Title

Protected landscapes in a world of rapid climate change: Identifying research needs to support resource management and policy development.

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Introduction

Climate change is influencing nearly every ecological system across the globe. All lands, regardless of ownership and management designation, are being increasingly subjected to the forces of a changing climate. However, because protected landscapes represent the endpoint of a gradient from natural to highly altered, they may serve as 'climate change sentinels' to climate-driven ecosystem changes. Consequently, observed changes in protected landscapes provide learning opportunities that can advance scientific understanding, guide policy development, and generate management-relevant information about climate change impacts in the absence of confounding factors prevalent in more human-modified areas. Furthermore, because protected landscapes are home to many plant and animal species and provide numerous ecosystem services (e.g. clean water) and recreational opportunities, there is an urgent need to better understand how climate change will affect these valuable resources.

This document summarizes pressing climate change related research needs relevant to terrestrial ecological systems within protected areas. Protected areas, in the context of this document, refer to terrestrial lands (i.e. marine protected areas are excluded) in the United States that are managed primarily to protect biological diversity or natural features. This generally corresponds to the International Union for Conservation of Nature (IUCN) category I through IV lands (https://www.iucn.org/theme/protected-areas/about/protected-areas-categories) and includes Designated Wilderness, National Parks, National Monuments, Wildlife Refuges, and some private conservation lands (e.g. TNC). Note that research needs pertaining to aquatic systems, water resources, and hydrology are not included in this document and will be addressed separately by the aquatic resources science planning team. Similarly, research needs pertaining to social science are beyond the scope of this document. In an effort to ensure a concise document that is relevant to both scientists and natural resource managers, we purposefully limited the list to include only six priority research needs that illustrate broader concerns.

Critical research needs relevant to protected landscapes

- ***Can protected areas serve as refugia and stepping stones** for organisms shifting in response to climate change?*

- As the climate warms, the geographic ranges of plants and animals are expected to shift in order to maintain the climatic conditions to which they are adapted. In fact, such shifts are already apparent (Parmesan and Yohe 2003). Indeed, many scientific studies have been conducted aimed at (1) predicting the geographic ranges of organisms in future decades (Bocedi et al. 2014), (2) identifying the demographic processes involved that serve as mechanisms of range shifts (e.g. mortality, dispersal, and recruitment) (Wilcove 2008, Santini et al. 2016), (3) predicting the speed of potential range shifts compared to the velocity of climate change (Loarie et al. 2009), and (4) identifying the factors that may facilitate or impede range shifts over mixed landscapes (Dobrowski and Parks 2016).

- Protected landscapes often contain high biodiversity and species of special concern. However, they are also often geographically limited areas nested within more complex landscapes of unprotected lands that are not immune from the effects of climate change (Monahan et al. 2016). Moreover, few studies have focused specifically on protected areas and the unique role they may play in climate change adaptation (although see Murphy et al. 2010). Therefore, scientific studies specifically focused on protected areas and whether they can serve as refugia and stepping stones for organisms shifting in response to climate change are necessary. These studies should explicitly incorporate mechanisms of range shifts (e.g. mortality, competition, and ability to disperse), climate change velocity, and factors that facilitate and inhibit movement among protected areas (e.g. landscape fragmentation and climatic connectivity).

- *How are **disturbance regimes** (i.e. fire, insects, and pathogens) expected to respond to a changing climate? How will these changes influence vegetation composition and structure in protected areas?*

- Disturbance regimes such as wildland fire, insect outbreaks, and pathogens will undoubtedly experience changes in frequency, intensity, severity, and seasonality as the climate warms. Some of these changes are already evident. For example, increases in fire season length and annual area burned have been attributed to climate change (Jolly et al. 2015, Abatzoglou and Williams 2016). Due to warming winter temperatures, certain beetle species are now able to complete their life cycle in one year compared to two years, resulting in high rates of population growth (Bentz et al. 2010); increased water stress also increases host susceptibility (Allen et al. 2010). Some research also suggests that the effects of insects and pathogens will have a stronger effect on forest composition and structure than the direct effects of climate change (Dukes et al. 2009). Simply put, vegetation composition and structure within protected areas will be strongly influenced by climate-induced changes to disturbance regimes.

- Pathogens may also affect the herbivores that help structure vegetation communities through selective grazing, browsing, seed transmission, and fertilization (nutrient feedback). Climate generally affects the health of animals either directly (e.g. thermal-neutral zone, heat stress) or, more often, indirectly by influencing the agents, vectors, and ecosystems with which animals live and interact (Murray et al. 2010, Kutz et al. 2012, Hueffer et al. 2013). The responses of disease agents to specific climate changes, however, are difficult to predict. Multiple, differential population changes may be reflected in changing biotic-abiotic interactions (i.e. a change in the organization of the ecosystem itself).

- Scientific studies focused on changing disturbance regimes and how they influence vegetation composition and structure should be conducted. These studies should address the frequency, intensity, severity, direct and indirect mechanisms, and seasonality of these disturbance regimes. These studies should include an assessment of short- vs. long-term impacts. In the short-term, for example, fire severity may increase in some forested systems as fire weather becomes more extreme, whereas in the long-term, fire severity may decrease as plant communities that are more suitable to the emerging climate and increased fire frequency establish (Parks et al. 2016). Short vs. long-term impacts to vegetation composition and structure relating to insects and pathogens are also expected and should be studied. The severity of the disturbance may influence post-disturbance successional trajectories and should be evaluated (e.g. Coppoletta et al. 2016). Interactions between disturbances (e.g. fire and bark beetle) should also be considered. Mechanistic, process-based landscape models (e.g. Fire BGC and LANDIS-II) could play a role in anticipating many of these responses (Keane et al. 2015).

- *How will climate change induced range shifts of* ***invasive species*** *influence protected landscapes?*

- Invasive organisms are a major threat to native flora and fauna (McKinney and Lockwood 1999), and once established, are extremely difficult to remove (Allendorf and Lundquist 2003). Invasive organisms have a myriad of pathways to negatively influence native flora and fauna: competition, niche displacement, hybridization, and predation (Mooney and Cleland 2001). Invasive organisms can also dramatically alter disturbance regimes (e.g. fire) (Balch et al. 2013). Because protected areas are often appreciated and managed for their natural and pristine state, invasions are a major concern.

- Just as climate change may cause shifts in the distributions of native species (see research need #1), climate change also has the potential to cause shifts in the distribution of invasive organisms. Invasive organisms compound the threat faced by extant native flora and fauna by climate change alone, so gaining a better understanding of how invasive species may shift in response to climate change is essential in terms of predicting and mitigating this threat to protected areas. Furthermore, the creation of novel assemblages in a warming world is not likely to be based on a simple reshuffling of native species, but an incorporation of those that are perceived to be exotic and perhaps invasive (Morton et al. 2017). Research focused on climate-induced range shifts of invasive species, and how such shifts influence protected areas, should be conducted. This research should consider feedbacks and interactions between invasive species and disturbance regimes that, for example, have been shown to convert landscapes to alternate stable states and effectively excluded previously dominant species. This research should also evaluate the effect of shifts in the distribution of invasive annuals and the associated increases in fire likelihood in desert ecosystems that are not adapted to fire. Range shifts associated with invasive insects and pathogens should also be addressed (also see research need #2).

- *What are the tradeoffs between active (e.g. assisted migration and planting blister rust resistant pines) and passive (i.e. "hands-off") management strategies to promote climate adaptation in protected areas? What are the tradeoffs between **resisting change** (e.g. fire suppression) vs. **facilitating or allowing change** to occur in protected areas?*

- There is increasing concern that the rate at which organisms shift their geographic ranges in response to climate change is slower than the velocity of climate change (Santini et al. 2016). These concerns are intensified by climatic barriers, habitat fragmentation, and human land-uses that increase resistance to movement by organisms (McGuire et al. 2016, Dobrowski and Parks 2016), as well as exotic plants, animals, and pathogens that have been highly detrimental to native organisms (e.g. white pine blister rust; Kinloch Jr 2003). Spirited debate regarding the tradeoffs between active and passive management strategies has ensued (McLachlan et al. 2007). For example, some scientists believe that assisted migration is absolutely necessary (Schlaepfer et al. 2009), whereas others are vehemently opposed (e.g Ricciardi and Simberloff 2009). Tradeoffs between active and passive management approaches are apparent (e.g. local extinction vs. introduction of invasive organisms, respectively). Consequently, a detailed review is necessary specifically pertaining to protected areas concerning the ecological consequences of active vs. passive management strategies to climate adaptation. This review does not need to address ethical or legal issues since climate change was not considered when most protected area networks were authorized (e.g. the Wilderness Act of 1964).

- Natural disturbances (specifically, wildland fire) are often suppressed in protected areas. Such disturbances are often considered catalysts of change (Gonzalez et al. 2010) and are essential, especially under a changing climate, to keep post-disturbance vegetation and successional trajectories are in equilibrium with the emerging climate (Millar et al. 2007). Although disequilibrium dynamics are natural and expected under a changing climate (Svenning and Sandel 2013), resisting change via activities such as fire suppression further escalates and compounds disequilibrium between plant communities and climate. A high degree of disequilibrium is generally considered undesirable and may result in more severe disturbances (e.g. wildland fire, insect-induced mortality) than would have otherwise occurred had previous fires not been suppressed. An alternative has been suggested in which wildland fire is not suppressed, thereby allowing change to naturally occur and promoting equilibrium between plant communities and climate (Calkin et al. 2015, Parks et al. 2016). Scientific studies and reviews are necessary to quantify and understand the tradeoffs associated with resisting change, allowing change, and perhaps even facilitating change to occur in protected areas. These studies should consider incorporating the use of prescribed fire (i.e. facilitating change) and the legacy of past fire suppression.

- *How will climate change affect **carbon storage** within protected landscapes? How do altered patterns of productivity and disturbance affect carbon dynamics in protected areas?*

- The effects of changing climate on carbon storage will not only vary as a function of the direction and magnitude of changes in climate, but also from associated changes to disturbance regimes. For example, in forested systems, the fundamental niche for mature trees is typically larger than for juvenile individuals; this could impact the ability of forests to regenerate under a changing climate (Liang et al. 2017). In the absence of disturbance, reduced tree regeneration will be less influential on carbon dynamics in the near-term (Liang et al. 2017). However, increasing disturbance frequency could fundamentally alter carbon dynamics. In drought-prone areas, higher temperatures are likely to increase the frequency of drought-induced tree mortality, leading to reduce carbon uptake (Allen et al. 2015, Schlesinger et al. 2015). The area burned by wildfire is projected to increase with changing climate, potentially reducing the amount of carbon stored in natural systems. Carbon storage could be further reduced if the interaction between climate change and disturbance regimes results in less carbon dense vegetation types (Hurteau and Brooks 2011, Westerling et al. 2011).

- While the potential for climate- and disturbance-driven reductions in carbon storage exists, our ability to project future carbon dynamics is limited in part by the spatial scale (i.e. the resolution) of projected climate data. These data do not account for potential climate refugia that can result from topographic variability; an attribute of many protected landscapes. Additionally, the area impacted by climate-driven changes in disturbance regimes is likely to increase (see research need #2). Thus, sustaining current rates of carbon uptake may not be realistic in many systems without active management, such as planting climate-adapted species (see research need #4), which is highly controversial in protected landscapes. Improving our ability to model these systems requires an empirical understanding of the physiological tolerances of species targeted for assisted migration and the ecological consequences of moving species. Given that many protected areas allow natural disturbances (e.g. wildland fire) to occur, that protected landscapes can serve as a valuable laboratory for better understanding carbon dynamics under a warming climate and changing natural disturbance regime.

- *What factors will govern the* ***resilience of populations and communities in protected landscapes****? When resilient capacity is exceeded, will the resulting ecological change result in altered and degraded ecosystems, or novel systems better adapted to emerging conditions?*

- All populations, communities, and species have some degree of resilience to environmental change and perturbation – else they could not exist in a non-stationary world. However, the pace, magnitude, and pervasiveness of environmental change, particularly in Earth's climate system, is posing novel challenges to managers of parks and protected landscapes. Despite the assumption that these areas are to some extent insulated from anthropogenic change, a changing world has reached the boundaries of even our most iconic protected landscapes. How they will respond ecologically is thus a central concern for coming generations of land managers (Millar and Stephenson 2015, Falk and Millar 2016).

- The first line of defense for any population is to *resist* change (Millar et al. 2007). Thick-bark trees can resist moderate fire effects; wildlife with broad environmental tolerance can wait out periods of unfavorable climate or reduced resource availability; drought-tolerant plants can survive and grow through climate episodes that would be lethal to other species. All of these are mechanisms for persistence of established individuals and populations. In some protected areas, such as Sequoia National Park, the persistence of individual organisms is central to the identity of the park and thus a primary management concern.

- When resistance is overcome and mortality occurs, the population-level response is *recovery*, the recruitment of new individuals to replace those that have been lost. This often occurs following disturbance events such as fires or insect outbreaks, but recovery is also important following episodes of drought-related mortality, disease, overgrazing, recreation-related erosion, and other disturbances. Recovery is primarily a population-level process leading over successional time to a community that bears some resemblance to the pre-disturbance condition (O'Connor et al. 2014). The recovery over time of burned areas across a range of severity is a common example of recovery processes in parks and protected areas.

- Under extreme conditions, both resistance and recovery potential are overcome, and the ecosystem begins to *reorganize* into a new configuration (Falk 2013). This response is sometimes referred to as a "tipping point", but reorganization is a natural process that occurs when climate, disturbance, and biota exceed interactive limits that favor a new state (Suding et al. 2016). For example, following severe forest wildfire in many U.S. parks and protected areas, many ecosystems are not returning to forest (recovery) but rather converting to shrubland or grassland states. These biome conversions can be highly persistent, and are reinforced by altered climate, invasive species, and anthropogenic disturbance (Falk 2017). Protected areas that have experienced major ecosystem type or biome conversions will present a new face to the public, and new challenges to managers. Translating resilience ecology into protected area management will require new criteria for evaluating sustainable land management (Falk 2016).

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