Anticipatory natural resource science and management for a changing future

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Prolonged shifts in long-term average climate conditions and increasing variability in short-term weather conditions affect ecological processes, and represent a fundamental challenge for natural resource management. Recent and forthcoming advances in climate predictability may offer novel opportunities, but capitalizing on these opportunities will require focusing scientific research on understanding the links between climate and ecological responses over multiple timescales, fostering programmatic links among science and management agencies, and developing new and flexible decision-making frameworks. Anticipating short- to near-term climate conditions can help managers mitigate land degradation driven by unfavorable conditions and promote actions that make the most of favorable conditions. Similarly, anticipating long-term, multidecadal climate trajectories can help managers to identify those species and communities that are most likely to remain viable throughout the 21st century. A focus on "anticipatory science and management" could substantially bolster natural resource planning and management but will require long-term investment and widespread adoption.

Front Ecol Environ 2018; doi: 10.1002/fee.1806

Climate change is expected to include both short-term increases in climate variability and long-term directional shifts in mean climate conditions (Stocker *et al.* 2013). These changes pose daunting strategic challenges for natural resource managers (Kemp *et al.* 2015) and considerable economic hurdles for policy makers (GAO 2016). However, as understanding of global climate dynamics improves, the diversity and quality of predictions, from subseasonal to seasonal ("s2s") weather forecasts to century-scale climate projections, will continue to improve (Meehl *et al.* 2009; Kirtman *et al.* 2013; Robertson *et al.* 2015; Srivastava and DelSole 2017). Conservation of natural resources in an increasingly dynamic environment can be empowered by incorporating these forecasts and projections. This requires a new paradigm of *anticipatory science and management*, in which scientists seek to understand the interactions between climate and ecological dynamics over multiple timescales, and natural resource managers apply these scientific insights to capitalize on short- to near-term (subseasonal to multiyear) forecasts to guide treatments and maximize successes, while also relying on updated long-term projections to facilitate planning decades in advance (Figure 1).

In the US and many other countries around the world, natural resource management theory and practice were designed around the basic principle of sustaining ecosystem structure and function, generally framed within the constraints of the historical range of variability exhibited by the system (Landres *et al.* 1999). However, as the 21st century unfolds, ecosystems and the services they provide will be chronically exposed to novel and extreme environmental conditions outside of their historical ranges. Furthermore, the effects of climate change on ecosystem dynamics will be amplified when coupled with other stressors, including an increase in the frequency and intensity of disturbances, propagation of biological invasions, and an escalation in land-use pressures caused by a growing human population. These interrelated agents of change have already led to systematic and directional shifts in ecosystem structure and composition (Vitousek 1994), which could very well exceed the rate at which ecosystems can be reassembled or replaced by functional

In a nutshell:

- Climate systems display predictable changes at timescales ranging from weeks to decades, and anticipating these dynamics could strengthen natural resource management
- Advances in our ability to predict climate conditions over months to a few years could be leveraged to optimize many facets of seasonal and annual planning and decision making for natural resource management, including the anticipation of favorable or unfavorable conditions so that operations can be tailored accordingly
- Projections of long-term climate trajectories could help managers identify and promote ecosystems that include species and communities able to thrive under future climate conditions, enhancing the long-term value of land-treatment investments
- Delivering relevant knowledge about climate predictions and ecological responses to resource managers can enable implementation of these anticipatory strategies, but requires continuing agency support and overcoming legal and institutional obstacles

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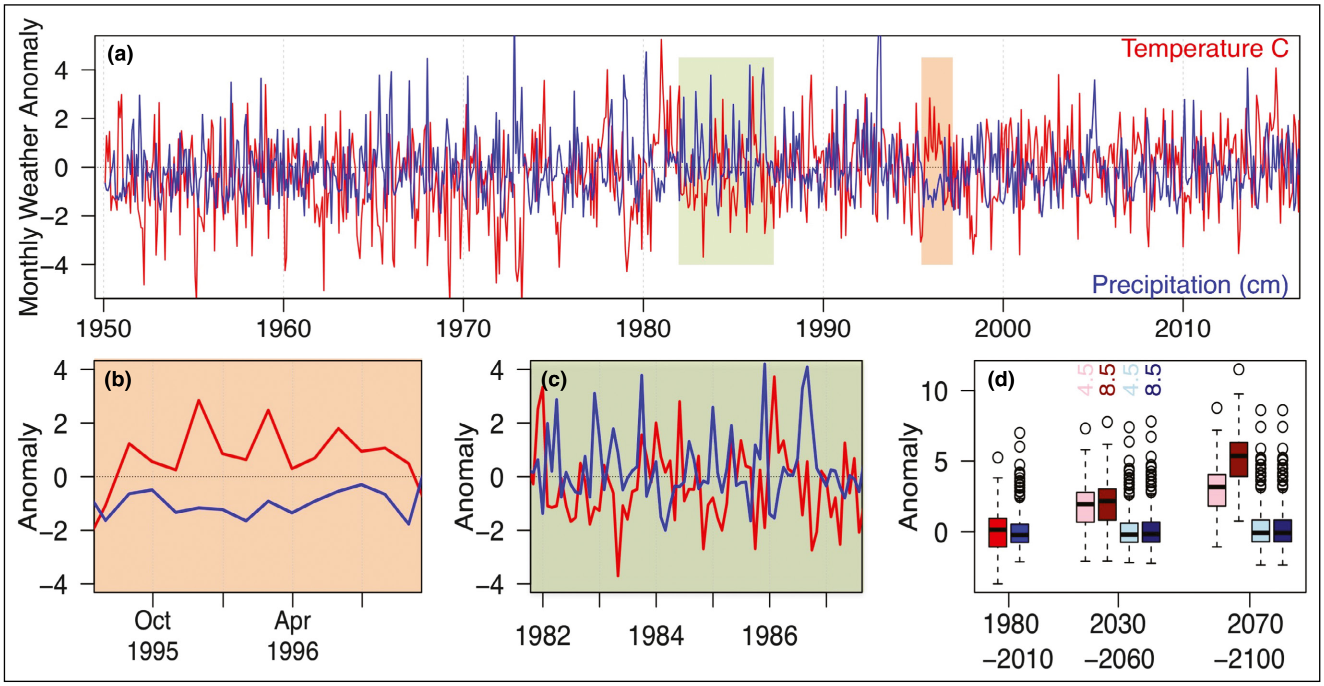

Figure 1. *Climate fluctuations over multiple temporal scales, as illustrated by changes in temperature (red) and precipitation (blue) in Flagstaff, Arizona. Forecasts of temporal fluctuations can be used to maximize the effectiveness of resource management. (a) Monthly anomalies over the period 1950–2015 demonstrate long-term patterns of variability. (b) An unusually warm and dry period in late 1995–early 1996 exemplifies climate variation at subseasonal to seasonal timescales. Forecasts at these scales can be used to guide implementation of strategies to cope with such adverse conditions. (c) An unusually wet and cool period from 1982 to 1987 exemplifies variation over multiple years to decades. Forecasts at these timescales could help resource managers take advantage of such periods of increased rainfall to achieve goals that would be difficult during times of drought. (d) Long-term climate projections (middle and end of the 21st century for representative concentration pathway [RCP] 4.5 [pink and light blue] and RCP 8.5 [red and dark blue]) indicate substantial increases in temperature and uncertain changes in precipitation. These projections can help managers identify and facilitate ecological transitions to future-adapted communities. Anomalies were calculated from mean conditions over the period 1980–2010, and box plots in (d) show variability between years.*

analogs (Petchey *et al.* 1999). To mitigate and prepare for future ecosystem transformations, resource managers must anticipate conditions and "stay ahead of the game".

Anticipating short-term (s2s) forecasts and near-term (multiyear) climate dynamics represents a chance for resource managers to develop strategies that make the most of opportunities during favorable periods and avoid adverse outcomes when conditions are unfavorable. Although most scientific research in recent decades has focused on long-term climate and ecological projections, short- and near-term climate forecasts may eventually prove to be just as useful for enhancing natural resource management. Anticipating short- to near-term climate fluctuations can help resource managers capitalize on complex ecological dynamics, including threshold responses (Suding and Hobbs 2009), abrupt state changes (Scheffer *et al.* 2001), and other effects that can be difficult to reverse (Beisner *et al.* 2003). In most cases, intervention is most effective in the early detection or recognition stages of ecological transitions, and can be futile during later stages. Early warning of associated shifts in natural resources may be best anticipated by examining short- to near-term climate forecasts, given that ecological transitions can often lag behind shifts in environmental conditions (Sala *et al.* 2012). Anticipating short- to near-term climate fluctuations and integrating these forecasts with ecological and evolutionary knowledge about ecosystem responses will help natural resource managers to make informed decisions that maximize the chances of desirable outcomes.

We are not the first to advocate for management practices designed with future environmental conditions in mind (eg Buizer *et al.* 2016; Tommasi *et al.* 2017), nor are we the first to recognize the potential benefits of applied ecological forecasting (Clark *et al.* 2001; Dietze 2017; Dietze *et al.* 2018), but we wish to emphasize here that recent and ongoing advances in climate forecasting across a range of temporal scales will facilitate the development of effective strategies that have yet to be widely incorporated into natural resource management. Furthermore, the potential value of these multiscale climate projections for such management initiatives highlights the need for robust ecological forecasting. Integrating ecological and climatological knowledge into operational forecast products can support forward-thinking management strategies that anticipate resource

Table 1. Timescales at which several example resource management decisions could be enhanced by anticipatory management

	Anticipatory timescale		
Management action	*Short-term (subseasonal to seasonal)*	*Near-term (~2–20 years)*	*Long-term (multidecadal)*
Avoid failure of drought-sensitive land treatments	✓		
Position fire suppression resources to maximize effectiveness	✓		
Predict outbreaks of water- or vector-borne diseases	✓		
Adjust grazing levels to avoid land degradation	✓	✓	
Specify fish and wildlife harvest intensity to ensure sustainable populations	✓	✓	
Facilitate regeneration of species requiring unusual conditions for juvenile survival	✓	✓	
Plan recreation intensity to minimize resource damage	✓	✓	
Implement control treatments on invasive species to reduce competition with natives	✓	✓	
Regulate water discharges from dams and reservoirs	✓	✓	✓
Allocate financial resources to areas with chronic challenges that are likely to worsen in coming decades		✓	✓
Manipulate vegetation structure (eg forest thinning) to enhance drought resistance		✓	✓
Identify appropriate adaptation or restoration strategies for long-lived species		✓	✓
Design infrastructure to reflect future climate extremes			✓
Triage conservation and restoration efforts to maximize effectiveness with limited resources			✓
Acquire new land and/or develop easements to sustain habitat abundance and connectivity			✓

dynamics over the next month, year, decade, and century (Table 1). The complexity and uncertainty of climate change often confound attempts to identify practical strategies, but this challenge can be partly met – and resource management decisions can be strengthened – by incorporating new and emerging climate forecasts and projections. These predictions need not be perfect to be useful; they only need to lead to decisions that are better than those based on historical conditions. Uncertainty in climate predictions and ecological responses over all timescales should be recognized. Furthermore, this uncertainty should be communicated to natural resource managers and policy makers in a format that appropriately represents the degree of confidence in predictions of both climate and ecological response.

Anticipating short-term climate variability

Relevant climate knowledge

The accuracy of climate model forecasts over s2s timescales is improving as climate models are better informed with initial and time-dependent boundary conditions (Meehl *et al.* 2009; Kirtman *et al.* 2013; Robertson *et al.* 2015; NASEM 2016). For example, sudden stratospheric warming (SSW; where the polar vortex of westerly winds in the winter hemisphere slows down or reverses direction within a few days) at high latitudes may offer weather predictability up to 2 weeks in advance, and recognition of the current state and trajectory of geographically broad, sustained climatic phenomena, such as the Madden–Julian Oscillation (MJO), have the potential to improve prediction accuracy of local weather conditions up to about 2 months in advance (Robertson *et al.* 2015). These advances suggest that s2s forecasts could be "as widely used a decade from now as weather forecasts are today" (NASEM 2016). Long-lead forecasts (up to 12 months into the future) for expected temperature and precipitation anomalies are already being delivered by the US National Weather Service (www.cpc.ncep.noaa.gov/products/predictions/90day). These s2s forecasts are continuously being improved (DelSole and Banerjee 2016; DelSole *et al.* 2017), and when well understood, s2s forecasts of metrics that exhibit broad spatial synchronies (high spatial autocorrelation) in climate and ecological variability can offer unique opportunities for regional cooperation and efficient deployment of management resources. An example is the long-recognized precipitation dipole in the western US, which creates synchronized but contrasting precipitation patterns between the Pacific Northwest and the Southwest. El

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Figure 2. *Drought-induced restoration failure could be minimized by anticipating future climate fluctuations at subseasonal to seasonal ("s2s") timescales. Dry conditions coupled with soil disturbance to reseed vegetation resulted in poor plant establishment and severe erosion in southwestern Utah (Miller* et al. *2012; Duniway* et al. *2015). Short-term s2s climate forecasts, now available through the US National Weather Service, can help managers avoid these undesirable outcomes and maximize the success of management activities, including restoration treatments.*

Niño or La Niña conditions and associated teleconnections can help anticipate precipitation patterns months in advance, potentially providing opportunities for moving fire suppression or prevention resources between regions (Swetnam and Betancourt 1990).

Management application

Management agencies can capitalize on these increasingly predictable spatiotemporal patterns in climate variability at s2s timescales when outcomes depend on specific conditions over the subsequent several months to seasons, particularly when the spatial dependency of the forecasts' accuracy is understood and incorporated into decision making (Table 1). For instance, plant regeneration in dryland ecosystems is only successful if seedlings can avoid drought-driven mortality as they develop root systems that access deeper soils with more reliable moisture levels (Muñoz-Rojas *et al.* 2016). Hardegree *et al.* (2017) illustrated in detail how s2s forecasts could be integrated into rangeland management to inform adaptive management practices and identify effective solutions to the substantial challenges of dryland revegetation. More broadly, s2s forecasts allow managers to adjust the timing of treatments to optimize the likelihood of success, given projected conditions. This means that s2s forecasts provide opportunities to maximize the effectiveness of many land treatments, including restoration, prescribed burning, livestock grazing, vegetation and soil treatments, dam releases to rivers, installation of flood control structures, and herbicide application (Holmgren *et al.* 2006; Sitters *et al.* 2012). Using these short-term forecasts can also help to prevent degradation of resources by giving managers time to adjust, and potentially moderate, practices that may contribute to further declines in ecosystem conditions (Figure 2; Miller *et al.* 2012; Duniway *et al.* 2015).

Anticipating climate fluctuations, incorporating natural resource monitoring results, and predicting how ecosystems will respond to both environmental conditions and treatments could substantially improve treatment success while reducing the likelihood of unintended outcomes. However, systematic and routine integration of s2s forecasts into natural resource management (Table 1) will require overcoming considerable social, institutional, and even legal obstacles (Craig *et al.* 2017). Implementation will demand flexibility in management strategies and treatments to respond to up-to-the-minute knowledge of weather and climate conditions that could influence eventual treatment success, rather than being locked into conventional responses (eg immediate seeding of grasses after wildfires regardless of current conditions and short-term forecasts; Barclay *et al.* 2004). Direct consideration of the social and economic aspects of natural resource management can create additional capacity to deal with new and unexpected challenges (Schultz *et al.* 2015). Appreciation of the advantages of coordinating short-term forecasts and management operations is likely to spread as forecasting skill increases and socioeconomic benefits become obvious.

Anticipating near-term climate patterns (~2–20 years)

Relevant climate knowledge

Due to the non-linear and chaotic nature of the Earth's climate system, current predictions of climate statistics are limited to a year or more in advance. However, improved understanding of varying degrees and sources of climate persistence (memory), and the increasing ability to observe and parameterize initial conditions in deterministic climate models, hold great promise for generating accurate near-term climate forecasts. Large-scale modes of variability in sea-surface temperature (eg the Arctic Oscillation, Atlantic Multidecadal Oscillation, El Niño–Southern Oscillation, Interdecadal Pacific Oscillation [similar to the Pacific Decadal Oscillation but covering a wider area]) and atmospheric circulation (the Northern Annular Mode [similar to the Arctic Oscillation], Pacific North American pattern, North Atlantic Oscillation) (Srivastava and DelSole 2017) display multiyear persistence and strong teleconnections that could potentially offer some degree of climate predictability months to years in advance using both statistical and deterministic models.

As uncertainties are resolved and climate models become more sophisticated, forecasts of temperature, precipitation, and drought severity years in advance will become available for routine integration into management decisions (Meehl *et al.* 2009; Kirtman *et al.* 2013).

These forecasts could be based on either deterministic (numerical) climate models, including both deterministic and statistical downscaling to the region of interest, or probabilistic projections based on historical or proxy data. An example of the latter is the use of a 500-year reconstruction of the Atlantic Multidecadal Oscillation to project the risk of a future climate shift (and its regional hydroclimatic consequences) as a probability function of the time that has elapsed since the previous one occurred (Gangopadhyay and McCabe 2010).

Management application

Natural resource managers could use multiyear forecasts of climate conditions to maximize the success of climate-sensitive operations that require multiple years to complete (Table 1; Figure 3). Projections of wet versus dry periods at these multiyear scales may be especially useful, as they provide managers with more lead time to plan treatments or emergency responses (eg reducing land uses that enhance stress to resources), and make geographical and/or temporal adjustments to budget allocations. For instance, anticipating multiyear forecasts affords the opportunity to target wet periods for implementation of disruptive management practices that may require longer periods of recovery, notably prescribed burning, treatment of woody vegetation, or wildlife harvesting. Similarly, regeneration of many late successional perennial species in water-limited systems is highly episodic and requires multiple years of relatively wet conditions to accomplish (Holmgren and Scheffer 2001). Consequently, anticipating the occurrence of prolonged wet conditions can be helpful for developing cost-effective strategies to re-establish woody plants. Just as forecasts of wet periods can be useful, advanced knowledge of impending seasonal or multiyear droughts would provide resource managers with the opportunity to modify or restrict land-use practices detrimental to ecosystems when productivity and recovery potential are low. In anticipation of unfavorable conditions, triage approaches that prioritize treatments based on site vulnerability and probability of success (with limited resources) could be incorporated into planning strategies.

Figure 3. *Failure of woody plant regeneration is an example of the resource management challenges that could be mitigated by anticipating climate fluctuations over multiyear timescales. Establishment of trees and shrubs in dryland areas is highly episodic, and requires a series of climate conditions suitable for seed production, germination, and root elongation. Nearly non-existent ponderosa pine (*Pinus ponderosa*) regeneration after a 1995 fire at this site near Flagstaff, Arizona, which was forested prior to the fire, illustrates the problem. Multiyear climate projections can help resource managers identify times and places where conditions are likely to support woody plant establishment, and focus planting efforts in those locations to recover previous plant communities and/or to use "prestoration" concepts (Butterfield* et al. *2016) to promote new communities well suited to future climate conditions.*

Anticipating long-term climate-change trajectories

Relevant climate knowledge

To guide long-term planning, natural resource management can incorporate multidecadal climate-change forecasts generated by general circulation models (GCMs). Climate projections vary among GCMs and scenarios, but this variability provides a measure of climatological uncertainty, and consensus trends from suites of GCMs can identify potentially important, consistent, and high-confidence attributes. In particular, forecasted rises in temperature are reasonably robust across GCMs and can be linked directly to important ecological responses, including increasing woody plant mortality (Allen *et al.* 2010), and decreased soil moisture and worsening drought in dryland environments (Schlaepfer *et al.* 2017). In addition, some regions have high-confidence features, notably predictions for rises in sea level (Rahmstorf 2007), ocean acidification (Feely *et al.* 2009), drought and loss of reliable snowpack (Stocker *et al.* 2013), earlier onset of spring (McCabe *et al.* 2012; Ault *et al.* 2015), and altered streamflow timing and magnitude (Milly *et al.* 2005). A number of organizations make long-term predictions from GCMs available in spatially downscaled formats that allow targeted examination of relatively small areas, thereby taking variability among models into account.

Management application

Expanding and evolving knowledge about the multidecadal spatiotemporal dynamics of climate variability and change can inform a wide variety of management planning processes (Table 1). Restoration and management strategies can incorporate long-term climate projections to define restoration targets based on ecological knowledge about which species will be viable under future

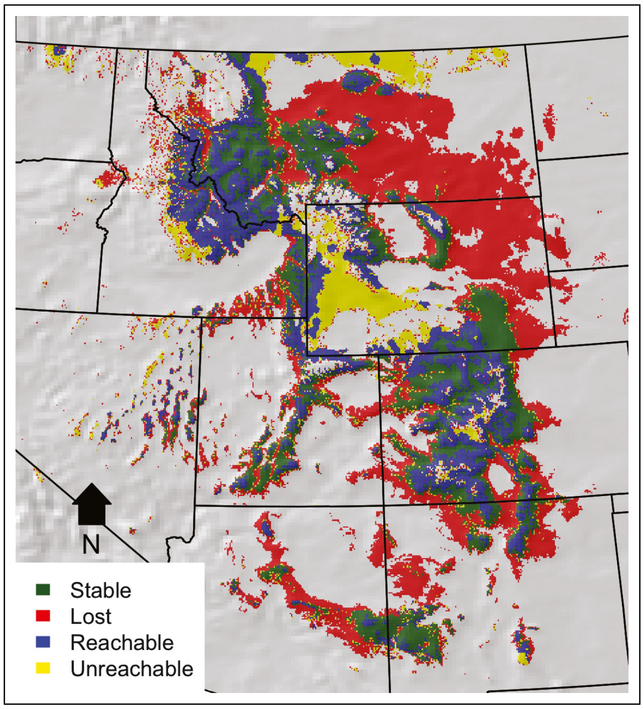

Figure 4. *Example of the need for assisted migration in response to shifts in the distribution of climatically suitable areas for important plant species (from Butterfield* et al. *2015). Assisted migration is the active movement of plant species from their present range to currently unoccupied areas that are expected to be suitable in the future, and is a practice that could be informed by anticipating long-term climate trajectories. This map illustrates how areas that will support Rocky Mountain juniper (*Juniperus scopulorum*) are anticipated to shift by 2080 using an ensemble of climate models under the Intergovernmental Panel on Climate Change's A2 emissions scenario. Yellow regions highlight where natural dispersal processes will likely be insufficient to allow colonization and where assisted migration may be necessary to enable Rocky Mountain juniper to occupy emerging suitable habitat; green regions are currently suitable and are expected to remain so in the future; red areas are expected to become unsuitable; and blue areas are emergent and reachable through natural dispersal. Range suitability was statistically developed, evaluated, and projected with WorldClim climate variables based on 1960–1990 norms.*

climate conditions. One well-recognized example of a long-term anticipatory strategy is the assisted migration of species (Figure 4) into fast-emerging, newly formed bioclimatic areas likely to support their future needs. While typically considered for rare, threatened, or endangered species, assisted migration should also be explored for more common species, short-circuiting inherently low probabilities of long-distance natural dispersal across increasingly fragmented landscapes. Furthermore, long-term climate projections could help identify buffer regions and/or refugia that may allow species to withstand harsh environmental conditions, migrate to suitable new habitats, and aid in the recovery of ecosystem processes (Keppel *et al.* 2015). These and many other strategies involving long-term climate projections can help natural resource managers maximize long-term recovery of degraded landscapes by promoting species and assemblages that are well suited for future climate conditions, and that foster greater ecosystem resilience to long-term changes (Prober *et al.* 2015).

Anticipatory science to inform management

Understanding ecosystem responses to environmental fluctuations is a common theme in ecological research but providing actionable knowledge for anticipatory management is a relatively new goal that can benefit most from a blend of old and new approaches, theories, and models (Mouquet *et al.* 2015). First, more research is needed to understand how alternative management actions interact with ecological dynamics at short- to near-term temporal scales in ways that could take advantage of ongoing and projected advances in short- and near-term climate predictability. In particular, research about what controls post-disturbance recovery patterns can help identify treatment options that shift the products of succession toward desirable conditions (Kildisheva *et al.* 2016). Data from monitoring programs, particularly those with relatively frequent re-measurements at levels of different land-use intensity, provide valuable insight into the status and trends of natural resources that can be examined to identify controls. Supporting and expanding these monitoring efforts is paramount. Synthesis and careful extrapolation of monitoring results to scales beyond a single management unit can help managers prepare for the broad scale at which climate variability and change is important and predictable.

Second, assumptions and data gaps inherent in many long-term climate and ecological projections need to be confronted. To compensate for the lack of long-term data, in particular spatiotemporally dynamic data, researchers often derive insights about long-term ecological response to climate shifts from the study of ecological variables across climatic gradients. This "space-for-time" approach assumes that spatial and temporal variations are equivalent (Pickett 1989), and has serious limitations for understanding dynamic responses in non-equilibrium conditions (Boiffin *et al.* 2017). Although phenotypic plasticity and adaptive capacity have been studied in some species to quantify the benefits of implementing assisted migration (Briske *et al.* 2015; Prober *et al.* 2015), most species have received little attention; focusing research on identifying strategies to sustain ecosystem processes and broad, generalized approaches (Beier *et al.* 2015) for the conservation of biodiversity and ecosystem structure may therefore be more relevant to management than often expensive and redundant single-species efforts. Tests of ecosystem resilience to disturbance, paired with climate manipulations across landscapes and gradient studies, are likely to yield informative, and perhaps unexpected, results. In addition, explicit recognition of uncertainty in both climate forecasts and ecological responses, especially when integrated into cost–benefit analyses, can help natural resource managers gauge confidence in outcomes and quantify the potential trade-offs between alternative actions.

Third, adaptive management partnerships need sustained support to test and refine feasible strategies to exploit eco-climatological forecasts, particularly over short- and near-term timescales (Hardegree *et al.* 2017). Adaptive management principles are used in many science–management partnerships to explore solutions to climate-change challenges. Systematic adaptive management trials of assisted migration using transplanted species and/or multispecies assemblages in varied biophysical settings could provide valuable insight into how biotic and non-climatic abiotic factors influence species' performance. These results can inform the structure of landscape-scale treatments designed to efficiently sustain ecosystem services. An excellent example is the Adaptive Silviculture for Climate Change (ASCC; www.forestadaptation.org/ascc) program, which is testing alternative forest treatment tactics, including assisted migration (Nagel *et al.* 2017). Many adaptive management studies are motivated by long-term climate projections, whereas relatively few take advantage of short- or near-term eco-climatological forecasts that will become increasingly reliable and accessible in the future.

Finally, promoting and rewarding scientific investigations focused on applied, feasible management strategies over time will enhance the breadth and depth of the knowledge needed to capitalize on short- and near-term forecasts, and sustain ecosystem services through continual and directional changes in climate. Identifying the potentially dramatic impact of climate change on ecosystems has emerged as a major theme in ecological research and management frameworks over the past several decades, but focusing only on quantifying impacts without attempting to identify anticipatory strategies or adaptive management solutions has limited value. This "doomsday" emphasis underplays potential management interventions and does little to help managers mitigate and adapt to expected changes in ecosystem performance. Studies that demonstrate "actionable science" and effective management strategies that promote adaptive capacity and maximize sustainability of ecosystem services are scarce. Effective land management in the context of climate change can be strengthened by an increased research focus on moving beyond *descriptive* investigations of climate-change impacts on ecosystems to *prescriptive* insights that quantitatively assess the effectiveness of specific natural resource management activities and strategies.

Programmatic opportunities for anticipatory science and management

Recent scientific advancements point to potential strategies for adapting to rapid changes in climate and climate variability. Despite growing knowledge about future global change drivers, increasing awareness of impacts to ecosystems, and emerging ideas about potentially effective management practices, the adoption and implementation of anticipatory natural resource management has been sluggish (Enquist *et al.* 2014; Kemp *et al.* 2015). A systematic suite of activities designed to enhance and leverage this knowledge, and to communicate it to resource managers, could accelerate implementation of anticipatory natural resource management. Potential programmatic strategies for promoting anticipatory science and management include:

- Initiate a multi-agency program to develop and disseminate knowledge about eco-climatological dynamics and related management opportunities, similar to the way in which the Joint Fire Science Program (www.firescience.gov) has informed wildfire science and practical fire management over the past ~20 years. This suggestion would be a logical enhancement of the US Government Accountability Office's recommendation that the federal government develop a program for standardizing and disseminating climate-related information (GAO 2016).
- Support and sustain effective decision-support frameworks (tools, science–management partnerships, etc) to expand the options available to natural resource managers. These frameworks may be most effective when targeting a specific management decision (eg seed selection: www.seedlotselectiontool.org/sst, https://seedmapper.shinyapps.io/seed_selector; Doherty *et al.* 2017). Likewise, drought predictions (eg www.drought.gov/drought/data-maps-tools/outlooks-forecasts) may be more useful when integrated into a user-friendly tool that delivers specific, applied information. However, broadly applicable, powerful, and accessible frameworks will require substantial investment, and cannot be sustained when produced as addendums to individual research projects.
- Restructure agency funding models to allow geographic and temporal flexibility in spending, so that managers can capitalize on opportunities and avoid costly failures. Spending is often constrained by location and fiscal year, creating incentives to conduct restoration or mitigation even when conditions are unsuitable. Costly failures could be minimized if natural resource managers were able to retain funds until conditions become favorable, or if agencies directed funds to locations with suitable conditions.
- Integrate natural resource monitoring efforts across agencies to track broad-scale trends in agents of change and resource condition, and inform management about extensive global change impacts (Jackson *et al.* 2016). This clearinghouse of mapped ecological disturbances and conditions could inform, for example, land treatment efforts to maintain natural variability in ecosystem structure and composition.

- Expand science–management partnerships that use adaptive management to develop strategies that leverage forecasts over all temporal scales, especially the short- to near-term forecasts that are currently underutilized.
- Encourage native seed and plant material programs, and the seed-producing industry, to consider future climates when developing seed sources (Butterfield *et al.* 2016). The implications of climate change for seed production are already being considered in agriculture (Singh *et al.* 2013), and could be integrated into ecological restoration to identify plant materials that improve restoration success under a changing climate (Havens *et al.* 2015).
- Implement an "adaptive management track" within administrative law for natural resource management agencies (Craig *et al.* 2017), to enable effective utilization of anticipatory and adaptive management. Legal structures and obligations have been an obstacle to adaptive management historically, and those challenges are likely to grow as changing conditions force agencies to consider management strategies that are increasingly divergent from traditional practices supported by legal precedent.

Recognition of the magnitude and direction of potential ecosystem transitions and their associated climate-associated drivers is the first step toward anticipatory natural resource management. In some cases, effective and regionally coordinated management practices can promote landscape resilience to future perturbations, for instance by using treatments that increase heterogeneity in post-disturbance successional trajectories and thereby enhance broad-scale variability in ecosystem structure and composition. In other cases, management intervention can do little to impede the momentum of ecosystem state changes, and anticipatory strategies must concede transformational shifts in composition, structure, and/or function toward conditions that differ substantially from the past or present. In these situations – that is, where long-term climatic trajectories suggest transformative shifts are likely – management can capitalize on favorable climatic conditions anticipated at s2s and multiyear timescales to facilitate beneficial state changes toward ecosystems that are well suited for future environments. Adaptive management has been successful in the past, but in a continuously and directionally changing world, management prescriptions and adjustments need to be more rapid, nimble, and broadly designed if they are to keep pace with the speed and extent of future environmental changes. Despite these challenges, advances in forecasting of both climatic conditions and ecological responses can provide a new toolset for natural resource management. Integrating knowledge about climate dynamics and ecological forecasting at multiple timescales will strengthen management decisions and help sustain ecosystem services in the coming decades.

Acknowledgements

This work was supported by the US Geological Survey's Ecosystems, Water, and Land Resources Mission areas, and by the Restoration Assessment and Monitoring Program for the US Southwest. Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the US government.

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