Examples of Existing Forecasts and Relevant Citations

National EDRR Framework:

- “Safeguarding America’s Lands and Waters From Invasive Species—A National Framework for Early Detection and Rapid Response” (https://www.doi.gov/sites/doi.gov/files/National%20EDRR%20Framework.pdf).

INHABIT project example of existing USGS capacity and investment:

- Beta-testing version: (https://engelstad.shinyapps.io/sandbox/)
- Permanent link (https://gis.usgs.gov/inhabit/dashboard_dev.rmd)

Current public-facing INHABIT tool website with the same content:

- https://engelstad.shinyapps.io/dashboard_dev/

Examples of invasive species mapping tools with interfaces designed for use by management, emphasizing maps of current distributions rather than forecasts:

- USGS BISON (not invasion specific)
- EDDMapS
- USDA Forest Service ‘Alien Forest Pest Explorer’ (https://www.nrs.fs.fed.us/tools/afpe/)

References Cited

Kass, J.M., Vilela, B., Aiello-Lammens, M.E., Muscarella, R., Merow, C., and Anderson, R.P., 2018, Wallace—A flexible platform for reproducible modeling of species niches and distributions built for community expansion: Methods in Ecology and Evolution, v. 9, no. 4, p. 1151–1156, accessed June 10, 2020, at https://doi.org/10.1111/2041-210X.12945.

Morisette, J.T., Jarnevich, C.S., Holcombe, T.R., Talbert, C.B., Ignizio, D., Talbert, M.K., Silva, C., Koop, D., Swanson, A., and Young, N.E., 2013, VisTrails SAHM—Visualization and workflow management for species habitat modeling: Ecography, v. 36, no. 2, p. 129–135, accessed June 10, 2020, at https://doi.org/10.1111/j.1600-0587.2012.07815.x.

U.S. Department of the Interior, 2016, Safeguarding America’s lands and waters from invasive species—A national framework for early detection and rapid response: Washington, D.C., U.S. Department of the Interior, 55 p., accessed June 10, 2020, at https://www.doi.gov/sites/doi.gov/files/National%20EDRR%20Framework.pdf.

Coastal Marsh Erosion

Forecasting Product Name

Forecasting erosion and deterioration of marsh seaward edges, interior marsh plains, and upland marsh migration in the face of sea-level rise

Desired Future State

Coastal planners and coastal wildlife refuge managers use probabilistic forecasts of marsh susceptibility to deterioration to inform marsh restoration and living shoreline placement. Forecasts and projections of upland marsh migration potential inform land management decisions that facilitate migration in the face of sea-level rise. In the future, coupling of marsh deterioration and migration potential forecasts with waterbird energetics models may inform estimates and forecasts of waterbird carrying capacity.

Expected Outcome

Limited resources are more effectively allocated to marsh restoration efforts and living shoreline placements in locations with the greatest probability of success. Probabilistic predictions of coastal shoreline change will inform the work of environmental planners and community leaders, helping them set evidence-based expectations and develop plans for sustainable coastal communities.

Expected Partners and (or) Collaborators

FWS, NPS, NOAA, EPA, State natural resource agencies, NGOs

Expected Stakeholders

FWS refuges, NPS, State natural resource agencies, NGOs, coastal communities

Product Description

Annually or event-based updated estimates of coastal marsh condition and erosion and (or) deterioration probability will be delivered at desired scales (for example, 30-meter pixel, marsh unit, coastal embayment). Model output will include physical map layers of seaward-edge vulnerability to wave erosion and overall marsh vulnerability to sea-level rise and shoreline erosion. These outputs can be used to develop probabilistic ecological forecasts of potential change in habitat or disturbance, and likelihood of landward transgression. Focal-area models can be nested within a regional model supported by broader synoptic information and remote sensing data (for example, LiDAR). Linking detailed observations in focal areas with remote sensing data will enable the application of widely available remote sensing data to drive forecasts over broader spatial extents.

Evaluation Against Standardized Criteria

Demand and relevance.—**High.** Forecasts will be used by refuge managers and local governments. Coastal wetland managers and environmental planners are requesting information on shoreline response to sea-level rise, as well as to changes in the magnitude and frequency of storms, to support siting of marsh restoration and living shoreline projects. Marshland evolution projections will also inform estimates of carrying capacity for waterbird and shorebird populations. Existing Federal, State, and local interagency partnerships in focal study areas can be leveraged to support development of forecasts of shoreline erosion and indicators of marsh vulnerability. Marsh vulnerability and coastal erosion science are directly related to Bureau, Departmental, and Administration priorities, and there are precedents for USGS authority to develop and deliver such forecasts.

State of the science.—**Relevant knowledge is high** for seaward marsh edge erosion (1 to 2 years), **moderate** for interior marsh plain deterioration (2 to 3 years), and **low** for upland marsh migration (5 years).

Driving variables, such as current water levels and erosion rates, wave climate, turbidity, salinity, and temperature trends, and submerged aquatic vegetation distribution and abundance, are readily available for Chesapeake Bay and, along with current mapping and modeling efforts and sea-level rise projections, can support a marsh edge erosion forecast in 1 to 2 years if additional resources are added.

Simplistic models extrapolating the unvegetated to vegetated marsh ratios that will be generated in the next 2 years can support a marsh deterioration forecast in 2 years given additional resources. A next-generation kalman filter-based forecast model would require more resources but would take greater advantage of multiple data streams and would provide more robust forecasting and uncertainty estimates.

Developmental work to clarify data collection and modeling requirements for upland marsh migration forecasting is in its early stages. Migration potential is a function of susceptibility to salinity intrusion, elevation gradient, and available forest-marsh edge for migration (that is, current and projected land use). Pilot efforts to integrate available data streams with new data collection and fine-scale modeling in a small number of Chesapeake Bay sub-embayments are underway.

Existing process and empirical models can be leveraged to develop and improve marsh erosion, deterioration, and migration forecast models, and the iterative process will improve existing system models. More modeling development is needed to generalize site-specific measurements and models from study areas to additional locations where management decisions are needed. Core parameters for tracking change and informing best practices are currently being designed and tested. Model design is targeted towards selecting locations for best management practice implementation. Rapid improvements in forecast skill are anticipated.

Operational implementation.—To operationalize an annual forecast of all three processes for marshes along the U.S. east coast would require about 0.5 to 0.75 FTE for each of three roles: a geospatial expert, a modeler capable of running wave models and hydrodynamic models, and an information specialist to support metadata and portal delivery. An annual forecast for the entire Nation would require a full-time dedicated team of three to four people. The estimated total cost per year for an annual forecast ranges from about $200,000 (east coast) to about $400,000 (Nation).

While marsh forecast models would be developed by building on existing real-time coastal wave and storm surge models, the management decisions targeted here do not require hourly-to-daily output. Management decisions likely occur on the scale of 2 to 5 years. The latency of additional data streams needed to drive marsh forecast models is approximately seasonal-to-annual, which is short enough to produce timely forecasts useful to management decisions. Event-based forecasting can also inform immediate and longer term best practice for mitigation or restoration management actions.

Nongovernmental entities such as The Nature Conservancy and collaborating academic institutions would be interested in adding value and (or) disseminating the forecast.

With the proper disclaimers communicated, there is little-to-no anticipated litigation risk related to disseminating and using these forecasts for decision making. As described above, forecast products can be delivered in a format and structure needed by resource managers.

Value for improving decision support.—Potential forecast producers and consumers have expressed interest in developing and using forecasts in a coproduction format. The process has the potential to enhance and support manager-researcher partnerships and adaptive decision making. There is currently no alternative source of this information. Managers currently lack information needed to decide which marshes to give up on and where to plan for migration, sustaining in place, or establishment of new marshes and wetlands. Cost savings could be substantial if managers knew where to focus limited resources.

Modeling Requirements

The COAWST model is slowly being applied to parts of the northeast coast as funding allows. The model, when linked with U.S. Army Corps of Engineers Hydrologic Engineering Center's River Analysis System modeling of river flooding predicts compound flood levels, storm surge, and sediment transport for predicting rapid disturbance scenarios. Probabilistic sea-level rise projections based on enhanced LiDAR data on coastal elevation and vertical land movement have improved estimates of likely future inundation levels. Sediment transport modeling at river outflows and nearby marshes provides better predictions of where marshes can accrete to keep up with sea-level rise. These models and others in development provide a hydro-dynamic framework for forecasting ecological response.

Concurrent research and model development on SAV, black ducks, migratory waterbirds, and fish is allowing improved understanding of ecological thresholds and vulnerabilities that in combination with the physical habitat forecasts can be applied for iterative EF of coastal marsh and forest habitat resilience.

Data Requirements

Iterative ecosystem forecasting for coastal environments requires physical, chemical, and biological data relevant to the whole system; full-life-cycle habitat characterization; and understanding of risks, vulnerabilities, and resilience of target biological resources. Historical data are available but need integration across spatial (multiple marshes) and temporal scales. Monitoring of some core parameters, such as LiDAR, are periodically updated. Whether periodicity is consistent with management need depends on timing of flights versus disturbance events. If processed LiDAR data are available, the Total Water Level and Coastal Change Forecast Viewer can produce forecasts of storm effects on a scale of hours. Established monitoring of some core parameters for marsh migration forecasts is still aspirational.

Additional considerations relevant to data requirements include the following:

- Annual mapping of marsh edges would require 1 FTE dedicated to LiDAR processing, with application of a new method for finding marsh scarp with errors of 5 to 50 cm. Because typical erosion rates at vulnerable marshes are often on a scale of 2 meters per year, these data would be sufficient to forecast erosion probability for the annually updated marsh deterioration forecast models described above. The same FTE could provide the frequent LiDAR processing required for near-term modeling of storm surge to support storm-specific erosion forecasts.

- The Google Earth engine and algorithms that will be published as part of currently funded work will require ongoing operational maintenance. Running algorithms through Google Earth, processing, metadata production, and publication in Science Base would require annual dedication of about 0.25 FTE.

- A real-time storm surge network is important for marsh migration forecasts, but the level of sampling intensity required to support fully data-driven forecasts is unlikely. A network sufficient to provide calibration data, especially for extreme events, may effectively support scenario-based projections.

- Additional required data streams include periodic marsh habitat characterization, marsh elevation, and erosion and sedimentation rates at strategically selected sentinel sites.

Cyberinfrastructure Requirements

The high-performance computing needed to run some of the models involved and to handle the large volume of supporting data streams would best be served by cloud-hosting. This would also enable wider access to the data for other projects. The alternative scenario—hosting data and models on local machines and clusters in specific offices—is less valuable.

The USGS Coastal and Marine Hazards and Resources Program has a data portal that could be enhanced as needed to accommodate and deliver access to multidisciplinary data on costal environments. The portal includes some modeling and derived data capabilities for support of varied interpretive efforts. The modeling for inundation and erosion from compound flooding does not require real-time or high-performance computing, greatly enhancing the utility of the model for event-based management decisions and iterative forecasts.

Human Infrastructure Requirements

Development of the coastal ecosystem forecasting capability will initially require dedicated staff to meet program development timelines, maintain relationships with partners (that is, NOAA, EPA, FWS, State agencies, and so forth) and coordinate project outcomes and dissemination. Field teams for periodic measurements and rapid deployment of sensors for forecasting the effects of storms can be assembled from existing field staff, with a few additional staff to compensate for an increased annual workload.

A team of four to five people, deploying the same methods for the east coast that the group has validated in the Chesapeake, could develop an east coast model in 1 year. To produce a forecast annually at the national scale would require a standing four-person team.

Opportunities for Emergent Advanced Technologies

Several advances in sensor technology, both for in situ, remote, and transitory measurements, have created new opportunities for improving forecasting capacity.

Opportunities exist to improve airborne LiDAR estimates with correction equations for marshes. Developing better sensors and methods for marsh edge delineation and open-water conversion would be useful.

Summary of Resource Requirements

The addition of 1 FTE to the ongoing 3-year Chesapeake Bay marsh vulnerability characterization and modeling project would enable development of a marsh erosion and deterioration forecast for Chesapeake Bay in 1 to 2 years. Extension to an operational annual forecast for the entire east coast would require the dedicated equivalent of 2 to 3 FTEs, spread across three areas of expertise. Forecasts would be best supported with cloud-based hosting of data and models.

Timeline With Milestones

Building on a Chesapeake prototype, the following is a timeline to develop an East Coast forecast with no Kalman filter modeling:

- Year 1: Build data layers and produce three static maps that document current state of coastal marsh shorelines, and that the maps will be used to inform projections.
- Years 2 to 3: Incorporate data and mechanisms into the Coupled Ocean Atmosphere–Wave–Sediment Transport (COAWST) coastal response model. Run additional wave scenarios under varying sea-level rise to estimate changes in seaward edge erosion. Use linear extrapolation for a simplistic forecast of internal marsh disintegration based on current open-water status.
- Years 3 to 4: QA/QC and publishing, while doing updating for the next year.
- Year 4 and onward: Operational mode.
- Year 5: Start building newer models of processes that don't require the same investment of time and resources (that is, proxies). Research, synthesis, synthesizing emergent insights on spatial patterns to guide next generation of modeling.

Examples of Existing Forecasts and Relevant Citations

Marsh erosion and deterioration—and eventually migration—forecasts will be built on existing experimental and operational coastal change forecast and scenario simulation models. Examples include the following:

- The COAWST modeling system is composed of the Model Coupling Toolkit to exchange data fields between the ocean model ROMS, the Weather Research and Forecasting model, the Simulating Waves Nearshore model, and the sediment capabilities of the Community Sediment Transport model. This formulation builds upon previous developments by coupling the atmospheric model to the ocean and wave models, providing one-way grid refinement in the ocean model, one-way grid refinement in the wave model, and coupling on refined levels (Warner, 2010).
- An experimental "Total Water Level and Coastal Change Forecast" model has been developed for several regions along the U.S. east coast by the USGS National Assessment of Coastal Change Hazards project, in collaboration with NOAA, and is viewable online. The experimental forecast combines NOAA wave and water level predictions with a USGS wave runup model and beach slope observations to provide a probability of dune erosion, overwash, and inundation and (or) flooding. Forecasts are typically updated daily and sometimes multiple times per day.

- A spatially explicit, probabilistic model of coastal response for the northeastern United States to a variety of sea-level scenarios has been developed. Model results (in the form of Geographic Information System layers) provide a prediction of the distribution of adjusted lane elevation ranges over a large spatial scale, with respect to predicted sea-level rise for the 2020s, 2030s, 2050s, and 2080s.

Reference Cited

Warner, J.C., Armstrong, B., He, R., and Zambon, J.B., 2010, Development of a Coupled Ocean-Atmosphere-Wave-Sediment Transport (COAWST) modeling system: Ocean Modelling, v. 35, no. 3, p. 230–244, accessed June 10, 2020, at https://doi.org/10.1016/j.ocemod.2010.07.010.

Phenology and Migration Hotspot Forecasting

Forecasting Product Name

Phenological forecasts

Desired Future State

Forecasts for management-relevant seasonal events in plants and animals, delivered at the geographic extent, spatial and temporal resolution, and in the appropriate formats to support and enhance management decisions by a wide range of stakeholders. A wide range of decision makers reference these forecasts prior to planning or taking management action.

Expected Outcome

Managers reference and use forecasts of phenological events and migratory hotspots to avoid costly choices. High-risk–high-value decisions are informed by predictions of key events.

Expected Partners and (or) Collaborators

Potential partners include NOAA, BOEM, NPS, and universities.

Expected Stakeholders

Stakeholders include USGS science centers and partners, the FWS, NPS, BLM, USFS, NOAA, BOEM, EPA, State extension agents, Tribal Nations, the general public, and private industry, notably arborists, forest managers, maple syrup producers, small farms, and so forth.

Product Description

Phenology refers to the timing of seasonal events in plants and animals, including events such as leaf-out, flowering, migration, and egg hatch. This broadly themed prospectus considers a wide range of phenological events that could be forecasted to support and inform management decisions. Great opportunity exists to build from several existing, operational phenology forecasts and recent research advancements.

The examples mentioned in this prospectus are simply demonstrative of some of the ways that phenology forecasts can be of use. These examples do not reflect our recommendation for forecasts that should be operationalized.

Forecasts at a single location.—These are site-specific decisions where actions are taken based on the timing of biological events. Typically, there is uncertainty regarding the timing of onset and end of the events and there are costs, risks, and (or) benefits to matching the timing of the management to the biological event. Forecasts of this nature are particularly useful in cases of competing resource uses. Examples of such decisions, and the associated valuable forecast are shown in table 3–1.

Forecasts across a region.—These are decisions where actions are taken based on location (or colocation) of species, biological events, and noncompatible human impacts and locations of human activities and uses must be decided dynamically to minimize unintended consequences to resources (or maximize uses of those resources). Decisions are dependent on understanding and protecting locations of concurrent or recurrent conservation-relevant phenological events across species. Examples of such decisions, and the associated valuable forecast, are shown in table 3–2.

Table 3–1. Management decisions and types of phenological forecasts for a single location that could assist managers in making these decisions.

Decision	Forecast
Scheduling use restrictions (hunting, fishing seasons)	Presence and (or) abundance of key wildlife and (or) fish species
Wildlife viewing	Presence and (or) abundance of key wildlife and (or) fish species
Area closures to protect key species	Timing of breeding in key species, such as ground-nesting birds, turtles, and so forth
Light restrictions to protect turtles during the hatching season	Turtle hatch
Timing and stock sizes of grazing activities	Timing and magnitude of grass green-up
Seasonal visitation to individual management units or site-specific cultural events, such as wildflower viewing, fall leaf peeping	Timing of flowering, leaf color change

Table 3–2 Management decisions and types of phenological forecasts at regional scales that could assist managers in making these decisions.

Decision	Forecast
Location of shipping lanes and fishing (or gear) restrictions to minimize noise impacts and other adverse consequences of human activity on aquatic animals	Location(s) of sensitive migratory species over the course of the season
Drawing boundaries between polar bear populations	Sea ice extent over the course of year
Location of polar wetland gas leases	Sea ice extent over the course of year; Location of key animals (bowhead whales beluga whales)
Dam operation	Salmon migration
Identification of areas to maximize opportunities for wildlife viewing, bird watching	Timing and location of key animal species over the course of the season (national scale)
Seagrass cover (an essential ocean variable)	Seagrass leaf out, flowering
Turning off offshore wind turbines to reduce collisions with migrating bird (and other) species	Timing and location of migratory birds (and other species) in locations of wind turbines
Offshore energy development—timing and location	Timing and location of wildlife, particularly migratory species
When to treat for invasive plant species, especially for species with a specific time to treat in the life cycle	Phenological status of species

Evaluation Against Standardized Criteria

Demand and relevance.—The need for advance warning of seasonal events in plants and animals, such as the timing and location of migrations in seabirds and marine mammals is acute. Such forecasts have the potential to improve many facets of natural resource management.

State of the science.—Approaches to predicting phenology have been evolving over many decades. Many deterministic phenology models exist, especially for plant life cycle events (for example, Basler 2016). There is generally a paucity of dynamical phenological models, however, although efforts to apply state-space approaches to phenology are emerging (for example, Viskari and others, 2015; Elmendorf and others, 2019). The advantage of a probabilistic, hazard model approach (Lin and Zhu, 2012) over the traditionally implemented deterministic, threshold-based approaches is that the probability of a state change (that is, switching from ‘not in flower’ to ‘in flower’) can be estimated conditionally on the state having not yet changed (Viskari and others, 2015).

In general, simple threshold-based approaches will be less expensive to develop and implement; however, uncertainty is more difficult to quantify in these approaches, and precision may suffer. The tradeoff for higher precision will likely be higher costs (including financial, time, and data requirements) of model development and operationalization. Costlier, more precise approaches may be merited in high-risk applications, however. Implementing ensembles of models is another approach that is taking root and showing improved performance over individual models (for example, Abrahms and others, 2019).

Connecting survey and telemetry data on moving populations (for example, Williams and others, 2017) and individual animals (for example, Hooten and others, 2017) to phenological processes is a critical area of future research. Formal statistical models that can combine multiple data sources and improve inference of responses to phenology are essential for modern management, monitoring, and conservation agencies and programs. Methodological developments are currently being initiated in this area (for example, Scharf and others, 2019), which is ripe for future breakthroughs, with an increasing emphasis and support for forecasting in agency priorities. Understanding animal migrations with contemporary statistical methods is a critical element in connecting ecological and environmental phenological processes (Buderman and others, 2016; Hooten and others, 2018).

There is a great deal of room for growth in this realm. A smart first step would be to undertake a thorough literature review and document existing efforts as well as to catalog available datasets. It will be critical to stay abreast of emerging phenology modeling efforts and efforts to characterize the current state for observed and modeled variables.

Operational implementation.—Many phenological events can be integrated into a modeling framework to generate forecasts. The cost of developing and implementing a forecast is the function of many variables, including the costs of collecting input data, developing and validating a model, and implementing and operationalizing a forecast. These costs need to be evaluated against the potential gain that might be made by implementing the forecast in a decision-making context.

Value for improving decision support.—Land managers are faced with a great diversity of decisions to make, and those decisions can be improved with forecasts of the timing of seasonal life-cycle stages in plants and animals. For example, advance warning of where and when birds will migrate could inform when to temporarily turn off wind turbines when birds are present to minimize bird deaths while maximizing energy generation. A knowledge of when ground-nesting birds are nesting can narrow the window of beach closures. Understanding of marine mammal migrations can improve shipping lane designations and fishing restrictions. The additional information provided in forecasts has the potential to minimize negative impacts to managed resources, improve efficiencies, and save money.

Modeling Requirements

Dependent upon the specific species event to be forecasted. In some cases, functional models exist (for example, growing degree day thresholds indicating developmental stages in insects [Herms, 2004; Murray, 2008]). In other cases, much work remains to be done to identify the drivers and develop a model that could be used to predict the event.

Data Requirements

Dependent upon the species and event of interest.

Cyberinfrastructure Requirements

Dependent upon the species and event of interest.

Human Infrastructure Requirements

Coordination between the USGS and other agencies is strongly encouraged to gain efficiencies. For example, in applications involving marine migratory species, the BOEM and NOAA are apt partners.

Prior to the work necessary to create and implement forecasts, human resources would be required to evaluate, prioritize, and select among the many potential ecological forecasts that could be generated.

If this effort is to be sustained and grown, one activity one would want to develop is an active and facilitated community of practice in developing forecasts based on phenology and potentially focused on the concept of species migration networks. This could be facilitated through the USGS Community for Data Integration within the Earth Science Themes Working Group (Hsu and Langseth, 2018). The chief product coming from the community of practice would be regular mapping of the scientific and technical landscape in this area. It would serve as an incubator for new ideas to help advance concepts toward development, testing, publishing, and production use. These could include Community for Data Integration funding opportunities, John Wesley Powell Center proposal development, Mendenhall Postdoc Opportunity development, and other options that could infuse resources into necessary and high-value points of investment into synthesis and integration.

Opportunities for Emergent Advanced Technologies

Examples of relevant emerging technologies are included in Wheeler and Dietze (2019).

Summary of Resource Requirements

To be determined; depends on forecast.

Timeline With Milestones

To be determined; depends on forecast.

Examples of Existing Forecasts and Relevant Citations

- Dynamic ocean management: https://www.openchannels.org/webinars/2019/managing-ocean-real-time-tools-dynamic-management.

- Sea ice phenology and marine mammal movement: During the sea ice melt season in the Arctic, polar bears spend much of their time on sea ice above shallow, biologically productive water where they hunt seals. The changing distribution and characteristics of sea ice throughout the late spring through early fall means that the location of valuable habitat is constantly shifting. Similar to the effect of green-up in vegetation on ungulate movement in terrestrial systems, the dynamic sea ice boundary acts as a resource for polar bears and other marine mammals. Coupling these types of spatio-temporal environmental mechanisms with statistical animal movement modeling based on telemetry data is a challenge that is relevant for many types of phenological processes. Scharf and others (2019) develop formal statistical methods for integrating environmental and ecological data types to better understand and account for phenology on wildlife populations.

- USA National Phenology Network's Pheno Forecasts: www.usanpn.org/data/forecasts (Crimmins and others, 2020).
- Wayne Thogmartin's temperature-influenced energetics model, which could be adapted to a forecast to assess the location of migratory birds, which can inform permitting and planning for hunting and conservation.
- BirdCast live migration maps: http://birdcast.info/live-migration-maps/.

References Cited

Abrahms, B., Welch, H., Brodie, S., Jacox, M.G., Becker, E.A., Bograd, S.J., Irvine, L.M., Palacios, D.M., Mate, B.R., and Hazen, E.L., 2019, Dynamic ensemble models to predict distributions and anthropogenic risk exposure for highly mobile species: Diversity & Distributions, v. 25, no. 8, p. 1182–1193, accessed June 10, 2020, at https://doi.org/10.1111/ddi.12940.

Basler, D., 2016, Evaluating phenological models for the prediction of leaf-out dates in six temperate tree species across central Europe: Agricultural and Forest Meteorology, v. 217, p. 10–21, accessed June 10, 2020, at https://doi.org/10.1016/j.agrformet.2015.11.007.

Buderman, F.E., Hooten, M.B., Ivan, J.S., and Shenk, T.M., 2016, A functional model for characterizing long distance movement behavior: Methods in Ecology and Evolution, v. 7, no. 3, p. 264–273, accessed June 10, 2020, at https://doi.org/10.1111/2041-210X.12465.

Crimmins, T.M., Gerst, K.L., Huerta, D.G., Marsh, R.L., Posthumus, E.E., Rosemartin, A.H., Switzer, J., Weltzin, J.F., Coop, L., Dietschler, N., Herms, D.A., Limbu, S., Trotter, R.T., III, and Whitmore, M., 2020, Short-term forecasts of insect phenology inform pest management: Annals of the Entomological Society of America, v. 113, no. 2, p. 139–148, accessed June 8, 2020, at https://doi.org/10.1093/aesa/saz026.

Elmendorf, S.C., Crimmins, T.M., Gerst, K.L., and Weltzin, J.F., 2019, Time to branch out? Application of hierarchical survival models in plant phenology: Agricultural and Forest Meteorology, v. 279, p. 107694, accessed June 10, 2020, at https://doi.org/10.1016/j.agrformet.2019.107694.

Herms, D.A., 2004. Using degree-days and plant phenology to predict pest activity, chap. 11 of Krischik, V., and Davidson, J., IPM (integrated pest management) of midwest landscapes: St. Paul, Minn., Minnesota Agriculture Experiment Station, p. 49–59.

Hooten, M.B., Johnson, D.S., McClintock, B.T., and Morales, J.M., 2017, Animal movement—Statistical models for telemetry data: Boca Raton, Fla., CRC Press, 320 p, accessed June 10, 2020, at https://doi.org/10.1201/9781315117744.

Hooten, M.B., Scharf, H.R., Hefley, T.J., Pearse, A., and Weegman, M., 2018, Animal movement models for migratory individuals and groups: Methods in Ecology and Evolution, v. 9, no. 7, p. 1692–1705, accessed June 10, 2020, at https://doi.org/10.1111/2041-210X.13016.

Hsu, L., and Langseth, M.L., 2018, Community for Data Integration 2017 annual report: U.S. Geological Survey Open-File Report 2018–1110, 19 p, accessed June 10, 2020, at https://doi.org/10.3133/ofr20181110.

Lin, F.-C., and Zhu, J., 2012, Continuous-time proportional hazards regression for ecological monitoring data: Journal of Agricultural Biological & Environmental Statistics, v. 17, no. 2, p. 163–175, accessed June 10, 2020, at https://doi.org/10.1007/s13253-011-0081-7.

Murray, M., 2020, Using degree days to time treatments for insect pests: Utah State University Extension Fact Sheet IPM–05–08, 5 p., accessed June 8, 2020, at https://digitalcommons.usu.edu/extension_curall/978/.

Scharf, H.R., Hooten, M.B., Wilson, R.R., Durner, G.M., and Atwood, T.C., 2019, Accounting for phenology in the analysis of animal movement: Biometrics, v. 75, no. 3, p. 810–820, accessed June 10, 2020, at https://doi.org/10.1111/biom.13052.

Viskari, T., Hardiman, B., Desai, A.R., and Dietze, M.C., 2015, Model-data assimilation of multiple phenological observations to constrain and predict leaf area index: Ecological Applications, v. 25, no. 2, p. 546–558, accessed June 10, 2020, at https://doi.org/10.1890/14-0497.1.

Wheeler, K.I., and Dietze, M.C., 2019, A statistical model for estimating midday NDVI from the Geostationary Operational Environmental Satellite (GOES) 16 and 17: Remote Sensing, v. 11, no. 21, article 2507, 13 p., accessed June 8, 2020, at https://doi.org/10.3390/rs11212507.

Williams, P.J., Hooten, M.B., Womble, J.N., Esslinger, G.G., Bower, M.R., and Hefley, T.J., 2017, An integrated data model to estimate spatiotemporal occupancy, abundance, and colonization dynamics: Ecology, v. 98, no. 2, p. 328–336, accessed June 10, 2020, at https://doi.org/10.1002/ecy.1643.

Vegetation Dynamics

Forecasting Product Name

Short-term vegetation and plant community forecasts to improve long-term projections

Desired Future State

Management.—Managers need to know how and when plant communities will change in the future in response to environmental conditions, disturbance events, land-use practices, and invasive species. This question has merit at site-to-landscape scales for a wide variety of resource management decisions.

Science.—Build a framework for improving long-term models of vegetation change by integrating short-term vegetation forecasts from the same models with vegetation monitoring data. Short-term model forecasts can be validated and calibrated on an annual basis with vegetation monitoring data, providing gradual iterative model improvement. The result will be better models for long-term vegetation that can be used to develop projections (long-term, scenario-based estimates) of vegetation composition and structure.

Expected Outcome

Management at the site scale.—Output from the improved long-term vegetation dynamics models can be leveraged to evaluate projected plant composition against seasonal habitat requirements on patches for species of interest. Plant composition presented by life form or by species would each have value. Life form information could inform analysis of structural suitability and may inform diet suitability. Plant species information could inform analysis of structure and diet suitability, as well as specific species-to-species relationships. These results will allow managers to design habitat improvement, rehabilitation, and other restoration projects to suit both current and projected conditions. Projections will help design site-level restoration and habitat improvement projects, establish realistic project objectives, and identify the most effective treatment prescriptions.

Management at the regional scale.—Long-term vegetation projections at regional scales will enable evaluation of expected plant communities distributions against habitat requirements of key wildlife species. Projections will inform near-term (approximately 5 to 10 year) decisions about where to conserve and restore land. Scenario-based projections of climate and ecological responses will help define and locate climate refugia and areas where intervention would be efficacious (for example, to sustain connectivity).

Science.—Projections of vegetation dynamics over long timescales in response to various scenarios of climate, land use, and other drivers have existed in the scientific literature for decades. Vegetation models have the capability to estimate these processes at both short- and long-term horizons. In addition, land management agencies currently collect a substantial amount of annual vegetation monitoring data that could be integrated with the vegetation models. Contrasting model forecasts (short-term) with monitoring data can yield iterative model improvements, enhancing the quality of long-term projections from the same models. Outputs can include long-term projections of both slow (for example, functional groups [grasses, forbs, shrubs], relative cover of priority habitat types [for example, sage brush, Sonoran desert scrub]) and fast variables (for example, annual grass cover and height, priority species abundance) that are available and updated annually. Short-term forecasts from dynamic vegetation models can be validated and calibrated annually with monitoring data collected by land management agencies (notably, BLM's AIM program, the Natural Resource Conservation Service's Natural Resource Inventory data, and the USDA Forest Service's FIA program). This process will improve the models, which can then be used to project longer term vegetation dynamics under various global change scenarios. Potential modeling approaches: individual-based model, state-and-transition simulation model, vegetation demographic Earth system models (for example, Fisher and others, 2018).

Expected Partners and (or) Collaborators

Land management agencies (State; Federal, such as the BLM, FWS, NPS; and Tribal Nations), USGS, university scientists, and the USDA NRCS.

Expected Stakeholders

Land managers (Federal land management agencies, State land management agencies, Tribal Nations, and private property owners and managers), and groups interested in specific wildlife or plant habitats and migration corridors.

Product Description

Managers need to make near-term decisions about where and when to allocate resources in a manner that will be effective over the long term. The uncertainty associated with ongoing climate change and variability makes that a challenge, however. For instance, there are situations where restoration has not been successful; in revegetation efforts along the border of the Mojave Desert and Great Basin, reseeded perennial grasses established but did not survive drought. Therefore, there is a need to produce and deliver information on the expected changes in vegetation that may result from climate change and management interventions (Butterfield and others, 2016).

There is an opportunity to leverage long-term climate data as well as emerging monitoring data to iteratively update scenario-based projections of vegetation composition in order to inform near-term management decisions. This forecast product would seek to deliver such information.

Evaluation Against Standardized Criteria

Demand and relevance.—Skillful projections of long-term trajectories in vegetation structure and plant community composition would be very relevant to natural resource policy and planning and have the potential to inform a wide variety of decisions.

State of the science.—Current scientific capacity is high with respect to the ability to perform remote sensing (and deliver indicators and indices that assimilate remote sensing data) to inform biophysical conditions (for example, soil moisture, vegetation response and composition, and disturbances) of the land surface at high spatial resolution on weekly to seasonal timescales.

Much lower skill in seasonal scale weather forecast (that is, precipitation and temperature). Long-term weather forecast information is largely restricted to the 3-month lead time. Longer-lead information on large-scale climate phenomena, such as El Nino, can be used to inform the model.

A grassland productivity forecast is available (Peck and others, 2019), and other vegetation modeling tools—for example, state-and-transition simulation models (Daniel and others, 2016) or plant community models (Palmquist and others, 2018)—could help meet the demand for projections of vegetation composition and productivity at various spatial and temporal scales.

Operational implementation.—Several relevant modeling approaches and data products already exist to put operational implementation within reach. Latency of the monitoring data (which would be used to iteratively update the forecast) is currently an obstacle (1-year), but AIM is moving toward near real-time delivery with ongoing pilot projects. Overall, updating this forecast on an annual basis with the latest monitoring data makes it operationally tractable.

Value for improving decision support.—Operational projections of long-term vegetation change could be directly integrated into adaptive management frameworks, promoting greater collaboration between scientists and managers, thereby improving the relevance of scientific research and the quality of management decisions.

References Cited

Butterfield, B.J., Copeland, S.M., Munson, S.M., Roybal, C.M., and Wood, T.E., 2016, Prestoration—Using species in restoration that will persist now and into the future: Restoration Ecology, v. 25, no. S2, p. S155–S163, accessed June 10, 2020, at https://doi.org/10.1111/rec.12381.

Daniel, C.J., Frid, L., Sleeter, B.M., and Fortin, M.J., 2016, State-and-transition simulation models—A framework for forecasting landscape change: Methods in Ecology and Evolution, v. 7, no. 11, p. 1413–1423, accessed June 10, 2020, at https://doi.org/10.1111/2041-210X.12597.

Fisher, R.A., Koven, C.D., Anderegg, W.R.L., Christoffersen, B.O., Dietze, M.C., Farrior, C.E., Holm, J.A., Hurtt, G.C., Knox, R.G., Lawrence, P.J., Lichstein, J.W., Longo, M., Matheny, A.M., Medvigy, D., Muller-Landau, H.C., Powell, T.L., Serbin, S.P., Sato, H., Shuman, J.K., Smith, B., Trugman, A.T., Viskari, T., Verbeeck, H., Weng, E., Xu, C., Xu, X., Zhang, T., and Moorcroft, P.R., 2018, Vegetation demographics in Earth system models—A review of progress and priorities: Global Change Biology, v. 24, no. 1, p. 35–54, accessed June 10, 2020, at https://doi.org/10.1111/gcb.13910.

Palmquist, K.A., Bradford, J.B., Martyn, T.E., Schlaepfer, D.R., and Lauenroth, W.K., 2018, STEPWAT2—An individual-based model for exploring the impact of climate and disturbance on dryland plant communities: Ecosphere, v. 9, no. 8, Article e02394, 23 p., accessed June 8, 2020, at https://doi.org/10.1002/ecs2.2394.

Peck, D., Derner, J., Parton, W., Hartman, M., and Fuchs, B., 2019, Flexible stocking with Grass-Cast—A new grassland productivity forecast to translate climate outlooks for ranchers: Western Economics Forum, v. 17, no. 1, p. 24–39, accessed June 8, 2020, at https://waeaonline.org/western-economics-forum/.

Dryland Restoration

Forecasting Product Name

Understanding and forecasting probability of establishment and persistence of seeded species relevant to post-disturbance recovery and restoration success

Desired Future State

Restoration and reclamation projects can achieve revegetation objectives and support landscape transitions resulting from drought and changing precipitation regimes. Allowing additional acres of successful land treatments to occur within existing budgets.

Expected Outcome

Forecasts of dryland restoration outcomes could lead to improved success of seeded events in the near term and use a suite of species that will catalyze, where possible, longer term shifts in vegetation communities. This might require two different products; capturing the near- and long-term needs is important. These forecasts would also reduce the expense to public land users through reduced reseeding efforts, and provide information to improve dryland management through the adaptive management loop.

Expected Partners and (or) Collaborators

USGS, BLM, other Federal, State, and Tribal land management agencies. Also, any private entities working to accomplish revegetation in dryland environments, which currently includes a wide array of energy development companies.

Expected Stakeholders

BLM, NPS, FWS, FS, Tribal Nations, State agencies, private organizations that manage lands (ranchers, developers, conservation NGOs).

Product Description

Government and private organizations spend many millions of dollars annually working to revegetate lands in the western United States that have been disturbed, degraded, or developed. Restoration, reclamation, and rehabilitation efforts all include critical components of revegetation (for example, establishing perennial plants); these efforts are designed to improve the condition of degraded lands and reclaim them after authorized surface disturbance activities. Seeded restoration treatments have limited success across in these dry environments, however, because most seeds fail because of drought. A forecast of the likelihood of plant establishment succeeding during the coming year could improve the likelihood of successful revegetation by identifying favorable windows of opportunity when conditions for plant establishment are likely to be good, as well as identifying unfavorable periods when establishment is not likely and revegetation resources should not be wasted. Such a forecast could be an iterative model that provides probabilities of emergence and persistence of desired vegetation based upon available moisture and temperatures conducive to successful land treatments. Structured decision making is a key process in the development, deployment, and improvement of this project. Feedback from the completed land treatment activities will inform and improve the adaptive management cycle leading to continuous improvement of treatment activities. The model is coproduced by a number of research institutions and land management agencies who are invested in improving restoration success.

Evaluation Against Standardized Criteria

Demand and relevance.—Improving the success of dryland plant establishment following seeding will save money and minimize the prevalence of degraded land that emerges from failed restoration and rehabilitation efforts. Ideally, this product will help reduce the failure of operator reclamation efforts and agency driven stabilization and restoration efforts. USGS researchers in the southwest are already using ecosystem water balance models to develop some of these forecasts. The USGS, especially in cooperation with land management agencies, has authority to develop and deliver this type of forecast. This product can be produced and delivered at the spatial and temporal scale needed for management decisions, with the caveat that the model will improve greatly with the improvement of seasonal weather forecasts.

State of the science.—Generating forecasts of dryland plant establishment requires skillful seasonal weather forecasts, soil moisture models (for near-term model), vegetation community shifts (for longer term model), and monitoring data for verification and model improvement. This monitoring data could include BLM AIM, State monitoring programs, USGS Land Treatment Digital Library, data from industry, and U.S. Department of Transportation. There are limitations in the accuracy of mid-term forecasts (next season or two). There is a need to identify specific conditions that relate to success or failure of seeding. To quantify the success of the model, restoration budget and expense data are critical and nearly nonexistent. For the process to be iterative, monitoring of treatments in locations of low and high predicted moisture will need to be fed back into the model. Other data sources include the Disturbance automated reference toolset and the Land Treatment Exploration Tool.

Operational implementation.—Public land users with obligations to reclaim authorized disturbances are interested in improving success, which gives the product immediate applicability. Agency directed stabilization and restoration efforts are interested in improving success, which gives the product immediate applicability.

Value for improving decision support.—Commitment for this type of product is likely high, but limitations exist with current methods of contracting and planning within the government agencies so that they can be more fluid with resource allocation at the scale of these forecasts. For example, creating a larger pool of restoration resource money that can be deployed to specific locations given model predictions. The current practices of restoration are not influenced by weather forecasts and, as a result, seeding success is low. There is room for improvement in these practices, even if model uncertainty is relatively high.

Modeling Requirements

Desire is to model future precipitation events to predict when the intensity and duration of moisture events coincide with the germination and establishment window for newly seeded areas. These models would need to be granular enough to inform a localized activity and regional activities.

Data Requirements

Data requirements include soil moisture models, temperature models, monitoring data at species level for emergence and persistence, information about expected seed mix, estimate of planting date, and forecasts of potential timing of precipitation and temperature post planting.

Reservoir Thermal Bank

Forecasting Product Name

Season ahead forecast of reservoir thermal bank for water release planning

Desired Future State

Reservoir operators are able to make decisions regarding release timing and temperature that take into account the immediate effects on downstream ecoflows; the effects of various operations strategies that balance various reservoir functions (for example, flood control, power generation, recreation, and ecosystem health) are quantified and translated into forecasted reservoir thermal conditions and the impacts on season-ahead management options.

Expected Outcome

To be determined.

Expected Partners and (or) Collaborators

Partners depend on locality and type of forecast; for example, a local project in the Delaware River Basin might include the Delaware River Master's office, NOAA, NYC DEP, and others.

Expected Stakeholders

Dam managers and anyone else involved in the decision (for example, USACE, local, FWS, TNC)

Product Description

A portable and transferable reservoir forecasting tool that would give managers a 30-day ahead forecast of downstream temperatures in a regulated river reach where managing for species of concern is a major factor in decision making. Outputs include temperature at key spots downstream with uncertainty and estimates of thermal bank through time in response to different management strategies.

Evaluation Against Standardized Criteria

Demand and relevance.—Resource management decisions can be improved by production of and access to this forecast. Dam operators face a challenging resource optimization problem that requires balancing ecosystem needs against other reservoir functions, such as power generation, flood control, and recreation. These decisions could be greatly improved with near- and mid-term forecasts.

In 2017, a policy was created for the Delaware basin signed by New York City and the basin States that created an agreement to set aside a bank of water for thermal release. There are management questions about how this resource will be managed effectively, and appropriate forecasts and tools would be useful to decision makers. There are potential partnerships to help advance forecast development and use and leverage resources; for example, in the Delaware basin and likely other interested partners in the southwest and northeast. The relevance of these forecasts to Bureau, Departmental, and Administration priorities and missions, and the statutory authority to develop and deliver such forecasts needs to be explored further; specifically, by engaging with the USGS office of the Delaware River Master. The spatial and temporal scales of the reservoir and reach-specific tools forecast tools can be aligned with scales appropriate for resource management.

State of the science.—Thermal forecasts seem to have excellent skill potential given the seasonal and daily patterns in the forcing that determines temperature change (solar radiation, longwave radiation, and other fluxes). Thermal forecasts are well represented in existing system models that could accelerate forecast development, and also potentially improve the system models themselves. Existing models and frameworks exist for both simulating reservoirs and also streamflow and stream temperatures. We anticipate better skill in thermal forecasts than other physically based forecasts because of the predictability of key drivers (for example, our products would be less sensitive to precipitation and more sensitive to air temperature and radiation). Historical data are available for synthesis to inform model structure. Temperature is the most widely available aquatic measurement. Surface temperature can be remotely sensed.

Operational implementation.—Expected cost needs to be determined, potentially with a business analysis. Most data streams needed to drive forecast models are monitored in real time and have latency short enough to produce timely forecasts useful to management decisions. Nongovernmental entities or other third parties are interested in adding value and disseminating the forecast. Additional products could be built on top of these. For example, business analyses for adding additional flexibility to dam management (such as variable depth releases). The litigation risk related to disseminating and using thermal forecasts is unknown. Forecast products can likely be delivered in a format and structure needed by resource managers, although this needs to be confirmed with more direct contact with decision makers.

Value for improving decision support.—Forecast producers and consumers would likely commit to developing and using the forecast—for example, through coproduction—and the forecast would likely help manager-researcher partnerships in the application of adaptive management. Understanding the potential magnitude of improvement in resource management decisions as a result of using thermal forecasts versus using alternative data sources needs to be explored through communication with decision makers.

Modeling Requirements

Iterative reservoir models with real-time monitoring data assimilation to improve forecasts. Medium-term weather forecasts are necessary for forward-looking predictions. Models need to have decision maker interfaces designed appropriately.

Data Requirements

Air temperature, radiation, flow forecasts, reservoir bathymetry, stream network spatial data, contextual data (for example, stream canopy shading, topography).

Disease Outbreaks in Waterfowl

Forecasting Product Name

Forecasting to reduce disease outbreaks in waterfowl

Desired Future State

Reduced avian deaths as a result of avian botulism outbreaks

Expected Outcome

Ability to act proactively by adjusting water levels in response to avian botulism risk will reduce overall impacts to waterfowl. Currently, refuge response is reactive following an outbreak of avian botulism.

Expected Partners and (or) Collaborators

FWS, USGS

Expected Stakeholders

FWS

Product Description

A web-based forecast of avian botulism that will help water managers proactively manage refuge units to prevent an outbreak of avian botulism based on abiotic conditions.

Evaluation Against Standardized Criteria

Demand and relevance.—The production of botulinum neurotoxin is driven by environmental factors that produce anoxic conditions, such as increased water temperatures and decreased water levels. Currently FWS refuge managers do not have a tool to help them proactively manage for this disease, which results in the mortality of tens of thousands of waterfowl each year. A forecasting tool that identified time and location of high risk for avian botulism would allow managers to proactively modify water levels on waterbodies with large numbers of waterfowl to reduce the likelihood and impact of avian botulism. The forecast tool is specifically designed for site-specific forecasting; however, the algorithm is relevant to and easily transferred to other refuges.

The forecast will be achieved through the collaboration of the USGS National Wildlife Health Center (NWHC) and the FWS Wildlife Health Program, which maintain historical records of avian botulism events dating to the early 1900s. Site level environmental data will be sourced from various data information systems housed at the FWS. The outcome of the forecast is directly applicable to the FWS's mission to conserve wildlife and their habitats. Additionally, this forecast will apply to those FWS refuges with enabling legislation specific to providing habitat for waterfowl. It also aligns the USGS Ecosystems Mission Area priorities to provide science to help achieve sustainable management and conservation of the country's biological resources.

State of the science.—The NWHC database contains greater than 1,500 mass mortality events attributed to avian botulism from 1910 until 2018 that are responsible for the mortality of an estimated 4 million waterfowl. The dataset is opportunistically collected, so care will need to be taken during analyses to adjust for the lack of absence data and for reporting errors (as suggested in Hefley and others, 2013).

Site level environmental data will be sourced from various data information systems housed at the FWS. Historical temperature and precipitation data will also be sourced from the Parameter-elevation Regressions on Independent Slopes Model (Oregon State University, http://prism.oregonstate.edu/), which interpolates station locations to a continuous raster format that is more consistent with the format of monthly long-range forecasts available from NOAA's National Weather Service (https://idpgis.ncep.noaa.gov/arcgis/rest/services/NWS_Climate_Outlooks/cpc_mthly_temp_outlk/MapServer).

Operational implementation.—Operationalizing waterfowl disease forecast delivery may require about 2 to 3 years to collate and clean the required abiotic environmental data and build the model, with an additional year to develop the application. The total programming and application costs are estimated to range between $175,000 and $200,000. The primarily data needed is abiotic environmental data and avian counts, both of which are easily collected on a weekly basis. To our knowledge, nongovernmental entities or other third parties are not potentially interested in adding value and (or) disseminating the forecast. We do not expect litigation risk related to disseminating and using the forecasts for producers and consumers, respectively. Forecast products can be delivered in a format and structure needed by resource managers, potentially in weekly reports.

Value for improving decision support.—Forecast producers and consumers will likely commit to developing and using waterfowl disease forecasts. The FWS Wildlife Health program has expressed a strong interest in this information as a way to proactively manage for the health of avian species. These forecasts can help manager-researcher partnerships promote adaptive management. The information achieved through proactive management of water levels will help managers determine if there are other underlying causes of avian botulism outbreaks that could be additionally modified to reduce impacts from this disease. Waterfowl disease forecasts could substantially improve resource management decisions. For example, currently there is not proactive management of avian botulism outbreaks. Current management options are reactive following an outbreak.

Salmon Population Dynamics

Forecasting Product Name

Forecasting salmon population dynamics and life cycle—From the watershed through the ocean phase and back

Desired Future State

Understanding the dependence of salmon populations (abundance and distribution) in response to environmental changes, for example, changing climate, drought, and so forth, management of water projects (for example, California Central Valley water and irrigation projects), and the effect of dams operation and (or) removal (for example, recovery in response to dam—Elwha-Klamath—removal).

Expected Outcome

A more holistic integration of biological and ecological, water, ocean, and management forecasting tools, to assist in better decision making, economic and ecosystem-science-based tradeoffs.

Expected Partners and (or) Collaborators

NOAA, USGS, BOR, State agencies (Alaska, California, Oregon, Washington), Tribal Nations, nongovernmental organizations, universities, and so forth—a rather long list given the complexity of the problem.

Expected Stakeholders

The above expected partners and (or) collaborators plus the Fishery Management Councils (Pacific—PFMC and North Pacific—NPFMC, dam operators (when to release water), State agencies (for example, assessing irrigation needs), and so forth.

Product Description

The life cycle of salmon populations naturally integrates our coastal watersheds, rivers, estuaries, and oceans. Throughout their life cycle, salmon face stressors associated with naturally and anthropogenically modified habitats (channelization of rivers, presence of dams, water diversion, heat, droughts, and so forth), predation by introduced nonnative fish species, rapidly changing oceanic environments (changes in the oceanic food web), and fishing pressure as well as predation by other protected species upon their return to their spawning sites. Management decisions are required almost every stage in the salmon's life cycle to ensure the health in their populations. These management decisions depend on models that vary in the spatial and temporal scale they target, yet sustaining salmon populations in a system that is dynamically and continually changing will require a more complete integration of management throughout the salmon lifecycle and critical salmon habitat. The proposed product is a better integrated suite of forecast models that will build on existing strengths, as well as an EF modeling suite that is better able to consider future scenarios.

Evaluation Against Standardized Criteria

Demand and relevance.—Droughts in California highlight the conflict between water needs for humans and wildlife populations. Water from the State and Federal water projects is vital to municipal water supply, agriculture, and fish and wildlife populations. Total revenue from California agriculture approaches $35 billion each year, but poor adult returns of fall Chinook salmon necessitate the closure of ocean harvest, resulting in the loss of 23,000 jobs and $3 billion in fishery-related revenue to the region. Further, drought conditions negatively impact federally listed populations of spring and winter Chinook, steelhead, and green sturgeon in the Central Valley.

State of the science.—State and Federal water projects have been developed in response to water scarcity, but many questions remain about how best to operate the system to meet its multiple objectives (including water storage and supply, flood control, recreation, and fish and wildlife conservation), and how the projects might be improved with new facilities, operations, and mitigation actions. Water project operations, coupled with other management actions (for example, habitat restoration, fishery and hatchery management) have profound and complex effects on migratory fish and their habitats. Successful management of this complex system requires robust decision support tools built on a solid foundation of information developed from appropriate monitoring and applied research. When management, decision support tools, monitoring, and research are well integrated, effective adaptive management is possible, and over time, we can learn how to achieve our multiple objectives for water and fisheries in the face of climate variability, climate change, and population growth.

Operational implementation.—A key element of a plan is a long-term research and monitoring effort designed to better understand how water operations impact migratory fish populations. In addition to quantifying all direct effects on populations, the research will also address the indirect effects that determine patterns of life-history diversity. Such diversity is what enables populations to weather periods of poor conditions and bounce back rapidly when conditions improve.

The ecosystems that support these fish populations are tightly linked socio-ecological-physical systems, and the programs in place reflect this. The main components are—

- Life-cycle models that can translate management actions into changes in the future viability of fish populations;

- Supporting process models, particularly hydrological models, that can predict how key aspects of the ecosystems will respond to climatic conditions and water operations;
- An enhanced monitoring program designed to support information needs of the model and consequently to decrease uncertainty in the decision-making process.
- A suite of feasible water management and habitat restoration actions to benefit fish populations and provide other ecosystem services;
- An economic framework to evaluate potential actions in terms of their cost effectiveness.

Value for improving decision support.—Collaborations are required with the NMFS West Coast Region, its Sacramento Area Office, and their water resource management partners to identify an initial suite of water resource management options to study. Identifying potential actions up front will help guide the modeling and monitoring efforts. A suite of actions under several time horizons include the following:

- *Short term.*—Emergency actions in response to extreme conditions, such as fish relocation or cool-water releases from storage reservoirs;
- *Medium term.*—Habitat restoration actions (such as riparian vegetation planting) and water management actions designed to ameliorate the effects of droughts;
- *Long term.*—The suite of actions, such as reintroduction to currently unoccupied areas, designed to restore populations to healthier levels.

Modeling Requirements

Salmon and sturgeon life-cycle models.—With support from the USBR, NMFS is developing a stage-structured stochastic life-cycle model for Chinook salmon that includes density-dependent reproduction and transitions among population groups (defined by developmental stage and geographic area). The structure of the model allows for responses not only in population size and growth rate, but also life history diversity (defined by trajectories through time and habitats). The NMFS is also developing and individually based dynamic energy budget models for salmon. Both models take as inputs the outputs of hydrologic and hydrodynamics models, allowing water and habitat management actions to translate into population-level effects. We intend eventually to merge these modeling approaches and develop similar models for green sturgeon. Academic partners include the University of California at Santa Barbara.

Process models.—Existing hydrologic, hydraulic, water quality, harvest, and other relevant process models will be reviewed, validated against existing information, and incorporated into the analysis framework. The models will be updated with existing information if results of validation studies indicate this is necessary, and they will be modified when new information on fish responses to water routing becomes available under this plan. Process model results become life-cycle model input values. Partners include the USBR and California Department of Water Resources.

Socioeconomic models.—Models of how different components of society respond to water management alternatives will be modified or developed and used to assess how agricultural, fisheries, water district, and residential customers change their behavior under alternative water management strategies. The goal is to estimate how the various components of California's economic productivity will be affected by different water management strategies to support informed decisions by managers that balance the environmental and economic services that the Central Valley ecosystem and economy provide. Economic costs from water management operations that alter water volume and timing available to agriculture and municipal water supply will be estimated and evaluated by natural resource economists. This will provide managers with the benefits and costs of any proposed changes.

Data Requirements

The analytic framework described above requires biological data to estimate model parameters. A substantial amount of monitoring already occurs in the Central Valley, but it is not sufficient. Advances are needed in the following areas:

Habitat monitoring using remote sensing.—Monitoring changes in habitat quantity and quality during the implementation period are needed to assess restoration progress relative to target levels and any further impacts of land and water use practices on stream and riparian habitats. The monitoring will use cost-effective remote sensing technologies (for example, LiDAR and hyperspectral imaging). Partners include NASA.

Life history diversity.—Life-history diversity provides resilience in fish populations. Variability in size at migration, migration and ocean-entry timing, and habitat use in juveniles and adults will be monitored using several approaches, including chemical signatures in otoliths. Partners include California Department of Fish and Wildlife, the FWS, and the University of California at Davis (UC Davis).

Fish tagging.—Acoustic tags provide detailed information on juvenile migration timing, travel speed, areas of delay, route selection, entrainment, habitat use, and reach and system-level survival over the complete migratory corridor. The NMFS and FWS have been conducting relatively modest studies based on acoustic technology since 2007 that have provided valuable results. Passive integrated transponder (PIT) tags are much cheaper and can provide the basis for routine estimates of survival over longer freshwater reaches. PIT tags also enable survival through the adult life stage to be estimated by monitoring the number of PIT-tagged adults that return to hatcheries and spawning grounds. PIT tags have not been used in the Central Valley for survival studies but have been used with great success on the Columbia River.

Annual juvenile population abundance and adult returns.—Ongoing systematic trawl sampling conducted by the FWS near Chipps Island will be used to estimate the abundance of the outmigrating juvenile salmon population each year. Existing (but new) salmon constant-fractional marking and spawner surveys will be used to assess population trends. Key partners include the FWS and California Department of Fish and Wildlife.

Water quality.—Agricultural return flows, wastewater discharges, and land-based runoff are increasing the exposure of salmon and sturgeon to agrochemicals (legacy and modern pesticides), pharmaceuticals, metals, hydrocarbons, and other toxins. Existing water-quality monitoring data will be used to identify priority chemicals of concern based on exposure and the potential for adverse health impacts to salmon and sturgeon populations. The potential for population-level effects will be determined from laboratory and modeling studies. UC Davis is a key partner.

Predator abundance and distribution.—Salmon mortality varies across locations in a way that strongly suggests that predation by other fish is the proximate cause. Also, salmon survival appears to have declined over time, concurrent with an increase in predatory fish, such as large-mouth bass. Systematic fish and habitat surveys and appropriate analysis are needed. Partners include the California Department of Fish and Game, the California Department of Water Resources, USBR and UC Davis.

Genetics.—Parentage-based tagging (PBT) can provide individual-specific tags for 100% of juvenile hatchery production, by genotyping broodstock used in spawning operations or adult spawners sampled nonlethally at a weir or fish trap. PBT will be used to assess the effects of different hatchery practices used in supplementation efforts and to guide and evaluate the effectiveness of reintroductions.

Ocean productivity.—Salmon populations are highly responsive to changes in ocean conditions, obscuring population responses to management if not accounted for. A coast-wide assessment of the productivity of the California Current ecosystem will be conducted each year. The pattern, magnitude, and effects of ocean climate variation will be incorporated into the analytical framework. Key partners include Scripps Institute of Oceanography, UC San Diego, UC Davis, Humboldt State University, and Oregon State University.

Information gaps.—Significant gaps in our current understanding of how fish will respond to water management alternatives and recovery actions in the Central Valley limit any ability to identify the most effective management actions. These gaps will be addressed by both the routine monitoring described above and by conducting focused research projects.

Cyberinfrastructure Requirements

Although life-cycle models require intensive computer time to run, computer time is a relatively cheap investment compared to the overall investment in personnel. Cloud services are an option; however, the type of computing we do—intensive computing at unpredictable times—might be not as effective as purchasing the needed hardware. NOAA Fisheries life-cycle modeling efforts would benefit from the purchase of several more servers.

Human Infrastructure Requirements

Life-cycle modeling is inherently multidisciplinary, requiring statisticians, hydrologists, ecologists, and field biologists. Currently, the NOAA Fisheries have sufficient staff to complete a basic level of modeling in support of Biological Opinions and Recovery efforts. However, additional dedicated staff (on the order of 10 new staff) are needed to advance the science and to model more populations.

It should note that partnerships are essential in these endeavors. Support has generally been in-kind—across agencies—as we have common interests in recovering salmon populations. The USGS has been particularly crucial in the support they provide. In the northwest, they have developed a life-cycle model for Snake River fall Chinook salmon, which have a particularly complicated life history. They have also developed Bayesian methods for analyzing mark-recapture data, which is the main data that supports the models. In the southwest, they have a major role in analyzing acoustic tag data in the confluence of the Sacramento River and the delta, which is complex region of high mortality.

Opportunities for Emergent Advanced Technologies

Life-cycle modeling requires the fusion of complex field data with sophisticated statistical methodology, particularly Bayesian statistical methods. In the field, we use passive integrated transponder (PIT) tags and acoustic tags to monitor the migrations of salmon and to estimate survival. This approach of mass marking wild populations of migratory animals has revolutionized the field. Coupling these marking methods with novel statistical approaches, such as using integrated population models, has allowed NMFS to be in the forefront of population viability analyses. The high number of peer-reviewed publications produced by NMFS scientists is testament to the approach.

Summary of Resource Requirements

Generally, we need to work across agencies and academic partners (for example, through the Interagency Ecological Program and the Cooperative Institute for Marine Ecosystems and Climate) and take advantage of expertise in both the NOAA Fisheries Science Centers, USGS, BOR, and so forth, to efficiently undertake the work outlined in the example above. Support is needed to initiate new activities, fund additional staff, develop field programs, strengthen data analysis, and enhance computational capabilities.

Appendix 4. Brainstorming of Forecast Products Discussed

This appendix summarizes the results of the breakout groups that brainstormed potential forecast products that could be linked to management decisions. The questions that guided the discussion included: “What decisions are being or need to be made that are candidates for ecological forecasting (EF)?” and “Provide some examples of forecasts that can support those types of decisions.” Results are grouped in table 4–1 into broad categories of potential forecast product types.

Table 4–1. Results of the discussions by workshop breakout groups that brainstormed potential forecast products and evaluations of them.

Forecast product type	Summary of discussion
Allocate resources and take actions	• How to allocate resources given probability of a successful outcome. For example, rain is limiting in many western ecosystems. If rain is predicted to be more likely in a given year for a particular region, can dollars for land treatments be allocated to that region based off those predictions? • What happens when we act or don’t act? For example, what happens when we revegetate to reduce bare ground or don’t do anything (quantify increase in erosion or decrease in water quality); what happens when we reduce invasive species cover or don’t (quantify fire risk or loss of habitat and diversity); what happens when farm ground is fallowed across a region (increase in dust emissions)?
Predict the success of an action	• What are the costs versus benefits of certain actions? For example, can forecasts show how spraying mosquitoes at a given time might also impact other insects, like butterflies? • What actions need to happen now to meet future mandates and, if actions are taken, when will one know if it is working? • What is the likelihood of success of vegetation treatment in both the short term and long term, especially given ongoing drought and conditions outside of historical averages? How accurate can the precipitation models get and what do we do with that information? Can we use restoration outcomes to create these forecasts?
Risk, degradation, and thresholds	• What is the future ecological condition based upon some standard, like ecological site descriptions? Can we predict thresholds in state-and-transition models? What is the mismatch between nearing thresholds and current usages of these places by people and species? What management changes do we need to be prepared to make today to support ecological functioning given trajectories in condition? What else might managers do with this information? • Can we look at contamination, invasion, and pests as part of a model that quantifies proximity to a threshold? For example, at what level will a contaminant have an adverse effect on a species or an ecosystem? • Where are predicted rates of change in temperature and precipitation happening and are these models correct? How are these changes impacting resources—habitats and human communities? • When to pivot management of a lake away from cold water fish and towards warm water fish? • What is the risk of flood, given extreme events? How can we use forecasting to better manage for these risks, and not get caught by surprise? • Fire management?

Table 4–1. Results of the discussions by workshop breakout groups that brainstormed potential forecast products and evaluating them.—Continued

Forecast product type	Summary of discussion
Development on public lands and waters	• Where to permit offshore energy development? Forecasts for direct drivers linked to joint species distribution models to track impacts of extreme events on systems that have lots of data, and how placement of energy development might affect species reacting to these events. • What are the landscape-scale effects of development? Can we use forecasts to show trends in development, mitigation success, and impacts to resources to help make decisions about when and where to permit for development?
Conservation and species of concern	• How can we learn more about distribution, abundance, and condition of resources of concern given rapidly changing conditions and inability to rely on historical averages? We need to know thresholds and which numbers matter. For example, species distribution for species of concern; ranges, timing of range shifts, phenological shifts; Early Detection and Rapid Response; knowledge about where to locate a species of visitor concern or interest; hazard risk (biological, chemical, geophysical); Clean Water Act attainment or nonattainment; and disease-pathogen-pest exposure and transition. • Can EF help support mandates from existing policies; for example, Endangered Species Act, Magnuson-Stevens Fishery Conservation and Management Act, Marine Protection Act, and those related to harmful algal blooms and hypoxia. Managers would find forecasts for species' abundance and critical habitat distribution helpful. Once and done forecasts for scenario-based planning—for example, setting boundaries of a marine sanctuary. • Can water be located as part of a critical flyway during spring migration routes as part of the Intermountain West Migratory Bird Joint Venture pilot project? • What resources might be at risk during a major event? Emergency management and broad risk assessment for infrastructure; this might also include recommendations for policy. • Where do animals move? Can gene flow be included for species of concern? • Predictions of all aspects of terrestrial ecosystems: carbon flux, water flux, vegetation productivity, fuel loads, disturbance recovery rates.
Early detection and rapid response—Invasion, disease, and toxins	• Improve prediction of invasive and nonnative species early detection and rapid response and invasive species management? • Where can we expect disease and pest outbreaks (in wildlife), including species affected, conditions for spread, and events that lead to an outbreak, based on environmental conditions. For example, models for reducing big horn sheep contact with domestic sheep to reduce pneumonia in big horn sheep. • What is the predicted duration, magnitude, frequency, of algal blooms, toxin production, exposure, and health affects in aquatic systems? • Where is the presence, abundance, and spread of ticks and Lyme disease?
Water management	• How can dam releases be managed for a variety of purposes—Temperature maintenance, flood control balances, environmental releases, water supply forecasting. • What do we know about water quality? Can we build off existing and new network infrastructure on stream quality? • What is the quality of the water? Can water quality be improved to conform to the Clean Water Act? • When will fish spawn? Can we optimize recreation or restrict use?

Table 4–1. Results of the discussions by workshop breakout groups that brainstormed potential forecast products and evaluating them.—Continued

Forecast product type	Summary of discussion
Recreation and human impacts	• Policy management of animals that are hunted and fished. Where are our management actions currently archaic (managing for conditions that are well gone), and how do we manage novel conditions? • What is the timing and location of culturally important species? For example, piñon pine seed harvest given precipitation or bowhead whale harvest given extent and distance of sea-ice from land. • Managing recreation: how does increasing visitor use affect resources; can EF be developed at a small scale to help recreationalists avoid sea lice or harmful algal blooms? • Waterfowl availability model for strategic placement of rest areas and other management areas for recreation. • EF for human health issues: dust, ozone, air quality, pollen, and mosquitoes.

Appendix 5. Ratings of Specific Potential Forecast Products by Topic

Breakout groups selected information needs and (or) ideas from the workshop brainstorming session (appendix 4) and refined the description as necessary to identify a potential forecast product. Each of these more specific products was then rated as low (L), medium (M), or high (H) on each of the four criteria for assessing the value of ecological forecasts: demand and relevance, state of the science, operational implementation, and value for improving decision support (table 2). Note that the importance of considering a product's relevance to supporting research-management integration was consistently identified during the evaluation process, so this was defined that as a separate criterion in subsequent rankings. In table 5–1, the listing of forecast products is further organized by management challenge, or topic.

Table 5–1. Ratings of specific potential forecast products by topic and product.

[—, None or not available].

Forecast product	Criteria 1—Demand and relevance	Criteria 2—State of the science	Criteria 3—Operational implementation	Criteria 4—Value for improving decision support	Notes and relevance to research-management integration
		TOPIC: Disease, toxins, and invasives			
Pollinators-pesticides	L	Not rated	Not rated	Not rated	Relevant to policy but not management because pesticides—that is, neonics—are avoided by Federal partners.
Big horn sheep pneumonia	M	H	Not rated	Not rated	Stakeholders with diverse objectives.
Avian malaria in Hawaii	M	Not rated	Not rated	Not rated	—
Chronic Wasting Disease	H	M	H	M	Stakeholders with diverse objectives.
Water management on refuges—impact on avian diseases	H	H	M	H	—
Harmful algal blooms and their toxins—Freshwater-water management options to control	H	M	H	H	—
Predicting contaminant effects on populations—Water management options to mitigate contamination	L	Not rated	Not rated	Not rated	Relevant to policy but not management because contaminants are avoided by Federal partners.
Non-point-source pollution on Florida coral	M	Not rated	Not rated	Not rated	We're not sure if the managers can control the water quality or if it is a policy issue.
HABs and toxins—Marine-water management options to mitigate	H	M	H	M	Not sure if Federal managers could affect a change in flow into estuarine systems given their ability (or inability) to control these sources.
White-nose syndrome	L	Not rated	Not rated	Not rated	Important disease but not sure how forecast would help.
Likelihood of emerging disease invasion	H	L	L	L	Policy relevant, but hard to manage for disease.
Treatment of plant invasives	H	M	M	H	—

Table 5–1. Ratings of specific potential forecast products by topic and product.—Continued

Forecast product	Criteria 1—Demand and relevance	Criteria 2—State of the science	Criteria 3—Operational implementation	Criteria 4—Value for improving decision support	Notes and relevance to research-management integration
TOPIC: Disease, toxins, and invasives—Continued					
Mosquitoes phenology, density, and management, and timing of treatment	L	Not rated	Not rated	Not rated	May be useful to species of concern; for example, sage grouse.
Early invasive arthropods (spotted lantern fly, longhorn ticks)—Early detection to allow for management	H	H (for some species)	M	H	—
Post-disaster detection invasives and hazard spread	M	Not rated	Not rated	Not rated	—
Integration of annual grass cover and fire	L	Not rated	Not rated	Not rated	—
Zebra and quagga mussels	L	Not rated	Not rated	Not rated	Important, but a forecast is not needed.
Iterative survey inventory for rapid response	H	M	M	M	—
Ticks—Lyme disease	M	Not rated	Not rated	Not rated	The team took into account that the project would benefit from an iterative forecast model and that it was applicable to DOI Federal land managers. The available management actions could affect the outcome.
TOPIC: Resource use and development—Migration					
Annually updated forecasts presented as vegetation maps; for example, cover of priority species in a priority habitat (for example, sage brush, Sonoran Desert scrub) or percent bare ground to support long-term projections	H	M	H	H	Where do we conserve and where do we restore habitat? Locate places where climate is changing faster than vegetation or species that cannot migrate, include fire risk prediction, temperature and precipitation forecasts, and fire modeling and (or) invasion. Can the timescale of the data match the timescale of management? Annual refresh makes it more operationally tractable.
Forecasted probability of establishment and persistence of seeded species given a seasonal climate window (maybe for dryland systems in intermountain west or maybe oil and gas pad reclamation at a particular field office)	H	H	L	H	Do we restore this year and when and where? Do we need species-specific information? Scale could be highly variable, location is unpredictable, or maybe the forecast could cover an entire Level III or Level IV ecoregion?

Table 5–1. Ratings of specific potential forecast products by topic and product.—Continued

Forecast product	Criteria 1—Demand and relevance	Criteria 2—State of the science	Criteria 3—Operational implementation	Criteria 4—Value for improving decision support	Notes and relevance to research-management integration
TOPIC: Resource use and development—Migration—Continued					
Green-up and production forecast for forage species in grazing allotments	H	H	M	M	How many animal use months do we issue for a given permit allotment? Potential controversy or implementation could be dependent on relationships between land managers and grazing permittees.
Joint species-food web distribution-migration forecast for marine systems	H	L	L	M	Identify appropriate use areas and closures. Need to conduct a pilot study heat map of diversity or some other food web metric. Difficult to model food webs. Limited by various data needs.
Timing and location of migratory hotspots	H	H	H	H	Relevant to use permits and conditions to permits. Can be applicable with any species or group in any region. Need to know when high densities of species occur on smaller timescales. Criteria changed depending on which system and organism, so we rated based on birds. Applicability for reducing restrictions based on broad knowledge of migratory pathways. Applicability for increasing tourism for events of interest (that is, blooms or whale migration).
Season-ahead scenario forecast for reservoir thermal bank and releases	M	H	M	H	When to release water to balance thermal and flow ecosystem needs with other reservoir uses (power, flood control, drinking water, and so forth)? Is the product niche (one system) or is it scalable? Difficult to alter dam operations that operate on plans that have multiple decade renewal cycles. Could design forecasts to be applied at any reservoir.
Water connectivity and dispersal forecast	M	M	M	Not rated	Useful for a number of purposes, for example, barrier removal impacts or invasive spread intervention.

Table 5–1. Ratings of specific potential forecast products by topic and product.—Continued

Forecast product	Criteria 1—Demand and relevance	Criteria 2—State of the science	Criteria 3—Operational implementation	Criteria 4—Value for improving decision support	Notes and relevance to research-management integration
TOPIC: Status and trends—Hazards					
Coastline, marsh loss and (or) migration forecast	H	M	M	H	—
Timing of phenological events forecast (plants, animals)	H	H	H	H	—
Post-disturbance recovery and restoration success forecasts (for example, post-fire in sage brush systems)	H	H	M	H	—
Salmon stock forecast	H	M	H	H	—
Abundance of freshwater species of concern (for example, endangered mussels, regulated invasives, migratory species)	H	H	M	H	—

Moffet Field Publishing Service Center, California
Manuscript approved for publication June 17, 2020
Edited by J.C. Ishee
Layout by Kimber Petersen

USGS

Bradford and others—**Ecological Forecasting—21st Century Science for 21st Century Management**—Open-File Report 2020–1073

ISSN 2331-1258 (online)