Delineating the Ecosystems Containing Protected Areas for Monitoring and Management

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Park managers realized more than 130 years ago that protected areas are often subsets of larger ecosystems and are vulnerable to change in the unprotected portions of the ecosystem. We illustrate the need to delineate protected area–centered ecosystems (PACEs) by using comprehensive scientific methods to map and analyze land-use change within PACEs around 13 US national park units. The resulting PACEs were on average 6.7 times larger than the parks in upper watersheds and 44.6 times larger than those in middle watersheds. The sizes of these PACEs clearly emphasized the long-term reliance of park biodiversity on surrounding landscapes. 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. Delineating PACEs more broadly will facilitate monitoring, condition assessment, and conservation of the large number of protected areas worldwide that are being degraded by human activities in the areas that surround them.

Keywords: protected area, ecosystem, land-use change, monitoring, management

The global portfolio of protected areas has been expanded dramatically in recent decades (Naughton-Treves et al. 2005). During this period, however, it has become increasingly evident that many established protected areas have undergone degradation (Gaston et al. 2008). Ecological processes such as disturbance regimes have been altered within protected areas, exotic species have expanded, and native species have gone extinct (Stohlgren 1998, Pringle 2001, Parks and Harcourt 2002). Recent assessments have found that most terrestrial reserves are adequately protected within their borders (Bruner et al. 2001). The predominant cause of degradation within protected areas is most likely growing human population density and land-use intensification on surrounding lands (Brashares et al. 2001, DeFries et al. 2005, Wittemyer et al. 2008). The current challenge is to maintain the ecological condition of protected areas, despite changes on the lands surrounding them (DeFries et al. 2007).

Scientists have long anticipated the potential for degradation of protected areas, having observed that protected areas are often subsets of larger ecosystems (Shelford 1933, Wright and Thompson 1935). Flows of energy, material, and organisms often occur over an expanse larger than the protected area, linking the protected area to the wider surrounding ecosystem (Hansen and DeFries 2007). Human activities on surrounding lands may either disrupt natural flows between the protected area and the surrounding ecosystem or create new, harmful flows, such as those of nonnative species. These alterations to flows may disrupt ecological function and the viability of native species within protected areas.

The need to identify the larger ecosystems around protected areas was realized just a decade after creation of the world's first national park, when the US Congress in 1882 considered legislation to expand Yellowstone's boundaries to accommodate migratory ungulates (Haines 1977). Subsequently, movements of wildebeest were used to delineate the Serengeti National Park (Pearsall 1957) and home ranges of grizzly bears were used to define the Greater Yellowstone Ecosystem (Craighead 1979). The boundaries of the Greater Everglades Ecosystem were based on hydrological processes (Davis and Ogden 1994). In the 1970s, the Man and the Biosphere Programme advocated the creation of buffer zones around protected areas to reduce negative outside influences (UNESCO 1974). More recently, researchers offered guidelines for mapping and managing the ecosystems around protected areas (Theberge 1989, Grumbine 1994, DeFries et al. 2010a, 2010b). The US National Park Service (NPS) advocated establishing buffer zones around parks for much of its history (Shafer 1999). However, this position became politically untenable in the 1980s, when private land rights emerged as a national issue.

Interest in connections between national parks and surrounding lands has increased in recent decades as a result of several factors. Changing patterns of fire, insect outbreaks, flooding, and wildlife disease have led many resource professionals to embrace management at larger spatial scales that

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involve multiple ownerships (Johnson et al. 1999). People living near national parks have increasingly recognized the socioeconomic benefits the parks provide and support incentive-based conservation on private lands to keep parks healthy (Theobald et al. 2005, DeFries 2010a). The NPS initiated the Inventory and Monitoring (I&M) program (Fancy et al. 2009) to assess conditions and trends in and around parks. Currently, many stakeholders would like a better understanding of the spatial domain of connections between parks and surrounding lands to help prioritize the locations of monitoring, research, and management efforts.

In addition to greater awareness of connections between national parks and surrounding lands, managers of national parks and protected areas are increasingly concerned about the potential for the dual impacts of climate and land-use change to affect ecological processes within parks and to degrade the ecologically significant areas surrounding parks. This presents a practical need for resource managers to design monitoring programs that include parameters able to capture changes in areas surrounding parks and protected areas. Beyond park boundaries, however, designating an appropriate region for monitoring is a difficult challenge, and no detailed, published methodology is available to assist park managers in defining geographic boundaries. At an operational level, the simple problem of selecting the area over which to calculate summary metrics can stymie the development of monitoring programs that would provide park managers useful information about ecologically significant changes occurring beyond park boundaries.

The goal of this study is to build on previous efforts and illustrate a comprehensive scientific methodology for delineating the boundaries of the ecosystems encompassing individual protected areas. In particular, we sought to identify the zone around each protected area wherein human activities may influence important ecological processes as well as the viability of populations of native organisms within the protected area. This larger zone becomes the logical focus of monitoring, research, and collaborative management needed to maintain protected area function and condition. We refer to these zones as protected area–centered ecosystems, or PACEs (see box 1). In this article, we present a conceptual framework for delineating PACEs, and then apply the framework to map PACEs around 13 US national parks, national recreation areas, or scenic rivers (hereafter termed park units). We then quantify land allocation and use in the PACEs to characterize the challenge of maintaining their ecological condition. Finally, we discuss the challenges and potential for integrating the PACE approach into protected area management more broadly in the United States and globally.

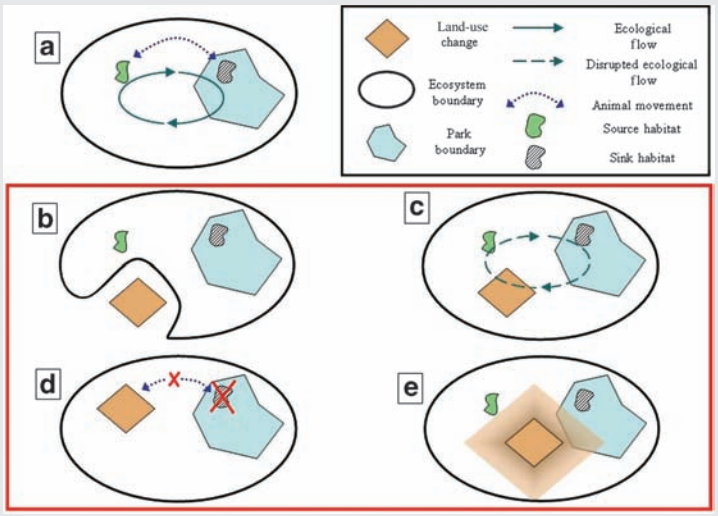
A framework for mapping PACEs

We aimed to develop a scientifically sound and repeatable method to map PACEs using objective ecological criteria and commonly available data sets. In order to make the results as relevant as possible to local resource managers, we incorporated local knowledge into the process. Our resulting framework (figure 1) derives polygons around protected areas using individual ecological criteria and then merges these layers to delineate PACE boundaries. We used widely available regional and national data sets for most criteria; these were supplemented with local data where available (e.g., for local fire regimes). Each individual layer was reviewed by local experts and the mapping products were refined to best reflect local conditions. Various methods can be used to join the individual layers to form the PACE, depending on local conditions and preferences. These include taking the union of the individual polygons, weighing the importance of locations within the union according to the number of criteria represented, and deriving the boundaries for the individual criterion using assumptions that bracket uncertainty in key parameters and then representing this uncertainty with "fuzzy" PACE boundaries. We chose the second approach to help managers prioritize the importance of locations within the PACE on the basis of the number of overlapping criteria.

We derived the ecological criteria used as the basis for the PACE mapping from the mechanisms described by Hansen and DeFries (2007). These mechanisms are thought to be the primary means by which land use in surrounding areas influences ecological processes and the viability of native species within protected areas. The mechanisms involve ecological flows, crucial habitats, effective size, and human edge effects in and around the protected areas (see box 1). The methods for mapping PACEs using these mechanisms are described below. Details of the methods can be found in the online supplementary appendix (*dx.doi.org/10.1525/bio.2011.61.5.5*); ArcGIS commands for executing the mapping are published in Piekielek and colleagues (2010).

Ecological flows include those that are waterborne or airborne and movements of disturbances such as fire. Water, sediment, nutrients, and organisms move with water flows through watersheds. Land use in upper watersheds may therefore alter flows into protected areas. Similarly, land use upwind of airsheds may change climate or pollution levels in downwind protected areas. Disturbances (e.g., fire) may originate outside of and move through a protected area. The condition of the disturbance initiation zone influences the likelihood of the disturbance moving into the protected area. Runout zones, defined as the places where disturbances terminate (such as debris flow deposition areas), may provide unique habitats for some species (Baker 1992). We mapped watersheds connected to protected areas using the hydrological units delineated in the Watershed Boundary Dataset developed by the US Natural Resource Conservation Service (*www.ncgc.nrcs.usda.gov/products/datasets/watershed*). Airsheds lack readily available national maps (unlike watersheds). Although regional data sets would allow airshed delineation for some national parks, such data were not available for the parks included in this study and the airshed criterion was not included in the mapping. For the disturbance criterion, we used historical data sets to

Box 1. The concept of protected area–centered ecosystems.



Many protected areas were designated using factors other than ecological completeness, such as scenic value. Thus, they may not include the area that is needed to maintain organism populations and essential ecological processes. In panel (a) of the figure, the protected area is strongly connected to a larger surrounding area by the flows of energy, materials, and organisms. Land-use change in the unprotected part of the ecosystem may disrupt ecological function and biodiversity within the protected area through any of four primary mechanisms.

- Effective size: Human activities 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, cause 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 (b in the figure).
- Ecological flows: Land use 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 (c in the figure).
- Crucial habitats: Land use may eliminate or isolate crucial habitats, such as seasonal habitats, migration habitats, or habitats that support source populations (d in the figure).
- Edge effects: Land use 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 (e in the figure).

In this article, we use these four mechanisms as a basis for objectively mapping the spatial extent of the ecosystems containing national parks. Mapping these protected area–centered ecosystems provides guidance to resource managers on where to concentrate monitoring, research, and collaborative management to maintain the health of the protected area.

Source: Adapted from Hansen and DeFries 2007.

map the boundaries of potential disturbance initiation and runout zones for protected areas that experience contagious disturbances (e.g., fire, flooding, insect infestations).

Seasonal habitats, population source areas, movement paths, or portions of large home ranges for populations within protected areas may lie outside the protected areas. Land use may alter or destroy these crucial habitats. The PACE should be of sufficient size to maintain self-sustaining populations of species with habitat requirements not met within the protected area. Typically, species-specific quantitative data are available only locally or for a limited number of species. For the crucial habitat criterion, we drew on such data, as well as local expert opinion, to identify and map crucial habitats outside protected areas that populations within protected areas require during important seasonal or life-history stages.

The habitat requirements and movements of many organisms are not known to a degree that would allow the quantification of their crucial habitats surrounding a protected area. We used a coarse-filter approach (Noss and Cooperrider 1994) to deal with these lesser-known species on the basis of species-area relationships. The number of species within a protected area is influenced by the size of the area and by its connectivity to adjacent habitats. An isolated protected area is expected to have fewer species than one embedded in a larger area of contiguous habitat (Cowlishaw 1999). For the effective size criterion, we determined the area of contiguous habitats surrounding a protected area needed to prevent the isolation-induced loss of species within the protected area, using the methods of Brooks and colleagues (1999).

Human presence on the periphery of protected areas may cause changes in ecosystem processes and biodiversity that extend varying distances into the protected area (e.g., through hunting, poaching, outdoor recreation, pet effects on wildlife, exotic species). The extent to which human activities outside protected areas may penetrate adjacent protected areas varies with activity and social and biophysical setting. For the edge effects criterion, we used a buffer of 25 kilometers (km) around the protected area, which was selected to exceed edge penetration distances known from the literature. Within this area, all private, nonprotected land was selected. Additionally, we included a 5-km buffer around private lands that lay outside the 25-km buffer but were adjacent to polygons selected by the crucial habitat criteria above. Edge effects from land-use intensification in this 5-km buffer could degrade crucial habitats and ecological processes that are more distant from the protected area; thus, they are also included in the PACE boundaries.

Applying the framework. We applied the methods to 13 US park units administered by the NPS (table 1). We selected only parks in the contiguous United States to increase the consistency of

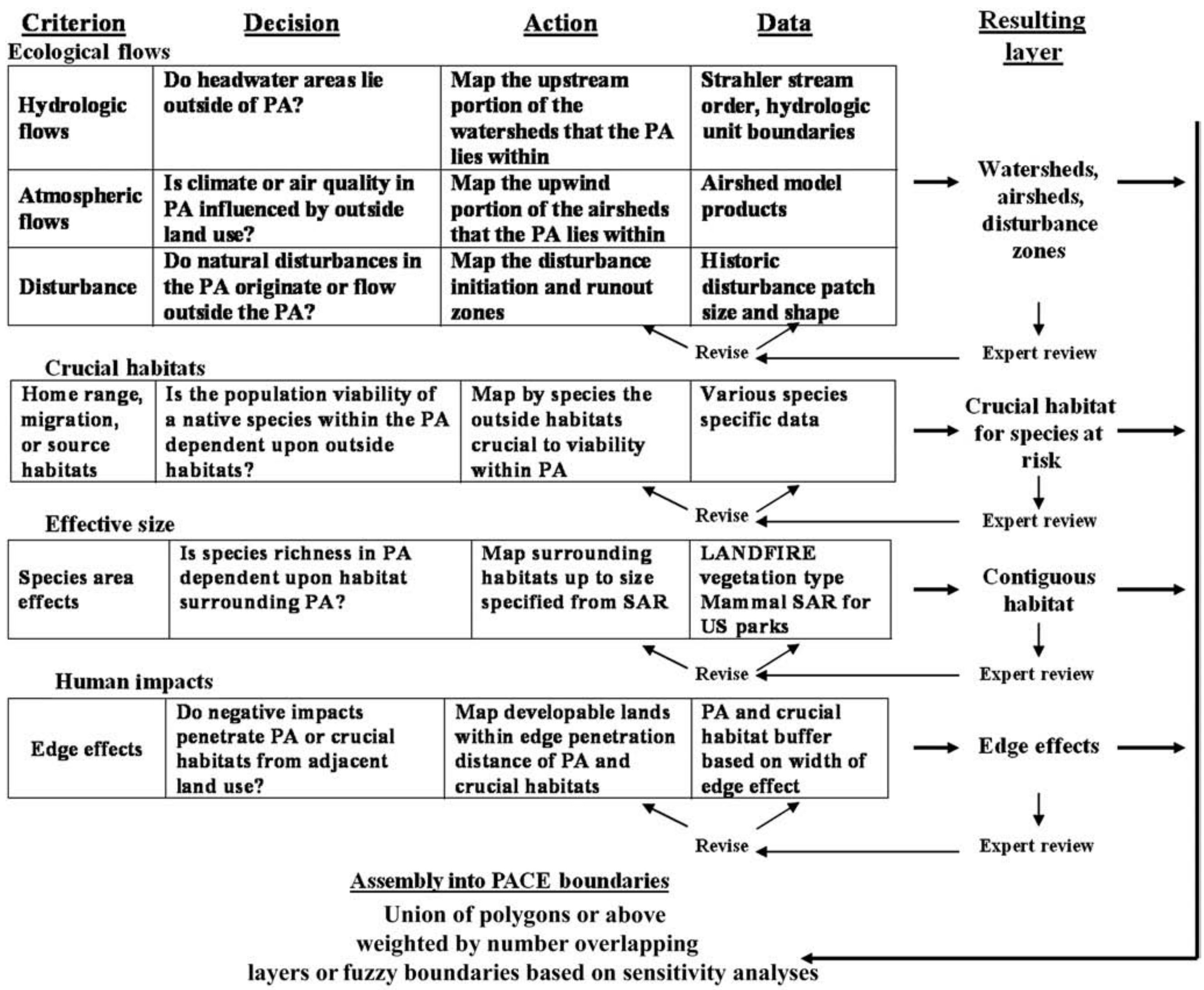


Figure 1. Framework for delineating protected area–centered ecosystems (PACEs) using data available for the United States. Abbreviations: LANDFIRE, Landscape Fire and Resource Management Planning Tools Project; PA, protected area; SAR, stock assessment review.

the biophysical data sets. Our goal was to include a representative subset of NPS units to demonstrate proof of concept and lay the foundation for application of the approach to additional NPS units and other protected areas. Criteria for selection were wide geographic, ecoregional, and physiognomic distribution; diverse land allocation types in surrounding areas; variation in park size and shape; and concentration within relatively few NPS I&M networks (to facilitate coordination with NPS personnel). The watershed, contiguous habitat, and human edge effect criteria were applied to all of the park units. The disturbance criterion was applied to North Cascades National Park Complex, Yosemite and Sequoia and Kings Canyon National Parks, and Yellowstone and Grand Teton National Parks, where fire is an important disturbance and the required data were available. The species for which we considered crucial habitats varied by park unit and were largely identified during the expert review phase. An initial PACE map was made using national data sets for the watershed, contiguous habitat, and human edge effect criteria. Consultations with local NPS I&M staff and park scientists were used to evaluate the airshed, disturbance, and crucial habitat criteria. The final maps were developed through two cycles of sending initial maps and descriptions of methods to local NPS scientists and then making modifications on the basis of their comments and the spatial data sets they provided.

The resulting PACE boundaries are depicted in figure 2 and their spatial characteristics are presented in table 2. The sizes and shapes of the mapped PACEs varied among the study units. The PACEs of parks in close proximity to one another merged into single ecosystems; this was the case for Yosemite and Sequoia and Kings Canyon National Parks; Yellowstone and Grand Teton National Parks and Bighorn Canyon National Recreation Area; and Delaware Water Gap National Recreation Area and Upper Delaware Scenic

Table 1. US National Park Service units included in this study, their locations, and the protected area–centered ecosystem mapping criteria that were uniquely applied to the units. The watershed, contiguous habitat, and human edge effect criteria were applied to all of the park units.

		Unique mapping criteria	
Park units	**Description**	**Disturbance**	**Crucial habitats**
North Cascades National Park Complex	Northwest Washington	Historic fire records	Salmon
Olympic National Park	Western Washington	Not applied	Salmon, spotted owl, marbled murrelet
Mount Rainier National Park	Southwest Washington	Not applied	Salmon, mountain goat, cascade fox, wolverine, white-tailed ptarmigan
Yosemite and Sequoia and Kings Canyon National Parks	Central California	Historic fire records	Great gray owl, Yosemite toad
Yellowstone and Grand Teton National Parks	Northwest Wyoming, Montana	Historic fire records	Elk and pronghorn antelope winter range and migration routes, bird source areas
Big Horn Canyon National Recreation Area	North-central Wyoming, south-central Montana	Not applied	Not applied
Rocky Mountain National Park	North-central Colorado	Not applied	Ungulate winter range, raptor foraging
Big South Fork National River and Recreation Area	South-central Kentucky, north-central Tennessee	Not applied	Endangered fish species
Great Smoky Mountains National Park	Eastern Tennessee, western North Carolina	Not applied	Not applied
Delaware Water Gap National Recreation Area and Upper Delaware Scenic and Recreational River	Eastern Pennsylvania, northwestern New Jersey	Not applied	Shad, amphibians, endangered bivalves

Table 2. Spatial characteristics (in square kilometers) of protected area–centered ecosystems (PACEs) and polygons derived for each criterion.

				Area of PACE criterion outside park (percentage unique)					
Park units	**Park area**	**PACE outside park**	**PACE to park ratio**	**Contiguous habitat**	**Watershed**	**Distur-bance**	**Crucial habitats**	**Human edge effects**	**Percent with two or more criteria**
North Cascades National Park Complex	2756	13,395	4.9	12,076 (43)	4233 (1)	800 (0)	1749 (4)	579 (0)	51
Olympic National Park	3700	12,385	3.3	12,221 (33)	4408 (0)	n/a	2199 (0)	4218 (1)	67
Mount Rainier National Park	952	8062	8.5	3736 (10)	1644 (1)	n/a	4138 (25)	2585 (9)	48
Yosemite and Sequoia and Kings Canyon National Parks	6530	32,360	5.0	142,886 (0)	4292 (0)	31,441 (27)	7262 (3)	36,570 (0)	57
Yellowstone and Grand Teton National Parks	10,159	32,362	3.2	24,876 (0)	12,881 (1)	32,158 (12)	13,758 (1)	4730 (3)	78
Big Horn Canyon National Recreation Area	484	31,370	64.8	6906 (4)	29,161 (73)	n/a	n/a	4074 (1)	20
Rocky Mountain National Park	1080	9450	8.8	6768 (43)	1690 (0)	n/a	1398 (0)	1986 (10)	35
Big South Fork National River and Recreation Area	471	7505	15.9	5515 (18)	2782 (3)	n/a	399 (4)	4627 (11)	61
Great Smoky Mountains National Park	2098	13,627	6.5	10,600 (40)	3558 (0)	n/a	n/a	6464 (13)	46
Delaware Water Gap National Recreation Area and Upper Delaware Scenic and Recreational River	432	14,046	32.5	7597 (2)	10,826 (22)	n/a	725 (0)	9282 (10)	63
Mean	2866	17,456	15.3	23,318	7547	21,466	3953	7511	52

n/a, not applicable

and Recreational River. For park units situated in the upper portions of watersheds, the portion of the PACEs outside of the park units were on average 6.7 times larger than the park units themselves. These PACEs were centered on the park units and their shapes tended to resemble those of the park units. For park units situated in the middle portions of watersheds (Big Horn Canyon National Recreation Area, Delaware Water Gap National Recreation Area, and Upper

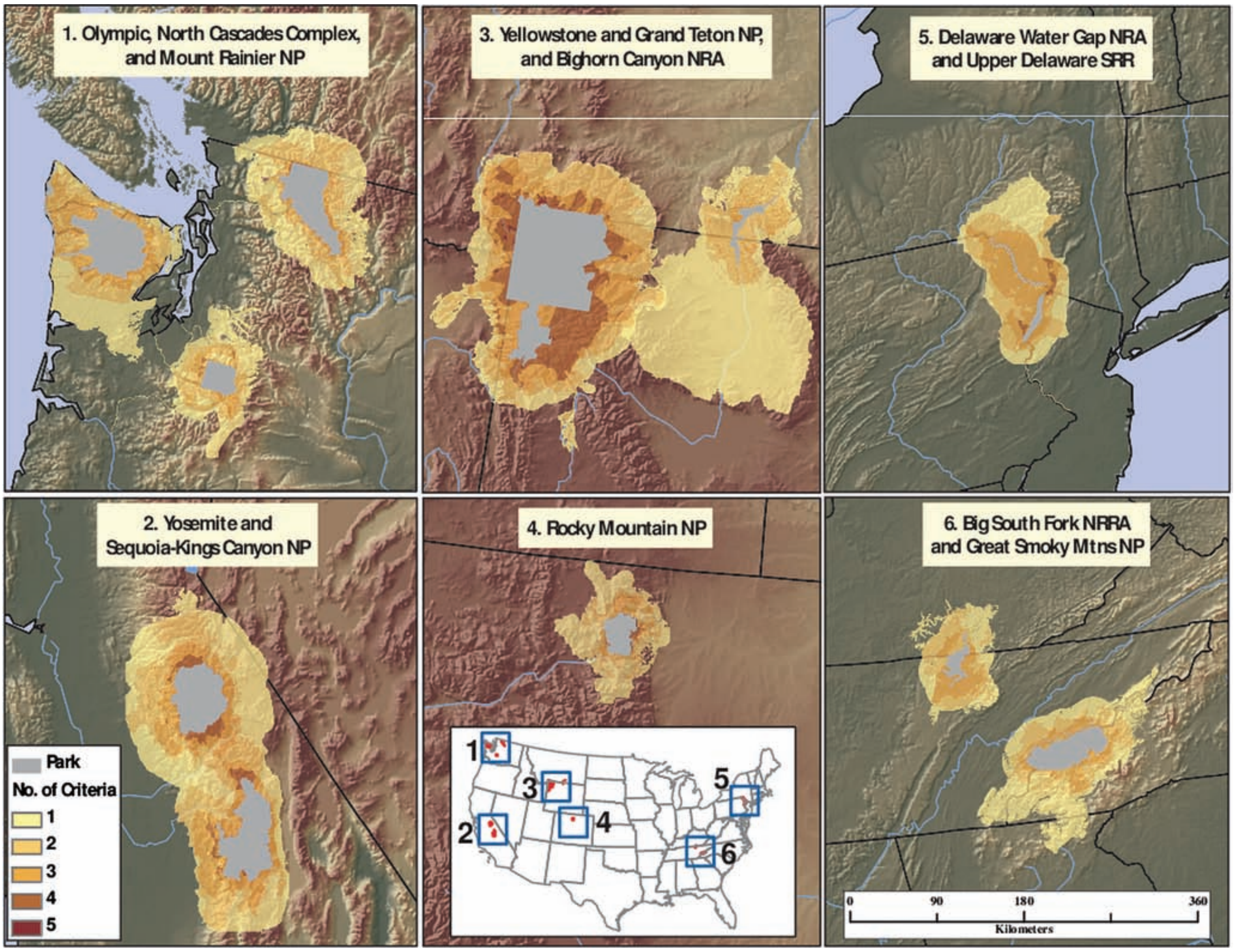


Figure 2. Maps of protected area–centered ecosystems delineated in this study for 13 US national park units. Gradations in color in the PACEs outside of the parks indicate the number of overlapping classification criteria. Places with many overlapping criterion may be considered more important for monitoring and management. Abbreviations: NP, National Park; NRA, National Recreation Area; NRRA, National River and Resource Area; SRR, Scenic and Recreational River.

Delaware Scenic and Recreational River) PACE size was 44.6 times larger than the area of the park unit. Their shapes reflected the nature of the upper and lower portions of the watersheds in which they lay.

Park managers were interested in the extent to which the final PACE boundaries were determined by a single criterion rather than two or more criteria. Therefore, in figure 2, gradations in color are used to indicate the number of overlapping classification criteria in the PACE. Places with many overlapping criteria may be considered more important for monitoring and management. Yellowstone and Grand Teton National Parks, Olympic National Park, and Delaware Water Gap National Recreation Area and Upper Delaware Scenic and Recreational River showed relatively high levels of overlap in criteria (67% to 78% had two or more criteria). In contrast, the watershed criteria uniquely covered 73% of the Big Horn Canyon National Recreation Area PACE and the contiguous habitat criterion uniquely covered 65% of the Rocky Mountain National Park PACE. Thus, managers of Big Horn Canyon National Recreation Area and Rocky Mountain National Park may wish to carefully scrutinize the use of these criteria in delineating final PACE boundaries.

Evaluation of land allocation and use within PACEs. We evaluated the characteristics of PACEs that may influence the challenge of maintaining ecological conditions within national parks. These characteristics included (a) ownership, the proportion of PACE area in public versus private ownership; (b) proportion developed, the percentage of the private lands in agriculture, near roads, or with home densities that exceeded a minimum threshold; (c) home density, the total number of homes in 2000 the (most recent Census); and (d) change in home density, the percentage change in home density from 1940 to 2000.

Ownership classes were primarily derived from the Protected Area Database, version 4.6 (IUCN 2003), with some additional data sets providing more recent data on protected lands. Percentages of private lands that were developed in 2000 were defined as the sum of areas of roads (USCB 2009), croplands (USGS 2005), and areas with home densities greater than 0.031 units per hectare, all divided by the total area of private land. Areas with home densities below this threshold were assumed to be little influenced by land use (Theobald 2005). The home density data were from Theobald (2005) and Bierwagen and colleagues (2010), who downscaled home density estimates from US Census blocks to a 1-hectare resolution on the basis of groundwater well density, accessibility to urban areas along roads, land-cover characteristics, and other factors for the period between 1940 and 2000. Roads layers were used to identify developed areas by including buffers of 5 to 15 meters, based on their level of use and following the work of Forman (2000).

The PACEs lay along gradients in ownership and land use. Big Horn Canyon National Recreation Area was unique in having relatively little private land and being very low in percentage of private land developed, home density, and home density growth rate since 1940 (figure 3). At the other extreme, the three easternmost PACEs had greater proportions of private land, and more of this land was developed. Delaware Water Gap National Recreation Area and Upper Delaware Scenic and Recreational River and Great Smoky Mountains National Park were also high in home density, and Great Smoky Mountains National Park and Big South Fork National River and Recreation Area had high growth rates of homes. The remaining PACEs were intermediate with regards to these axes. Thus, the evaluation of the PACEs revealed that the parks differ substantially in the land use of their surroundings. Big Horn Canyon National Recreation Area, and to a slightly lesser extent Yellowstone and Grand Teton National Parks and North Cascades National Park Complex, were unique in being embedded in large, semiwild landscapes of mostly public lands, with relatively little development on adjacent private lands. At the other extreme were Great Smoky Mountains National Park, Delaware Water Gap National Recreation Area and Upper Delaware Scenic and Recreational River, and Big South Fork National River and Recreation Area, which were surrounded mostly by private land, much of which is in exurban, suburban, and urban land uses. It is noteworthy that growth in home density since 1940 was higher in areas surrounding Great Smoky Mountains National Park and Big South Fork National River and Recreation Area than other parks, suggesting that these park units have been losing natural habitat in their PACEs faster than other park units. These findings suggest that maintaining ecological condition will be least challenging in Big Horn Canyon National Recreation Area, Yellowstone and Grand Teton National Parks, and North Cascades National Park Complex; of intermediate difficulty in Yosemite and Sequoia and Kings Canyon National Parks, Rocky Mountain National Park, Mount Rainier National Park, and Olympic National

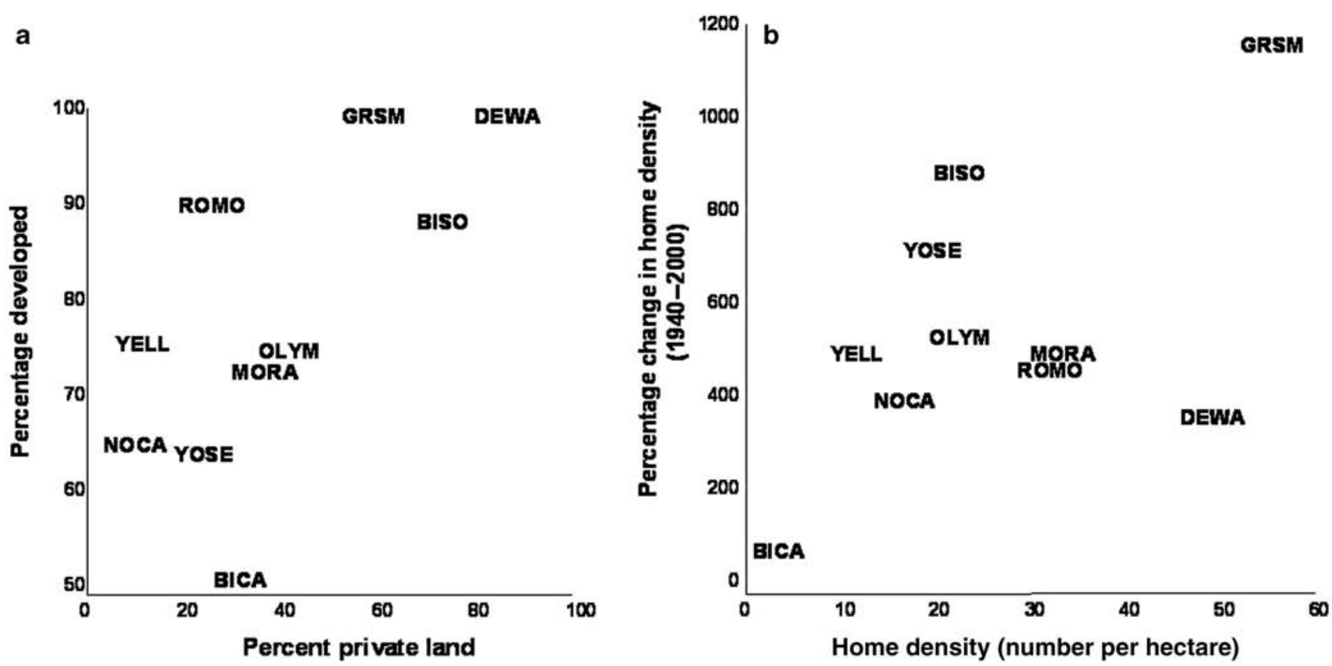


Figure 3. (a) Location of the protected area–centered ecosystems along gradients in land ownership and land development (home densities of > 0.031 units per hectare [ha], roads, or agriculture lands) and (b) home density (units per ha) and percent change in home density from 1940 to 2000. Abbreviations: BICA, Big Horn Canyon National Recreation Area; BISO, Big South Fork National River and Recreation Area; DEWA, Delaware Water Gap National Recreation Area; GRSM, Great Smoky Mountains National Park; MORA, Mount Rainier National Park; NOCA, North Cascades National Park Complex; OLYM, Olympic National Park; ROMO, Rocky Mountain National Park; YELL, Yellowstone National Park; YOSE, Yosemite National Park.

Park; and most challenging in Big South Fork National River and Recreation Area, Delaware Water Gap National Recreation Area and Upper Delaware Scenic and Recreational River, and Great Smoky Mountains National Park.

Coping with the challenges of defining PACEs

We believe this mapping is the first attempt to develop and apply an objective framework for delineating ecosystems surrounding NPS units. Although the concept of PACEs has been long recognized, several theoretical and logistical issues make their delineation challenging. First, the spatial domains of ecological processes and organisms often do not have discrete boundaries (Theberge 1989). Rather, strength of interaction decreases as a function of distance and other factors. Objective rules for specifying the strength of interaction necessary for inclusion in the PACE are difficult to derive. Second, ecosystem components often differ in their spatial domains (e.g., hydrologic flows may not correspond with movements of migratory species). Thus, separate boundaries could be defined for each ecosystem component of interest. Third, the spatial domains of some ecosystem processes may be orders of magnitude larger than others. Air pollution, climate, and long-distance migrations of organisms are examples of factors that may be expressed at continental or global scales. Lastly, knowledge is often lacking about the spatial domains of key ecological components in particular protected areas.

Our PACE framework builds on earlier studies (Craighead 1979, Theberge 1989, Davis and Ogden 1994, DeFries et al. 2010a, 2010b) to overcome both theoretical and logistical challenges. We derived the mapping criteria from sound ecological theory (Hansen and DeFries 2007). We defined thresholds in strength of interaction using objective criteria where possible (e.g., watershed boundaries), and using local knowledge where key data were lacking (e.g., crucial habitats). We suggest that sensitivity analyses be used to map “fuzzy” boundaries for individual criteria when there is uncertainty the level of strength of the interaction. We emphasized regional rather than continental-scale interactions in deriving PACE boundaries because protected area managers often operate at regional scales. Our framework recognizes that different methods may be used to join the maps of individual criteria to define the PACE. A simple union of the individual maps provides a tangible boundary, which may help communicate the PACE concept to nonscientists. An alternative is to weight the PACE map according to the number of criteria that overlap. Areas with high weight (many overlapping criteria) may be considered more important for monitoring and management. Finally, our framework also recognizes that knowledge and quantitative data will often be lacking for some criteria. Therefore, we integrate expert review and local knowledge into the process in order to take advantage of the best available current knowledge. We recommend that the process be repeated periodically to adjust for changing conditions and improved knowledge at intervals relevant to the particular protected area. The location and areas of the PACE can indicate landscape change and aid in establishing fundamental linkages between the patterns of land-use change and ecological processes.

Implications for conservation and management

The primary contribution of this work is the use of the long-recognized concept of protected areas as parts of larger ecosystems as a basis for mapping, analyzing, and managing these larger areas. We have attempted to develop a credible, repeatable, science-based framework for delineating PACEs. The application of our methods to a collection of US national parks demonstrated how ecological theory, widely available data sets, GIS (global information systems) software, and local expertise can be integrated to map the boundaries of such ecosystems. Rather than be considered as final PACE boundaries, we offer the results of this mapping effort as examples that can be refined by the NPS or other entities. The application also provides guidance on ways to modify and improve the framework as our knowledge and data improve.

The value of identifying PACEs

Identifying PACEs may assist in management of protected areas in several ways.

Understanding connections. PACEs should help managers, scientists, and local citizens better understand the connections between protected areas and surrounding lands. Such connections can be difficult to perceive, especially in the absence of remotely sensed data, animal movement data, and other evidence of such connections. Recognition of these connections is requisite to further action to maintain ecological condition of the protected area in the face of change in the surrounding ecosystem.

Monitoring. Delineating PACEs helps identify locations critical for monitoring. Monitoring of biophysical factors, organisms, and human land use, demographics, and socioeconomics provides a context for understanding changes in PACEs and can provide early warning of impending threats to the protected area (Jones et al. 2009). The NPS I&M program has developed, and is implementing, such monitoring (Fancy et al. 2009). A key question faced by NPS I&M scientists is how large an area around parks should be included in the monitoring program. The PACE is a logical choice for this, as it represents the area where there are strong connections between the protected area and surrounding landscape.

Reporting summary indicators. For monitoring, the PACE can be used as the spatial unit for reporting summary indicators such as rates of habitat loss, land-use intensification, disturbance events, the total area affected by invasive species, and other factors, as recommended by the NPS I&M (Fancy et al. 2009) and the H. John Heinz III Center (2003). These summary indicators can be compared between protected areas and the surrounding PACEs, and among protected areas across the country. The outcome of such comparisons can be used to identify which places within a PACE, or which PACEs in a network, are undergoing the most rapid negative change and are thus the highest priorities for research and management.

Stimulating research. Delineating the PACE should stimulate research on cross-boundary interactions. Potential gaps in knowledge that arise during delineation may become high-priority topics for research by protected area staff, improving the understanding of interactions between the protected area and the surrounding PACE.

Focusing conservation actions. Perhaps most importantly, identifying the PACE should help focus conservation actions aimed at maintaining ecological conditions within protected areas. In cases where protected areas were established in the centers of large wildernesses, the PACE approach gives guidance on how to manage future human activities in the surrounding environs to maintain the protected area. Typically, PACEs include considerable private lands or more intense human land uses. In these cases, keeping protected areas functioning will probably require both management within the protected area boundary to buffer outside influences and management of surrounding lands to minimize negative influences. Examples of potential management strategies in PACEs include conservation easements on important private lands, land-use planning to better optimize ecological and socioeconomic goals, and education programs for local landowners to help them minimize negative effects on ecosystems (Theobald et al. 2005).

Identifying other areas for protection. Finally, the PACE framework could be used in the establishment of new protected areas to help ensure that their boundaries include essential components of the ecosystem.

The future of the PACE framework

Although the PACE framework is based on the effect of land use on protected areas, it is widely recognized that climate change is substantially influencing many protected areas (NPCA 2009). A next step for the PACE framework could be to develop objective criteria to identify areas around protected areas that are vital to the adaptation of protected area organisms to a changing climate or are needed to allow movement among protected areas to adjust to changing conditions. If not already included in the PACE, these areas could then be incorporated and monitored. Such approaches may be especially relevant to the emerging US Department of the Interior (DOI) Landscape Conservation Cooperatives (LCCs) (USFWS 2009).

An important practical consideration with regard to the PACE approach is the potential influence on local residents and stakeholders. Delineation of PACEs may generate considerable concern or interest among local residents and other stakeholders. Around some US national parks, the history of lands taken by the federal government, as well as other factors, have created considerable concern over retaining private property rights. Shafer (1999) chronicled how more than a century's effort by the NPS and others to expand US national parks and create buffers around them was largely halted in the 1980s by private land rights issues. Since that time, the NPS has put considerable effort into strengthening trust with parks' neighbors. Our NPS collaborators have emphasized that delineation of PACE boundaries should be done in consultation with local stakeholders in order to maintain that trust.

In the United States since the 1980s, regulatory approaches have largely been replaced by incentive-based approaches to achieve conservation objectives. Many citizens increasingly recognize substantial benefits from living near healthy ecosystems (Power 2008). Ecosystem goods and services involving food, water, nature-based livelihoods, and aesthetics are thought to partially explain why a disproportionate number of people live near protected areas globally (Rasker and Hansen 1990, DeFries et al. 2007, Wittemyer et al. 2008) and why development is disproportionately high near US protected areas (Radeloff et al. 2010, Wade and Theobald 2010). Residents who value the ecological goods and services from protected areas may have high incentives to support collaborative management strategies in the PACE to maintain ecological conditions within the protected area. Evidence of this is the vast acreage of private land that has been protected under conservation easements through the efforts of citizen-supported nongovernmental organizations, public open-space initiatives, and conservation land buyers (Theobald et al. 2005). The identification, monitoring, and evaluation of PACEs can be used to guide incentive-based conservation efforts to the lands most important for maintaining protected area condition.

While we have defined PACEs on the basis of potential land-use effects on the ecological condition of protected areas, DeFries and colleagues (2010a, 2010b) also mapped the zone of influence of protected areas on surrounding human communities. Such an approach recognizes protected areas and the surrounding human communities as a "coupled natural human system" (Liu et al. 2007) with strong interactions and feedbacks among the human and ecological components of the system. This latter approach is more difficult to map objectively and communicate to stakeholders. However, it may ultimately be better to allow local people to understand the socioeconomic benefits of protected area conservation.

We hope that this work stimulates application of the PACE approach, both within the United States and internationally. The NPS is well equipped to apply the framework. Reception of the PACE conceptual approach and results by NPS personnel have been very positive. The Sierra Nevada NPS I&M network, for example, is using the PACE approach to define an ecologically meaningful regional context for a natural resource condition assessment underway at Sequoia and Kings Canyon National

Park. Similarly, Badlands National Park is organizing its climate change assessment within PACE boundaries. NPScape, the NPS I&M landscape dynamics monitoring project, is interested in using PACEs for reporting at a landscape scale the natural systems, anthropogenic drivers, and conservation context of all 270 park units with significant natural resources. In a related project, we have defined PACEs surrounding a total of 60 US park units and quantified land use and climate change in them as a basis for assessing vulnerability to future change. We encourage the NPS to evaluate this approach and where appropriate to use it for all ecologically significant park units. Applications to other US federal lands could be facilitated through the emerging DOI LCCs, established by DOI Secretarial Order 3289. Currently, the Great Northern LCC is considering using the PACE approach as a basis for developing conservation goals for the Rocky Mountain subunit (Tom Olliff, Great Northern LCC, personal communication, 12 October 2010). Internationally, the PACE framework could be applied within countries by national protected area management agencies and across networks of countries by collaborations among national entities and nongovernmental organizations with active conservation programs. DeFries and colleagues (2010a, 2010b) demonstrated this using a similar approach for six protected areas in the humid tropics. To the extent that the PACE approach is employed internationally, a central database of PACE boundaries, such as in the International Union for Conservation of Nature Protected Areas Database (IUCN 2003) would make the boundaries widely available and thus facilitate monitoring, evaluation, and conservation.

In conclusion, it has long been recognized that many protected areas are incomplete subsets of larger surrounding ecosystems that are often unprotected and vulnerable to human impacts. Before and since the creation of the NPS, park managers have advocated for park expansion and the creation of protective buffer zones; however, during the 1980s, private land rights issues made these positions politically untenable. Using modern ecological theory, extensive spatial data sets, and geospatial analysis hardware and software, we have illustrated a comprehensive and scientifically defensible approach to delineating PACE boundaries. Maturation of incentive-based approaches to conservation in recent decades may now allow key locations within PACEs to be managed to better maintain ecological condition in areas adjacent to protected areas. The need to identify, monitor, study, and conserve PACEs is now crucial, as land-use intensification threatens many of the world's protected areas.

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