

# Rethinking success and quality in ecological forecasting

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Ecological forecasts are increasingly required to inform science, policy and action in the face of rapid environmental and societal change. However, differences in how developers and end-users judge the value of ecological forecasts may limit their utility and uptake in real-world decision-making. Here, we use a participatory approach to propose a novel, holistic framework for the evaluation of ecological forecasts along two intersecting axes: quality and success. Quality is defined by the defensible development and predictive performance of ecological forecasts, while success captures the usefulness of a forecast in achieving its intended aim. We propose twelve shared criteria for evaluating quality and success spanning the forecasting process, set-up, and outputs while capturing forecast development, communication, performance, and operationality. Together, these criteria provide a common basis for the co-development of ecological forecasts, and better connect science with forecast-informed decision-making.

**In a nutshell:** (100/100)

As academics, practitioners and users of ecological forecasts, we recognised a fundamental gap in evaluative frameworks currently used to assess forecast value; most focused solely on predictive performance, despite performance being a poor predictor of whether a forecast meaningfully informs science, policy or practice. We therefore used participatory methods to explore what constitutes a “good” ecological forecast and co-developed a framework centred around two axes - quality and success – each of which can be assessed by a shared set of criteria. The framework enables holistic evaluation of ecological forecasts, and we hope will drive improvement in both quality and success.

## **Main text:**

### *The need for holistic evaluation*

Anticipating how ecosystems respond to global change is essential for planning and adapting to growing climate, economic and societal uncertainty. International commitments, including the Kunming-Montreal Global Biodiversity Framework (Convention on Biological Diversity, 2022), set ambitious targets for biodiversity conservation and ecosystem restoration, requiring decisions about where, when, and how limited resources are deployed. Such decisions are complicated by uncertainty, both in ecological responses to global change and outcomes of management interventions. Ecological forecasts (Panel 1) therefore offer an increasingly important means to anticipate responses and inform decision-making (Mouquet et al., 2015).

Ecological forecasts can inform policy, practice and science if they are sufficiently reliable, relevant, and useable (Bodner et al., 2021; Evans et al., 2013). Yet, what makes a forecast “good enough” for its intended purpose remains poorly defined within a comprehensive and operational framework. This limits our ability to evaluate and improve ecological forecasts systematically and to understand when they can responsibly inform decision-making. As such, relatively few ecological forecasts have been translated into real-world decisions and action (Dietze et al., 2024).

Conventionally, ecological forecasts are evaluated on predictive performance, and numerous metrics of “skill” exist (e.g., root mean square error, bias metrics, continuous ranked probability scores, Brier scores; Simonis et al., 2021). However, predictive accuracy represents only one criterion of a “good” forecast. Other attributes valued by the scientific community, but less consistently evaluated, include the forecast horizon (Petchey et al., 2015; Wesselkamp et al., 2025), transparency of the forecasting pipeline (Roche et al., 2022), comprehensive uncertainty accounting (Simmonds & Jones, 2024), and computational efficiency (Törnquist et al., 2023). Nevertheless, even this broader set of criteria fails to sufficiently capture many attributes that determine whether forecasts are used in practice.

Effective integration of ecological forecasts into real-world decision-making requires an appreciation of the broader societal context, including policy processes, stakeholder priorities, the social acceptability of forecast-informed actions, and the capacity of institutions and actors to implement them (Bodner et al., 2021). End-users may therefore evaluate a forecast based on its timeliness, interpretability, on the scale and metrics being forecast, and its relevance to the decision-making context. These factors shape how forecasts are understood, trusted and ultimately used by different audiences, and may be as important in forecast evaluation as conventional measures of predictive performance.

Despite growing recognition of the broader range of attributes essential for “good” ecological forecasting (Lewis et al., 2022), to our knowledge, no holistic framework integrating both scientific performance and practical usefulness exists. We therefore propose a multi-perspective framework for assessing the overall value of ecological forecasts. Our aim is to reconcile attributes most valuable to decision-makers and those prioritised by researchers.

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## Panel 1. Glossary.

- **Ecological forecast:** A prediction of the state of ecosystems over a defined temporal horizon, with fully specified uncertainties, and contingent on explicit scenarios of climate, land use, human population, technologies, and economic activity (Clark et al., 2001).
  - **Forecast horizon:** The dimensional distance in, e.g., time, space, or phylogeny between the current state of the system and the forecast.
  - **Forecast uncertainty:** The uncertainty associated with forecast outcomes, arising from, e.g., observation error, model structure, parameter estimation, process variability, and uncertain future drivers or scenarios.
  - **Prediction:** An estimate of unknown ecosystem states based on currently available data and models.
  - **Skill:** The predictive performance (accuracy and precision) of a forecast when evaluated against observations, often relative to a benchmark or reference model.
  - **Usefulness:** In a scientifically- or decision-oriented context, how a forecast improves outcomes, or reduces uncertainties, from a no-forecast baseline or in comparison to alternative forecast products.
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### *Co-designing an evaluation framework*

Comprehensive evaluation of ecological forecasts necessitates consideration of many attributes from diverse perspectives. To capture scientific and applied perspectives, we co-created our evaluation framework through a participatory process (Luskin & Ho, 2013; Patton, 2003). This process was led by a working group of the European Chapter of the Ecological Forecasting Initiative and comprised participants spanning academia, public bodies and conservation organisations from across Europe, representing different stages of the forecasting process, from development through use and evaluation.

Framework development followed an iterative process in which potential evaluation criteria were identified, refined and synthesised through engagement within the working group and the wider ecological forecasting community. Engagement included online questionnaires and workshops, in-person meetings (British Ecological Society Annual Meeting, December 2025), and collaborative manuscript development.

### *Success and quality: A backbone for holistic assessment*

To date, efforts to formalise what constitutes a “good” ecological forecast have primarily focused on the modelling process and predictive performance. The modelling process emphasises rigour – reproducibility, transparency, interoperability and evaluation – as outlined in the PERFICT principles for predictive ecology (McIntire et al., 2022), as well as modelling components including computational complexity, model class, inputs and parameters (Malmborg et al., 2024). Predictive performance focuses on skill and the temporal horizon over which forecasts remain skilful (Petchey et al., 2015). While consideration of these attributes is necessary, “good” process and performance do not guarantee a forecast is useful. Another axis

is therefore needed to assess how well a forecast fulfils the purpose for which it was developed. We propose a unifying framework in which ecological forecast value is evaluated along two complementary axes: **success** and **quality** (Figure 1).

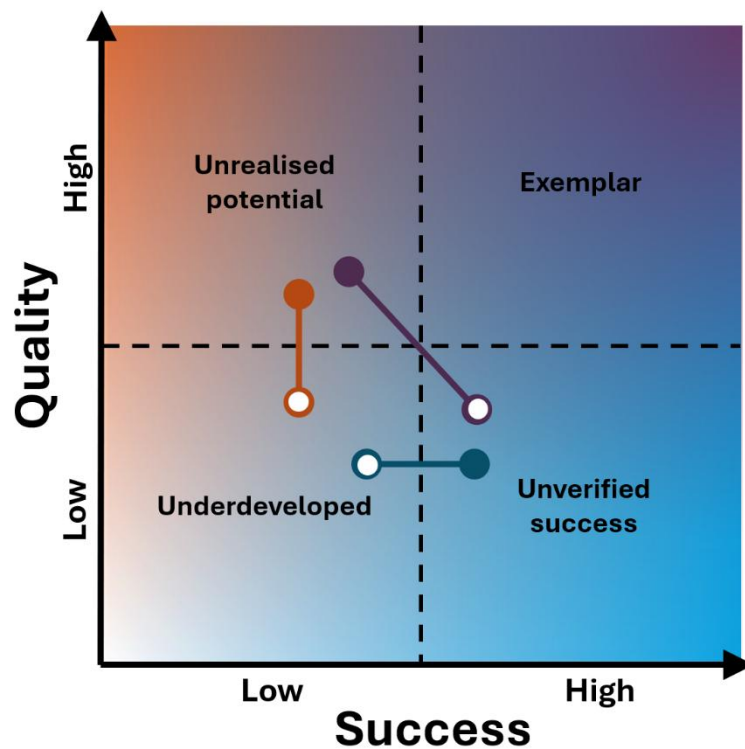


**Figure 1.** Axes of ecological forecast success and quality. The axes intersect such that quality and success may vary independently. Lines indicate opportunities for improvement from a start point (open circles) to an end point (closed circles) along the axis of success (blue) or quality (orange), while the purple line demonstrates trade-offs between success *and* quality.

Following existing practice, we define **forecast quality** in terms of both the quality of the forecasting process and the quality of the resulting predictions. The forecasting process must be defensible, where each development decision has been made in an evaluative, collaborative and justified fashion, with a high standard of integrity, transparency and rigour. Then, the forecast must perform well in terms of the accuracy and precision of its predictions, either as measured against actual outcomes retrospectively, or as assessed provisionally through space-for-time substitutions or hindcast evaluation (although neither guarantee quality predictions in future).

Forecast success is more challenging to define, acknowledging the diverse and multifaceted purposes an ecological forecast may seek to serve: from formalising existing knowledge and advancing ecological theory, to informing decisions, or simply encouraging discussion. Consequently, success can only be evaluated in relation to the purpose for which a forecast was developed. Where the primary aim of a forecast is scientific (i.e., to advance knowledge through quantitative testing and refinement of an ecological hypothesis; Lewis et al., 2023),

judgement of success will differ substantially from a forecast developed to inform management decisions or policy. For such decision-oriented forecasts, success is contingent on close collaboration with end-users throughout the development process to ensure questions addressed, scenarios evaluated, spatiotemporal scales considered, and outputs produced align with real-world decision-making needs (Bodner et al., 2021; Lazurko et al., 2026a).

We therefore define **forecast success** in terms of a forecast's ability to achieve its intended purpose, be that scientifically- or decision-oriented. This necessitates that forecast development decisions are aligned with user needs (Starfield, 1997), which for many, marks a stark departure from standard academic practice (Runge, 2011). Success further encapsulates usefulness, or how a forecast changes outcomes and/or reduces uncertainties against a benchmark. This may be in a decision-making context or purely scientific, e.g., what decision would be made, or how would science progress, in the absence of the forecast? A successful forecast improves outcomes and reduces the likelihood of undesirable consequences relative to a counterfactual situation in which the forecast was not available.

Crucially, we believe both quality and success must be accounted for in the evaluation of ecological forecasts. However, high-quality does not necessarily guarantee success, or vice versa. Indeed, there are instances in which high-quality forecasts are unsuccessful because they do not meet user needs (Cash et al., 2003; Norström et al., 2020). Conversely, for a forecast to correctly inform decision-making or scientific understanding, a minimum quality is required. Quality and success should therefore be evaluated jointly, while recognising that they can vary independently; as we illustrate with examples in Panel 2.

#### *Success and quality criteria*

Rather than evaluating success and quality via separate frameworks, we identify a shared set of criteria by which quality and success can be assessed in tandem but scored independently (Table 1). For each criterion, we ask both whether the forecast is well constructed (quality) and whether it provides actionable science or knowledge (success; Palmer & Boyd, 2025). Neither question answers the other, and a given forecast may score highly along one axis whilst scoring poorly on the other. Sometimes, success and quality criteria interact positively, e.g., greater skill is typically good for quality *and* success, while at other times will involve trade-offs, e.g., balancing model complexity and realism against practical feasibilities of running the forecast within a decision-making timeframe (Figure 1, purple line).

We further recognise that, depending on an individual or organisation's role in the ecological forecasting process (i.e., developer, end-user or evaluator), different criteria may be more or less relevant, and in some cases may be impossible to score (e.g., if information is not provided or capacity is insufficient to interpret it). For example, for some, correctly identifying rare but high-impact events, with significant ecological and socioeconomic costs, is crucial (e.g., disease vulnerability; Pearce-Higgins et al., 2025). Thus, more weight can be placed on the appropriate calibration of the forecast's risk profile: decision-makers may be more willing to tolerate false-alarms, so long as forecasts minimise the risk of missing a high-impact event. In other cases, unnecessary intervention may be costly, and thus false-alarms must be minimised (e.g., when implementing controversial management decisions; Bolton et al., 2007). Similarly, some decisions may prioritise highly accurate timing and spatial localisation (e.g., assessing

flood risk; Tsakiris, 2014), while others require only qualitative estimates of directional change (e.g., climate vulnerability assessment; Foden et al., 2019).

We aim to provide a flexible framework for the holistic evaluation of ecological forecasts, allowing for variable weighting of success and quality criteria to accommodate differing forecast purposes and roles of those interacting with forecasts. Further, criteria may be assessed during forecast design and development, or retrospectively once predictions and their consequences can be examined.

**Table 1.** Criteria for the evaluation of ecological forecast success and quality.

| Criteria                    | Quality                                                                                                                                                                                                                                                                                                                                                                        | Success                                                                                                                                                                                                                                                                                             |
|-----------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Modelling choices</b>    | <ul style="list-style-type: none"> <li>▪ <b>Model type</b> appropriate given the system, data availability, and question.</li> <li>▪ Use of existing <b>theory</b> is well-justified.</li> <li>▪ Multiple <b>sources of knowledge</b> considered and appropriately integrated.</li> <li>▪ Model not unnecessarily <b>complex</b>.</li> </ul>                                   | <ul style="list-style-type: none"> <li>▪ The <b>metric</b> being forecast is meaningful to the question and context (decision-related or purely scientific).</li> </ul>                                                                                                                             |
| <b>Spatiotemporal scale</b> | <ul style="list-style-type: none"> <li>▪ The scale of inputs, processes, and outputs match in <b>space</b> and <b>time</b>. This may be achieved through resampling/aggregation.</li> <li>▪ Alternatively, mismatches are acknowledged and modelled explicitly.</li> </ul>                                                                                                     | <ul style="list-style-type: none"> <li>▪ The scale of inputs and outputs matches that of the question in <b>time</b> and <b>space</b>.</li> </ul>                                                                                                                                                   |
| <b>Input data</b>           | <ul style="list-style-type: none"> <li>▪ Input data are of <b>sufficient</b> sample size or length of time series (e.g. for the number of parameters considered), and are of <b>high quality</b> (low missingness, sampling bias, measurement error).</li> <li>▪ Alternatively, limitations of input data are known and implications for prediction are recognised.</li> </ul> | <ul style="list-style-type: none"> <li>▪ Input data on all necessary variables are available and incorporated (can be through proxies if acknowledged and treated correctly).</li> <li>▪ Any important missing variables are agreed with users and the resulting limitations understood.</li> </ul> |
| <b>Scenarios</b>            | <ul style="list-style-type: none"> <li>▪ Sufficient plausible scenarios are explored to answer the question and <b>capture uncertainties</b> in future conditions.</li> <li>▪ Scenarios defined following <b>best practice</b> (e.g., Lazurko et al., 2026), and have a clear spatiotemporal horizon.</li> </ul>                                                               | <ul style="list-style-type: none"> <li>▪ Scenarios are <b>relevant</b> to the user and <b>representative</b> of stakeholder views (ideally co-designed).</li> </ul>                                                                                                                                 |

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|------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Uncertainty</b>     | <ul style="list-style-type: none"> <li>▪ All relevant uncertainties are <b>quantified</b> correctly and <b>propagated</b> both spatially and temporally (as relevant).</li> <li>▪ Alternatively, omissions of uncertainty are acknowledged.</li> </ul>                                                                                                                                                                                                                                                                                                                            | <ul style="list-style-type: none"> <li>▪ Uncertainty is <b>communicated transparently</b> and accessibly such that it can be used in decision-making.</li> </ul>                                                                                                                                                                                                         |
| <b>Skill</b>           | <ul style="list-style-type: none"> <li>▪ Prediction accurately and precisely forecast change through time and/or variation in space.</li> </ul>                                                                                                                                                                                                                                                                                                                                                                                                                                   | <ul style="list-style-type: none"> <li>▪ Accuracy and precision are <b>sufficient</b> for the intended use, whether scientifically- or decision-oriented.</li> </ul>                                                                                                                                                                                                     |
| <b>Operationality</b>  | <ul style="list-style-type: none"> <li>▪ Efforts made to minimise the computational and environmental <b>costs</b>.</li> <li>▪ Findability, Accessibility, Interoperability, and Reusability (FAIR) <b>reporting</b> of the methods, results, forecasts, outputs (Wilkinson et al., 2016).</li> </ul>                                                                                                                                                                                                                                                                             | <ul style="list-style-type: none"> <li>▪ Forecast can <b>feasibly</b> be run (in terms of computation, environmental impact, users' capacity) at the required frequency (e.g., daily/monthly/annually).</li> <li>▪ <b>Cost-effective</b> relative to other approaches.</li> <li>▪ Methodology communicated effectively to enable the running of the forecast.</li> </ul> |
| <b>Trustworthiness</b> | <ul style="list-style-type: none"> <li>▪ Forecast is <b>validated</b> at the appropriate scale with a high-quality dataset.</li> <li>▪ Validation is <b>internal and external</b> (out-of-sample), with consideration given to the appropriateness of out-of-sample data (e.g., space for time substitutions)</li> <li>▪ Validation is <b>iterative</b>, acknowledging initial conditions, drivers and relationships may change in future.</li> <li>▪ Validation, along with assumptions and limitations, is <b>documented</b> transparently to allow for replication.</li> </ul> | <ul style="list-style-type: none"> <li>▪ Forecast communicated through existing <b>trusted channels</b> or with sufficient support to garner trust.</li> <li>▪ The forecast is subject to best practice scrutiny (e.g., peer review) and validation.</li> </ul>                                                                                                          |
| <b>Usefulness</b>      | <ul style="list-style-type: none"> <li>▪ <b>Iterative</b> forecasting pipeline, allowing for updating of the model as new data becomes available.</li> <li>▪ <b>Representativeness</b> and <b>generalisability</b> of forecast are clearly communicated in terms of spatial, temporal, or other axes across which the forecast could be applicable (e.g., another species or threat).</li> </ul>                                                                                                                                                                                  | <ul style="list-style-type: none"> <li>▪ Elevates scientific understanding, practice, or decision-making beyond what could have been achieved without the forecast.</li> <li>▪ Results and their implications (e.g., actions) <b>understood</b> by the intended audience.</li> </ul>                                                                                     |

|                     |                                                                                                                                                                                                                                                                                                                                   |                                                                                                                                                                                                                                                                      |
|---------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Timeliness</b>   | <ul style="list-style-type: none"> <li>Model <b>updated</b> at a frequency that keeps pace with how quickly the underlying system changes.</li> </ul>                                                                                                                                                                             | <ul style="list-style-type: none"> <li>Delivered within the timeframe required for decision-making and forecast-based action (Boult, 2023).</li> </ul>                                                                                                               |
| <b>Inclusivity</b>  | <ul style="list-style-type: none"> <li>Forecast (modelling decisions, scenarios, communication channels and format) is <b>co-designed</b> with relevant parties.</li> </ul>                                                                                                                                                       | <ul style="list-style-type: none"> <li>Forecast developed via <b>participatory</b> processes.</li> <li>There is <b>buy-in</b> from users.</li> <li>Success could also be measured in terms of capacity building, knowledge exchange, relationships.</li> </ul>       |
| <b>Risk profile</b> | <ul style="list-style-type: none"> <li>Forecast minimises <b>false-positives and false-negatives</b>.</li> <li>Alternatively, balances false-positives and false-negatives appropriately for the application.</li> <li>The risk profile and any trade-offs for users are <b>reported</b> explicitly and transparently.</li> </ul> | <ul style="list-style-type: none"> <li>The balance of false-positives and false-negatives <b>matches</b> the risk profile of the application and the costs (ecological, socioeconomic, reputational) of inappropriate inaction versus unnecessary action.</li> </ul> |

**Panel 2.** Examples of ecological forecasts spanning the success-quality continuum.

**Fire forecasting illustrates how quality and success can vary independently.**

Fire forecasting has progressed from relatively simplistic fire-weather indices (e.g., Fire Danger Index) towards probabilistic systems integrating climate forecasts and real-time monitoring of relevant environmental variables (e.g., ProbFire; Nikonovas et al., 2022). Such improvements in quality meant the 2015 Indonesian fires were forecast 60-180 days in advance (Shawki et al., 2017). However, by our definition, the forecasts were unsuccessful because responsibilities, intervention options and decision thresholds were poorly specified within the forecast-to-action chain (Purnomo et al., 2017), preventing effective intervention. By contrast, relatively simple fire forecasts based on local knowledge of burning practices in the Brazilian Cerrado have reduced late-dry season fires by 45-75% (Franke et al., 2024; Schmidt et al., 2018). Compared to data-driven approaches, these forecasts are low quality (no uncertainty quantification or propagation, localised potential) but highly successful because they closely align with local knowledge, management practices and decision contexts.



**Forecasting impacts of offshore wind: highly successful despite moderate quality.**

Environmental impact assessments for offshore wind developments increasingly use forecasts to predict impacts of underwater noise on marine mammals and inform permitting, mitigation and monitoring. These forecasts typically rely on sparse and uncertain data, combining estimates of noise exposure, animal behavioural responses and demographic rates (Pirotta et al., 2018; Railsback et al., 2025) through agent-based (e.g., DEPONS; Nabe-Nielsen et al., 2018) and demographic models (e.g., iPCoD; King et al., 2015). Scenario analysis is the primary output, allowing decision-makers to compare development and mitigation options, with scenarios frequently co-designed by developers, regulators and practitioners.

Given their central role in regulatory decision-making, these forecasts are highly successful. However, opportunities for true validation remain limited - excess mortality and reduced reproductive rates are difficult to observe and cannot be unambiguously attributed to windfarms. Consequently, forecast quality is often moderate despite substantial influence on management decisions.

### *Way forward*

We have presented a novel, holistic framework for assessing the value of ecological forecasts, addressing two fundamental gaps in current practice. First, criteria enable simultaneous assessment of multiple dimensions of forecast success and quality, including the forecast's development, communication, performance and operationality. Second, criteria formalise the co-development of forecasts, offering a shared framework for dialogue between developers and users (Massingham et al., 2026). Further, by centring evaluation on the intended purpose of a forecast, whether scientific or decision-oriented, the framework supports applications spanning discovery science, policy and management.

An important next step is to test and refine the framework across contrasting scientific and decision-making contexts. It would additionally be helpful to define quantitative scoring systems for quality and success, such that improvements and trade-offs in forecast development are objectively defined.

Ultimately, we hope our framework supports the effective integration of ecological forecasts in the advance of scientific knowledge and in decision-making.

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Panel 2 image credits: Fire management in the Brazilian Cerrado, Alessandra Fidelis; Composite illustration created from an original harbor porpoise photograph (Cara Gallagher) and an adapted offshore wind farm photograph by Andy Dingley (CC BY-SA 3.0).

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