Useful Ecological Forecasting: A Literature Review

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0. Introduction

In recent years, climate change and other anthropogenic factors have affected ecosystems at an unprecedented rate and triggered rises in disease, insect outbreaks, invasive species, and other ecosystem disasters (Dietze et al. 2018, Bodner et al. 2021). Historical experience in harvesting natural resources and navigating the environment is becoming less reliable as a tool for decision-making (Hobday et al. 2019). Ecological forecasting, the practice of using models to predict ecosystem states, addresses the need to forecast the near or long-term future of ecosystems in a rapidly changing environment. Forecasts typically use environmental data to predict the distribution of a species a set amount of time in the future, e.g. days, weeks, or years. Ecological forecasting rose to prominence with the publication of Clark et al. (2001), a landmark paper that defined eco-forecasting as a field and emphasized its potential for environmental decision-making. Clark argued that forecast projections, even if imperfect and highly uncertain, can still anticipate change and be useful for policymakers. Exploring different conservation scenarios with forecasting can provide options for decision-makers or target unanticipated weaknesses in management plans for an ecosystem.

The definition of a “useful” forecast for environmental decision-making is under active development. Clark defined a useful forecast as one that is motivated by management or conservation scenarios and specifies uncertainty. While these tenants are widely accepted within the forecasting community, additional detail on these tenants and other proposed optimizations are subject to debate and new discussions. There are three principal stages of forecast development to optimize: Scoping, Development, and Delivery.

1. Scoping Phase

In the scoping phase of a forecast, the researchers define a problem, identify collaborators and funding sources, and determine the goals of the end product. The literature widely agrees that forecasts should be designed to be decision-relevant. If possible, forecasts should be designed in active collaboration with end-users such as stakeholders, decision-makers, and rights-holders to define and understand desired outputs (Dietze et al. 2018, Hobday et al. 2019, Bodner et al. 2021, Van Horne et al. 2023). Sun et al. (2022) in particular emphasizes the importance of involving end-users in forecast definition, providing several examples of case study forecasts such as Wild-Allen et al. (2020) where a lack of collaboration with policymakers prevented full usage of the model.

1.1. Spatial and Temporal Scale

Early and traditional forecasting primarily predicted changes in broad ecosystems over long time scales, such as the IPCC emissions scenarios for 2050 and 2100 (Emissions Scenarios 2000, Dietze et al. 2018). It is desirable to instead tailor the spatial and temporal scales of forecasts to local needs, especially as ecological data increases in volume and availability (Dietze et al. 2018, Hobday et al. 2019). The landmark paper by Dietze et al. (2018) popularized near-term, iterative forecasts as the gold standard for forecasting. Near-term forecasts on a scale of days to years align better with decision-making timelines and allow for continuous model improvement. Pershing et al. (2018), similarly, advocates for consideration of spatial scales. It presents an example of a state-wide Gulf of Maine lobster forecast, which lobstermen found hard to apply to their local shores.

1.2. Indigenous and Local Forecasting Collaboration

Forecasting collaborations have traditionally involved Western scientists, industry partners, and government agencies (Van Horne et al. 2023). An increasing number of publications are calling for the inclusion of local communities and traditional knowledge systems in the forecasting design process (Bodner et al. 2021, Van Horne et al. 2023). Van Horne et al. (2023) refers to "Funds of Knowledge": historically accumulated, culturally developed bodies of knowledge needed for the well-being of community members. Van Horne argues that Funds of Knowledge can add invaluable perspective to the design and dissemination process so that research can optimally benefit communities. Sun et al. (2022) agrees with this sentiment, pointing out that ecological forecasting researchers are primarily from the Global North and generally do not possess lived experience relying on the ecosystems they predict.

Collaboration with Indigenous communities can also provide invaluable knowledge for forecasts (Bodner et al. 2021, Nyadzi et al. 2022). The Indigenous Circle of Experts (2018) appeals for resource allocation to Indigenous-led conservation and engagement. Indigenous perspectives on land and water consider elements of nature indivisible – land is not separate from the air, wind, water, and humans. While Western forecasting might prioritize restrictions on activities or access, Indigenous conservation techniques involve the restoration of sustainable relationships with natural ecosystems. Nyadzi et al. (2022) implemented this theory by developing agricultural forecasts using a combination of Western scientific forecasts and indigenous forecasts. Nyadzi found that the integrated forecast performed better on a seasonal scale and was preferred by 93% of local farmers compared to the pure scientific forecast, evidence that incorporating indigenous knowledge can increase forecast reliability and usage.

1.3. Equitable, Impactful Funding

The literature generally agrees that impactful forecasts are best funded by sources such as governmental agencies which can support forecasting programs for communities long-term (Dietze et al. 2018, Sun et al. 2022). However, some publications argue that current funding models further inequities and devalue impactful forecasts. Van Horne et al. (2023) points out that many application-based funding programs can disproportionately benefit communities with well-established environmental programs. For example, applications to the CARB Community Air Grant (2020) required significant coordinated effort and time investments. As a result, communities with significant air exposure issues that lacked the time and resources to prepare the application did not receive the grant. Van Horne suggests that funding agencies and research scientists should direct funding and resources to support the participation of marginalized communities in research programs. Funding needs for community engagement should be considered in the upfront costs rather than as an afterthought.

Flagg (2022) additionally argues that many large-scale funding programs value scientific novelty over actionable impact. One example is the US National Science Foundation's Small Business Innovation Awards, for which the first criterion is "intellectual merit" (National Science Foundation). However, it is equally if not more important that research leads to applied benefits for communities and that funders track, measure, and award societal impact. The entrepreneurship 'valley of death' when trying to turn research advances into applications for communities, especially in critical but lower-profit areas such as sustainable ecosystems, prevents discoveries from being useful. Flagg proposes that funding agencies should value community impact in their award systems and specify key metrics to objectively measure actionable impacts for proposals.

2. Development Phase

In the development phase of a forecast, the researchers build and refine mechanistic or probabilistic models which use environmental data to predict ecosystem states. The literature widely agrees that the most critical component of forecasting development is definite measurements of uncertainty (Clark et al. 2001, Lacey et al. 2015, Dietze et al. 2018, Hobday et al. 2019, Bodner et al. 2021). Scientists have an obligation to carefully consider the risks associated with their research and clearly present them to end-users (Lacey et al. 2015). While measurements of uncertainty can be confusing to stakeholders without scientific backgrounds, Hobday et al. (2019) argues that discarding measurements of uncertainty is unethical and provides false confidence in projections to end-users, even if the omission is meant to improve readability. There is some debate over using Bayesian or traditional Frequentist approaches to determine forecast uncertainty, with Bayesian approaches becoming increasingly popular (Doll and Lauer 2014).

2.1. Social-ecological feedback systems

A recent development in forecast models is the proposed inclusion of social-ecological feedback systems in data models. While modeling techniques typically address environmental issues in isolation, Bodner et al. (2021) argues that social and environmental systems are interdependent and should be researched as such. Social factors that influence ecosystems are themselves influenced by forecasts. Sun et al. (2022) proposes that models should be built to include social-ecological drivers if data is available or otherwise contextualize forecast results. Including social factors in models can better account for variations in human behavior, acknowledge inequities due to structural racism and other societal systems, and understand community response to forecasts (Bodner et al. 2021, Van Horne et al. 2023).

3. Delivery Phase

In the delivery phase, the forecasts are presented to end-users through a short or long-term delivery method. A useful forecast may employ a variety of delivery methods, such as websites, memos, or maps. Similar to uncertainty, the literature widely agrees that delivery formats should be understandable to the end user. In the case where there are multiple end-user groups, delivery should be adjusted for different potential groups to meet their needs. For example, projections for the Delaware Bay Atlantic Sturgeon System (Breece et al. 2017) were primarily presented using a web-based map application. However, to account for fishers who may be in the open ocean and lack access to a large computer or reliable internet, the study also employed an SMS text messaging system to communicate.

3.1. Concerns with forecast delivery

While forecasting is generally considered beneficial to ecosystem conservation and communities, it can have negative impacts when delivered naively. Forecasters must accept ethical responsibility for their forecasts and thoroughly understand and communicate the potential consequences of their research (Lacey et al. 2015).

Local communities may not want to receive forecasts. A psychology study by Gigerenzer and Garcia-Retamero (2017) found that over 70% of participants did not want to know about future events, positive or negative. One reason they posited was that ignorance maintains fairness. For example, some fishermen believe that they can handle unanticipated changes in fish stock and that forecasts would give their competition an unfair advantage (Hobday et al. 2019). Hobday et al. (2019) also points out that the delivery of a forecast to specific groups can have unintended consequences and influence winner-loser dynamics. For example, forecasts within the fishing industry are usually proprietary and can give industry leaders an additional advantage. In another example, a 2016 forecast of early lobster catches made dealers offer lower prices to lobstermen than expected, putting harvesters at an unanticipated disadvantage due to the forecast (Pershing et al. 2018).

Hobday also warns that forecasts can potentially damage ecosystem health. Natural resource forecasts can provide information to users that eliminate the time/space refuge prey require to maintain population size. Sustainable harvesting must be carefully considered and model output adjusted as necessary, potentially even removing information from model delivery. This has additional considerations when a forecast is publicly available. For example, one concern with the Delaware Bay Sturgeon conservation program is that some fishers may use the forecasts to illegally target sturgeon (Wild-Allen et al. 2020, Hobday et al. 2019).

4. Conclusion

Ecological forecasting overall is a rapidly expanding field with increasing application as data collection techniques advance, more forecasts and data move to open-source methods, and forecasts improve through iterative design (Dietze et al. 2018). Forecasts have demonstrated utility in environmental decision-making, but not all forecasts are impactful. Careful consideration of properties defining useful forecasts will allow for further advances in the field and better-informed environmental decision-making.

5. Literature Cited

Bodner, Korryn, et al. "Bridging the Divide between Ecological Forecasts and Environmental Decision Making." *Ecosphere*, vol. 12, no. 12, 2021, p. e03869. *Wiley Online Library*, https://doi.org/10.1002/ecs2.3869.

Breece, Matthew, et al. "Dynamic Seascapes Predict the Marine Occurrence of an Endangered Species: Atlantic Sturgeon Acipenser Oxyrinchus Oxyrinchus." *Methods in Ecology and Evolution*, vol. 7, Feb. 2016, p. n/a-n/a. *ResearchGate*, https://doi.org/10.1111/2041-210X.12532.

California Air Resources Board. *Community Air Protection Program*. 2020, https://ww2.arb.ca.gov/capp.

Clark, James S., et al. "Ecological Forecasts: An Emerging Imperative." *Science*, vol. 293, no. 5530, July 2001, pp. 657–60. *www-science-org.ezproxy.neu.edu (Atypon)*, https://doi.org/10.1126/science.293.5530.657.

Dietze, Michael C., et al. "Iterative Near-Term Ecological Forecasting: Needs, Opportunities, and Challenges." *Proceedings of the National Academy of Sciences - PNAS*, vol. 115, no. 7, 2018, pp. 1424–32. *onesearch.library.northeastern.edu*, https://doi.org/10.1073/pnas.1710231115.

Doll, Jason C., and Thomas E. Lauer. "Comparing Bayesian and Frequentist Methods of Fisheries Models: Hierarchical Catch Curves." *Journal of Great Lakes Research*, vol. 40, Jan. 2014, pp. 41–48. *ScienceDirect*, https://doi.org/10.1016/j.jglr.2014.07.006.

Emissions Scenarios: Summary for Policymakers; a Special Report of IPCC Working Group III. Intergovernmental Panel on Climate Change, 2000.

Flagg, Melissa. “Reward Research for Being Useful — Not Just Flashy.” *Nature*, vol. 610, no. 7930, Oct. 2022, pp. 9–9. *www.nature.com*, https://doi.org/10.1038/d41586-022-03131-7.

Gigerenzer, Gerd, and Rocio Garcia-Retamero. “Cassandra’s Regret: The Psychology of Not Wanting to Know.” *Psychological Review*, vol. 124, no. 2, Mar. 2017, pp. 179–96. *DOI.org (Crossref)*, https://doi.org/10.1037/rev0000055.

Hobday, Alistair J., et al. “Ethical Considerations and Unanticipated Consequences Associated with Ecological Forecasting for Marine Resources.” *ICES Journal of Marine Science*, vol. 76, no. 5, Sept. 2019, pp. 1244–56. *Silverchair*, https://doi.org/10.1093/icesjms/fsy210.

Lacey, Justine, et al. “Informed Adaptation: Ethical Considerations for Adaptation Researchers and Decision-Makers.” *Global Environmental Change*, vol. 32, May 2015, pp. 200–10. *DOI.org (Crossref)*, https://doi.org/10.1016/j.gloenvcha.2015.03.011.

National Science Foundation. “How We Make Funding Decisions.” *NSF - National Science Foundation*, https://new.nsf.gov/funding/merit-review. Accessed 2 Aug. 2023.

Nyadzi, Emmanuel, et al. “Towards Weather and Climate Services That Integrate Indigenous and Scientific Forecasts to Improve Forecast Reliability and Acceptability in Ghana.” *Environmental Development*, vol. 42, June 2022, p. 100698. *DOI.org (Crossref)*, https://doi.org/10.1016/j.envdev.2021.100698.

Pershing, Andrew J., et al. “Evidence for Adaptation from the 2016 Marine Heatwave in the Northwest Atlantic Ocean.” *Oceanography*, vol. 31, no. 2, 2018, pp. 152–61.

Sun, Chaojiao, et al. “Ecological Forecasting and Operational Information Systems Support Sustainable Ocean Management.” *Forecasting*, vol. 4, no. 4, 4, Dec. 2022, pp. 1051–79. *www.mdpi.com*, https://doi.org/10.3390/forecast4040057.

The Indigenous Circle of Experts. *We Rise Together: Achieving Pathway to Canada Target 1 through the Creation of Indigenous Protected and Conserved Areas in the Spirit and Practice of Reconciliation*. Parks Canada, 2018.

Van Horne, Yoshira Ornelas, et al. “An Applied Environmental Justice Framework for Exposure Science.” *Journal of Exposure Science & Environmental Epidemiology*, vol. 33, no. 1, Jan. 2023, pp. 1–11. *PubMed*, https://doi.org/10.1038/s41370-022-00422-z.

Wild-Allen, K., et al. *Macquarie Harbour Oxygen Process Model*. CSIRO Oceans & Atmosphere, 2020.