

REVIEW

Forecasting for intended consequences

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Abstract

Restoration and conservation innovations face numerous challenges that often limit widespread adoption, including uncertainty of outcomes, risk averse or status quo biased management, and unknown trade-offs. These barriers often result in cautious conservation that does not consider the true cost of impeding innovation, and overemphasizes the risks of unintended consequences versus the opportunities presented by proactive and innovative conservation, the intended consequences. Simulation models are powerful tools for forecasting and evaluating the potential outcomes of restoration or conservation innovations prior to on-the-ground deployment. These forecasts provide information about the potential trade-offs among the risks and benefits of candidate management actions, elucidating the likelihood that an innovation will achieve its intended consequences and at what cost. They can also highlight when and where business-as-usual management may incur larger costs than alternative management approaches over the long-term. Forecasts inform the decision-making process prior to the implementation of emergent, proactive practices at broad scales, lending support for management decisions and reducing the barriers to innovation. Here we review the science, motivations, and challenges of forecasting for restoration and conservation innovations.

KEYWORDS

anthropogenic change, conservation, forecasting, landscape management, restoration, simulation modeling

1 | INTRODUCTION

There are barriers to any conservation action, including cost of implementation, environmental regulations, local acceptance (or lack thereof) of intervention, and the lack of monitoring to inform conservation action selection and document system response (Knight, Cowling, & Campbell, 2006). Innovative or novel conservation (e.g., genomic translocations, restoration silviculture, floodplain engineering, soil amendments) faces additional challenges that may limit widespread adoption,

including the uncertainty of outcomes and unknown trade-offs compared to established management approaches. Risk averse policy and management may avoid novel solutions when the trade-offs among risks and benefits are unclear and the uncertainty of consequences is high. These additional barriers often result in conservation that fails to deviate from past management approaches, a status quo bias (Samuelson & Zeckhauser, 1988), particularly when the perceived costs and risks of innovation are high relative to established strategies. We have personally witnessed how the same

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conservation and restoration practices are used repeatedly across agencies because it is easier and more acceptable to use techniques that have a proven track record of at least modest success rather than to risk the funding and social capital on a new idea. Traditional approaches may, however, be detrimental under global change, when past management interventions may not be sufficient to maintain (or adapt) ecosystems under novel conditions (Hobbs, Higgs, & Harris, 2009; Lindenmayer et al., 2008) and an ever-changing future (Hodgson, Thomas, Wintle, & Moilanen, 2009; Kujala, Burgman, & Moilanen, 2013; Polasky, Carpenter, Folke, & Keeler, 2011). Here we highlight how forecasting can be used to evaluate the consequences (intended and unintended) of conservation decisions and provide examples of how forecasting has been used to support conservation decision-making and implementation. We further suggest opportunities where forecasting can inform promising new conservation applications, and finally, describe the risks of forecasting and where we see opportunities for improvement to fully realize the potential of forecasting for intended consequences of conservation innovation.

2 | THE ROLE OF FORECASTING

Simulation (or “computational”) models are powerful, well-established tools for forecasting and evaluating conservation actions, allowing managers to address some of the barriers to conservation innovation (Brum, Pressey, Bini, & Loyola, 2019; DeAngelis et al., 1998; Larson, Thompson III, Millspaugh, Dijak, & Shifley, 2004; Nilsson et al., 2005; Ravenscroft, Scheller, Mladenoff, & White, 2010; Tulloch, Hagger, & Greenville, 2020; Twilley, Rivera-Monroy, Chen, & Botero, 1999). Simulation models and their associated visualizations inform many critical policy and decision-making endeavors today (Börner, Rouse, Trunfio, & Stanley, 2018), including global climate change (Lempert & Groves, 2010; Neilson et al., 2005), pandemic spread and response (Giordano et al., 2020; Hall, Gani, Hughes, & Leach, 2007), transportation planning and operation (Robinson, 2012), homeland security risk assessment (Ezell, 2012), and business process efficiency and performance (Diaz, Behr, & Tulpule, 2012) among others. Forecasting has rapidly developed over the past decade thanks to improvements in software and hardware (Scheller, 2018) and, combined with the rise in availability of large ecological data sets that expand the scales of observation, is being increasingly used to examine pressing ecological problems (Cheruvilil & Soranno, 2018). Forecasts now have the capacity to project ecosystem and landscape changes in response to environmental drivers,

such as climate variability or disturbance events, or in response to human actions, such as land use change or management (NOAA, 2016).

Simulation modeling for conservation decision-making is typically operated under a “scenario” framework (Peterson, Cumming, & Carpenter, 2003; Soares-Filho et al., 2006) whereby multiple competing conservation strategies are compared using consistent inputs that represent a variety of possible futures of the modeled system. Such information can subsequently inform ongoing discussions about the proper pace and scale of management actions and can support the design of robust management strategies under global change (Lempert, Groves, Popper, & Bankes, 2007). The formation of scenarios that encapsulate a range of possible futures allows forecasts of social-ecological systems (Schlueter et al., 2012; Thompson et al., 2012) to explicitly incorporate many of the key uncertainties of the system into the decision-making process, for example, CO₂ emissions scenarios (van Vuuren et al., 2011), land use change futures (Thompson, Foster, Scheller, & Kittredge, 2011), sea level rise (LaFever, Lopez, Feagin, & Silvy, 2007), and shifting wildfire and disturbance regimes (Borchers, 2005). These scenarios are then combined with proposed management actions to capture the uncertainty that will influence management response (e.g., Maxwell, Serra-Diaz, Scheller, & Thompson, 2020; Scheller et al., 2011) (Figure 1). By directly incorporating uncertainty, land managers gain a “bigger picture” focus that allows them to conceptualize a broader range of consequences, so that they become better equipped to proactively manage for the future.

3 | CURRENT APPLICATIONS OF FORECASTING FOR CONSERVATION INNOVATION

3.1 | Assessing conservation innovations in silico

Forecasts of the consequences of conservation are particularly valuable for assessing emergent or experimental practices and for identifying the associated trade-offs between effort and efficacy of new strategies. Field-testing of many innovative practices is inherently expensive, and depending on the management action, can take years or decades to conduct; true replication is generally not feasible. Forecasting allows for the replicable assessment of these innovations at a pace and cost much more amenable to management timelines and budgets (Torrubia et al., 2014). Additionally, forecasts can represent the implementation of innovative practices across an entire landscape, where the full costs and benefits of

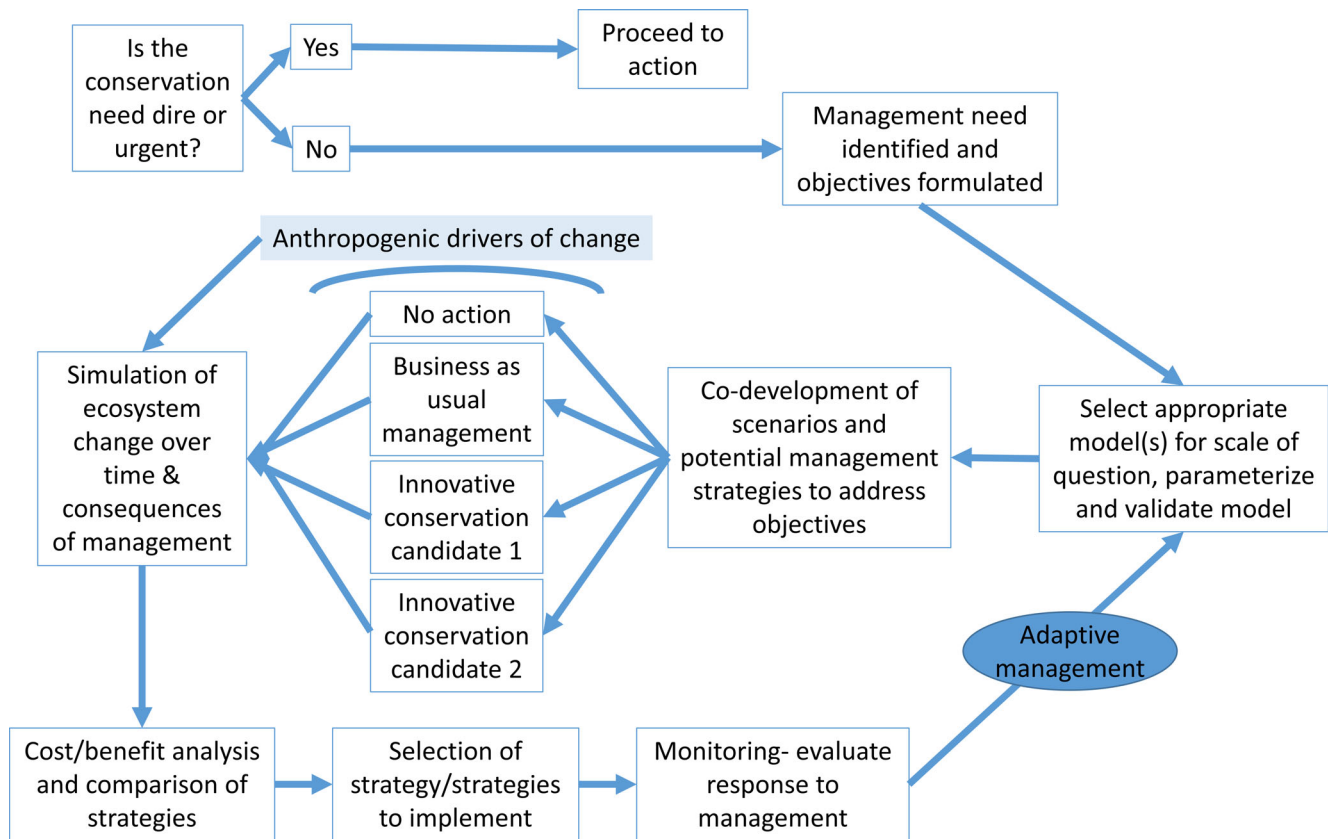


FIGURE 1 Workflow describing the use of forecasting to assess the intended consequences of conservation and restoration actions and foster conservation innovation

management are typically revealed. They can validate whether a novel strategy achieves its target goals (e.g., its intended consequences), how long it takes to achieve those goals, and the cost to achieve intended goals, all before deployment. In doing so, forecasting allows managers to evaluate the potential outcomes from a variety of restoration and conservation strategies on their landscapes, ranging from the familiar to the highly innovative (Perring et al., 2015). It also plays a critical role in reframing which sources of uncertainty are most important, especially for landscapes with a high potential for unprecedented change (Martin et al., 2011). As anthropogenic change accelerates and many landscape and management precedents cease to apply (Lindenmayer et al., 2008), forecasting can help managers to confront novel ecosystems and new management challenges and assess the ability of conservation innovations to achieve their intended consequences.

3.2 | Facilitating the decision-making process

Forecasting facilitates large-scale conservation and restoration planning across agency and ownership boundaries,

supporting collaborative efforts, pooling of resources and knowledge, and enabling co-management among decision-makers, scientists, and stakeholders (Berkes, 2009). It can support structured decision making (SDM) whereby multiple parties engaged in the decision-making process explicitly identify objectives and performance metrics, assess alternatives, and make decisions based on stakeholder values and system uncertainties (Gregory & Long, 2009). Once objectives are specified, forecasting can play a critical role in the SDM process, representing system behavior and projecting system responses to candidate management actions. Because forecasting provides information about the trade-offs among actions—both business-as-usual and more proactive approaches—and outcomes (Martin, Runge, Nichols, Lubow, & Kendall, 2009; Spies et al., 2017), it enables a more collaborative decision analytical framework and facilitates co-production of knowledge. Stakeholders can become full partners in the process of forecasting by sharing data and local knowledge, assessing model outcomes, and ensuring that outputs meet their needs (Armitage, Berkes, Dale, Kocho-Schellenberg, & Patton, 2011). This can be combined with participatory modeling, in which stakeholders formulate management problems and help to develop and

test feasible solutions, to allow managers to collaboratively identify possible futures across a range of likelihoods and assess potential management responses (Voinov et al., 2018, Vukomanovic, Skrip, & Meentemeyer, 2019). By encouraging managers and stakeholders to consider a broader future through participating in forecasting efforts, they are given a greater license to imagine more intensive interventions, bridging the gap between risk averse and risk inclined managers.

3.3 | Business-as-usual management

Finally, forecasting can also highlight when business-as-usual management will not be sufficient and when more innovative practices will be required to achieve the intended consequences. Projecting the approximate magnitude of intervention that could be required from the outset might help managers to make more realistic decisions (Brudvig, 2011; Hobbs, 2007). It will also highlight when managers need to deploy new practices to achieve a goal. This is especially pertinent when the goal is to recreate a historic reference point despite anthropogenic change, or after some threshold of irreversibility has been crossed (Aronson, Floret, Le Floch, Ovalle, & Pontanier, 1993; Hobbs et al., 2009; Jackson & Hobbs, 2009; Suding, Gross, & Houseman, 2004).

4 | CASE STUDIES

Here we provide three applications where forecasting has been or is being used to support restoration and conservation planning, particularly in regards to the consequences of and trade-offs among potential actions that drive the decision-making process.

4.1 | Forecasting for restoration planning

Forecasting has demonstrated utility for projecting the potential for ecological restoration on degraded landscapes (Cantarello et al., 2011) and for comparing the costs and benefits of various restoration strategies to inform restoration planning (Birch et al., 2010; Keane, Holsinger, Mahalovich, & Tomback, 2017). Identifying where and how to restore a landscape after anthropogenic degradation plays a critical role in determining project success or failure. These decisions are difficult and complex, and include (but are not limited to) contending with multiple land owners, budgetary constraints, and the numerous potential restoration strategies available.

Uncertainty associated with global change compounds these challenges as climate change, land use change, altered disturbance regimes, and unknown interactions between agents of change can all influence restoration project outcomes in unanticipated ways.

Cantarello et al. (2011) used simulation modeling to examine the feasibility of passive restoration on a tropical dryland forest landscape undergoing multiple interacting anthropogenic disturbances. Using a spatially explicit model of forest dynamics, the authors simulated passive restoration—allowing the natural regeneration, dispersal, and colonization of vegetation after the removal of the causes of ecological degradation—on two landscapes in Mexico and assessed this restoration approach under multiple disturbance regimes. This allowed for the anticipation of restoration outcomes and revealed the dynamic impacts of interacting disturbances on restoration success. Results showed that passive landscape-scale restoration was a viable option for tropical dryland forest recovery but that the combined effects of livestock grazing and fire reduced forest cover and lessened the efficacy of restoration efforts.

In another example, Birch et al. (2010) used forecasting to evaluate the ability of passive and active restoration to combat environmental degradation in Latin America. The authors compared the cost effectiveness of three restoration strategies (passive, passive with fencing and fire suppression to protect the area, and active [tree planting, fencing, and fire suppression]) by estimating the net value of ecosystem services provided under the different forest restoration scenarios and weighing this against the cost of implementation. Using a simulation model to construct these restoration scenarios, they performed a cost-benefit analysis to compare the cost of each restoration approach to the monetized estimates of a suite of ecosystem services derived from model outputs, including carbon sequestration, timber production, and tourism. These modeling efforts revealed that ecosystem service benefits varied not only by the restoration strategy used but also between study areas, though passive restoration was demonstrated to be the most cost effective approach overall. The incorporation of forecasts enabled not only the assessment of restoration action cost and benefit trade-offs across a suite of regionally important ecosystem services, but also informed the selection of site-specific restoration strategies.

4.2 | Protecting threatened or endangered populations

Conservation forecasting has been extensively deployed in the context of protecting threatened and endangered

(T&E) species (e.g., Akçakaya, Radeloff, Mladenoff, & Hong, 2004; Scheller et al., 2011). The task of recovering T&E species has grown more complicated as the active management for these populations may conflict with other landscape goals, including restoration goals. For example, in the western United States, the locally-distinct population of the fisher (*Pekania pennanti*), which requires old-growth habitat for nesting and denning, has been historically reduced by logging and trapping (Zielinski, Kucera, & Barrett, 1995). Although fishers persist, their habitat is now fragmented and at risk due to large and intense wildfires. This threat is anticipated to grow due to climate change and a more active wildfire regime. Simultaneously, forest managers want to restore a fire regime characterized by more frequent and less intense wildfires (Klimaszewski-Patterson, Weisberg, Mensing, & Scheller, 2018) in order to increase forest resilience to climate change (North et al., 2015). Doing so will require the extensive use of fuel treatments, including forest thinning. Although fuel treatments will reduce the long-term risk of fires that may be catastrophic to fisher persistence, their immediate effect will be a reduction in local fisher habitat quality. As a result of the uncertainty of outcomes, fuel treatments have been widely contested by many environmental groups, who have promoted the precautionary principle whereby interventions should be avoided unless positive outcomes are certain.

Scheller et al. (2011) used forecasting to assess the trade-offs between short-term reductions in habitat quality and long-term reductions in wildfire risk to fisher populations, particularly given the uncertainty introduced by climate change. To do this, they coupled a landscape-change model that simulated forest succession, wildfires, and fuel treatments (Syphard, Scheller, Ward, Spencer, & Strittholt, 2011) with a metapopulation model of fisher dispersal, births, and mortality (Spencer et al., 2011). The authors forecasted and compared the direct (reduced habitat quality) and the indirect (reduced probability of habitat loss from wildfire) effects of fuel treatments on fisher metapopulation dynamics over time. They concluded that fuel treatments were more effective at restoring high frequency, low severity fire regimes under climate change due to a greater probability of intersection between fire and treatment areas (Syphard et al., 2011). And fuel treatments reduced the loss of fisher habitat to wildfire, conferring significant benefit to fisher populations despite the large variability and uncertainty generated by climate change (Scheller et al., 2011). The research also highlighted the risk to non-contiguous fisher habitat (Spencer et al., 2011) and the need for reintroductions to formerly occupied areas to reduce the risk of local extirpation. Their research demonstrates the

use of forecasting to assess trade-offs between controversial management actions and conflicting management objectives before actions are undertaken.

4.3 | Consequences of reintroductions and translocations

American chestnut (*Castanea dentata*) was decimated by fungal blight nearly a century ago and is functionally extinct today. Genetically engineered blight resistant chestnuts are actively being developed (Westbrook et al., 2020) with the intention of releasing them onto their native landscapes. Although chestnut restoration in general is not widely opposed, some groups have opposed the use of genetic engineering to achieve this aim. Aside from the novelty of genetic manipulation to confer resistance to a wild population, a landscape-scale (extending across much of the eastern United States) restoration of this magnitude has not been previously attempted. Prior to investment in such a significant and contested restoration effort, forecasting can inform critical questions about restoration cost and feasibility including: How much effort (area per year) would be required to restore chestnut to the landscape, and at what expense (Westbrook, Holliday, Newhouse, & Powell, 2020)? And what are the consequences for ecosystem structure and functioning (Jacobs, Dalglish, & Nelson, 2013)? To address these considerations, Gustafson et al. (2017, 2018) simulated the reintroduction of blight-resistant chestnut using a suite of increasingly aggressive restoration approaches and forecasted its long-term effects on forest composition and carbon storage in Maryland, USA. They found that restoration would need to be extensive and committed to succeed within a reasonable time frame (50–100 years). Furthermore, they found that the reintroduced chestnut would not extirpate any existing tree species nor would it substantially alter carbon carrying capacity, providing support for this introduction of genetically engineered trees.

Climate change threatens forest health (Seidl et al., 2017; Vose et al., 2018), and facilitated migration has been proposed as a technique to ensure long-term functioning (Duveneck & Scheller, 2015; Millar, Stephenson, & Stephens, 2007). Similar to the landscape-scale introduction of a novel chestnut trait, facilitated migration would need to occur at an unprecedented scale to be effective. In this case, entirely novel communities would be created that have never existed before. Facilitated migration is not restoration but is instead the intentional creation of novel communities for the purpose of ensuring ecosystem functionality and service provision under climate change. Ideally, these communities would naturally perpetuate themselves as intentionally introduced species become

established so as to eliminate their long-term management overhead. Duveneck and Scheller (2015) used a simulation framework to assess the potential for facilitated migration (aka “climate suitable planting” of trees) to increase forest carbon storage and improve functional diversity in the Midwest, USA. Although simulations of facilitated migration resulted in self-sustaining forest communities (the intentionally introduced species successfully established and reproduced) and increased forest carbon, the effects on functional diversity were projected to be negligible due to the loss of existing species on the landscape due to climate change. Lucash, Scheller, Gustafson, and Sturtevant (2017) similarly compared climate suitable planting against more traditional silvicultural approaches in the Midwest and found that climate suitable planting had the capacity to substantially increase forest resilience under climate change. In both studies, the model simulation results indicated that extensive and committed management would be required to achieve the stated goals of self-sustaining climate suitable planting.

5 | EMERGING OPPORTUNITIES TO FORECAST INTENDED CONSEQUENCES

The advancement of many technologies and the progression of conservation and restoration theory have created opportunities to substantially expand the utility of forecasting. Here we outline near-term needs and opportunities where forecasting is well-positioned to improve the decision-making process, particularly given the conservation actions that are being proposed (Seddon, Moehrenschrager, & Ewen, 2014).

The ability of scientists to develop forecasts that allow for the assessment and vetting of innovative practices before widespread deployment has particular resonance today because of the variety and scope of emergent conservation innovations. These innovations are energizing and exciting but also fraught with challenges due to their associated uncertainty: any true innovation is relatively untested and therefore inherently uncertain as its risks, benefits, and odds of success are unknown. Forecasting scenarios can elucidate worst-case outcomes and landscape responses to innovations. Forecasts can also help to distinguish innovations that are both practical and effective given the magnitude of forthcoming global changes from those that may not be the best use of resources (Perring et al., 2015). Conservationists are starting to envision the “Accretocene,” an era when we will begin to recover species and ecosystem functionality faster than our current rate of loss (Wright, 2020). Simulation modeling will be a valuable asset to test big ideas that will allow

us to intentionally shape the ecological trajectory of landscapes and usher in the Accretocene.

The incorporation of large geographic areas and long-time horizons combined with the freedom to explore intensive and creative ideas at relatively low cost allows managers to take a big picture approach to stewarding the future of their landscapes. Managers are empowered to think about how their decisions can shape the course of their landscapes, not just in terms of what can be accomplished in one funding cycle or even one 50-year plan. One such idea is the concept of rewilding, which aims to increase biodiversity while reducing past and present human impacts by restoring species and ecological processes to the landscape (Donlan, 2005; Lorimer et al., 2015; Svenning et al., 2016). A central focus of the rewilding movement is to use species introductions, reintroductions, or de-extinctions to address trophic cascades (Fuhlendorf, Engle, Kerby, & Hamilton, 2009; Lorimer et al., 2015). De-extinction (the resurrection of an extinct species, Shapiro, 2017) and novel species introduction (Schlaepfer, Sax, & Olden, 2011) are exciting but potentially risky concepts that would benefit from forecasting, which could be used to simulate the addition of a species to a new system. Managers and decision-makers could then assess whether de-extinction is feasible/practical, or the potential consequences from the reintroduction of an extinct species or the introduction of a species previously not found in that ecosystem (i.e., a functional trait-based approach to restoration, Funk, Cleland, Suding, & Zavaleta, 2008; Laughlin, 2014). For species for which we have little data (e.g., an extinct species), forecasts can use functional information, validated with information from closest living relatives, to estimate plausible reintroduction outcomes. If de-extinction efforts fail across all scenarios, or only succeed with heavy, continuous management intervention, this may be cause for reconsideration (Nogués-Bravo, Simberloff, Rahbek, & Sanders, 2016). Likewise, if the introduction of a novel species fails to fill the intended ecological niche, managers may be more inclined to consider a different course of action. In the case study above, we highlight how forecasting has been used to inform the management required in tandem with functional de-extinction (a species that has been functionally removed from a landscape, even if some survivors persist in a diminished role).

Similarly, conservationists should consider forecasting the adaptive capacity of new, genetically engineered or modified species or genomic translocations and their effects at landscape scales prior to widespread use. Such innovations have been proposed to accelerate population and landscape responses to rapid change, but the outcomes of largescale implementation are largely unknown (Rice & Emery, 2003). Considering the consequences of

genomic interventions at the landscape scale is currently outside the scope of most simulation models. Modest but essential new investment is necessary to sufficiently capture the spread of the intervention, including potential hybridization with the existing population. The scaffolding already exists in most simulation models, although modifications are required. As an example, if simulating genomic intervention of plants, a new plant trait would need to be added that indicates whether the genome has been altered and its effects on other traits already represented. If simulating the genomic intervention of an animal population, it would be critical to capture its effect on population and metapopulation dynamics.

Forecasting could also prove useful for the assessment of landscape and ecosystem responses to aggressive, intensive, and largescale management efforts like those required for the removal of invasive species or the remediation of ecological degradation. In these scenarios, the management investments required to achieve targeted outcomes are time and money intensive. By simulating a spectrum of removal approaches and forecasting interspecific interactions and species responses to management and environmental conditions, managers can estimate what species will recolonize and dominate after invasive plants or animals are removed; how much management effort will be required for eradication; and which management strategies resulted in the strongest and most long-lasting outcomes. Critically, forecasting may also be able to inform the unintended consequences and secondary effects of invasive species removal in more detail than qualitative evaluation, especially in instances of multiple invaders (Zavaleta, Hobbs, & Mooney, 2001). Using forecasting to answer these questions can provide important information for deciding whether invasive species removal is practicable and/or the best use of resources. On highly degraded areas, land managers can also use forecasting to assess what is feasible and the amendments or interventions that may be necessary to enable restoration. For example, soil amendments have been proposed and tested on small scales to restore ecological function (e.g., Hemes et al., 2019; Silver, Vergara, & Mayer, 2018). Forecasting could assess large-scale rollouts of different soil amendments or seed enhancement technologies (e.g., Clemente et al., 2004; Madsen, Davies, Boyd, Kerby, & Svejcar, 2016) in different proportions, assessing vegetation growth and recruitment responses, to optimize restoration outcomes and vet the cost of implementation. Similarly, forecasting could be used to assess the benefits of intermediate planting that might be required for soil remediation before restoration planting, evaluating restoration project response with and without remediation efforts (Stanturf, Palik, & Dumroese, 2014). For hydrologic engineering, forecasting

could include climate change forecasts to assess long-term efficacy before substantial investments in infrastructure are made (Day Jr. et al., 2005; Poff et al., 2016).

6 | CAVEATS AND ROOM FOR IMPROVEMENT

Despite their promise, simulation models are not always the appropriate tool and their deployment requires a non-trivial investment of resources that in some instances may be better allocated. Forecasts are not appropriate when the conservation situation is dire and/or immediate. When the ecological consequences of doing nothing are very large and the problem is urgent, the risks of action are clearly justified and forecasting would only delay a response. For example, removing rodents from small oceanic islands has immediate, large, and proven benefits for biodiversity (Howald et al., 2007; Keitt et al., 2011). The value of information provided by forecasting would, in this case, be small relative to the cost of delaying action. Though often less expensive and less time-intensive than full-scale, on-the-ground experimentation, developing forecasts still requires considerable time invested in data collection, parameterization, and validation (testing against empirical data) that would slow conservation response to an emergency situation. The information to be gained from forecasting should be weighed against the seriousness and immediacy of the conservation need when deciding its usefulness. Under such circumstances, alternatives such as expert opinion should be considered.

Additionally, forecasting comes with its own set of risks and uncertainties that can constrain the use and usefulness of modeling efforts (Table 1). Insufficient data and software bugs can curtail the use of simulation modeling altogether. Models operated on the wrong scale or across scenarios that are too timid can reduce the value of information they provide to managers and fail to contribute meaningfully to conservation and restoration decision-making. Uncertainty surrounding future drivers of ecological change can instill a false sense of confidence that the model is capturing a range of representative possible futures. Fundamental misunderstandings of the system being modeled can produce model outputs that fail to reflect current *and* future trajectories of the system, leading to inappropriate or ineffective management decisions. Still, there are potential solutions to reduce these risks and improve model performance to the benefit of future conservation and restoration planning and innovation.

We also do not want to imply that forecasting is capable of addressing all management needs, particularly as new innovations are imagined, developed, and delivered at an ever increasing pace. Many improvements are

TABLE 1 Risks that can hinder the utility and feasibility of simulation modeling for conservation and restoration innovation, and how to deal with those risks for better modeling outcomes

Forecasting risk	Consequences	Potential solutions
Insufficient buy-in from key stakeholders	If the decision-makers do not agree on the value of forecasting or on the correct approach, the results will be contested and resources will be wasted. Too frequently, forecasters overwhelm decision-makers with complexity before they are comfortable with the process.	An incremental approach can build confidence in the forecasting approach by iteratively testing larger landscapes, more conservation alternatives, and/or including more future drivers of change. Frequent and early sharing of forecast results allows decision-makers to learn about the merits and limitations of the knowledge produced.
Insufficient data	Without sufficient data, simulation model parameterization is either infeasible or results in models that fail to replicate system dynamics closely enough that model outputs are useful for making decisions about that system.	Ongoing monitoring and data collection can fill in data gaps and allow simulation models to better capture system dynamics. The rise in availability of large-scale ecological datasets is also shrinking prospective data limitations.
Future drivers of change are unpredictable	Global change is laden with uncertainty because long-term actions and policies are uncertain. In addition, forecasts cannot accommodate all uncertainties; there are many unknown unknowns ("black swans") that cannot be anticipated or incorporated, into simulation models (Taleb, 2007).	Scenarios of global change should contain a broad range of plausible futures therefore providing a "stress test" of proposed conservation actions. These scenarios do not typically include all possible futures as represented by black swans. Decision-makers must be provided the proper context: All decisions are made with a large degree of uncertainty about the future.
Scenarios are too timid	When scenarios are too timid, they often tell modelers and stakeholders what they already knew rather than allowing them to learn from potential ecological changes in the future.	Modelers should assemble a diverse group of stakeholders to co-design a spectrum of scenarios that range from conservative to highly innovative (McBride et al., 2017). Facilitators are often required to ensure that decision-makers are considering options beyond what is immediately possible given resource constraints.
Increasing model complexity raises the risk of software bugs	Software bugs in the model can produce spurious results or can result in unnecessary delays if the bugs cannot be quickly resolved.	If forecasting informs critical decisions or resource allocations, conservation organization should seek out open-source models with a rigorous design and proven testing (Scheller, Gustafson, Sturtevant, Ward, & Mladenoff, 2010). In addition, open-access software repositories provide transparency and ready reporting of software errors.
Selecting a model that was designed for use at a different scale	The utility of forecasts and their appropriate applications are scale-dependent. Every forecasting tool has an optimal scale for which it was designed and at which its expected bias is minimized (Obeysekera & Rutchey, 1997).	Select a model that matches the scale of the question(s) asked. Avoid model selection based on external pressures or favoritism. Large ecological questions that cross multiple scales may require the integration of multiple models.
Decision-makers do not understand forecasting uncertainty	Decision-makers may develop a false sense of accuracy, a belief that the model is capturing the real world. Conversely, decision-makers may reject model outcomes if they do not understand the uncertainties in the data or future drivers of change.	Forecasters need to work closely with decision-makers to ensure that they are aware of all sources of uncertainty (e.g., Dietze, 2017) before forecasts are produced. Multiple iterations allow decision-makers to provide feedback throughout the process.
Unclear management objectives	When managers and decision-makers are unclear about management objectives, forecasting is often used to ask/inform the wrong questions that ultimately do not	The use of a decision theory framework can help managers set explicit objectives prior to any modeling work, enabling forecasting that asks questions useful for informing management

TABLE 1 (Continued)

Forecasting risk	Consequences	Potential solutions
	contribute meaningfully to management decisions.	decisions and supporting management objectives (Milner-Gulland & Shea, 2017).
Misunderstanding system dynamics	Fundamental misunderstandings about the system being modeled can lead to erroneous assumptions about model selection and parameterization, yielding model results that do not reflect the future trajectory of the system.	Model validation using either a subset of reserved data or historical trajectories is essential to determine if model outputs are an acceptable/appropriate representation of the system's current conditions. If forecasts fail to reflect system dynamics, further observation of the system is needed to inform model parameterization.

necessary to fully realize the potential of forecasting for conservation and restoration innovation. As an example, the integration of forecasting could streamline the adaptive management process. Adaptive management is a continuous loop of management strategy design, implementation, and monitoring used to systematically test assumptions, learn from past efforts, and adapt management actions to improve outcomes (Salafsky & Margoluis, 2001). While adaptively managed conservation is the gold standard, it has proven difficult to effectively implement due to issues of multiple scales and stakeholders (Gregory, Ohlson, & Arvai, 2006) and funding and time limitations (Westgate, Likens, & Lindenmayer, 2013). Incorporating forecasting into the adaptive management framework can reduce time and funding constraints by virtually assessing potential adaptive management strategies prior to implementation to inform management action selection. However, doing so will require forecasts that are embedded within the conservation process and the minimization of many of their barriers: cumbersome interfaces, high programming skill requirements, data availability, and data management, among others. Additionally, integrating remote sensing and artificial intelligence-powered monitoring into forecasting would allow managers to proactively manage landscapes across larger scales. We see these as substantial and much needed improvements for forecasting.

Forecasting outcomes of conservation interventions would also benefit from a more fully realized integration of social-ecological systems into simulation modeling, including positive and negative feedback loops (Jacobs et al., 2013; Levin et al., 2013). The science of “ecological forecasting” (Clark et al., 2001) has made tremendous progress. The science of “social-ecological forecasting” is in its relative infancy. Most social-ecological forecasting is “top-down” whereby the social system influences the ecological system but not vice-versa. Recent advances in social-ecological forecasting suggest that a shift is on the horizon (Sotnik, 2018) although these advances have not reached the maturity necessary to be incorporated into

restoration and conservation planning (Bolte, Hulse, Gregory, & Smith, 2007). A greater incorporation of complex human decision-making and its associated uncertainties, and the inclusion of more explicit, detailed feedbacks between social and ecological systems are needed to truly capture the influences of management on social-ecological systems (Schlueter et al., 2012).

Finally, particular attention needs to be focused on how the community of managers engages with simulation models and their outputs to ensure that forecasts are easily accessible, interpretable, and useful for decision-making. Recent advances in visualization offer a way to make findings more approachable to managers, including the use of tangible landscapes and virtual reality to translate model outputs into observable landscape elements (Huang, Lucash, Simpson, Helgeson, & Klippel, 2019; Lewis & Sheppard, 2006; Tabrizian et al., 2016). They can also more tangibly connect managers with the realities and challenges of the novel landscapes they may be managing in the future (Rubio-Tamayo, Barrio, & García, 2017). However, these advances in immersive visualization are not yet widely utilized, in part because their application to ecology and environmental science is in its relative infancy (Huang, Lucash, Scheller, & Klippel, 2020). Providing platforms for enhanced visualization of model outputs and broadening the use of immersive experiences holds great promise for improved accessibility and more effective communication with managers and decision-makers.

7 | SUMMARY

Global change is adding substantial uncertainty to the management of landscapes for biodiversity conservation, making it harder for managers to anticipate which conservation and restoration approaches are most likely to achieve their intended consequences. This is especially true for emergent or novel management interventions, the consequences of which are often unknown. Forecasting allows managers to test candidate management actions

across a range of possible futures and uncertainties and receive feedback on performance, often in less time and at less expense than on-the-ground experimentation. In this way, forecasting can facilitate the adoption of innovative new management strategies by equipping managers with information about potential trade-offs and response trends, crucial considerations when deciding how to invest limited conservation resources. As landscape change accelerates, forecasting can help both risk averse and risk inclined managers to visualize and evaluate potential outcomes of conservation and restoration innovations, supporting management advances under global change.

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AUTHOR CONTRIBUTIONS

Both authors conceptualized the contents of this article. Tina G. Mozelewski led the drafting and editing of the article but both authors contributed to writing and editing. Both authors reviewed all drafts of the manuscript and gave their final approval for publication.

CONFLICT OF INTEREST

The authors have no financial or other conflicts of interest to report.

DATA AVAILABILITY STATEMENT

Data used for this study belongs to the authors. Access to the data will be granted upon request.

ETHICS STATEMENT

No ethics review for animal handling or human subjects was necessary for the work described in this article.

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