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PERSPECTIVE

Understanding and managing the interactions of impacts from nature-based recreation and climate change

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Abstract Disturbance to ecosystems in parks and protected areas from nature-based tourism and recreation is increasing in scale and severity, as are the impacts of climate change—but there is limited research examining the degree to which these anthropogenic disturbances interact. In this perspective paper, we draw on the available literature to expose complex recreation and climate interactions that may alter ecosystems of high conservation value such that important species and processes no longer persist. Our emphasis is on ecosystems in high demand for tourism and recreation that also are increasingly experiencing stress from climate change. We discuss the importance of developing predictive models of direct and indirect effects, including threshold and legacy effects at different levels of biological organization. We present a conceptual model of these interactions to initiate a dialog among researchers and managers so that new research approaches and managerial frameworks are advanced to address this emerging issue.

Keywords Climate change · Nature-based tourism · Park and protected area management · Recreation ecology

INTRODUCTION

Parks and protected areas (PPAs) such as national parks, wilderness areas, and nature reserves are essential to species conservation while simultaneously providing nature-based tourism and recreation activities that are enjoyed by hundreds of millions of people worldwide (Balmford et al. 2015). This "dual mandate" to protect habitat critical for conservation and allow people to access PPAs to experience nature has often been described as a significant management challenge (Hammitt et al. 2015). Even in PPAs that are highly managed, non-consumptive recreation and tourism (i.e., photographing wildlife, hiking, mountain biking, camping, etc.) often result in ecological disturbance. Recent reviews in this field of study, often called recreation ecology (e.g., Monz et al. 2010, 2013; Hammitt et al. 2015; Sumanapala and Wolf 2019), generally suggest that ecological responses to recreation disturbance are often highly influenced by human factors such as use type and behavior, but also depend on the ecosystem and species that are affected. For example, trampling disturbance from activities such as hiking can result in reduced vegetation cover and a shift in species composition toward ruderal species (Cole and Monz 2002; Ballantyne and Pickering 2015; Pickering and Barros 2015), but spatial confinement of intense recreation disturbance often limits the disturbance to acceptable levels (Cole et al. 2008; Hammitt et al. 2015). Broadly, recreation and tourism activities often result in vegetation disturbance and soil erosion and, depending on the activity, may impact other ecosystem properties via air and water pollution, noise, wildlife disturbance, and associated feedbacks (Monz et al. 2013; Hammitt et al. 2015; Buxton et al. 2017; Gutzwiller et al. 2017).

Historically, nature-based tourism and recreation most often have been concentrated in only some parts of PPAs, but this may be changing due to increasing demand, combined with new technologies that increase access to and within protected areas. A good example of this phenomenon is winter recreation—it has become easier for people to access remote terrain via improvements in ski technology, more capable snowmobiles, and in some cases via helicopter (Olson et al. 2017). Similarly, the spread of e-mountain bikes and other ridable technology is allowing easier access farther from park entrances. These trends, combined with the increasing use and availability of

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communication technology and social media to publicize new and unique experiences, suggest a broadening of the spatial scale and an increase in intensity of recreation use. Understanding the consequences of both acute and chronic disturbance across spatial scales is essential for developing sustainable management solutions in this era of rapid change (Gutzwiller et al. 2017).

These trends of increased use and associated disturbance are co-occurring with a rapidly changing climate, yet only limited research has conceptually or empirically examined the interactions of these phenomena (Buckley 2013). Climate change is already having significant impacts on a range of ecosystems popular for nature-based recreation and tourism. These include Arctic and alpine ecosystems (e.g., Ernakovich et al. 2014; Verrall and Pickering 2020), forests (e.g., Dale et al. 2001), deserts (Bachelet et al. 2016), and river and lake ecosystems (Hunt et al. 2016). New disturbance regimes may emerge as climate change not only alters the frequency, intensity, duration, and timing of wildfire and drought, but also enhances the spread of many invasive species including weeds, feral animals, and pathogens (Schoennagel et al. 2004).

Given these changes and associated potential management challenges, we propose that five major themes of research should be pursued to fully understand and help manage effects of recreation–climate interactions. These include use-level responses and spatial context, interactions with animals, interactions with vegetation, visitor-use effects and feedbacks, and impacts to cultural ecosystem services.

THE “GRAND CHALLENGES”: IDENTIFYING KNOWLEDGE GAPS

Use-level responses and spatial context of PPAs

While empirical work is limited, existing ecological knowledge suggests that disturbance from nature-based tourism and recreation and climate are likely to interact in ways that alter both visitor behavior and biophysical conditions. Our conceptual model (Fig. 1) of these interactions forms a basis for the following discussion, although we do not comment on every possible interaction. For example, outdoor recreation and tourism are expected to shift to higher elevations and latitudes as the climate warms and the season for snow- and ice-free recreational activities such as hiking, kayaking, climbing, and biking lengthens in higher altitude regions (Fisichelli et al. 2015; Hewer and Gough 2018; Koutroulis et al. 2018). At the most extreme, diminishing sea ice in the Arctic has resulted in northward shifts in cruise tourism and increased wildlife viewing (Stewart et al. 2010). “Last-chance tourism” has also become a phenomena as tourists travel to see the Arctic environment, polar wildlife and even coral reefs before these environments become terminally altered by climate change (Lemelin et al. 2010; Piggott-McKellar and McNamara 2017). Likewise, park visitation in the USA has been found to increase with warmer temperatures until a threshold of approximately 25 °C, after which visitation declines (Fisichelli et al. 2015). In Europe, visitation to wild areas in the Mediterranean is expected to decline in the warmest months, creating a “two-shoulder” visitation pattern earlier and later in the summer season (Koutroulis et al. 2018). Changing rainfall, increased frequency of extreme events such as flooding, storms, drought, and wildfires, and an earlier spring season also can influence the timing of recreation and tourism activities. For example, storm surges and flooding in South Africa are already impacting nature-based tourism (Hoogendoorn and Fitchett 2018); the change in timing of cherry blossom blooms and autumn foliage peak times are affecting popular cultural events in Japan (Liu et al. 2019); and changing rainfall will have implications for popular tourism events such as wildlife migration in Serengeti National Park (Hoogendoorn and Fitchett 2018). The extensive 2019–2020 fire season in Australia, which was associated with hotter and dryer conditions, burned many protected areas and has altered the concept of summer “bush” holidays.

Depending on their landscape and regional context, some PPAs will be more exposed to recreation-climate interaction effects than others. PPAs within moderate driving distances of major human populations may experience additional recreation disturbances as populations increase (Hansen and DeFries 2007), while visitation is often limited when PPAs are distant from urban areas (Norman et al. 2019). Concomitant changes in land use in areas adjacent to PPAs can reduce habitat amount and connectivity for native species. Loss of habitat usually leads to declines in populations and loss of physical or functional connectivity, and may reduce dispersal pathways that would enable species to track suitable climate spaces over time (Hannah 2015). If such changes occur near protected areas, species’ populations in those areas may become less functional as source populations for PPAs, and populations inside the protected areas themselves may consequently decline (Hansen and DeFries 2007) and become more vulnerable to recreation and climate stresses.

Higher latitudes and elevations are already experiencing significant climate change (Hansen et al. 2010; Brusca et al. 2013). PPAs in these places may therefore face greater climate impacts than those at lower latitudes and elevations. Some species at extreme latitudes and elevations have already been adversely affected (Grebmeier et al. 2006; Hannah 2015; Verrall and Pickering 2020), and

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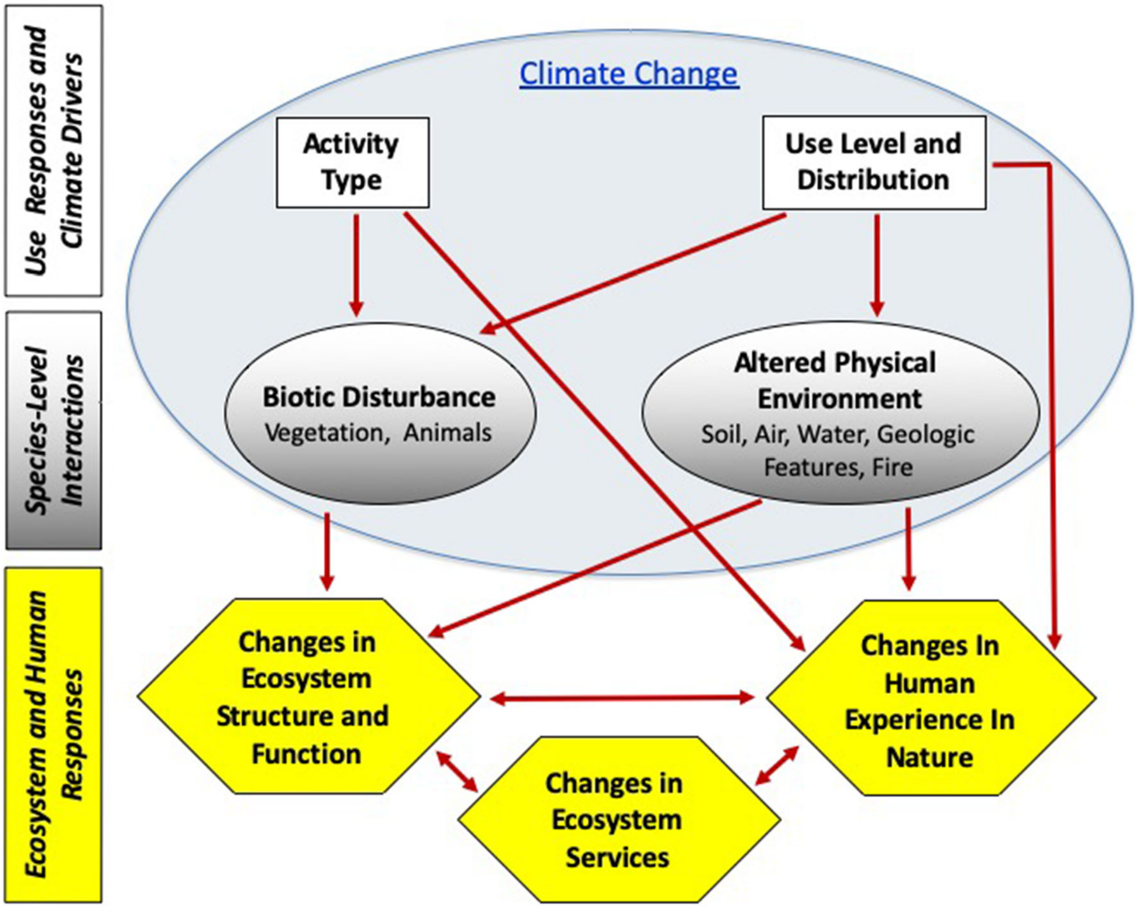

Fig. 1 A conceptual model of the complex interactions of nature-based tourism and recreation use and climate change and the consequences on biophysical resources. Climate change can have direct effects by influencing tourism and recreation use and distribution. Interactive effects are possible as climate alters biophysical resources that can also be affected by disturbance from tourism and recreation activities

protected areas may lose species as suitable climate spaces shift beyond present park boundaries (Peters and Darling 1985; Heller and Zavaleta 2009). Climate warming has caused significant upslope shifts in the distributions of many organisms (Chen et al. 2011). Warming climates have even influenced disease dynamics, leading to amphibian losses in South America (Pounds et al. 2006) and bird population declines in Hawaii (Benning et al. 2002). Some montane plant species have exhibited upslope shifts in their lower or upper elevation limits in response to warmer and drier conditions (Brusca et al. 2013). Therefore, it is especially likely that in protected areas at higher latitudes and elevations, recreation disturbance has the potential to exacerbate the effects of climate-induced stress.

Species level interactions: Animals

In tourism and recreation, animal species can act either as attractions, as victims, or as threats (Buckley 2019). As attractions, they may be either a primary or secondary component of a nature-based experience. As victims, animal species and populations may suffer from a wide range of recreation impacts and disturbances. These may affect habitat, foraging and energetics, social interactions and reproduction, migration, seasonality, and diurnal activity patterns (Steven et al. 2011). As threats, animal species may act either directly on individual humans, or as vectors for pathogens.

Climate change can affect all aspects of wildlife tourism and recreation: tourism and tourists, animal ecology and distribution, and the interactions between animals and tourists. As summarized below, the effects of climate change on recreation (Fang et al. 2018) and animal species (Hoffman et al. 2019) have been subject to considerable research. The interactions, however, have not. For plants, the first experimental study of ecological interactions between recreational impacts and climate change was conducted over two decades ago (Monz et al. 1996). For animals, in contrast, there seems to be little comparable research. Consequently, for primary direct effects we summarize published literature, but for interactive and

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indirect effects we suggest mechanisms and cases based on popular accounts and personal experience. This is thus an area heavily in need of rigorous research.

Climate change can affect the distributions and ecology of animal species through temperature, drought, glacier and ice-melt, sea level and storm surge, floods, fires, and extreme weather events such as cyclones and hurricanes. For different species, climate change may affect latitudinal and elevational range (Freeman and Freeman 2014); local distribution relative to forage or prey; habitat selection, foraging patterns and energetics; social interactions and reproduction; migration (Both et al. 2009); and phenology, seasonality, and diurnal activity patterns (Thackeray et al. 2016; Cohen et al. 2018). Climate change has already caused both local, and in some cases, global extinctions of individual animal species (Urban 2015; Wiens 2016). Species differ in resilience and susceptibility (Moritz and Agudo 2013).

There are few published case studies of interactions between recreation impacts, and climate change impacts, at the scale of individual animal species and subpopulations. Polar bears (*Ursus maritimus*) in Canada now experience shorter seasons on sea ice, where they feed on seals. In consequence, at least some subpopulations are experiencing severe energetic stress, culminating in starvation. There may be more bears on land where tourists can see them most easily, but they are in worse condition. News images of bears in poor condition may make bear viewing destinations less attractive.

Coral reefs in tropical oceans, supporting a global dive-tourism industry, are suffering extensive die-off from a combination of heat stress due to climate-induced ocean warming, storms, and pollution, with agriculture and coastal tourism development as key additional factors (Wilkinson 1999). Even though deeper reefs may maintain high coral quality, news reports of reef damage reduce the attractiveness of dive tourism destinations.

Climate change also can modify distribution and seasonal activity of animals posing a threat to tourists, as summarized by Buckley (2019). In the UK, for example, snakes such as adders (*Vipera berus*) are now active year-round, instead of only in summer. As another example, irukandji jellyfish (e.g., *Malo* and *Carukia* spp.) in Australia, potentially lethal to ocean bathing tourists, are now reported in subtropical as well as tropical waters. Similarly, mosquito species transmitting malaria and dengue fever have expanded their ranges, and so have larger cold-water shark species. Distributions of plant and animal pathogens, including those affecting species attractive to tourists, also may be affected by climate change (Buckley 2019).

For animal species that may be suffering population declines from climate change, additional impacts from tourism and recreation may accelerate this effect. Similarly, for species experiencing impacts from recreation and tourism, the effects of climate change can exacerbate such impacts. For example, climate change may reduce the geographical range of a species, and recreation may increase disturbance within that range. If disturbance affects reproduction or migration, the consequences can be amplified accordingly.

To quantify the interacting impacts of climate change and tourism and recreation for individual animal species, the most rigorous and reliable tool would seem to be a population viability analysis. This approach requires considerable prior ecological knowledge of individual species and subpopulations, such as habitat area and density, age and gender distributions, reproduction and mortality rates, and in-migration and out-migration. It also requires that all significant impacts from all sources, including climate change, tourism and recreation, and other anthropogenic impacts, can be expressed in terms of these population parameters (Buckley et al. 2016). The principal obstacle to this approach is the scarcity of species for which adequate ecological data are available.

Species level interactions: Vegetation

Nature-based tourism and recreation are increasingly recognized as having a wide range of effects on plants and plant communities (Barros et al. 2015) and in many cases are one of the most common threats to plants already at risk of extinction (Wraith and Pickering 2017). Climate change also is rapidly altering the distribution of plant species and communities and is the most important threat globally to natural ecosystems (Díaz et al. 2019). Although specific research is sparse, there are important straightforward interactions; e.g., well-documented impacts such as those showing trampling on vegetation has greater impact when conditions are warmer (Monz et al. 1996). Other interactions are more complex, reflecting the interplay between climate, tourists, and management. We illustrate some of the links and complexities with specific examples including weeds, feral animals, fires and trampling.

Non-native invasive species are one of the major threats to biodiversity globally and a major management challenge in PPAs (Pickering and Mount 2010). With warming conditions, range expansions are likely for many invasive plants, including into areas of high conservation value (Shrestha and Shrestha 2019). As people act as unintentional vectors for a wide diversity of weed seeds (Ansong and Pickering 2014), those visiting remote areas can inadvertently introduce new species into areas where climatic conditions used to be unfavorable, amplifying the rate of biological invasions.

Non-native animals such as horses, mules and donkeys are often used by park visitors and/or valued by them, but

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they can damage vegetation and waterways (Pickering et al. 2010). With warmer conditions resulting in a capacity to access more remote areas, there is likely to be pressure from tourists and operators to use these forms of transport more often, further damaging fragile ecosystems, particularly in mountain regions. In some cases, tourists see feral animals in PPAs as attractive, despite well-documented damage to vegetation and soils (Robertson et al. 2019). With climate warming, damage to vegetation from these and other feral animals is increasing, but control options are sometimes limited due to these animals' perceived value (Williams 2019).

A major effect of hotter and drier conditions is increased wildfire, with recent megafires in the Mediterranean, California, and Australia resulting in millions of hectares of PPAs burning. An emerging body of research is beginning to examine the consequences of altered fire regimes on tourism and recreation (e.g., Otrachshenko and Nunes 2019). Some of these fires extend into plant communities that previously rarely burned, including rainforest and high-altitude plant communities. Visitation to these areas soon after the fires can cause further damage, with impacts from activities as simple as trampling being greater post-fire (Growcock et al. 2004).

Specific studies of these types of interactions remain limited—greater recognition, research and management action are needed. A rare documented example of research on how climate change, fire and tourism amplify stress on plants resulting in management action can be seen for an endangered plant community in Australia. Trampling by hikers was found to damage the dominate shrub in the endangered *feldmark* plant community, limiting its capacity to support other endemic plants (Ballantyne and Pickering 2015). Research also documented how hotter and dryer conditions created unprecedented fires that burned areas of this plant community, which exhibit limited recovery after 15 years, and resulted in colonization of burned areas by more competitive species (Verrall and Pickering 2018). As a result, the park management recently spent over US$1.3 million moving a walking trail away from the plant community to limit further tourism damage, and prioritized controlling the spread of fires into the community in the future.

People and nature

Research on observed or potential effects of climate change on visitor behavior has focused primarily on impacts of changing weather on a few types of recreation that tend to take place in more developed settings: tourism (especially in national parks); snow skiing; and golfing (Verbos et al. 2018). Nature-based tourism and recreation have received relatively little attention. Generally, predictions of climate-change impact on recreation visitation depend on the types of changes to the recreation setting and on characteristics of the visitor population. Significant changes to a setting, such as a shift from snow-dominated to rain-dominated winter weather (Pouta et al. 2009) or from a cold-water to a warm-water fishery (Paudyal et al. 2015), are likely to cause significant impact on recreation visitors. However, projected changes in recreation demand tend to be less where similar weather conditions will prevail but relative length of seasons will change, e.g., Rocky Mountain National Park, USA (Richardson and Loomis 2004), or the north shore of North America's Lake Superior (Smith et al. 2016). Changes in use pattern are more likely among recreationists who are already alarmed about climate change (Paudyal et al. 2015; De Urioste-Stone et al. 2016), or who consider an activity culturally or personally important (Pouta et al. 2009).

Nature-based tourism and recreation are likely to be more susceptible to weather changes and extreme events than other activities. Activities are more likely to be weather-dependent if they occur in locations with less infrastructure, rely on human-powered transportation, occur in expansive topography, and require extensive planning—all characteristics of dispersed and backcountry recreation activities (Verbos and Brownlee 2017). The consequences of increased temperatures depend on whether warming will make weather more clement or more extreme. Warmer weather has been linked to higher levels of visitation at Rocky Mountain National Park, Colorado (Richardson and Loomis 2004), but it reduced summer visitation at national parks in the Utah desert (Smith et al. 2018). Temperature effects do not appear to be influenced by the origin of the visitors, as people who live in different climates tend to have the same climate preferences for leisure activities (Lise and Tol 2002). Recreation demand is highest on sunny days, and when springtime temperatures are unusually warm, but demand decreases on the hottest days (Dwyer 1988). We might expect, then, that rising temperatures would result in a shift of use away from the hottest times of year while increasing use during the spring and fall. Such changes could have negative feedbacks for plant and animal species. Effects of springtime vegetation trampling, if it occurs at summer rates, would likely have greater impact on plant populations if it occurs when individuals are smaller and have less well-developed root systems and stem structures, or when soils are wetter. Similarly, recreation use could have greater negative impacts on wildlife if it increases during breeding and early rearing of young animals.

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Less attention has been given to the effects of non-temperature-related impacts of climate change on recreation use patterns. In this review we are assuming the use of coping behaviors by visitors, especially as the impacts of climate change become more obvious. However, such behaviors are more likely to be employed by some users and in some contexts than others (McCreary et al. 2019). A Utah, USA, a study found that precipitation was a poor predictor of national park visitation except when there is snow (Smith et al. 2018). Demand for winter recreation does increase as the amount of snow increases, assuming other factors such as price and access are held constant (Englin and Moeltner 2004). Changes in snowpack could have feedbacks for a wide range of montane species that experience negative impacts of outdoor winter sports, including grouse (Patthey et al. 2008), wolverines (Heinemeyer et al. 2019), and marsupials (Sanecki et al. 2006). An online survey of visitors to Acadia National Park, Maine, USA, found that recreation users expected extreme weather and sea level rise to be the most likely near-term effects of climate change, along with higher levels of mosquito and tick infestation (De Urioste-Stone et al. 2016); the latter may dampen visitation during early to mid-summer. Effects of sea level rise on recreation use, and subsequent feedbacks to littoral and marine species, are unknown but are likely to depend on site-level changes in access to launch sites or suitability of shoreline environments to support recreation activities. An impact that has received some attention from limnologists is a climate-induced increase in harmful cyanobacterial algal blooms (Paerl et al. 2016; Chapra et al. 2017). Decreased water quality has a negative impact on recreation experience, even when affected waters are not closed off from recreation use entirely (Ferguson et al. 2018); however, these effects may be less influential in backcountry settings where anthropogenic impacts on water quality are smaller. It is not known whether decreased recreation use in affected waters could reduce impacts on aquatic species sufficiently to offset negative ecological consequences of cyanobacterial blooms in these systems.

Also unknown is the extent to which visitors will be willing to alter their behaviors to mitigate climate change impacts. A variety of climate change adaptation strategies are available to land managers, including alterations to the setting, educational programs, and changes in visitor access to sensitive resources (O'Toole et al. 2019). A scenario-planning exercise in Jasper National Park, Canada, found that a majority of visitors would support climate change adaptation strategies that limited visitation as long as opportunities were not foreclosed entirely (Weber et al. 2019). Further research is needed to understand the climate-change contexts and climate-adaptation strategies that are more likely to result in visitor behavior change that could offset negative impacts.

Ecosystem and human responses: Cultural ecosystem services

Cultural ecosystem services (CES) refers to the non-material benefits that people derive from ecosystems, and includes among other things, the physical and experiential interactions people have with nature, their appreciation of natural scenery, and the deep and emotional bonds people have to specific places or species (MEA 2005; Daniel et al. 2012). More than any other services, CES are defined by human preferences, values, and needs. Their full realization relies on visitors' opportunities to access and experience natural ecosystems. People engage with and value nature for a variety of reasons, and these values change over time and across places, making the impacts of climate change on CES challenging to measure and generalize. To date, no studies have specifically assessed the impacts of climate change on CES. In a recent systematic review of climate-change impacts on ecosystem services, CES were under-represented in the peer-reviewed literature (< 15 references), with the limited research focused primarily on nature-based tourism, outdoor recreation opportunities, and aesthetics in the USA and Europe (Runting et al. 2017). These services are regarded as key for increasing public engagement with nature. The physical and experiential interactions with natural ecosystems through visitation to protected areas generate US$825 billion per year worldwide (Balmford et al. 2015), and access to such recreation areas is crucial for the physical and mental health of the general population (Thomsen et al. 2018; Buckley et al. 2019).

Climate change influence CES indirectly through biodiversity loss and change in species composition. Nature-based tourism is more frequent in protected areas, and particularly those that are more diverse, older, larger, more accessible and at higher elevations (Chung et al. 2018; Runge et al. 2020). Primarily charismatic species such as mammals, birds, wildflowers and butterflies are appreciated, and people are willing to travel further to experience such CES (Runge et al. 2020). In southern Africa, visitation is related to the diversity of larger mammals (Arbieu et al. 2018), many of which are currently declining because of reduced mean annual precipitation (Pacifici et al. 2018). Species richness is, however, a poor indicator for bird-watching supply, as it depends on the season and on the birds' migratory status (Graves et al. 2019). Similarly, the link between wildflower diversity and aesthetics is not evident, and the diversity of traits such as color and shape matters more than species richness (Tribot et al. 2018). These services could be linked to the presence, abundance, diversity, and/or functional traits of biotic communities. Changes in species composition from native to non-native species also could benefit different types of CES. For

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example, native tree species on the Iberian Peninsula are perceived as more beautiful and attractive on nature routes and by local users, but non-native species are more appreciated as monument trees and tourism services (Vaz et al. 2018). Climate changes resulting in loss of habitats and biodiversity may also evoke emotional responses similar to grief as documented for both tourists and residents in the Great Barrier Reef (Marshall et al, 2019).

Climate change affects people whose livelihood, culture and traditions depend on natural resources. Climate change has been found to negatively affect sense of place and the physical, mental and emotional health of Inuit people through changing the means of harvest and transport in natural landscapes (Cunsolo Willox et al. 2012). Change in species distributions of culturally important plant species will significantly affect the indigenous Maori cultures in New Zealand (Bond et al. 2019). Climate change also is a major threat to culturally and spiritually important landscapes, e.g., in Nepal through the melting glaciers (Mukherji et al. 2019), and to Sámi landscapes in Scandinavia through changing weather and snow conditions (Hausner et al. 2011; Turunen et al. 2016). Understanding CES in the context of changing socio-ecological dynamics and bio-cultural values is a major research need for future climate impact assessments (Fauchald et al. 2017; Sterling et al. 2017).

THE PATH FORWARD: STUDY DESIGNS AND APPROACHES TO INFORM MANAGEMENT

Developing sustainable management strategies and practices to respond to climate change will require new knowledge about recreation–climate interactions (RCIs) that incorporates both ecological and social factors. New management approaches will need to be developed, along with policies and programs to provide the necessary funds, mechanisms, and flexibility to implement adaptive management approaches applicable to broad ecological and managerial scales.

Climate change is a worldwide phenomenon that individual managers cannot influence by themselves; hence, most efforts to protect natural systems against climate change involve minimizing the impacts of other ongoing threats (loss of habitat amount and connectivity, spread of invasive species, etc.) that can be managed in some situations (Hannah 2015). The rationale is that a species will have a better chance of persisting in the face of climate change if it has, for example, more habitat that is connected across landscapes and regions, and if it experiences fewer adverse effects (competition, predation) from invasive species. Fortunately, recreation disturbance in protected areas is a threat that *can* be managed, and this situation provides opportunities to implement some control of the impacts of RCIs. At present, virtually nothing is known about the prevalence (temporal and spatial) and severity of such interaction effects, or the recreation variables (type, frequency, seasonal timing, etc.) that may be involved. Without this information, little direction on how to preclude or reduce climate-recreation interaction effects can be provided to managers.

APPROACHES FOR FILLING KNOWLEDGE GAPS

Causal understanding and predictive capability

Proactive and effective management of the effects of RCIs will be advanced through an understanding of causal relationships and the ability to reliably predict the location, occurrence, and severity of influences. Uncovering the drivers of RCI effects and the mechanisms by which they operate will expand knowledge of causes, and hence the potential for insights, that may be generalizable outside of a given park. Such information may help to reduce the need for separate studies in every protected area. Identification of causes also can help managers to resolve recreation disturbance problems more quickly and thereby lessen the spatial extent, frequency, and intensity of impacts. Predictive relationships that have been validated across space and time, along with additional analyses and projections (Gutzwiller et al. 2017), may enable managers to anticipate and perhaps preclude or ameliorate RCI effects.

It will be important for recreation ecologists to develop causal understandings and predictive capabilities for complex influences of RCIs, especially cumulative, ripple, threshold, and legacy effects. The potential for these four types of recreation disturbance effects has previously been brought to the attention of wildlife researchers and managers (Gutzwiller and Cole 2005), but have not received research attention as they relate to RCIs. Cumulative effects accrue from influences that occur at multiple locations or times, and their combined influence is greater than that from any single component effect (Riffell et al. 1996). Ripple effects are influences that are transmitted between levels of biological organization, between trophic levels, or between places. For example, the effects of an RCI on a plant community (e.g., an increase in invasive non-native species) may negatively affect the survivorship of individuals of a native plant species via competition for resources; negative RCI effects on predator populations may lead to increases in prey populations; and impacts of RCIs on habitats that supply nectar may induce high competition for nectar in remaining distant patches of this habitat. A threshold effect occurs when a small change in a driver variable (e.g., land cover) results in an abrupt and

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important change in a response variable (organism distribution) (e.g., Gutzwiller et al. 2015). Legacy effects (e.g., Harju et al. 2010; Walker et al. 2013) occur as a consequence of time lapses (lags) in responses to RCIs. Lack of evidence of immediate influence may make it appear that there are no RCI effects and hence no need for management. But by the time an RCI effect becomes apparent (i.e., after the lag has transpired), significant damage may have accrued. All of these complex effects can make it more difficult to detect and manage RCIs (Gutzwiller and Cole 2005).

Study design and analytical considerations

Experiments, including management experiments (Gutzwiller 1993), are needed to establish causal relationships, but they tend to be expensive and logistically difficult to execute at larger spatial extents (Gutzwiller 1991; Gutzwiller and Cole 2005). Observational studies can be easier and less expensive to conduct, and they can make use of data from a range of spatial and temporal scales. Extraneous effects that might ordinarily be controlled for in experiments can, in observational studies, be accounted for analytically using covariates (Huitema 1980). Simulation analyses (e.g., Bennett et al. 2009; D'Acunto et al. 2018) will be essential for studying RCI phenomena that are too difficult (logistically, financially, ethically, or politically) to address via experimental or observational designs. Simulation analyses will often involve long time frames, large spatial extents, species with very small populations, or other intractable situations. All of these designs will be needed to fully understand the impacts of RCI effects.

Climate change is a long-term broad-scale phenomenon, whereas recreation disturbance can be both temporally acute and chronic but is usually confined to smaller spatial extents. RCIs may therefore typically involve cross-scale interactions, which occur when the interacting variables reflect conditions at different spatial or temporal scales. Cross-scale interactions may involve different temporal scales (e.g., climate for decades, and recreation disturbance for days, seasons or years), or different spatial scales (e.g., climate at a regional scale, and recreation disturbance at a local scale). For example, the influence of mountain biking disturbance (smaller-scale factor in space and time) on ungulate reproduction (response variable) may vary with the amount of climate warming (broader-scale factor in space and time). Statistical methods for studying cross-scale interactions include hybrid modeling that combines regional, landscape, and individual-based models (Girard et al. 2015); Bayesian or non-Bayesian hierarchical models (Soranno et al. 2014); and use of standard interaction terms (Neter et al. 1989) in analysis of variance and regression.

Among the various statistical approaches for prediction (e.g., Kuhn and Johnson 2016), some machine-learning methods (e.g., multivariate adaptive regression splines, neural networks, support vector machines, and classification and regression trees) offer promise for uncovering complex relationships in big data and providing superior predictive ability without overfitting the data (Lantz 2015). Prediction uncertainties for models can be characterized using confidence intervals on expected (mean) values of the response variable and on metrics of prediction accuracy (Chuang and Chang 2014; Hauduc et al. 2015). To judge whether an RCI effect is meaningful in a practical sense (e.g., biologically, physically, or socially important), and therefore whether management action is warranted, recreation ecologists will need to estimate RCI effect sizes (see Neter et al. 1989; Gutzwiller et al. 2010).

RCI effects may vary through time and space. Accordingly, it will be essential to monitor climate metrics, recreation activities, and protection-area response variables over long time periods to check for interannual variation (Gutzwiller and Barrow 2001; Riffell and Gutzwiller 2009) in RCI effects. Similarly, monitoring these variables across various spatial scales will provide data for assessing the degree to which RCI effects are location-specific. Long-term (White 2019) and multiscale monitoring data also will provide a sound foundation for time-series and spatial analyses that can be used to steer adaptive research and management of RCI effects. Monitoring can be expensive and time-consuming, but having rigorous data can enable recreation ecologists to detect and effectively manage important RCI effects and thereby prevent permanent damage to protected-area resources. In some cases, it may be possible to reduce the cost and effort of monitoring climate metrics and other variables using publicly available remotely sensed data.

CONCLUSIONS

- Spatial and temporal shifts in the type, frequency and intensity of recreation and tourism activities and associated disturbance to ecological systems are likely under future climate-change scenarios. Some shifts in use patterns are already occurring as participants avoid times of year with undesirable weather, take advantage of warm season access to locations heretofore inaccessible (such as polar regions), and engage in snow-free activities for longer periods.
- Significant changes to a setting, such as a shift from snow- to rain-dominated winter weather, are likely to significantly affect nature-based recreation experiences. Changes in recreation demand will tend to be less

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where similar weather conditions prevail, but there will be changes in the relative length of seasons.

- The disturbance to ecosystems from RCIs is largely uninvestigated; however, several likely generalizations can be made based on existing literature. Many current threats associated with nature-based tourism are likely to be amplified by climate change, including those from feral animals and plants, fires and trampling.
- Most threatened animal species are subject to a wide range of anthropogenic impacts. In many cases, habitat loss and direct poaching or harvesting are currently more severe than either tourism or climate change. To generate accurate results, analyses of impacts must also consider the effects of a changing climate and impact mechanisms simultaneously.
- Different animal species, even closely related and similar species, can react in different ways to the various mechanisms of impact from either climate change, or tourism and recreation. Results from one species or subpopulation are not necessarily applicable to others.
- Although climate change, tourism and recreation typically create negative impacts on species populations and ranges, positive impacts also are possible. For example, in some cases ranges may expand rather than contract. These changes in populations and ranges are highly relevant to the management of PPAs and to the visitors that experience these locations.
- Change in biological diversity and species composition resulting from RCI effects can have impacts on peoples' experiential interactions with nature and evoke emotional responses important for well-being. There are few studies addressing these concerns.
- Recreation ecologists need to develop causal understandings and predictive capabilities for cumulative, ripple, threshold, and legacy effects of recreation-climate interactions. Machine-learning statistical methods offer promise for uncovering and predicting complex relationships such as those likely in recreation–climate interactions.

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