Ecological forecasts to inform near-term management of threats to biodiversity

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Abstract
Ecosystems are being altered by rapid and interacting changes in natural processes and anthropogenic threats to biodiversity. Uncertainty in historical, current and future effectiveness of actions hampers decisions about how to mitigate changes to prevent biodiversity loss and species extinctions. Research in resource management, agriculture and health indicates that forecasts predicting the effects of near-term or seasonal environmental conditions on management greatly improve outcomes. Such forecasts help resolve uncertainties about when and how to operationalize management. We reviewed the scientific literature on environmental management to investigate whether near-term forecasts are developed to inform biodiversity decisions in Australia, a nation with one of the highest recent extinction rates across the globe. We found that forecasts focused on economic objectives (e.g., fisheries management) predict on significantly shorter timelines and answer a broader range of management questions than forecasts focused on biodiversity conservation. We then evaluated scientific literature on the effectiveness of 484 actions to manage seven major terrestrial threats in Australia, to identify opportunities for near-term forecasts to inform operational conservation decisions. Depending on the action, between 30% and 80% threat management operations experienced near-term weather impacts on outcomes before, during or after management. Disease control, species translocation/reintroduction and habitat restoration actions were most frequently impacted, and negative impacts such as increased species mortality and reduced recruitment were more likely than positive impacts. Drought or dry conditions, and rainfall, were the most frequently reported weather impacts, indicating that near-term forecasts predicting the effects of low or excessive rainfall on management outcomes are likely to have the greatest benefits. Across the world, many regions are, like Australia, becoming warmer and drier, or experiencing more extreme rainfall events. Informing conservation decisions with near-term and seasonal ecological forecasting will be critical to harness uncertainties and lower the risk of threat management failure under global change.

Keywords
climate change, conservation decision-making, ecological prediction models, fire management, habitat restoration, invasive species, near-term ecological forecasting, species reintroduction, species translocation, threatening processes
Anthropogenic threats, such as habitat loss, resource exploitation, invasive organisms and interactions among these drivers, have led to catastrophic recent declines in the numbers and sizes of populations of species across the globe (Ceballos, Ehrlich, & Dirzo, 2017). Rapid changes in natural processes have also occurred during this time, leading to disrupted climate and fire regimes that can interact synergistically with anthropogenic threats, enhancing negative impacts (Geary, Nimmo, Doherty, Ritchie, & Tulloch, 2019). Urgent decisions are needed about where, when and how to allocate scarce conservation resources to mitigate threats and recover populations. However, uncertainty in the likely effectiveness of threat management actions slows conservation decisions and decreases the effectiveness of actions. This can result in species extinctions if actions are delayed too long (Martin et al., 2012). In the fields of marine fisheries and agricultural production, managers face similar issues of global change and future uncertainty, and have begun tackling such issues using near-term and seasonal forecasting models (Hobday, Spillman, Eveson, & Hartog, 2016; Klopper, Vogel, & Landman, 2006; Meinke & Stone, 2005; Spillman, Alves, Hudson, Hobday, & Hartog, 2011). Seasonal forecasts predict environmental conditions at daily, weekly and monthly intervals up to a year into the future (e.g. Spillman & Alves, 2009). By providing more definitive and accurate short-term yield or stock predictions (Brown, Hochman, Holzworth, & Horan, 2018), these forecasts enable more effective operationalization of decisions and increase the economic benefits of resource management choices (Gunda, Bazuin, Nay, & Yeung, 2017; NOAA, 2016). Applying such forecasts to predicting the future state of ecological systems should have similar benefits for management and conservation of terrestrial ecosystems (Clark et al., 2001; Dietze, 2017). Despite this, the extent to which near-term forecasting is currently integrated into terrestrial conservation research is unknown. Here, we conduct a review of research informing management of threats to biodiversity to determine whether forecasts are potentially useful for informing near-term operational conservation decisions, and in which contexts near-term ecological forecasting might improve conservation management success.

For both conservation managers and policy makers, success in dealing with environmental change rests with a capacity to anticipate and predict the future state of a system or study species (Clark et al., 2001). Many previous attempts to predict how to manage and prevent biodiversity declines relied solely on our understanding of the past, for example, by setting historical baselines in ecological condition then striving to reach these baselines through one or more ecosystem recovery actions. This is problematic because our systems are rapidly moving outside known historical or natural variability into a new Anthropocene era (Pędzich et al., 2017). Whilst the past tells us about the historical state and responses to change of populations, it may no longer be the most appropriate benchmark for the management of ecological communities today and into the future (Dietze et al., 2018; Hobbs, Higgs, & Harris, 2009; Hobday, 2011; Maron, Rhodes, & Gibbons, 2013).

Ecological predictions range in their precision from ‘hunches’ to conceptual and qualitative models based on practitioner learnings and experience (Tulloch, Possingham, & Wilson, 2011) to complex quantitative models based on long-term empirical data (White et al., 2019). Many formal predictions are conducted once and never updated or assessed (Dietze et al., 2018), despite this being best practice (Hobday et al., 2019). For most of earth’s systems that are undergoing rapid change, such ‘once-off’ models are neither realistic nor are they practical, as they will become outdated and provide inaccurate recommendations when system conditions change. The increasing recognition that more frequent, extensive and intense extreme weather events and their associated events (e.g. wildfires, coral bleaching) are impacting biodiversity persistence makes accurate, useable forecasts even more critical (Maxwell et al., 2019). Without regular updates to such forecasts, conservation management decisions will lack the most current data, and the longer a prediction remains out of date, the less accurate it becomes (Dietze et al., 2018; Petchey et al., 2015).

How can the scientific community provide the best available scientific predictions of what will happen in the future to managers and policy makers? Ecological forecasting is the ‘process of predicting the state of ecosystems, ecosystem services and natural capital’ under future scenarios such as for climate, land use and human population, with clearly specified uncertainties (Clark et al., 2001). It aims to answer questions about the future condition of ecosystems as well as their likely responses to actions. Until recently, the bulk of model-based ecological forecasts were scenario-based projections focused on climate change responses on multidecadal timescales. Forecast timelines were driven by underlying climate projections and their scenarios, such as the Intergovernmental Panel on Climate Change 2100 decadal projections (IPCC, 2014), which were first based on Global Circulation Models, and later included Representative Concentration Pathways to provide additional needed climate-model inputs such as emissions, concentrations and land use/cover (Moss et al., 2010). However, recent studies have pointed to a potential mismatch between such long planning timelines and the timescales of environmental decision-making, which tend to require near-term (daily to decadal) data-initialized predictions, as well as projections that evaluate decision alternatives (Hobday et al., 2016). Near-term forecasts solve this problem by providing the opportunity to iteratively cycle between performing analyses and updating predictions in light of new evidence, depending on the forecast model used (Dietze et al., 2018). This iterative process of gaining feedback, building experience and correcting models and methods is critical for improving forecasts (Tetlock & Gardner, 2015). Management responses can be evaluated and implemented ahead of time to reduce impacts that result from unfavourable conditions and maximize opportunities when optimal conditions occur. Monitoring of management outcomes enables decision-makers to iteratively update the next forecast cycle.
Whilst an increasing number of examples of iterative and near-term ecological forecasts now exist in a range of fields from fisheries management (Hobday et al., 2016), to crop designs (Rodriguez et al., 2018), to managing human disease spread (Shaman & Karspeck, 2012), there has been limited effort to track the different ecological forecasts in use today (but see Payne et al., 2017 for an examination of some marine forecast products). Aside from one recent study (Hagger, Dwyer, Shoo, & Wilson, 2018), there have also been no efforts to independently assess how near-term forecasts might improve conservation decisions. To rectify this gap in knowledge, we explore whether near-term and seasonal forecasts are being produced by the conservation literature compared with the resource management and agricultural production literature across marine, freshwater and terrestrial ecosystems. We evaluate whether the iterative nature and shorter timelines of marine and terrestrial near-term forecasts enable a greater breadth of operational questions to be answered. We focus on Australia as a case study, as the Australian continent holds one of the worst contemporary and rapid (<200 years) extinction records and continues to grapple with how to effectively respond (McDonald et al., 2015). Australia's threatened species continue to decline from multiple threats, including widespread land clearing and habitat loss driven largely by agricultural and urban development, invasive species such as cats, foxes, weeds and feral herbivores, disease and altered fire regimes (Doherty, Glen, Nimmo, Ritchie, & Dickman, 2016; Kearney et al., 2019; Reside et al., 2017; Ward et al., 2019). We review the scientific literature on the historical effectiveness of management actions to mitigate these threats across the terrestrial bioregions of Australia. We determine which threat mitigation actions might benefit from near-term forecasts that reduce uncertainty in seasonal conditions. Finally, we evaluate what gaps exist in our ability to predict management outcomes successfully.

2 | MATERIALS AND METHODS

The first goal of this review was to determine what types of forecasts are produced by literature focused on managing threats to biodiversity (conservation-focused), compared with literature focused on managing biodiversity as a natural resource, for example, fisheries and forestry or agriculture (production-focused). We reviewed peer-reviewed literature (Web of Science, accessed 7 November 2018) to create a database of articles with the following search terms: (forecast* OR predict* OR project*) AND future AND (climate change OR global change OR anthropogenic change OR weather OR threat) AND (species OR ecosystem*) AND: (manage* OR protect* OR restore*) AND Australia*. Criteria for inclusion in our review were: (a) focused on Australia’s terrestrial, marine or freshwater natural resources; (b) considered a management or planning action; (c) considered objectives beyond economic development or health; and (d) made at least one time-bound prediction of the future state of the system or species. Of the 281 articles, 182 were excluded due to not meeting at least one of these criteria.

We reviewed the remaining 99 articles to determine key characteristics of each study and how these characteristics related to the timescale of prediction. To link study objectives to the types of forecast used, we first characterized: (a) study system: terrestrial, marine or freshwater; (b) broad management target: resource production/management (e.g. agriculture, fisheries, forestry) or biodiversity conservation (populations of species, ecological communities or ecosystems), (c) broad planning timeline: long-term ‘strategic’ planning (>10 years into the future) or shorter term ‘operational’ planning (<10 years into the future) and (d) objectives of management: where to allocate resources, how to allocate management (e.g. which actions to do), when to do management or which components of biodiversity to manage. A study could be characterized as more than one of each criterion if appropriate (e.g. targeting both when and how to allocate management). We then determined the timescale for each article’s forecast in terms of the lead time to the first prediction (taken as the first prediction year for the forecast minus the study’s publication year, such that if a paper was published in 2000, and made its first forecast for the year 2100, then the lead time is 100 years), the number of time periods predicted (i.e. number of forecasts) and the overall time period for all forecasts.

For marine, freshwater and terrestrial systems, we first built contingency tables quantifying the frequency of broad management target (production or conservation) and planning goal (long term or near term), and calculated Fisher’s exact test statistics for each study system due to small sample sizes to test whether the planning timeline was independent of the management goal at \( p = .05 \) significance level. There were not enough freshwater studies to compute this statistic. We then combined all the ecosystems and built three generalized linear regression models (GLMs) in R version 3.5.1 (R Core Team, 2019) to ask whether the planning goals of a study influenced either the lead time to an article’s forecast (i.e. the minimum time to the first prediction in months in years, a Gaussian-distributed dependent variable), the maximum length of the article’s forecast in years (a Gaussian-distributed dependent variable) or the number of forecasts produced (a Poisson-distributed dependent variable representing the number of different timelines the study produced forecasts at). Planning goals were represented by two categorical variables, planning goal and broad management target. Each of the three models included an interaction between the two categorical predictors to explore whether planning goals affected the forecast characteristics independently or together. We also used generalized linear regression to evaluate the relationship between the lead time to an article’s forecast and the total number of forecasts produced by an article.

To ask whether near-term forecasts enable a greater breadth of management questions to be answered, we used ordinal logistic regression in R (package MASS version 5.1.4, Venables & Ripley, 2002). We built a single variate model with independent
variable representing the timescale of an article’s forecast, that is, whether a forecast focused on shorter (<10 years) or longer term (i.e. >10 years) outcomes, and the breadth of management objectives addressed as dependent variable (categorical with possible values of 1, 2, 3 or 4, representing how many of the following objectives were addressed: ‘when’, ‘how’, ‘where’ and ‘which species’).

The second goal of the review was to explore reporting of weather impacts on terrestrial management actions to discover opportunities for near-term forecasting to inform operational management decisions. We evaluated the historical effectiveness of eight management actions to mitigate the most destructive threats to biodiversity in Australia (Kearney et al., 2019). These actions were: habitat restoration, weed control, livestock management (typically grazing exclusion and destocking), managing feral herbivores, managing invasive predators, disease control, managing fire regimes and species translocations or reintroductions. We conducted a second review of the peer-reviewed environmental and ecological management literature to determine, for each action, which management outcomes have been impacted by near-term or seasonal issues (e.g. drought, cold/hot temperatures, rainfall). We created an initial database of articles by searching for the following terms in Web of Science (accessed 14 November 2018): (impact* OR effect* OR response* OR respond*) AND (conservation OR biodiversity) AND (species OR ecosystem*) AND Australia*. Within this database, we then searched for terms specific to each of the eight management actions (e.g. for weed control, additional terms of ‘weed*’ AND (management OR control* OR eradicat*) were used to siphon out articles related to eradicating, controlling or managing weeds in Australia (see Appendix S1 for full list of search terms for each management action and number of articles reviewed). Criteria for inclusion in our review were: (a) focused on Australia’s ecosystems or species; and (b) evaluating the outcomes of a management action to restore or maintain biodiversity. Due to high overlap between weed control articles and habitat restoration articles, we decided to combine these two categories, resulting in seven threat management actions and 241 articles for evaluation.

For each study, we collected the following data: specific action and ecosystem being targeted for management, type of weather impact (dryness/drought, high temperatures, cold temperatures/frost, flooding, strong winds, cyclones, rain), the timing of the impact (before, during or after management action was implemented), the direction of the impact (positive, negative or uncertain) and how management outcomes were affected (partial or complete failure). We also collected data on the location of management actions (spatial context—latitude and longitude if available, spatial scale of management, bioregion), timing of management (temporal context—year management commenced, year management ended, year of management evaluation), other non-weather-related operational issues affecting management outcomes. If a study reported management in more than one independent (i.e. spatially disjunct) location, we evaluated effects of weather on management at each location. Similarly, if an action was carried out over more than one time period, we reported weather effects in each time period separately. This resulted in a final data set of 484 ‘action-by-site-by-time-period’ combinations for review.

### 3 RESULTS

#### 3.1 Availability of ecological forecasts to manage Australian environments

The types of forecasts in the scientific literature to inform management decisions differed depending on whether they were focused on long-term ‘strategic’ versus near-term ‘operational’ planning, henceforth long term and near term respectively (for details, see Appendix S1). Planning timelines (near term vs. long term) and management goals (conservation vs. production) were not independent (Fisher’s exact test, \( p = .0002 \)). Conservation studies typically

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**FIGURE 1** Distribution of forecasts for biodiversity conservation versus resource management and production, (a) across freshwater (\( n = 11 \)), marine (\( n = 21 \)) and terrestrial (\( n = 67 \)) study systems, and (b) across four forecast objectives of how, where or when to do management. Both graphs indicate the relative proportion of each system or goal targeted towards broad planning goals of either long-term (>10 years into the future) strategic planning or near-term (<10 years into the future) operational management.
focused on long planning timescales, whereas production articles were more evenly spread across near- and long-term planning (Figure 1a).

The planning timeline and the management goal independently influenced a study’s forecast timelines, with conservation-focused studies and strategic planning studies having significantly longer lead times to the first forecast in comparison with production-focused and operational studies that developed forecasts with significantly shorter lead times (Figure S2 and Table S3 in Supplementary Material). There was also a significant interaction between planning timelines and management goals, with studies that were focused on operations and production having significantly shorter maximum forecast times than other production and conservation studies (Table S3). Operational forecasts

**FIGURE 2** Near-term weather impacts on the effectiveness of seven management actions in studies for biodiversity conservation in Australia, showing (a) the percentage of management studies impacted by weather versus non-weather issues, (b) the percentage of weather-impacted studies that were impacted positively (where near-term weather effects improved outcomes) versus negatively (where near-term weather effects worsened outcomes), (c) the percentage of weather-impacted studies that were affected either before, during or after management actions took place and (d) the percentage of actions that were either negatively or positively impacted by each of nine weather effects. Note that for (a), some studies reported both weather and non-weather effects, so percentages do not add up to 100.
also produced significantly more forecast outputs—on average, 31 \((\pm 29.50 \text{ SE})\) forecasts per study for conservation and 22 \((\pm 8.35 \text{ SE})\) forecasts per study for production studies, compared with strategic long-term forecasts which produced 4.27 \((\pm 1.46 \text{ SE})\) and 3.27 \((\pm 0.82 \text{ SE})\) forecasts per study for conservation and production goals respectively. There was a significant positive relationship between the lead time to first forecast and the number of forecast outputs, with long-term studies producing significantly fewer forecasts (i.e. a fewer number of timelines forecast) compared with near-term studies (GLM: \(\beta = -0.197 \pm 0.058, p = .001, R^2 = .11\)).

For terrestrial systems, planning timescales were independent of management goals (Fisher’s exact test, \(p = .216\)), whereas there was a significant interaction between the planning timeframe and management goal (production or conservation) for marine system studies (Fisher’s exact test, \(p = .007\)). Whilst a third of marine studies developed forecasts targeted at near-term decisions (mostly for fisheries goals), only 7% of terrestrial (predominantly for production goals), and no freshwater studies developed near-term forecasts, focusing instead on long-term planning for biodiversity conservation (Figure 1a).

The breadth of management questions (when, where, how, which species) differed between long- and near-term forecasts. Near-term forecasts addressed significantly more management questions than long-term forecasts \((2.7 \pm 0.31 \text{ SE} \text{ and } 1.34 \pm 0.06 \text{ SE} \text{ questions per study, respectively; \text{ordinal logistic regression: } \beta = -0.012 \pm 0.008, p < .001})\). Regardless of whether they targeted biodiversity conservation or resource management, forecasts focused on near-term goals answered more questions about when to allocate resources (33% of conservation- and 100% of production-focused near-term forecasts) compared with long-term forecasts, which mostly answer the question of where to allocate management (78% of conservation- and 68% of production-focused long-term forecasts; Figure 1b). However, where to allocate resources was still an important question for near-term forecasts (67% of conservation and 89% of production focused).

### 3.2 | Near-term weather impacts on terrestrial management actions

Half (49.8%) of 484 threat management actions across Australia were impacted by at least one near-term weather issue. The prevalence of weather impacts on management effectiveness varied across actions. Disease control, species translocation/reintroduction and habitat restoration (including weed control) were most frequently impacted by weather issues (62%, 84% and 59% of actions, respectively, Figure 2a). Feral herbivore control actions were least frequently impacted by weather (65% of actions did not report weather impacts, Figure 2a). For most actions, weather was more likely to have a negative impact than a positive impact on outcomes (Figure 2b). Weather impacts were most prevalent during management implementation compared with before or after actions were completed (mean percentage of studies impacted before, during or after: 27.4 \((\pm 3.7 \text{ SE})\), 53.5 \((\pm 3.7 \text{ SE})\) and 27.6 \((\pm 6.2 \text{ SE})\), respectively; Figure 2c). Impacts were more likely to be negative for most weather effects except for flooding and high rainfall (Figure 2d).

Negative weather impacts on management occurred due to a variety of reasons. For example, unforeseen dry conditions prevented fungicides from effectively penetrating Phytophthora management sites (Dunstan et al., 2010), and reduced the survival and recruitment of translocated and reintroduced species such as threatened eastern barred bandicoots (Perameles gunnii; Todd, Jenkins, & Bealnin, 2002) and black-footed rock-wallabies (Petrogale lateralis; West, Ward, Foster, & Taggart, 2017). Although negative impacts were more common for most management actions (Figure 2b), positive impacts of weather were more frequent for grazing management, and were most often associated with higher than average rainfall in eastern temperate and subtropical bioregions that resulted in increased plant and animal recruitment and biomass in destocked sites (Edwards, Croft, & Dawson, 1996; Frank, Wardle, Dickman, & Greenville, 2014; Kutt, Vanderduys, & O’Reagain, 2012; Page & Beeton, 2000; Zimmer, Mavromihalis, Turner, Moxham, & Liu, 2010; Figure 2d).
The most frequently reported weather impacts were drought or dry conditions and high rainfall (28% and 25% of all studies respectively). Dry conditions and drought were the most common weather impacts for translocations/reintroductions, fire management, disease control and habitat restoration (Figure 3). Rainfall was the most frequently reported weather factor for grazing management, feral

![Map of Australia showing weather impacts](image)

**Figure 4** Reviewed management studies in different biogeographical (IBRA) regions of Australia, showing (a) the proportion of reviewed studies that were impacted by weather, (b) the proportion of studies where weather negatively affected management outcomes, (c) the proportion of studies where weather negatively affected management outcomes, (d) the proportion of all studies impacted by rainfall and (e) the proportion of all studies impacted by dry conditions or drought. Dots indicate approximate locations of 257 reported study sites.
herbivore control and invasive predator control (Figure 3). The least reported weather impacts were cyclones/strong winds and flooding, each affecting only 3% of all studies (Figure 3).

Weather impacts were spread across the entire continent, with studies in Central and Western Australia's arid and semi-arid rangelands more frequently impacted than other parts of Australia (Figure 4a). Only 33% of regions with studies reported more positive than negative impacts of weather (Figure 4b), with positive impacts mostly confined to the eastern temperate and subtropical bioregions (most often due to high rainfall assisting with recolonization or survival of managed biodiversity; Appendix S2). Negative impacts were more frequent in the western arid bioregions, southern alpine, montane and semiarid bioregions, northern savannah and south-west biodiversity hotspot (Figure 4c). Weather impacted all published management studies in 10 bioregions (6% of IBRA regions). Rainfall and drought impacted actions in 33 (55%) and 39 (66%) of bioregions respectively (Figure 4d,e).

4 | DISCUSSION

The demand for forecasts that predict how ecosystems might respond to intervention is increasing in land and sea applications, driven by an international shift in environmental change research from detection to mitigation and adaptation (Dietze et al., 2018; Payne et al., 2017). Near-term forecasts are already in use in many production-focused disciplines (Figure 1; Payne et al., 2017), as well as in public health, human disease and medical applications (Lowe et al., 2017; Thomson et al., 2006). However, our review shows that biodiversity conservation research still focuses on long-term forecasts of up to 100 years into the future to inform decisions, a timeline set by the limits of global long-term climate models (IPCC, 2014) rather than management needs. Biodiversity conservation needs to anticipate and adapt to climate changes, building ecological predictions that target management in a way that spends limited resources effectively whilst accounting for avoidable impacts such as near-term weather issues. Such impacts cannot be ignored—near-term weather impacts such as drought and rainfall have affected biodiversity management across 60% of the Australian continent’s terrestrial bioregions over the past four decades (Figure 4). For some terrestrial management decisions, weather affected up to 80% of reported actions (Figure 2), and more impacts were negative than positive. Failed management could lead to economic and biodiversity losses that might have been prevented or mitigated if near-term forecasts using readily available weather data had been built (Hagger et al., 2018).

Predicting the likely success or failure of management makes sense not just from an economic perspective—it is crucial to adaptation in an age of rapid environmental change. According to a range of modelled scenarios, many arid, semiarid and temperate regions across the world are likely to become warmer and drier over the next 20 years due to human-induced climate change, whilst many tropical regions could experience more extreme and damaging rainfall events (IPCC, 2014). For example, southern Australia has experienced increases in the frequency of extreme heat events and decreases in rainfall over the past decade (Bureau of Meteorology & CSIRO, 2018). Climate fluctuations are inherently unpredictable beyond a few years to a decade (Branstator & Teng, 2010). Although long-term projections of management success will be hugely uncertain, near-term forecasts have higher accuracy due to their ability to be iteratively updated to constantly improve models over time through validation and performance testing (Hudson, Shi, et al., 2017). Our study shows that predicting weather impacts in the short term can be equally or more important to the success or failure of biodiversity management actions compared with long-term and non-weather impacts such as climate change, legacy effects of historical management and insufficient effort and intensity (Figure 2; Figure S4). The management actions we reviewed are not confined to Australia, as threats such as disease, changed fire regimes, livestock grazing and habitat degradation are global drivers of biodiversity declines.

Whilst our review successfully revealed that weather impacts in the near term are important to the success or failure of biodiversity management actions, it did have some limitations. Because research does not always begin as applied, our focus on only scientific articles might have underestimated the lead times of forecasts that may have started off as strategic but later have been operationalized after uptake from end-user organizations. Furthermore, most studies did not explicitly link weather to outcomes, instead discussing the reasons for management success or failure. Failure to explicitly report effect sizes is a common problem in meta-analyses (Geary, Doherty, Nimmo, Tulloch, & Ritchie, 2020). If effect sizes are not evaluated, it is difficult to know the full scale of the weather impact, information that is needed by land managers to make decisions on trade-offs. For example, if effects are small, is delaying due to forecasted ‘bad weather’ worse than losing a year in undertaking the conservation action?

An additional challenge in any meta-analysis is that non-significant results and ‘failed’ management experiments (e.g. activities that were unsuccessful due to climate anomalies) are less likely to be published in primary literature and therefore would have been less likely to be included in this review (Koricheva, Gurevitch, & Mengersen, 2013). Because of this, our study possibly underestimated forecasting potential for many regions and actions. We found few management studies in central and northern Australia, perhaps because of a lack of reporting and evaluation, or due to the remoteness and difficulty in undertaking research and management in some regions. More studies were from south-eastern and south-western Australia (Figure 4a), which comprise some of Australia’s greatest population pressures and biodiversity hotspots, with many species and ecosystems likely to benefit from efforts to forecast the effectiveness of conservation outcomes. The challenges and outcomes of biodiversity management in better studied Australian regions, and the effect of weather, may not be applicable to other regions and parts of the world where there are few or no management studies. Furthermore, in regions with more predictable monsoonal weather patterns, such as in tropical northern Australia, managers might be better prepared for seasonal impacts of weather on
biodiversity conservation actions and therefore more knowledgeable about when and where to act to avoid negative impacts of weather. However, even ‘predictable’ monsoonal regions have future uncertainty in the frequency and intensity of extreme weather events such as cyclones and flooding (Knutson et al., 2010), and many locations are likely to experience increased temperatures and intensified droughts (Dai, 2011). Such changed and variable weather patterns may affect the success of numerous timing-critical management actions including fire management (due to increased fire risk under drought situations, Herawati & Santos, 2011) and habitat restoration (Chadzon, 2003). Priority should be given to synthesizing existing knowledge on the impacts of short-term weather on management outcomes, through additional channels such as expert workshops, eliciting anecdotal information from practitioners and traditional owners and grey literature review.

Near-term forecasting requires time series or repeated measurement data (Dietze et al., 2018). Data are required on the study system or species and on environmental conditions relevant to the dynamics of the system (e.g. weather). To evaluate management success, we also require a measure of how the management action may affect the system or species, gained either from historical control-impact studies or expert estimation (e.g. for novel actions). The data must be at a time and spatial scale similar to the ecological processes of interest and all data must be interoperable, that is, able to work together within the modelling framework (Dietze et al., 2018). With the growth of open data sets, many relevant data sets for forecasting are now available. However, the lack of a nationally funded strategic long-term population monitoring programme in Australia (Lindemayer, 2017) has undermined Australia’s ability to accumulate the data needed for near-term forecasting. Such long-term monitoring is vital to measure the success of management actions and iteratively update models to better direct resources, particularly after unprecedented disturbance events, such as the 2019–2020 wildfire season (Nolan et al., 2020). Despite most terrestrial management actions being at risk of weather-related disturbance impacting success to some degree (Figures 2 and 3), most do not prepare for such risk through developing near-term forecasts (Figure 1).

We suspect that the lack of near-term forecasts in terrestrial biodiversity conservation is due not only to a lack of long-term ecological data but also to inadequate reporting of management outcomes and data on critical climate drivers such as rainfall. Aspects of rainfall such as spatial heterogeneity, intra-annual rainfall variability and seasonality have been identified as key drivers of diversity, structure, function and natural selection in terrestrial ecosystems (Engelbrecht et al., 2007; Knapp et al., 2002; Siepielski et al., 2017). Inaccurate rainfall data and mapping lead to high variability and uncertainty in predictions (McCain & Colwell, 2011), which could lead to reduced user confidence in near-term climate forecasts for terrestrial systems compared with marine systems that are driven by variables that are more accurately predicted, such as temperature (Doney et al., 2012). Indeed, the low reliability and skill of seasonal climate forecasts in certain environments was identified as one of the most important reasons for the lack of seasonal ecological forecasting by European organizations (Bruno Soares & Dessai, 2016). Australia’s conservation scientists might lack confidence in climate predictions themselves, or in how to incorporate their data with climate forecasts; alternatively, they might lack capacity, time or funding to develop and interpret complex models prior to action; or see low applicability to some contexts (Bruno Soares & Dessai, 2016; Hagger et al., 2018; Tulloch et al., 2016). Close, long-term interactions with climate forecast providers and organizational expertise and capacity are critical enablers to the use of seasonal climate forecasting (Bruno Soares & Dessai, 2016). Increasing uptake would require validation of forecast skill for the regions, seasons, variables and lead times of interest, and quantifying the ecological and financial benefits that can be provided, recognizing that forecasts are probabilistic and will be wrong in some years. Developing user-friendly web-based forecasting tools (e.g. R Shiny web apps) that require minimal technical expertise and provide information on how to interpret uncertainty would enhance the application of near-term forecasting to real management problems (see Hazen et al., 2018 for an example of such a tool for marine forecasting).

Australia’s unique environment and changing climate lead to distinct opportunities and challenges for near-term forecasting. The Australian Community Climate Earth-System Simulator-Seasonal (ACCESS-S1) is the new version of Australia’s seasonal prediction system. At a resolution of 60 km, ACCESS-S1 predicts Australian climate drivers, including the El Niño Southern Oscillation and the Indian Ocean Dipole, across the different regional climates of Australia’s Great Dividing Range and the eastern seaboard. It offers improved forecast skill for rainfall, maximum temperature and minimum temperature on multi-week timescales compared to the previous seasonal prediction system (Predictive Ocean Atmosphere Model for Australia, POAMA; Hudson, Alves, et al., 2017). However, the forecast skill of ACCESS-S1 varies with region, time of year, variable and forecast lead time, and is reduced in places with high interannual variability (e.g. much of Australia’s arid zone). Forecasts for temperature are generally more accurate than rainfall, and overall skill decreases as lead time increases (Hudson, Shi, et al., 2017). Near-term weather forecasting models built in other regions of the world include the North American Multi-Model Ensemble (NMME; Kirtman et al., 2014), which provides free publicly available hindcast and real-time prediction data, and the United Kingdom’s Met Office global seasonal forecast system (GloSea5; MacLachlan et al., 2015), whose products are currently only available to licensed users. Each model has costs and benefits in terms of spatial and temporal resolution, forecast skill and accessibility (Barnston, Tippett, Ranganathan, & L’Heureux, 2019; MacLachlan et al., 2015; Shukla et al., 2019).

Although near-term ecological forecasts appear to be limited in terrestrial and freshwater ecosystem research, especially in conservation applications, in marine ecosystems, they are increasingly commonplace (Figure 1). In fact, until recently most biodiversity-focused near-term and seasonal forecasts in Australia (and the globe) came from fisheries and marine conservation (Payne et al., 2017). Their progress in this area came from a combination of massive advances in global climatic and oceanographic mapping, a wealth of
observational data from historical and current monitoring of fish stocks (Eveson, Hobday, Hartog, Spillman, & Rough, 2015) that allows relationships between the environment and the species to be well characterized, a study system with a long ‘memory’ where the variables that modulate species’ abundances and distributions (e.g. temperature) are predicted directly by climate forecast systems (Payne et al., 2017), strong relationships between fisheries and climate researchers and an economic incentive to maximize fisheries production outcomes. In fisheries and aquaculture operations, seasonal forecasting is used to reduce uncertainty and manage business risks, including developing species-specific habitat forecasts for Southern Bluefin Tuna in the Australian Bight to improve operational planning of fishers (Eveson et al., 2015; Hobday et al., 2016). In marine conservation, seasonal forecasts of sea surface temperatures inform Great Barrier Reef management actions for predicted coral bleaching events (Smith & Spillman, 2019). By collaborating with and learning from advances in the marine research community, researchers in terrestrial and freshwater environments can harness important skills and experience without the need to start from scratch.

For near-term ecological forecasting to be useful, there must be management decisions that can be adapted to avoid or mitigate the impacts, at lead times that match the skill of the seasonal forecast (Hobday et al., 2018). For those conservation actions where management failed due to weather prior to implementation (e.g. fire management and invasive predator control), the decision lead time required may be too long, and the forecast skill during the critical environmental period for adapting decisions may decline. For example, drought prior to baiting of invasive predators can increase the effectiveness of baiting programmes likely because of prey reductions (Burrows et al., 2003; Claridge, Cunningham, Catling, & Reid, 2010). However, requiring a drought prediction of up to a year before baiting would render the forecast skill at the time of implementation to be inadequate. A more useful timescale may be to avoid baiting before the prediction of heavy rainfall, which can diminish the toxicity of uneaten baits for predators (Allsop et al., 2017; Burrows et al., 2003).

Our review demonstrates that there is potential for near-term ecological forecasting to improve decision-making in conservation management. Key priority areas include forecasting the likely impacts of drought and extreme rainfall on scheduled biodiversity conservation actions, which might also help manage other weather-influenced processes such as wildfire (Chikamoto, Timmermann, Widlansky, Balmaseda, & Stott, 2017). Moving forward, it is important to determine the type of ecological forecast that is most useful for each conservation action, and what management decisions are available to respond to forecasts given time, skills, funding and capacity constraints. In addition to changing or adapting management decisions to near-term forecasting, resilience planning in conservation management can also help mitigate the potential negative impacts of extreme weather and climate, for example, restoring diverse communities that may be more resistant and resilient to climate events (Isbell et al., 2015). The opportunity to combine both seasonal and long-term forecasting tools is now emerging to allow planning at timescales previously considered separately to manage risks due to short-term environmental variability and long-term change (Hobday et al., 2018). Near-term forecasting is likely to play an increasing role in planning, scheduling and delivery of conservation actions that rely on suitable weather conditions. By learning from advances in other disciplines, engaging meaningfully with on-ground management and identifying opportunities where the benefits of producing forecasts outweigh costs, biodiversity conservation scientists can close the gap between the potential and the reality of near-term ecological forecasting.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in figshare at https://doi.org/10.6084/m9.figsh are.12616787.
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SUPPORTING INFORMATION
Additional supporting information may be found online in the Supporting Information section.

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