Part III
Managing Protected Areas at System Scales

9

Toward Assessing the Vulnerability of US National Parks to Land Use and Climate Change

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Introduction

European colonization of the new world led to rapid conversion of wildlands to agricultural and urban landscapes. The desire to protect remaining natural lands, in the late 1800s, emerged as the modern concept of protected areas. The argument for formal landscape protection was that by removing the influence of humans, natural ecosystems would continue to maintain native species and natural ecological processes (Gaston et al., 2008). There is growing evidence, however, that protected areas are not presently functioning as originally envisioned. Ecological change within protected areas has been brought about by land use intensification on surrounding lands (DeFries et al., 2005; Wade & Theobald, 2009; Radeloff et al., 2010; Piekielek & Hansen, 2012). Introduction of invasive species has resulted in the extinction of native species within protected area boundaries (Newmark, 1985; Parks & Harcourt, 2002; Sanchez-Azofeifa et al., 2003). And in recent years, the effects of human-induced climate change within protected areas have become apparent on such variables as decreasing snowpack, increased rates of disturbance, prevalence of pests, and forest die-off (Loarie et al., 2009).

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The extent and rate of such global changes differ across the Earth's surface as does the sensitivity of ecosystems to these changes (Running et al., 2004). Concomitantly, protected areas differ in their vulnerability to land use change, invasive species, and climate change. There is a need to assess vulnerability across networks of protected areas to determine those most at risk and to develop management and adaptation strategies that are tailored to local conditions and desired outcomes.

A promising framework for developing climate change adaptation strategies was recently developed by Glick et al. (2011). The four steps of the framework are:

1. Identify conservation targets.
2. Assess vulnerability.
3. Identify management options.
4. Implement management options.

The vulnerability assessment in step 2 includes four components (Turner II et al., 2003; IPCC Secretariat, 2007; Glick et al., 2011). "Exposure" is the degree of change in climate and land use, which are key drivers of ecological processes and biodiversity. "Sensitivity" is the degree to which species and ecological processes respond to a given level of exposure, largely based on the environmental tolerances of organisms. "Potential impact" results from the interaction of exposure and sensitivity. "Adaptive capacity" is the ability of a system to adjust to climate and non-climate change. It is the interaction of potential impact and adaptive capacity that determines "vulnerability."

Assessing vulnerability across networks of protected areas is a substantial challenge for several reasons. First, the managers of individual protected areas are typically so consumed with within-park issues such as managing visitor use that they often do not focus on the effects of land use changes outside their boundaries. Second, it is often unclear what parts of the surrounding landscape are strongly connected to the protected area and should be monitored and managed. Third, datasets for quantifying the four components of vulnerability are typically not available. Fourth, the spatial scales of analysis needed for assessing vulnerability to climate change are at a regional or subcontinental scale and not easily applied to conditions in a given ecosystem. Most protected area staff members are not well equipped to perform analyses at these scales. Fifth, protected areas are often considered as individual units and are managed in isolation from other protected areas.

Viewing individual protected areas as components of a network and assessing vulnerability across entire networks can reveal which protected areas face similar threats and allow synergies in adaptation strategies among them (Davis & Hansen, 2011). For example, those areas with low exposure and sensitivity may be best managed under the philosophy of maintaining "naturalness," more specifically, under the strategies of Natural Regulation (Boyce, 1998) or Historic Range of Variation (Keane et al., 2009). In contrast, protected areas with high exposure, high sensitivity, and low adaptive capacity are expected to undergo dramatic ecological change that will exceed any historic condition. Management in such cases should be aimed at promoting ecological integrity and resilience under changing future conditions (Hobbs et al., 2010). The goal of this chapter is to illustrate the initial steps in an assessment of vulnerability to land use and climate change for the network of national parks in the contiguous United States. The objectives are to:

- Delineate the lands surrounding protected areas where land use change can most impact protected areas.
- Quantify the exposure of protected areas to land use and climate change over the last century.
- Summarize potential protected area exposure and impact in the coming century.
- Consider implications for protected area management.

Delineating PACEs

Many protected areas were originally designated for reasons of scenic or recreational value, rather than any concern for ecological completeness or its adaptive capacity to respond to change. Thus, they may not include adequate area that is needed to maintain organism populations and essential ecological processes. Ecological processes such as nutrient flows, organism movements, disturbance regimes and population dynamics may operate over areas larger than the park itself. Land use intensification outside of protected areas may disrupt these flows and alter ecological processes and biodiversity within parks. Hansen & DeFries (2007) drew on ecological theory to identify mechanisms linking land use in surrounding lands with the ecological function of protected areas (Hansen & DeFries, 2007; Hansen et al., 2011). These mechanisms are summarized below:

- **Effective size:** Changing land uses may destroy natural habitats and reduce the effective size of the larger ecosystem, which can simplify the trophic structure as species with large home ranges are extirpated, because the size of the ecosystem to fall below that needed to maintain natural disturbance regimes, and reduce species richness through the loss of habitat area.
- **Ecological flows:** Changing land uses may alter characteristics of the atmosphere (climate, pollution), water (quantity, quality, nutrients, waterborne organisms), and natural disturbance (frequency, size, intensity) moving through the protected area.
- **Crucial habitats:** Changing land uses may eliminate or isolate crucial habitats, such as seasonal habitats, migration habitats, or habitats that support source populations.
- **Edge effects:** Changing land uses may increase human activity along park borders and result in the introduction of invasive species, increased hunting and poaching, and higher incidence of wildlife disturbance.

Hansen et al. (2011) measured these four mechanisms to quantitatively assess the impact of changing land uses on the ecosystems containing protected areas. They delineated protected area centered ecosystems (PACEs) around 13 US national park units using comprehensive scientific methods to map and analyze land use change within these PACEs. The PACEs were delineated based on five ecological criteria: Contiguity of surrounding natural habitat, watershed boundaries, extent of human edge effects, crucial habitats, and disturbance regimes (Davis & Hansen, 2011). The resulting PACEs were on average 6.7 times larger than the parks located in upper portions of watersheds and 44.6 times larger than those located in middle portions of watersheds. These results illustrated that human activities across relatively large areas surrounding protected areas may impact ecological factors in the protected areas. PACEs in the eastern United States were dominated by private lands with high rates of land development, suggesting that they offer the greatest challenge for management. Davis & Hansen (2011) used a similar method to map PACEs around the 57 largest US national parks in the contiguous United States and quantified land use change for the period 1940 to the present (Table 9.1). We draw on the results of these analyses in this chapter as a measure of exposure of 48 of these PACEs to land use change. Similarly, Haas (2010) quantified climate change during the past century within these PACEs, and we also summarize those results here (Haas, 2010).

Exposure to land use and climate change in the last century

Human activities have altered land use and climate in and around protected areas over the century since North American parks were established. This exposure to past changes may have pushed some protected areas closer to sensitivity thresholds and increased their vulnerability to recent changes. Moreover, spatial variation in past exposure among protected areas may be an indication of vulnerability under future land use and climate change. Thus, we summarize here past land use, invasion by nonnative species, and climate change for the US national parks and associated PACEs.

Davis & Hansen (2011) used six variables to determine the current level and extent of development: population density, housing density, and percentages of land with impervious surfaces, in agriculture, covered by roads, or in public land. Time series of population density, housing density, and land in agriculture were used to analyze changes over time. Cluster analysis was used to determine if patterns in major land use typologies could be distinguished. The authors found that population density within PACEs increased on average 224% from 1940 to 2000 and housing density increased by 329%, both considerably higher than average rates of change nationally. On average, 24% of private lands in PACEs were in exurban and rural housing densities. Individual PACEs differed substantially in area of public versus private (and thus developable) lands, the percent of the

Table 9.1 **Land use properties of the PACEs surrounding the US national park units included in this study.**

Park	PACE code	Date of park establishment	Park area (km^2)	PACE:park area ratio	PACE in public land (%)	Undeveloped private, 2000 (%)	PACE typology
Arches	ARCH	1929	309	29	93	88.9	Wildland protected
Badlands	BADL	1929	982	15	20	95.3	Wildland developable
Big Bend	BIBE	1935	3,291	8	20	99.6	Wildland developable
Bighorn Canyon	BICA	1964	484	33	33	96.1	Wildland developable
Big South Fork	BISO	1974	496	32	27	56.0	Exurban
Big Thicket	BITH	1974	359	15	5	63.4	Wildland developable
Blue Ridge Parkway	BLRI	1936	366	81	15	19.6	Exurban
Buffalo River	BUFF	1972	389	31	23	64.0	Agriculture
Canyon de Chelly	CACH	1931	375	18	6	92.3	Wildland developable
Colorado River*	CORI†	1908–1964	18,295	5	76	93.6	Wildland protected
Crater Lake	CRLA	1902	736	7	85	92.9	Wildland protected
Craters of the Moon	CRMO	1924	1,901	9	76	93.8	Wildland protected
Death Valley	DEVA	1933	13,764	4	79	80.7	Wildland protected
Delaware Water Gap	DEWA	1965	278	24	20	15.0	Exurban
Dinosaur	DINO	1915	853	22	74	94.7	Wildland protected
El Malpais	ELMA	1987	473	17	38	96.1	Wildland developable
Everglades, Big Cypress	EVER	1934, 1974	9,179	3	62	57.0	Urban
Glacier	GLAC	1910	4,080	5	80	77.9	Wildland protected
Great Basin	GRBA	1922	312	21	93	95.7	Wildland protected
Great Sand Dunes	GRSA	1932	496	18	43	91.1	Wildland developable
Great Smoky Mountains	GRSM	1926	2,098	7	43	15.1	Exurban
Guadalupe Mountains	GUMO	1966	356	21	44	99.5	Wildland developable
Joshua Tree	JOTR	1936	3,211	7	74	62.9	Wildland protected
Lake Roosevelt	LARO	1946	424	39	22	91.3	Agriculture
Lassen Volcanic	LAVO	1907	434	9	47	92.2	Wildland developable
Missouri River	MNRR	1978	279	71	6	82.4	Agriculture
Mojave	MOJA	1994	6,433	3	94	88.9	Wildland protected

(*Continued*)

Table 9.1 **(Continued)**

Park	PACE code	Date of park establishment	Park area (km²)	PACE:park area ratio	PACE in public land (%)	Undeveloped private, 2000 (%)	PACE typology
Mount Rainier	MORA	1899	952	6	70	80.2	Wildland protected
New River Gorge	NERI	1978	285	28	15	42.1	Exurban
North Cascades Complex	NOCA	1968	2,756	6	91	73.8	Wildland protected
Olympic	OLYM	1909	3,700	5	47	65.1	Wildland developable
Organ Pipe Cactus	ORPI	1937	1,338	8	43	99.1	Wildland developable
Ozark	OZAR	1964	333	29	29	82.8	Wildland developable
Petrified Forest	PEFO	1906	903	11	25	97.3	Wildland developable
Pictured Rocks	PIRO	1966	298	17	60	82.5	Wildland developable
Point Reyes, Golden Gate	POGO	1962, 1972	617	10	28	32.6	Urban
Redwood	REDW	1968	468	15	60	82.2	Wildland developable
Rocky Mountain	ROMO	1915	1,080	8	83	53.6	Wildland protected
Saint Croix	SACN	1968	396	21	15	66.5	Agriculture
Saguaro	SAGU	1933	378	48	55	57.2	Exurban
Santa Monica Mountains	SAMO	1978	619	9	33	27.6	Urban
Shenandoah	SHEN	1926	782	14	16	19.8	Exurban
Sleeping Bear Dunes	SLBE	1970	284	16	36	22.7	Exurban
Theodore Roosevelt	THRO	1947	285	30	41	95.8	Agriculture
Voyageurs	VOYA	1971	829	11	77	80.6	Wildland protected
White Sands	WHSA	1933	617	17	34	74.3	Wildland developable
Yellowstone Grand Teton	YELL	1872	10,159	3	93	73.3	Wildland protected
Yosemite, Sequoia-Kings Canyon	YOSE	1890	6,521	3	90	66.2	Wildland protected
Zion	ZION	1909	598	14	69	87.1	Wildland protected
Mean			2,140	18	49	72.62	

Source: From Hansen et al. (2014).
*Colorado River parks are: Canyonlands, Capitol Reef, Glen Canyon, Grand Canyon, and Lake Mead.

private lands that had been developed, and the land use type and housing densities on those private lands.

Five categories of PACEs with similar patterns of development were distinguished using statistical clustering analysis (Figure 9.1):

- Wildland protected
- Wildland developable
- Agriculture
- Exurban
- Urban

PACEs within a category tended to occur in particular regions of the country. For example, both types of wildland PACEs were in the mountain west and southwest deserts. Agriculture and exurban PACEs were in the Great Plains and eastern United States. The unique management challenges and opportunities faced by each group of PACEs were identified, with the goal of allowing managers to collaborate with each other based on similarity of challenges that they face. This is the

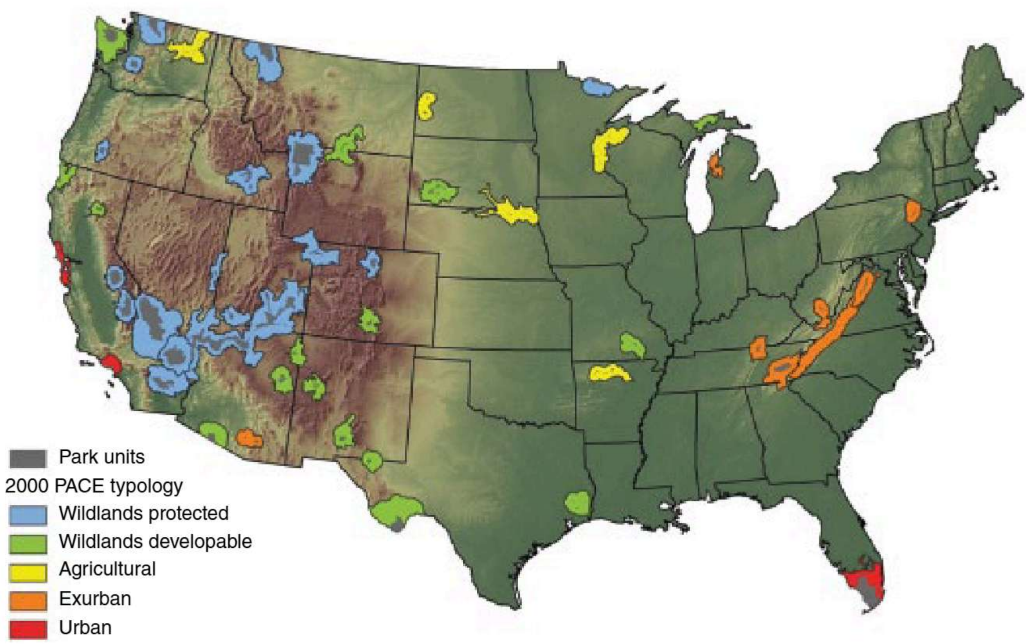

Figure 9.1 **Protected area centered ecosystems (PACEs) surrounding each US national park, color-coded by land use typological membership. Classification criteria were as follows: wildland protected, >65% public; wildland developable, <65% public, >60% private undeveloped, <16% private agriculture; agricultural, <65% public private, >60% undeveloped, >16% private agriculture; exurban, <65% public private, >60% undeveloped, <15% private dominated by exurban or urban; urban, <65% public private, >60% undeveloped, >15% private dominated by urban or urban. Source: From Davis & Hansen (2011). © Ecological Society of America**

first effort to develop a typology of protected areas based on land use change in the surrounding ecosystem. Other networks of protected areas may find this methodology useful for prioritizing monitoring, research, and management among groups with similar vulnerabilities and conservation issues.

Haas (2010) quantified trends in climate across these PACEs for the period 1985–2009. She drew on the precipitation elevation regressions on independent slope model (PRISM) climate dataset (Daly et al., 2002), which uses observations from meteorological stations to produce a spatially continuous 4 km surface of spatially interpolated climate values. These data were used to estimate 100-year trends in mean annual temperature, mean annual precipitation, and a moisture index derived from precipitation and potential evapotranspiration (a function of temperature and solar radiation). Results indicated that 78% of the PACEs warmed significantly (~1°C per 100 years). The highest rates of warming (2°C per 100 years) occurred in the mountain west. Precipitation increased significantly in 22% of the PACEs, largely in the midwest United States. The moisture index revealed that 17% of the PACEs increased in water balance while 3% decreased in water balance, largely due to increased evapotranspiration due to warming.

There were also biological changes associated with the changes in land use and climate over time. Invasive species are a good indicator of stress in protected area ecosystems. Hansen et al. (2014) found that the proportion of vascular plants that were nonnative correlated with the land use change typology. Wildland PACEs (protected and developable) had the lowest proportion of nonnatives, agricultural and exurban PACEs had intermediate levels, and urban PACEs had the highest proportions.

The relative magnitude of past change in climate, land use, and invasive species for each PACE was calculated as the percentage of the highest value among the PACEs for each variable. These percentages were summed to represent the relative magnitude of the combined exposure to these three components of global change (Figure 9.2). Notice that some PACEs had high rates of warming; others had high

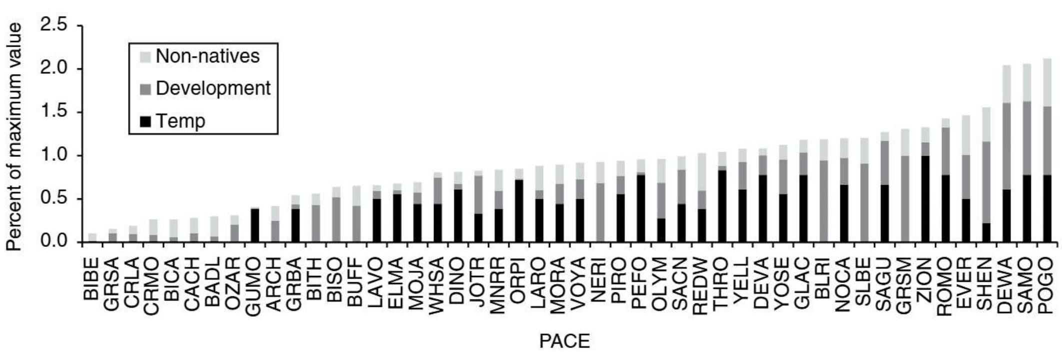

Figure 9.2 **Relative levels of temperature change, proportion of PACE developed, and nonnative vascular plants among PACEs. The data are expressed as the percentage of the highest value among the PACEs for each variable, and these percentages are summed to represent the relative magnitude of the combined exposure to these three components of global change**

rates of development and invasive species, while some had high rates of all three, and a few PACEs had relatively little change in any of the three factors. This illustrates how exposure can differ dramatically among PACEs. PACEs such as Santa Monica and Point Reyes in southern California and Delaware Water Gap and Everglades in the eastern United States had total rates of change more than five times those in Great Sand Dunes and several other western PACEs.

Forecasting change in climate and biome location: 2010–2090

Climate change over the past century has altered or disrupted ecosystems in some geographic locations. In the western United States, increased temperature and drought stress have led to reduced snowpack and runoff, increasingly severe fire and pest outbreaks, and forest die-off (US Global Change Research Program, 2009). Spatial variation in ecosystem response to climate change is a result of variation in rates of climate change and in the key factors that limit plant growth. Across terrestrial biomes, plant growth is generally limited by low temperatures across northern latitudes, water shortage in middle latitudes, and radiant energy in the humid tropics (Running et al., 2004). Individual plant species exhibit specific tolerances to climate conditions. It is when climate change exceeds the tolerances of plant species that widespread plant mortality can occur (Allen et al., 2010). In many places around the earth that are water limited, increased drought has resulted in forest die-off (Anderegg et al., 2012). Future climate change and vegetation mortality are expected to lead to major shifts in the location of biome types. Such biome shifts are particularly worrisome with regard to protected areas because climate conditions within them may become unsuitable for ecosystems that define them such as the potential for the giant sequoia to no longer inhabit Sequoia National Park. In this section, we report on the projected change in temperature and biome type across US national parks.

Rehfeldt et al. (2012) used current climate and downscaled global climate model projections to develop climate niche models for biomes of North America and to project change in area and distribution under six climate change scenarios (Rehfeldt et al., 2012). Projected future temperature under a midrange emissions scenario indicated that individual PACEs will warm between 1.1 and 2.5°C by 2030, a magnitude slightly in excess of the average 1°C rise reported by Haas (2010) over the past century and a rate more than three times faster than has been experienced in the recent past (Figure 9.3). By 2090, mean annual temperatures are projected to be 3.4–6.0°C warmer than present. PACEs with the highest projected warming are in the upper midwestern United States and in the western mountains and deserts. Projected temperature increases in these locations are up to twice as great as in PACEs on the east and west coasts of the United States, where maritime effects are thought to moderate climate change.

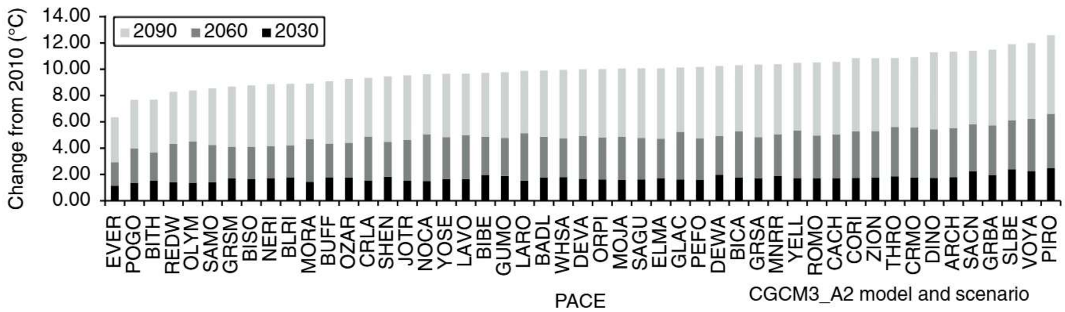

Figure 9.3 **Projected change in mean annual temperature within protected area centered ecosystems (PACEs) surrounding US national parks under the CGCM3_A2 model and scenario. Source: Data from Rehfeldt et al. (2012)**

In order to gauge the possible response of vegetation to projected climate change in these PACEs, Hansen et al. (2014) used Rehfeldt's (2012) maps of projected change in biome suitability to quantify the proportion of each PACE that is projected to undergo a shift. The results strikingly illustrate how the potential impact of climate change may vary among protected areas. Many PACEs in the midwestern and eastern United States are projected to undergo less change in biome type by 2090 than PACEs in the mountain west by 2030 (Figure 9.4). Note that the four PACEs in the upper midwest that have high rates of projected future warming undergo little projected change in biome type. Vegetations in these areas are more temperature limited than water limited and are not expected to undergo drought stress under future climates. It is drought stress that drives the projected strong biome shifts in many western mountain and desert PACEs such as Zion.

More generally, ecosystems with the higher sensitivity to climate change are expected to be those supporting species with narrow climate tolerances, locations near the edge of zones of climate suitability, and species and communities subject to higher disturbance rates (e.g., fire, pests). Ecosystems also differ in adaptive capacity. Those dominated by plants with shallow rooting, short life spans, and limited dispersal abilities are expected to be less able to adapt to changing climate conditions. Alternatively, forests that are long-lived, deeply rooted, and resilient to disturbance may be able to persist for lengthy periods of time at a site that has undergone substantial climate change even when future climate is no longer suitable.

Cumulative effects of past and projected future climate and land use

Land use change is expected to reduce the ability of ecosystems to adjust to changing climate. Land use is associated with increased invasion by exotics, for example, which may take over sites under changing climates. Land use also reduces

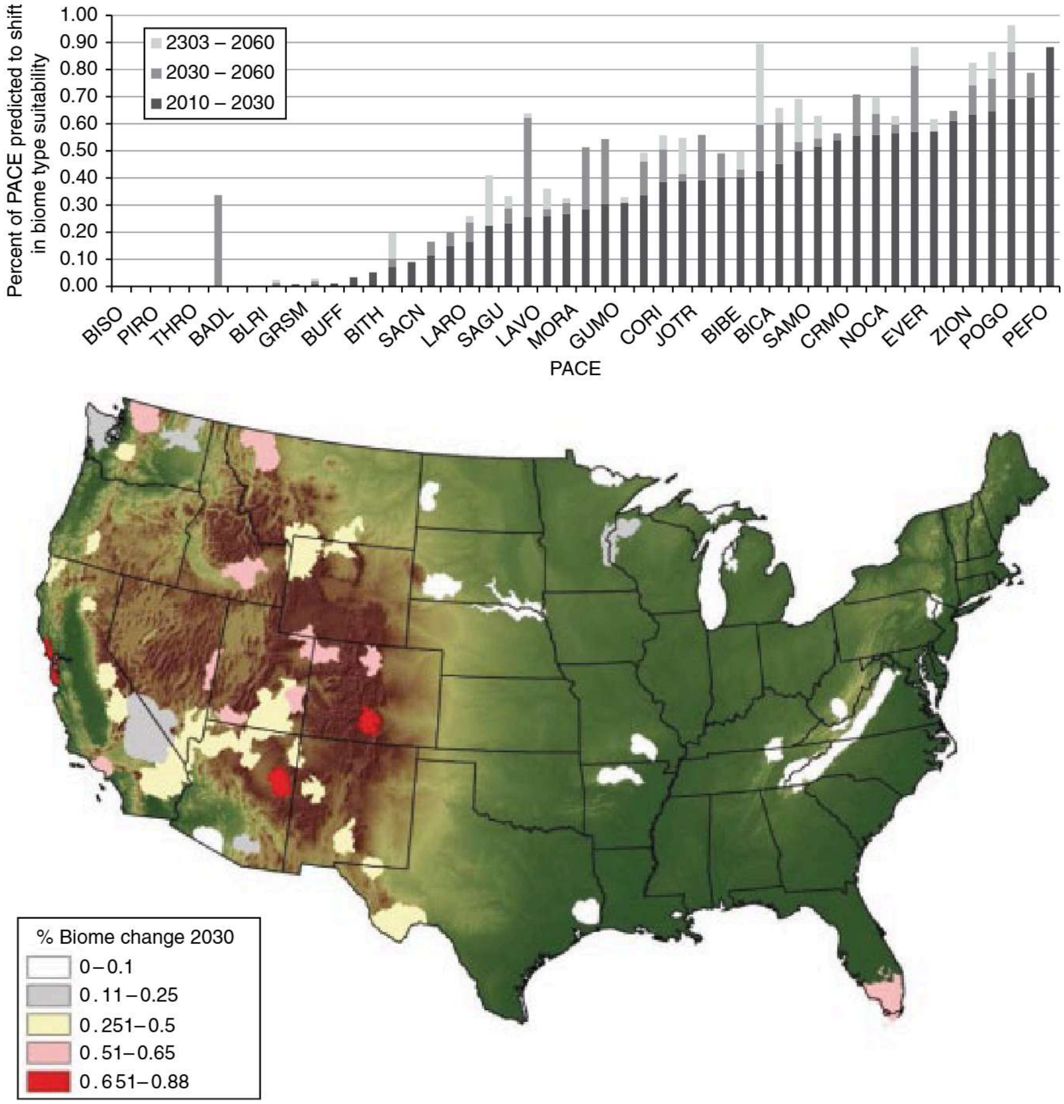

Figure 9.4 **Percent of each protected area centered ecosystems (PACEs) projected to shift in biome type suitability under the consensus of six climate models and scenarios (above) and color-coded level of biome suitability shift by 2030 mapped across the United States. Source: From Hansen et al. (2014)**

connectivity across the landscape and thus reduces the ability of native species to disperse to newly suitable habitats. Thus, the potential vulnerability of PACEs needs to be assessed by considering both past land use and potential impact of future climate. Hansen et al. (2014) positioned each PACE in the space defined by percentage of the PACE developed in 2010 and by the percentage of the PACE projected to undergo a biome shift by 2030 (Figure 9.5). This plot reveals that many PACEs are low in both land use intensity and potential climate impact, others are high in either land use intensity or potential climate impact, and a few PACEs are high in both land use intensity and potential climate impact.

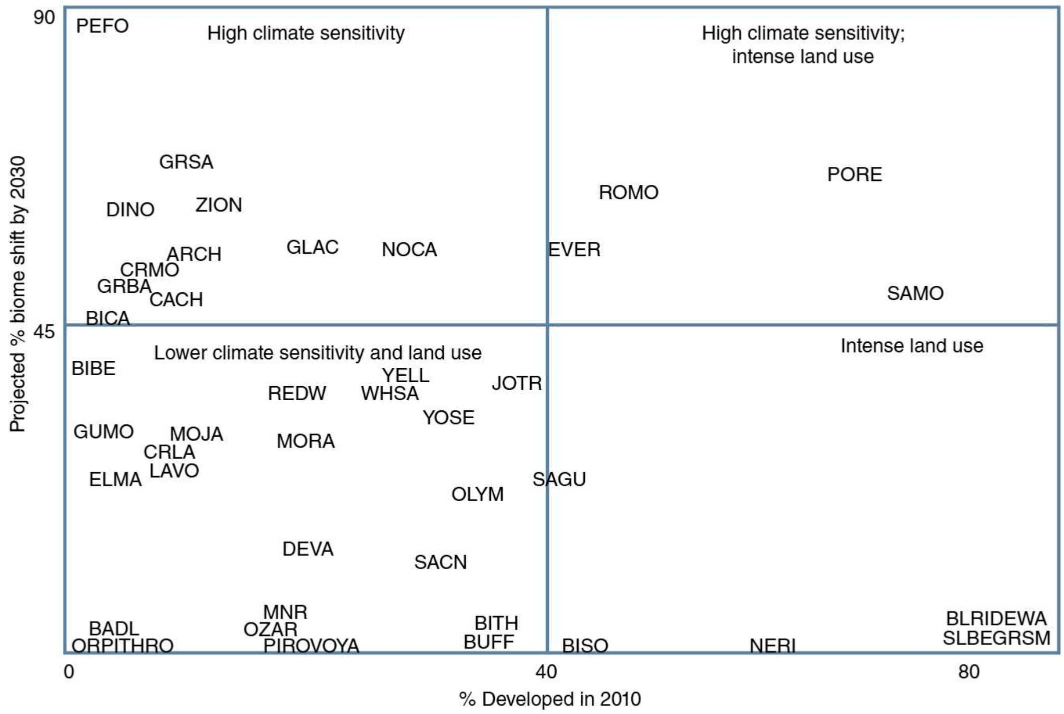

Figure 9.5 **PACEs positioned in the space defined by the percentage of the PACE developed in 2010 and by the percentage of the PACE projected to undergo a biome shift by 2030. Source: From Hansen et al. (2014)**

Implications for management

The third step in climate adaptation planning (Glick et al., 2011) is to evaluate management options. Knowledge of the components of vulnerability provides a basis for evaluating the need for management and the management approaches that might be most effective. Places that are low in exposure to climate and land use change, low in sensitivity, high in adaptive capacity, and thus low in vulnerability may be a relatively low priority for global change adaptation management (Hansen et al., 2014). Current ecological conditions are likely to persist in such places. Alternatively, those that are highly vulnerable may be difficult to save through management actions. Such ecosystems are likely to cross ecological thresholds and undergo changes of state in ecological function and biodiversity. Management of such ecosystem may be best aimed at encouraging adaptation to new conditions. Ecosystems of moderate vulnerability may be the highest priority for active management strategies to maintain current conditions.

What management philosophies can best help us achieve ecological objectives under climate and land use change? There is currently a vigorous debate between advocates for managing for "naturalness" versus advocates for managing for change to impending future conditions. Keane et al. (2009) represent the "naturalness" position. Termed the Historic Range of Variation approach or the Ecological Process

Management, the goal is to perpetuate natural pattern and ecological function in the face of change. The general management strategy for achieving this goal is to maintain landscape patterns and ecological processes within the range of variation in place prior to European influence. Under this philosophy, active management is generally dissuaded for fear of causing harm to the ecosystem or compromising our ability to learn from the effects of change in unmanaged ecosystems (i.e., parks as natural laboratories). Active management is used only where needed to restore lost ecological patterns or functions. Reintroducing an extirpated keystone predator would be an example of this management philosophy as was done with the reintroduction of the gray wolf into Yellowstone National Park (Boyce, 1998).

In contrast to the "naturalness" point of view, Hobbs et al. (2010) argue vigorously that many ecosystems have been or will be so altered by land use and climate change that current patterns and function will have little resemblance to historical conditions (Hobbs et al., 2010). Consequently, the goal of management should be to promote ecological integrity and resilience under future changing conditions. This "first principles" approach advocates designing future ecosystems based on guiding principles, including historical fidelity, autonomy of nature, ecological integrity and resilience, as well as managing with humility. Active management strategies such as translocating species to newly suitable habitats to encourage range shifts would be an example of implementing this approach.

Hansen et al. (2014) suggested that the vulnerability of protected areas to global change can be used as a guide to the management philosophy that is most appropriate for a given area. "Historic range of variation" or "natural process management" would seem appropriate for protected areas with low vulnerability to global change. Patterns and dynamics typical of pre-European settlement are expected to continue into the future in such systems. Management to keep the system within this historic range is feasible and desirable. An example may be Olympic National Park on the Pacific coast of the northwest United States. Past climate and land use change in this PACE have been low to moderate. Future climate change might be low relative to other PACEs due to the moderating influence of the Pacific Ocean. The tall and long-lived rain forest species that dominate this PACE are resilient to shifts in climate and disturbance. Managers in this region are more concerned about maintaining disturbance regimes and the full suite of several stages required for high biodiversity in this ecosystem than they are about the effects of climate change. Historic range of variation continues to be the guiding philosophy of management in this region.

The Santa Monica PACE near Los Angeles in southern California, in contrast, shows high vulnerability to global change and management for future conditions may be the only viable approach. This national park is surrounded by urban areas, with some 72% of the PACE being developed. Nearly a quarter of the vascular plants are nonnative. Temperature has warmed substantially in the past century and this trend is projected to continue in the coming century. More than 50% of the PACE is projected to undergo a biome shift by 2030. Clearly, management to retain pre-European disturbance (such as natural fire regimes) or ecological conditions in this ecosystem would be either futile or socially unacceptable. Instead, managers here must decide what ecological conditions and ecosystem services they wish to achieve under future global change and develop active management strategies to produce and maintain this condition and these services.

Most PACEs in the United States lie somewhere between these two extremes in vulnerability. For such PACEs, some combination of the two management philosophies may be most appropriate. Both Keane et al. (2009) and Hobbs et al. (2010) conclude that both looking at past conditions and considering future conditions can inform management.

Concluding remarks

Maintaining native biodiversity and ecological function in protected areas is an enormous challenge in a world increasingly dominated by humans. Our key conclusion is that protected areas potentially differ in each of the components of vulnerability to land use and climate change and that knowledge of these differences can be used to guide the development of locally appropriate adaptation strategies. A first step in quantifying vulnerability of protected areas is to delineate the surrounding lands that are strongly connected to the ecological functioning of the protected area and summarizing past and projected future land use and climate change in these PACEs. Within 48 PACEs focused on US national parks, we found that exposure to land use and climate change and sensitivity of vegetation and potential impact on biome types varied dramatically. Among these PACEs, some showed high components of vulnerability to land use or potential impacts on biome shifts due to climate change or both. While our analysis to date did not deal with all components of past and future vulnerability, it illustrates the utility of such approaches for designing adaptation strategies. PACEs with low vulnerability may best be managed with the well-developed strategies related to maintaining “naturalness.” PACEs with high vulnerability are candidates for strategies that focus on maintaining ecological function under the future conditions that the PACE is expected to face. This approach to assessing vulnerability should be applied to other networks of protected areas around the world to provide a basis for effective management and adaptation.

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