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The Future of Ecological Forecasting

A Statement of the American Meteorological Society

(Adopted by AMS Council on 19 January 2025)

Environmental change is a defining challenge of our time. The unprecedented nature and pace of change means that historical patterns can no longer be relied upon to inform environmental decision making. Ecological forecasts respond to this challenge by predicting likely changes in ecosystems and the services they provide, such as food, water, fuel, security, shelter, medicine, and supporting services such as photosynthesis and nutrient cycling in response to natural and human-induced drivers. Applications of ecological forecasts include wildfires, pollen and other aeroallergens, marine and freshwater algal blooms, drought, agricultural productivity, biological invasions, wildlife activity, disease and pest outbreaks, carbon sequestration, and even human behavior. Societal demand for these forecasts has increased as decision makers and natural resource managers incorporate aspects of ecosystem services into management frameworks for various sectors.

Ecological forecasting unites researchers, practitioners, and decision makers across all sectors to predict ecosystem changes and meet environmental challenges with opportunities for innovation, economic development, sustainable resource management, and improved well-being. The purpose of this Statement is to encourage AMS members to apply decades of modeling and forecasting experience toward partnerships with scientists, resource managers, and forecasters in adjacent fields to advance ecological forecasting into operational domains for societal applications.

Transformational increases in data availability, scientific understanding, computing power, model sophistication and integration have moved ecological forecasting capabilities from the research realm to proactive management applications. Predicting the evolving environment in which human communities adapt and thrive is the bedrock of operational weather, climate, ocean, and hydrological forecasting. The lessons learned from 70 years of numerical weather prediction and modeling infrastructure development can be leveraged to accelerate national capabilities in ecological forecasting. More skillful predictions of ecosystem change, and biodiversity will accelerate with integration, testing, and iterative evaluation of ecological models within forecasting systems. The transdisciplinary nature of ecological forecasting to integrate natural, social, and health sciences will enable co-design of research questions leading to co-production of knowledge, forecasts, and decision support guidance.

Growing Communities of Practice

Multiple stakeholder groups require reliable and accurate ecological forecasts at different spatial and temporal scales, creating a challenge to define a single community of practice. Instead of being a single entity, the ecological forecasting community of practice is rapidly growing and brings together broad groups of ecological specialty areas, including wildfire specialists, public health practitioners, marine biologists, urban and restoration ecologists, wildlife managers, and fisheries and forestry managers.

In the United States, federal agencies are developing infrastructure to support and grow ecological forecasting. The National Oceanic and Atmospheric Administration produces operational ecological forecast products, including marine hypoxia, harmful algal blooms, pathogens, and marine habitat, guided by an Ecological Forecasting Roadmap that prioritizes community needs. The National Aeronautics and Space Administration and the US Geological Survey have prioritized ecological forecasting as an essential component of understanding and conserving life on this planet. Ecological forecasting could be considered a part of the National Nature Assessment led by the White House Office of Science and Technology Policy, especially through ecosystem valuation in cost-benefit analyses that consider status, trends, and future projections of ecosystem services and biodiversity.

As a growing community of practice, the Ecological Forecasting Initiative (EFI) is a grassroots network that unites researchers and practitioners across organizations (government and non-government) to facilitate knowledge sharing and co-development of ecological forecasting infrastructure. EFI works with the National Ecological Observatory Network to run a nationwide forecasting challenge. There have been over 40,000 unique forecasts submitted to the challenge, demonstrating the extensive interest in ecological forecasting, open science, community model development, and data requirements for rapid advancement of forecasting capabilities and skill.

Forecast-based Actions and Impact-Based Decision Support Services

How are forecasts designed to result in actionable information, decisions, and responses to challenges facing the Earth's ecosystems in a changing world? Traditional management assumes ecosystems fluctuate within a statistically stable envelope of variability – an assumption now rendered increasingly unviable by human-induced ecosystem disturbances and climate change. Uniting predictive frameworks across spatial and temporal scales in non-stationary environments can provide ecological forecasts of when and where environmental change will pose the greatest and most immediate threats and help identify best responses to those threats.

Negative impacts on human health may result from climate change and changes in land use through farming practices, transportation networks, industrial activities, urbanization, and encroachment on natural habitats. In 2010, far-flung problems from Canada to Russia to Australia due to fires, flooding, and drought increased the global food price index by 32 percent, cited as a trigger for social unrest in several countries. Remote changes in sea surface temperatures have effects on severe storms and rainfall distributions that may promote outbreaks of diseases such as dengue. These examples illustrate the importance of developing and integrating forecasts across different disciplines to anticipate events with significant humanitarian or ecosystem impacts.

In operational weather forecasting, Impact-Based Decision Support Services enable meteorologists to provide core partners with better understanding of potential impacts from specific forecasts, facilitating proactive decisions that reduce socioeconomic impacts before, during, and after events such as extreme storms. Similarly, the food/water/energy production, human health and security, and conservation communities recognize the need for ecological forecasts to inform Forecast-Based Actions (FbA). FbA involves the development of emergency response plans before disasters occur, and then automatically activating them based on forecasted thresholds set prior to the event itself. Examples include deploying aid in response to drought forecasts before crop failures have occurred, or anticipating wildfires to prepare for impacted ecosystems, safety and resilience of communities, and response and restoration.

Many operational ecological forecasting systems use weather or ocean observations or forecasts to produce "proxy" models, using heat indices, precipitation, or large-scale weather patterns coupled with biological data, to predict ecological outcomes such as coral reef bleaching, rangeland productivity, or species abundance. Explicit forecasts that use process models to predict ecological variables directly are rapidly advancing as reliable observations allow for data assimilation and validation of forecasts. Given the close relationship between weather, water, climate, and ecological forecasts for a wide range of interrelated issues, there is a clear opportunity to accelerate predictive capabilities through more deliberate connections between the meteorological and ecological forecasting communities.

Opportunities for Development

The topical areas where collaboration between the AMS and the ecological community is needed to accelerate the development of ecological forecasting applications in human and natural systems include:

- *Theory.* Understanding the mechanisms driving ecological changes in structure and processes to generate accurate forecasts beyond the range of previously observed conditions. Understanding the patterns of predictability across ecological systems will allow improved predictions even in under-monitored systems.
- *Prioritization.* Definition and promulgation of programmatic and societal objectives to guide research and funding opportunities that support specific model and forecasting requirements. Cost benefit analysis studies are needed to identify forecast products and pathways with the greatest return on investment and societal benefit.
- *Modeling*. Coordinated model development within the frameworks of Earth System Science that couples the atmosphere, land, ocean, biosphere, and the effect of human activities on ecosystems.
- *Standardized data.* Observations to support ecological forecasting are diverse, and their reliable and continuous distribution within national data systems incorporating data standards, interoperability, reporting, and data dissemination is critical.
- *Infrastructure and computational support.* Construction of operational environmental modeling backbone(s) and communications capability required to collect and provide a consistent set of forcing and boundary conditions, run models, assimilate observations, and disseminate forecasts. High performance and cloud computing resources should be evaluated as to accessibility and equity for data access and software development by all parts of the community.
- *Inclusivity*. Common tools, guidelines, and standards to strengthen the credibility, legitimacy, and integrity of forecasts, while fostering innovation by lowering barriers to entry. Collaborative frameworks that include decision-makers and diverse audiences would enhance co-production of ecological forecasts for a broad suite of user communities, such as the Environmental Data Science Innovation & Inclusion Lab (ESIIL).
- *Products and services.* Stakeholder-driven ecological forecasting products and services, with uncertainty estimates based on needs of decision-makers, with collaborative efforts across academia, private sector, government, non-governmental, and tribal organizations.
- *Transitioning research to operations, applications, and commercialization.* Definition and coordination of organizational responsibilities and agreements to generate, curate, and distribute the products that serve forecast consumers efficiently and effectively.
- *Workforce.* Workforce development necessitates an inclusive community among ecological forecasting educators and open, extensible teaching and training materials at the undergraduate, graduate, and professional levels. Early education and supported pipelines for students are key to building STEM professions related to ecology and forecasting. Curricula that include varied knowledge are needed to

train and certify operational ecological forecasters who can deliver and communicate authoritative information to the public.

The Role of Professional Societies

Professional societies serve their members with venues to publicly discuss, peer-review, and advance many aspects of building and implementing operational ecological forecasting systems from research, data, models, computational infrastructure, distribution of products and services, and workforce development. Professional societies serve as catalysts to share knowledge through annual meetings, chapters, sections, publications, public affairs, and policy arms to build awareness of issues as they evolve within each discipline.

The National Research Council (2003) report "Fair Weather: Effective Partnerships in Weather and Climate Services" recommended the AMS as a neutral broker for broad dialogue across the public, private, and academic sectors in the Weather, Water, and Climate Enterprise. Sustained discussions among the sectors guide the national underpinnings of research, accurate and continuous observations, data acquisition and management, modeling and forecasting, policy and services, both public and commercial. Members of the Ecological Society of America have expertise in theoretical, statistical, and process-based modeling of biodiversity, species distributions and demographics, community ecology, ecosystem ecology, and ecosystem services, representing enormous capacity to develop and support the integration of ecological forecasting into the national forecasting enterprise. ESA has a Four-Dimensional Ecological Education Framework for higher education of ecologists and can explore offering a professional certification track for ecoforecasters.

The American Geophysical Union membership spans the basic and applied research domains needed to advance foundational biogeophysical sciences in support of full earth system modeling and forecasting. In 2021, the American Fisheries Society and AMS Committee on Ecological Forecasting jointly hosted a special symposium on ecological forecasting for fisheries management to discuss emerging fisheries models and forecasting development. The American Public Health Association identifies climate change and environmental health as public health and equity issues and supports national dialogue and policy development in these areas. International capability with virtual teams across these and other professional societies could allow innovative, specialized meetings to integrate findings for rapid knowledge transfer and broad acceptance of results across disciplines.

Call to Action

Forecast-based actions and impact-based decision support tools that are meaningful to end users require transdisciplinary integration of biology, ecology, and human activities into Earth System and regional modeling frameworks.

Next steps to advance the field of ecological forecasting from research toward an ecological forecasting enterprise include:

- Identify and engage with stakeholders such as supporting organizations, federal/state/local agencies, academic institutions, professional associations, and the private sector to quantify user needs that could be satisfied by ecological forecasting products and services.

- Consolidate priority mission and decision support needs for ecological forecasting from multiple reports and planning documents.
- Develop formalized processes for integrating ecological forecasting in and across agencies or entities with predictive missions involving ecosystem services. Add biological components to modeling systems that support Earth System predictions and modeling frameworks for a Climate-Ready nation.
- Conduct specialty workshops and transdisciplinary technical meetings to inform co-development, priorities, and methodologies for community models and operational products, including validation and verification.
- Categorize ecological forecasting products and services by user requirements to align with associated funding vehicles and qualified opportunities.
- Define existing operational platforms and architectures for ecological forecasting and respective products, including "backbone" observations for iterative/assimilating model development or environments such as Digital Twins.
- Quantify infrastructure needs (data, models, computational infrastructure, dissemination, and distribution) for sustained ecological forecasting that span multiple entities.
- Develop a governance structure to organize emerging interests in ecological forecasting equivalent to the Interagency Council for Advancing Meteorological Services.
- Develop a new model of inter-societal programs envisioned for forecasting.
- Optimize and focus funding such that competing interests are addressed in one place or a portfolio and increase scope of funding mechanisms to release financial support in advance of anticipated events.

The AMS Statement on the Future of Ecological Forecasting presents an opportunity for the AMS membership to work with other professional communities on requirements, priorities, and policies needed to accelerate operational and actionable ecological forecasts. This statement sets forth a call for action for the AMS and its sister organizations, agencies, academic institutions, and private sector partners to consider and develop an enterprise approach from research towards operational ecological forecasting in national and international interests.