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Trajectories in land use change around U.S. National Parks and challenges and opportunities for management

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Abstract. Most protected areas are part of a larger ecological system, and interactions with surrounding lands are critical for sustaining the species and ecological processes present within them. Past research has focused on how development rates around protected areas compare to development rates across a wider area as measured within varying sizes of buffer areas or at the county level. We quantified land use change surrounding the 57 largest U.S. National Parks in the contiguous United States for the period 1940 to the present and grouped the parks based on patterns of change. Land use was analyzed within the area considered essential to maintaining natural processes within each park, the protected-area centered ecosystem (PACE). Six variables were measured to determine the current level of development: population density, housing density, 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. Population density within PACEs increased 224% from 1940 to 2000, and housing density increased by 329%, both considerably higher than national rates. On average, private land in PACEs contained a combined 24% exurban and rural housing density, and these increased by 19% from 1940 to 2000. Five distinct land use classes were identified, indicating that groups of parks have experienced differing patterns of development on surrounding lands. The unique management challenges and opportunities faced by each group are identified and can be used by managers to identify other parks to collaborate with on similar challenges. Moreover, the results show park managers how severe land use changes are surrounding their park compared to other parks and the specific locations in the surrounding landscapes that influence ecological function within the parks. This is the 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.

Key words: *development; ecosystem; land use change; management; national park; protected area.*

Introduction

Protected areas form the core of many species and habitat conservation efforts across the globe (Gaston and Fuller 2008). The intention is that biodiversity will be maintained within the protected area and will be separated from land use activities occurring outside its borders (Margules and Pressey 2000). However, the boundaries of most U.S. protected areas were established to provide scenic or recreational values rather than to support organisms or ecological processes (Pressey 1994), and they often occur in less productive locations (Scott et al. 2001). Consequently, many protected areas are not large enough to encompass natural processes such as disturbance or to maintain adequate populations of all local species within their borders. Therefore, since most protected areas are part of a larger ecological system, interactions with surrounding lands are critical to sustain the species and ecological processes present within them (Hansen and DeFries 2007). In addition, as some species' distributions respond to changing climates (Parmesan and Yohe 2003), understanding and accommodating movements outside protected-area boundaries becomes more vital.

Scientists and land managers have long recognized that protected areas could become isolated patches within a degraded landscape and that parks could be impacted by activities on surrounding lands (Shelford 1933*a*, *b*, Wright et al. 1933, Leopold et al. 1963, Pickett and Thompson 1978, Newmark 1985, Grumbine 1990, U.S. GAO 1994, Shafer 1999). There have been efforts to surround protected areas with buffers in which some activities would be restricted and to work with adjacent landowners or inhabitants to reduce impacts on wildlife populations (MAB 1995). Other authors (DeFries et al. 2010, Hansen et al. 2011) have identified the area outside protected areas that directly influence processes and populations within the protected area. The U.S.

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National Park Service (NPS) has recognized the influence of outside pressures and recommended assessing their impacts on park resources (Robbins 1963, NPS 1993, 2006). Accordingly, the NPS Inventory and Monitoring Program has recently begun to monitor land use changes around U.S. National Parks (NPScape; *available online*).[2]

Human populations and intense land uses have increased rapidly in recent years around U.S. protected areas, mirroring or surpassing national or regional rates of development. For example, the counties around Yellowstone and Grand Teton National Parks were among the top 10th percentile in population growth in the United States from 1970 to 1997 (Hansen et al. 2002), and the proximity to the parks was found to be positively correlated with, and a predictor of, rates of rural residential development (Gude et al. 2006). Across the United States, rates of development have been found to be significantly greater in areas with proportionately more protected land (McDonald et al. 2007, Kramer and Doran 2010). From 1940 to 2000, the number of housing units within 50 km of U.S. National Parks increased on average by 57% every decade, well above the national average of 21% (Radeloff et al. 2010). Most of the new housing development (97%) within 10-km buffer areas around U.S. protected areas between 1970 and 2000 was at exurban densities as opposed to urban or suburban densities (Wade and Theobald 2010). Rates of development during this time period were dependent on the size of the protected area and its geographic location. Protected areas in the eastern United States tended to be smaller and had proportionately higher development rates than in the western United States (Parks and Harcourt 2002, Wade and Theobald 2010). Agriculture is also a prevalent land use near U.S. protected areas; in 2001, 73% of counties near U.S. National Parks had at least twice the area of agriculture as protected land (Svancarra et al. 2009).

Previous research has focused on comparing development rates around parks to development rates across a broader area away from parks. Our goals were to characterize land allocation and use around the network of U.S. National Parks and to identify groups of parks with similar types and rates of land use change as a context for management. The U.S. Department of the Interior (DOI), in which the NPS resides, is increasingly developing a broader network perspective for their lands (e.g., Fancy et al. 2009, U.S. DOI 2009). Rather than consider each protected area as a unique case, the DOI is interested in grouping units based on their vulnerabilities to land use and climate change. We develop and apply a method that uses the variation in land use patterns to group parks with similar changes. The resulting "typology" of parks provides a basis for prioritizing monitoring, research, and management among groups with similar vulnerabilities and conservation issues.

Rather than use uniform buffers as have previous studies (Kramer and Doran 2010, Radeloff et al. 2010, Wade and Theobald 2010), our desire was to quantify land use change on the lands where this change is likely to influence conditions in the parks. Buffers may not encompass the area required for ecological maintenance of the protected area or they may include areas that are unimportant to the ecological functioning of the park. Land use effects on protected areas need to be quantified within an area identified as having direct influence on the organisms and processes that cross the protected-area boundary. We analyzed multiple land use variables within the area surrounding each park that are essential to maintaining natural processes within the park, the "protected-area centered ecosystem" (PACE; Hansen et al. 2011). Identifying the area that is directly influential to the protected area can help to engage surrounding communities in discussions regarding the role of surrounding lands in maintenance of protected areas, which many landowners and businesses have a vested interest in (Machlis and Field 2000).

Herein, we compare current levels and past rates of land use change around the 57 largest National Park units in the contiguous United States for the period 1940 to the present. We also discuss the unique challenges and opportunities faced by parks undergoing similar changes. Our analysis focused on three questions: (1) What is the current state of development surrounding U.S. National Parks? (2) How are lands surrounding parks distributed among major land use typologies? (3) How have rates of land use change in the areas around U.S. National Parks, and parks' corresponding representation in major land use typologies, varied from 1940 to the present?

Methods

Parks evaluated in the study

Park units selected for inclusion in this study were the 57 largest parks in the contiguous United States with significant natural resources. From this list we removed parks primarily surrounded by water (i.e., Channel Islands National Park, Gulf Islands National Seashore, Isle Royale National Park, and Padre Island National Seashore) or managed for cultural resources (i.e., Illinois and Michigan Canal National Heritage Corridor). Two units were added for better representation in the eastern United States: Delaware Water Gap and New River Gorge. The final park units (Appendix A: Fig. A1) were recognized as having "significant natural resources" by the NPS Natural Resource Challenge (NPS 1999), represent a wide distribution of climate and land use gradients, and are primarily managed for natural values, biodiversity, or recreation. The units represent a range of management designations (i.e., park, preserve, monument, river, scenic riverway, lakeshore, seashore, parkway, and recreation

[2] ⟨http://science.nature.nps.gov/im/monitor/npscape/index.cfm⟩

area) and are, hereafter, referred to as parks. Park boundaries were downloaded from the NPS Data Store (*available online*).[3] Some parks were combined for analysis because they shared borders or were managed as a single unit, leading to a total of 49 different analysis units. Park sizes (Appendix A: Table A1) ranged from 278 km^2 (Delaware Water Gap) to 18 295 km^2 (combined Colorado River parks). Park establishment dates ranged from 1872 (Yellowstone National Park) to 1994 (Mojave National Preserve) with a mean establishment date of 1942. Parks that were established more recently were formerly managed as public land, but only recently added to the National Park system. The study area was confined to the contiguous United States to increase availability and consistency of data sets.

Protected-area centered ecosystems

Land use was quantified within the area considered essential to maintaining natural processes within each park, and we refer to these as protected-area centered ecosystems (PACEs). We drew on ecological mechanisms (Appendix B: Table B1) known to link protected areas to surrounding land use (Hansen and DeFries 2007) to develop criteria for delineating PACE boundaries. The process merges data on five criteria relating to: contiguity of surrounding natural habitat, watershed boundaries, extent of human edge effects, disturbance initiation and run-out zones, and crucial habitats outside the park required seasonally or as migration corridors for local organisms (Hansen et al. 2011). Their objective was to map the spatial domain of the area of strong effects between each of these five criteria and the protected area for 13 park units. For this analysis, PACEs were objectively mapped using national data sets of the first three of these criteria. The latter two criteria, disturbance zones and crucial habitats, require local knowledge, and acquiring such data for each park was impractical for this study. Therefore, the PACEs used here may be slightly smaller than those estimated using all five criteria.

Methods used to delineate PACEs are described in detail in Hansen et al. (2011) and are summarized here. National data sets were used to identify contiguous habitat, watersheds, and areas of potential human edge effects. We used data from the LANDFIRE Existing Vegetation Type layer (U.S. Department of Interior and US Geological Survey, *available online*)[4] to represent currently existing vegetation community classes. To determine which habitat types to include and where on the surrounding landscape this area should be placed, a cost-weighted distance analysis in ArcGIS 9.3 (ESRI 2009) was used to select vegetation community classes outside of the protected area that were similar to those within the protected area. This was done by weighting vegetation classes based on their proportional representation within the protected area such that classes with higher proportional abundance were favored, as were pixels nearer to the park boundary. The model was allowed to expand to a maximum extent based on the number of mammal species in each park and known species–area relationships. Hydrologic unit boundaries (HUCs; USDA and Natural Resources Conservation Service, Watershed Boundary Dataset, *available online*)[5] of three different sizes were used to emulate watersheds. The HUCs data divides and subdivides the United States into nested levels of watersheds. A combination of 8-, 10-, and 12-digit HUCs was selected based on the greatest existing Strahler stream order within a watershed (U.S. Environmental Protection Agency and USGS, National Hydrography Dataset Plus, *available online*)[6] as follows: stream orders 1–3, 12-digit HUC; stream orders 4–6, 10-digit HUC; and stream orders 7–10, 8-digit HUC. To address where human development may impact a park through edge or other effects, a 25-km buffer around each park was created and within this area all private, non-protected land was included in the PACE. This buffer width was selected because it exceeds the zone of influence of rural land development reported in the literature. The polygons derived for each criterion were then overlaid to define the PACE boundary. Boundaries for parks near the Canada or Mexico border (i.e., Glacier, North Cascades, Lake Roosevelt, Voyageurs, Organ Pipe Cactus, and Big Bend) were delineated only on the United States side of the border due to lack of consistent data sets in neighboring countries. Similarly, PACEs for coastal parks (e.g., Sleeping Bear Dunes, Everglades, and Santa Monica Mountains) were only designated on the landward side and not extended into the water.

Land use variables

All land use variables (Table 1) were quantified within the PACE boundary and included the park, with the exception of a time series data set for agricultural land, which was analyzed at the county level. Six variables determined the current level of development: population density, housing density, and percentages of land with developed 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. Each of the variables was selected for inclusion because of known effects on ecological systems (Appendix B: Table B2). The data sets we used and how they were quantified within the PACEs are described in the next subsections.

Land ownership.—We determined the percentage of the PACE area in public vs. private ownership. Tribal lands were included within private land since develop-

[3] ⟨http://science.nature.nps.gov/im/monitor/npscape/index.cfm⟩

[4] ⟨http://www.landfire.gov/⟩

[5] ⟨http://www.ncgc.nrcs.usda.gov/products/datasets/watershed/⟩

[6] ⟨http://nhd.usgs.gov/⟩

Table 1. Land use variables quantified for each protected-area centered ecosystem (PACE).

Variable	Year(s)	Resolution (m)
Current metrics		
Population density (no./km^2)	2007	100
Density of housing units (no./km^2)	2000	100
Area in undeveloped/low rural housing class, private (%)	2000	100
Area in rural housing class, private (%)	2000	100
Area in exurban housing class, private (%)	2000	100
Area in suburban/urban housing class, private (%)	2000	100
Area in agriculture, private (%)	2007	county
Mean percent impervious surface, private (%)	2001	30
Area of roads, private (%)	2009	100
Area of public land, PACE (%)	2008	100
Change-over-time metrics		
Change in population density, private land (%)	1940–2007	100
Change in area of agriculture (%)	1900–2007	county
Change in density of housing units, private (%)	1940–2000	100
Change in undeveloped/low rural housing density on private land (%)	1940–2000	100
Change in rural housing density on private land (%)	1940–2000	100
Change in exurban housing density on private land (%)	1940–2000	100
Change in suburban/urban housing density on private land (%)	1940–2000	100

Note: Current metrics were analyzed for the most recent year of data and change-over-time metrics over a range of years.

ment can occur on these lands. Private land protected through a conservation easement were only included when quantifying agriculture since many easements contain farmland. Military lands were the only areas not included in either category. Ownership classes were primarily derived from the Protected Area Database v4.5 (Conservation Biology Institute 2006) that provides updates on 17 states to provide more recent data on public and private protected lands (D. M. Theobald, *unpublished data set*). Though population and housing density were summarized on private land over time, the area of private land remained constant because it is based on a recent model of ownership.

Population density.—The population for each PACE was determined decennially from 1940 to 2000 using U.S. Census Bureau survey data and for 2007 using an annual estimate. For the period 1940–1960, a county-level data set (Waisanen and Bliss 2002) standardized for changes in county boundaries was analyzed. For 1970–2007, U.S. Census county-level data obtained from Woods and Poole Economics (2008) were used. Population was spatially distributed within counties using a dasymetric method (Mennis and Hultgren 2006). This method determines the population per pixel based on classes of an underlying dataset, in this case home densities (described in the next section; Theobald 2005). Population for each PACE was extracted at the 100-m cell resolution, which is the resolution of the housing density data. Although population is strongly correlated with housing density, population distributions based on housing will slightly overestimate populations for areas that have a high density of vacation or second homes that are not used as primary residences (Theobald 2005). Population density was determined by dividing the total population for the PACE by the PACE area.

Housing density.—To quantify housing densities, data developed using the Spatially Explicit Regional Growth Model (SERGoM; Theobald 2005, Bierwagen et al. 2010) was utilized. The model first removes areas where homes are unlikely to be built: specifically, public lands and areas of water. Homes were then dispersed using a weighted distribution based on: census data for housing units per block, counts of groundwater well permits, and road densities at a 100-m spatial resolution. The data extend from 1940 to 2000 and are calculated decadally at a 100-m resolution. Housing densities were summarized for each PACE within four mutually exclusive classes: undeveloped/very low density (0–0.031 housing units/ha), rural ($\geq$0.031–0.063 units/ha), exurban ($\geq$0.063–1.45 units/ha), and urban/suburban (>1.45 units/ha). The density of housing units was determined each decade by multiplying the midpoint of each density range by the area covered by that class. For current levels of development, the density of housing units on private land in 2000 and the percentage of private land in each housing density class in 2000 were quantified. Percentage change in the number of housing units, in the density of housing units, and the change in area of each housing density class from 1940 to 2000 were included in the change-over-time analysis.

Land in agriculture.—Two sources were used for agricultural data. For a recent measure, appropriate classes from the National Landcover Dataset (NLCD) 2001 (Homer et al. 2004) were quantified on private land within each PACE. Cropland, hay, and pasture classes at a 30-m resolution were overlaid with all private land and the percent of these lands covered by these classes was determined. A time series of changes in agricultural land (Waisanen and Bliss 2002) was used at the county level and summarized for the period 1940–1997, with updates from the National Agricultural Statistics Service (USDA) for 2002. Data on agricultural land have been collected in the United States approximately every five years during this time period. Counties that contained at least 10% of a PACE or that had at least 40% of their area covered by a PACE were selected. The total percentage change in agriculture was determined by dividing the total area of the selected counties by the difference in area of agriculture between 1940 and 2000, and multiplying by 100. The NLCD data allowed for a more spatially accurate measurement for the recent time period for each PACE than the county-level assessment.

Impervious surfaces.—The 2001 National Land Cover Database (Homer et al. 2004) includes an urban impervious surface layer at 30-m resolution. It was developed using 1-m Digital Ortho Quads for training data to determine the percentage of impervious surface within each 30-m cell and ancillary data including the following layers: a digital elevation model, slope, aspect, land cover, roads, and city light data. The mean percentage of impervious surface area was determined for 2001 by summing the values of all pixels in the PACE and dividing by the total number of pixels.

Area of roads.—We identified roads and railroads using the 2009 Tiger/Line shapefiles (U.S. Census Bureau, *available online*).[7] Highways and railroads were buffered by 15 m per side, primary roads by 7.5 m, and secondary roads by 5 m to create conservative but realistic road widths (Theobald 2010). The percentage of private land within the PACE covered by roads was then determined by extracting the road areas that overlaid private land and dividing this area into the total amount of private land, and multiplying by 100.

Statistical analysis

Univariate and multivariate statistical methods were used to identify patterns in land use development surrounding parks. Pearson correlation coefficients for all variables were inspected prior to analyzing current levels of development or the change over time of land use. If a correlation coefficient was greater than 0.8, then a decision was made to remove one variable or the other based on correlations with other variables. All statistical analyses were conducted using R version 2.11.1 (R Development Core Team 2010).

To determine the current state of development surrounding parks, we created univariate distributions for each of the current development variables remaining after the correlation analysis. The original predictors for each PACE were: population density on private land in 2000, the density of housing units on private land in 2000, the percentage of private land in each of four housing density classes (undeveloped, rural, exurban, and suburban/urban) in 2000, the mean percentage of area as private land in agriculture in 2001, of impervious surface in 2001, of public land in 2007, and of land covered by roads in 2008. Univariate plots and maps were created to determine patterns and geographic trends in the current state of development for each PACE.

[7] ⟨http://www.census.gov/geo/www/tiger/tgrshp2009/tgrshp2009.html⟩

The remaining uncorrelated land use variables were then used in a cluster analysis to determine how lands within PACEs were distributed and if patterns in major land use typologies could be distinguished. The objective of cluster analysis is to maximize the homogeneity among members of a cluster and to maximize the heterogeneity between clusters. Several potential numbers of clusters were tested using the *stride* command from the *optpart* package in R. We used two frequently cited and complementary methods for determining the optimal number of clusters: silhouette widths and partana ratios. These two evaluators complement each other in that one is based on dissimilarities and the other on similarities (Aho et al. 2008). Silhouette width is calculated for each object (i.e., park) by measuring its dissimilarity to other objects in its current cluster to its dissimilarity to objects in the next most similar cluster. The mean silhouette width for a given number of clusters ranges from -1 to 1, with larger positive values suggesting a better fit (Fielding 2007). Silhouette width scores can also be determined for each object individually and a unique plot, the silhouette plot, will show which parks could potentially be placed in multiple clusters. Partana ratio, or partition analysis, is the ratio of within cluster similarity to between cluster similarity (Aho et al. 2008). The algorithm maximizes homogeneity within clusters and minimizes homogeneity among clusters. The approach is iterative where objects are initially assigned to clusters at random, the partana ratio is calculated, objects are then reassigned and new ratios are calculated. The assignments are ranked and the process continues until no improvement on the ratio can be made. Scores for both evaluators were examined for a range of potential cluster numbers. Ideally, scores for both measures will be high for the same number of clusters. However, if needed, a compromise between high scores can be used to determine the final number of clusters for the analysis.

Once the optimal number of clusters was determined, the variables were standardized for use in the cluster analysis. We used the partitioning-around-mediods (PAM) clustering method (Kaufman and Rousseeuw 1990). This method is similar to a k means approach, but is more robust because it uses the dissimilarity matrix as opposed to Euclidean distances. PAM starts by considering all of the parks as one group and then divides them based on dissimilarities. The algorithm groups objects by iteratively minimizing the sum of dissimilarities between data points randomly selected to be the center of a cluster and all other data points. The number of clusters is chosen a priori and the best-fit cluster scheme minimizes the squared error of the distances. Once the optimal clustering scheme was identified, we inspected the ranges and means of each variable by cluster. We then created a set of rules based on the means and ranges that defined each cluster. The parks were then classified into land use typologies according to the rules.

These rules were also used to classify parks each decade to determine how representation within each land use typology has shifted over time. We determined the number of parks in each typology from 1940 to 2000 and counted the number of parks shifting from one class to another each decade. To see which parks have changed the most in land use over time, we also inspected univariate plots of each of the change-over-time predictors: absolute and percentage changes in population density (1940–2000), the percentages of change in the number of housing units (1940–2000), in the area of private land in each housing density class (undeveloped, rural, exurban, suburban/urban), and in the area of agriculture.

Results

Using three delineation criteria (contiguous habitat, watersheds, and human edge effects), PACE areas outside the park were, on average, 18 times the size of the park (range: 2–80 times; Appendix A: Table A1). Long, thin parks tended to have the largest PACE-to-park ratios, including Blue Ridge Parkway (80 times), Missouri River (70 times), and Saint Croix Riverway (47 times), because large areas of watersheds were included in the PACE. The contiguous habitat criteria was, on average, the largest PACE component (mean = 73% of PACE), followed by watersheds (43%) and human edge effects (6%). Two additional delineation criteria (i.e., disturbance zones and crucial habitats), were included for mapping the PACE for a subset of 13 park units based on unique input from each park (Hansen et al. 2011). Comparing the sizes of the PACEs drawn for these 13 parks using three and five criteria showed that using three criteria resulted in PACEs 22% smaller on average (range: −24% to 54%) than when using five criteria. Therefore, the PACEs used in this study may be slightly underestimated, though we believe our boundaries based on ecological criteria are more meaningful than simple buffers or political boundaries.

Current development

Most land use variables ranged widely among parks, though geographic trends were usually apparent. The PACEs consisting primarily of private land (i.e., private and tribal) are mostly either in the Midwest or East (Table 2). A few PACEs are dominated by tribal land (i.e., Canyon de Chelly 94% and Badlands 49%) and are thus high in developable land, though rates of development may not be as rapid as on other private land. Most western PACEs have a high proportion of public land and some consist almost entirely of public land. The PACEs with the highest average population densities (Table 2) contained major urban centers within their PACEs, and the lowest population densities were mostly in the desert Southwest. The mean population density for all parks was 52 people/km^2. The mean percent of private area in agriculture was 11.8% (Table 2). The lowest percentages of agriculture were at Southwest desert parks and all of the parks in the East and Midwest were in the top half of the distribution, with >10% of their private land in agriculture.

The mean density of housing units (Table 3) was 22 units/km^2. Not surprisingly, parks with high densities of housing also had the highest percentages of urban area (Table 3), as these two variables were highly correlated ($r = 0.87$). The lowest housing unit densities and urban areas were in the Southwest. The mean area in exurban housing density was 16% of the total area in private land, with the highest percentages in eastern parks and the lowest values in the Southwest (Table 3). Private land with no development or very low density housing, on average, made up 73% of all PACEs with eastern parks having considerably less undeveloped private land than parks in the West (Table 3). Undeveloped densities were highly negatively correlated with density of housing units ($r = -0.84$) and with exurban densities ($r = -0.94$). The mean area covered by impervious surfaces for all PACEs was 2.0%, which was very similar to the area covered by roads, 1.9% (Table 3). These variables were highly correlated ($r = 0.89$). Neither park area nor PACE area was highly correlated with any of the land use variables (i.e., all $r < 0.45$).

Several land use variables were highly correlated (i.e., $r > 0.8$), and consequently, four current variables were removed prior to the cluster analysis: population density, density of housing units, mean impervious surface, and percentage of private land in roads. The percentage of private land in suburban/urban housing density remained in the analysis as a measure of high development. The percentages of private land in exurban and in undeveloped housing densities were also highly correlated ($r = -0.94$). However, we decided to keep both variables in the analysis because they are particularly important to defining different levels of development that we were interested in. The other remaining variables were: percent of private land in each of undeveloped, rural, and agriculture, and the percent of public land.

Both methods for identifying the optimal number of clusters showed that six clusters were best (Appendix C: Table C1). The average silhouette width using six clusters in PAM was 0.36. One park, Saguaro, had a negative score, suggesting it could have been placed in one of two clusters. The partana ratio for six clusters was 1.56, only slightly higher than seven (1.54) clusters. Several other numbers of clusters were analyzed, and most of the group assignments remained relatively constant, with only a few parks switching membership each time. The means and ranges for each variable within each cluster (Table 4) suggested groups of parks could be classified by particularly high values for a specific variable or by ranges of multiple variables. Based on these unique values a set of classification rules (Table 5, Fig. 1) was developed to determine a final classification based on land use variables. The parks in one of the clusters were distributed to other clusters

TABLE 2. Current levels of private land and human development within protected-area centered ecosystems (PACEs), with parks listed in descending order of population density.

Park	PACE in public land (%)	Population density, 2000 (people/km^2)	Private land in agriculture, 2002 (%)	Mean impervious surface on private land, 2001 (%)	Private land covered by roads, 2009 (%)
Santa Monica Mountains	74	1649	8.4	27.42	8.56
Point Reyes/Golden Gate	93	813	0.8	12.42	5.14
Everglades/Big Cypress	64	456	22.7	9.02	3.90
Saguaro	84	225	2.8	5.74	3.44
Joshua Tree	59	169	6.1	5.15	3.09
Delaware Water Gap	40	104	16.5	1.62	3.06
Rocky Mountain	7	66	4.1	1.15	2.44
Shenandoah	7	60	38.0	2.05	3.28
Olympic	71	59	3.0	2.38	2.13
Saint Croix	56	56	29.7	1.54	2.04
Blue Ridge Parkway	95	54	21.9	1.69	3.32
Great Smoky Mountains	85	51	16.7	1.05	3.10
Death Valley	94	48	2.3	2.08	2.65
Colorado River†	45	44	1.2	1.51	1.10
Yosemite/Sequoia-Kings Canyon	77	43	3.8	0.62	1.72
Mount Rainier	85	42	2.8	1.71	2.19
White Sands	52	42	2.4	1.25	1.85
Big Thicket	43	36	10.7	2.08	2.07
Mojave	40	34	0.6	0.99	1.56
Sleeping Bear Dunes	62	32	14.3	1.45	2.21
New River Gorge	45	29	14.0	1.40	2.31
Redwood	73	24	2.0	0.73	2.15
Glacier	53	22	9.3	0.74	1.50
Big South Fork	30	19	10.8	1.06	0.02
North Cascades	69	19	2.7	1.07	1.21
Voyageurs	11	18	3.2	0.92	0.80
Yellowstone/Grand Teton	66	18	23.9	0.46	1.62
Zion	16	18	3.5	0.84	1.50
Buffalo River	84	15	26.0	0.73	1.66
Lake Roosevelt	21	15	29.3	0.85	1.45
Arches	26	13	12.8	0.89	1.63
Lassen Volcanic	75	9	0.2	0.03	1.92
Dinosaur	30	7	7.6	0.58	1.12
Missouri River	80	7	47.4	0.46	1.17
Ozark	16	7	22.5	0.37	1.39
Pictured Rocks	42	7	0.7	0.33	1.25
Bighorn Canyon	24	5	14.4	0.47	0.85
Canyon de Chelly	57	5	0.0	0.29	1.61
Craters of the Moon	9	5	50.0	0.59	1.58
Great Sand Dunes	15	5	13.9	0.69	1.40
Crater Lake	80	4	24.4	0.38	1.58
El Malpais	47	4	0.1	0.06	1.08
Badlands	13	3	6.8	0.31	0.66
Organ Pipe Cactus	6	3	0.1	0.12	0.53
Great Basin	10	2	11.9	0.25	1.08
Petrified Forest	37	2	0.4	0.14	1.21
Theodore Roosevelt	6	2	30.1	0.35	1.29
Big Bend	6	1	0.1	0.24	0.00
Guadalupe Mountains	24	0	1.9	0.13	0.81
Mean	41	51.7	11.8	2.01	1.94
Median	36	4.8	7.6	0.85	1.62

† Colorado River parks are: Canyonlands, Capitol Reef, Glen Canyon, Grand Canyon, and Lake Mead.

based on the classification rules (Table 5), and consequently, the final classification consisted of five well-defined classes (Table 5).

Parks in cluster 1 were characterized by particularly high proportions of public land. These parks all consisted of >69% public land, with three exceptions (i.e., Pictured Rocks, Redwood, and Olympic), which had between 47% and 60% public land. Consequently, these three parks were removed from the group and a defining rule of >65% public land was chosen for the remaining parks in the cluster. The group was called "Wildland protected" to suggest that development surrounding these parks was not as large of a threat as other parks because of the amount of land in public ownership. These parks also tended to have little agriculture, except Craters of the Moon, and high amounts of undeveloped private land. There were 17 parks classified into this type and almost all were located in the West (Fig. 2).

Parks in cluster 2 were characterized by a high proportion of private land in undeveloped housing

TABLE 3. Recent levels of housing densities on private land within protected-area centered ecosystems (PACEs), with parks listed in decreasing order of density of housing units.

Park	Density of housing units, 2000 (units/km^2)	Percentage of private land, by category			
		Undeveloped, 2000 (%)	Rural housing density, 2000 (%)	Exurban housing density, 2000 (%)	Suburban/urban housing density, 2000 (%)
Santa Monica Mountains	128.2	27.6	4.59	17.05	41.16
Point Reyes/Golden Gate	82.2	32.6	8.24	30.52	20.91
Everglades/Big Cypress	69.2	57.0	3.44	15.05	20.39
Delaware Water Gap	66.0	15.0	11.91	67.51	5.06
Great Smoky Mountains	58.6	15.1	15.31	66.71	2.56
Saguaro	52.9	57.2	6.64	22.22	12.54
Blue Ridge Parkway	52.2	19.6	20.08	56.99	2.80
Shenandoah	48.8	19.8	23.65	53.47	2.47
Sleeping Bear Dunes	43.5	22.7	26.57	48.41	1.90
Joshua Tree	37.5	62.9	6.53	21.46	7.17
Rocky Mountain	31.8	53.6	12.02	32.01	2.24
New River Gorge	28.6	42.1	25.53	30.33	1.36
Olympic	28.0	65.1	6.71	24.58	2.92
Yosemite/Sequoia-Kings Canyon	23.1	66.2	8.13	24.26	1.20
Big Thicket	22.8	63.4	13.39	20.12	2.16
White Sands	22.1	74.3	4.18	18.77	2.37
Big South Fork	21.4	56.0	19.11	24.05	0.53
Saint Croix	17.8	66.5	14.25	16.85	1.20
Mount Rainier	16.0	80.2	4.11	13.75	1.52
Yellowstone/Grand Teton	15.6	73.3	10.11	15.76	0.77
Buffalo River	15.4	64.0	19.68	15.60	0.60
Death Valley	15.2	80.7	4.92	11.98	1.68
North Cascades	13.7	73.8	11.08	13.90	0.56
Redwood	13.7	82.2	4.64	11.72	1.20
Glacier	13.6	77.9	7.25	13.98	0.55
Voyageurs	12.0	80.6	7.54	10.98	0.76
Ozark	9.9	82.8	7.28	9.43	0.42
Zion	9.8	87.1	4.51	7.17	1.01
Missouri River	9.5	82.4	7.71	9.50	0.24
Arches	9.3	88.9	2.42	6.98	0.92
Pictured Rocks	9.0	82.5	8.64	8.44	0.34
Mojave	8.8	88.9	2.57	7.61	0.58
Colorado River†	8.7	93.6	1.14	2.79	1.85
Lassen Volcanic	7.4	92.2	1.45	5.59	0.62
Lake Roosevelt	5.6	91.3	4.49	3.55	0.49
Canyon de Chelly	5.1	92.3	3.37	4.14	0.16
Dinosaur	4.9	94.7	1.61	3.35	0.33
Great Sand Dunes	4.7	91.1	5.13	3.68	0.10
Badlands	4.3	95.3	1.48	2.95	0.22
El Malpais	3.9	96.1	1.21	2.46	0.20
Crater Lake	3.8	92.9	4.31	2.73	0.04
Craters of the Moon	3.7	93.8	3.67	2.12	0.19
Bighorn Canyon	3.2	96.1	2.05	1.61	0.17
Theodore Roosevelt	3.0	95.8	2.35	1.83	0.03
Great Basin	2.9	95.7	2.50	1.79	0.00
Petrified Forest	2.6	97.3	1.34	1.23	0.06
Organ Pipe Cactus	2.1	99.1	0.32	0.44	0.08
Big Bend	1.7	99.6	0.17	0.14	0.04
Guadalupe Mountains	1.7	99.5	0.28	0.19	0.01
Mean	21.95	72.62	7.54	16.08	2.99
Median	13.62	80.74	4.92	11.72	0.76

† Colorado River parks are: Canyonlands, Capitol Reef, Glen Canyon, Grand Canyon, and Lake Mead.

density. In conjunction with the first rule developed for cluster 1, the first two defining rules for this group were: (1) <65% public land and (2) >60% private land undeveloped. Cluster 2 also tended to have less agriculture than all other clusters and so a third rule was implemented: <16% of private land in agriculture. The three exceptions from cluster 1 were added to this group. This group was called "Wildland developable" because the parks currently have low levels of development, but have the potential for considerably more development because of relatively high amounts of private land. The final 16 parks in this group also tended to have very little urban area, moderate amounts of public land, and were relatively remote (Fig. 2).

Parks in cluster 3 had particularly low percentages of public land, but fell within the middle range for all of the

TABLE 4. Means and ranges (in parentheses) of land use variables within each cluster, prior to final classifications.

		Percentage of private land, by category					
Cluster	No. parks	Agriculture (%)	Undeveloped housing density (%)	Rural housing density (%)	Exurban housing density (%)	Suburban/urban housing density (%)	PACE in public (%)
1	19	6.6 (1–24)	80.0 (54–96)	5.8 (1–12)	12.4 (2–32)	1.3 (0–7)	78.2 (47–94)
2	11	3.7 (0–14)	93.9 (74–99)	1.9 (0–5)	3.7 (0–19)	0.4 (0–2)	32.0 (6–47)
3	5	18.2 (11–30)	58.4 (42–67)	18.4 (13–26)	21.4 (16–30)	1.2 (1–2)	16.9 (5–27)
4	5	21.5 (14–38)	18.4 (15–23)	19.5 (12–27)	58.6 (48–68)	3.0 (2–5)	25.8 (15–43)
5	5	35.9 (23–50)	89.2 (82–96)	5.1 (2–8)	5.3 (2–10)	0.3 (0–0.5)	34.8 (6–76)
6	4	8.7 (1–23)	43.6 (28–57)	5.7 (3–8)	21.2 (15–31)	23.8 (13–41)	44.1 (28–62)

other variables. Consequently, the five parks were not classified into their own unique group, but eventually were classified within groups based on rules developed for other clusters.

Parks in cluster 4 had much higher percentages of private land in exurban housing and very little public land. Therefore, the rules for this group were: (1) <65% public land, (2) <60% private land undeveloped, and (3) private land dominated by exurban (or urban <15%). Seven of the final eight parks in this "Exurban" group were located in the East, the exception being Saguaro outside Tucson, Arizona.

Parks in cluster 5 had particularly high proportions of private land in agriculture (mean = 36%). Craters of the Moon had 50% of its private land in agriculture and was originally placed in this cluster. However, we moved it to "Wildland protected" because it had 76% public land. The rules for this "Agricultural" group were the same as for the "Wildland developable" group, except the amount of agriculture was >16%. The final five parks also had little public land, moderate levels of exurban housing, and were mostly located in the Midwest (Fig. 2).

Parks in cluster 6 had much higher percentages of urban housing density and lower percentages of undeveloped land. The same rules were used as for "Exurban," except the private land was dominated by urban or had at least 16% of private land in urban. The "Urban" group consisted of only three parks: Everglades/Big Cypress, Point Reyes/Golden Gate, and Santa Monica Mountains. These parks did have moderate amounts of public land, but they were almost entirely surrounded by urban and exurban housing.

Changes in development, 1940–2000

The mean increase in population density from 1940 to 2000 (Table 6) across all PACEs was 62 people/km^2, though the median was 13 people/km^2. The largest changes in population density occurred at urban parks, and a small number of parks in the Southwest and Midwest exhibited slight declines in population density. The largest percentage increases in population density

TABLE 5. Classification rules and final typological assignments.

Category	Wildland protected	Wildland developable	Agricultural	Exurban	Urban
Classification	1) >65% public	1) <65% public 2) private >60% undeveloped 3) private <16% agriculture	1) <65% public 2) private >60% undeveloped 3) private >16% agriculture	1) <65% public 2) private <60% undeveloped 3) private dominated by exurban or urban <15%	1) <65% public 2) private <60% undeveloped 3) private dominated by urban or urban >15%
List of parks	Arches, Colorado River,† Crater Lake, Craters of the Moon, Death Valle, Dinosaur, Glacier, Great Basin, Joshua Tree, Mojave, Mount Rainier, North Cascades, Rocky Mountain, Voyageurs, Yellowstone/Grand Teton, Yosemite/Sequoia-Kings Canyon, Zion	Badlands, Big Bend, Big Thicket, Bighorn Canyon, Canyon de Chelly, El Malpais, Great Sand Dunes, Guadalupe Mountains, Lassen Volcanic, Olympic, Organ Pipe Cactus, Ozark, Petrified Forest, Pictured Rocks, Redwood, White Sands	Buffalo River, Lake Roosevelt, Missouri River, Saint Croix, Theodore Roosevelt	Big South Fork, Blue Ridge Parkway, Delaware Water Gap, Great Smoky Mountains, New River Gorge, Saguaro, Shenandoah, Sleeping Bear Dunes	Everglades/Big Cypress, Point Reyes/Golden Gate, Santa Monica Mountains

† Colorado River parks are: Canyonlands, Capitol Reef, Glen Canyon, Grand Canyon, and Lake Mead.

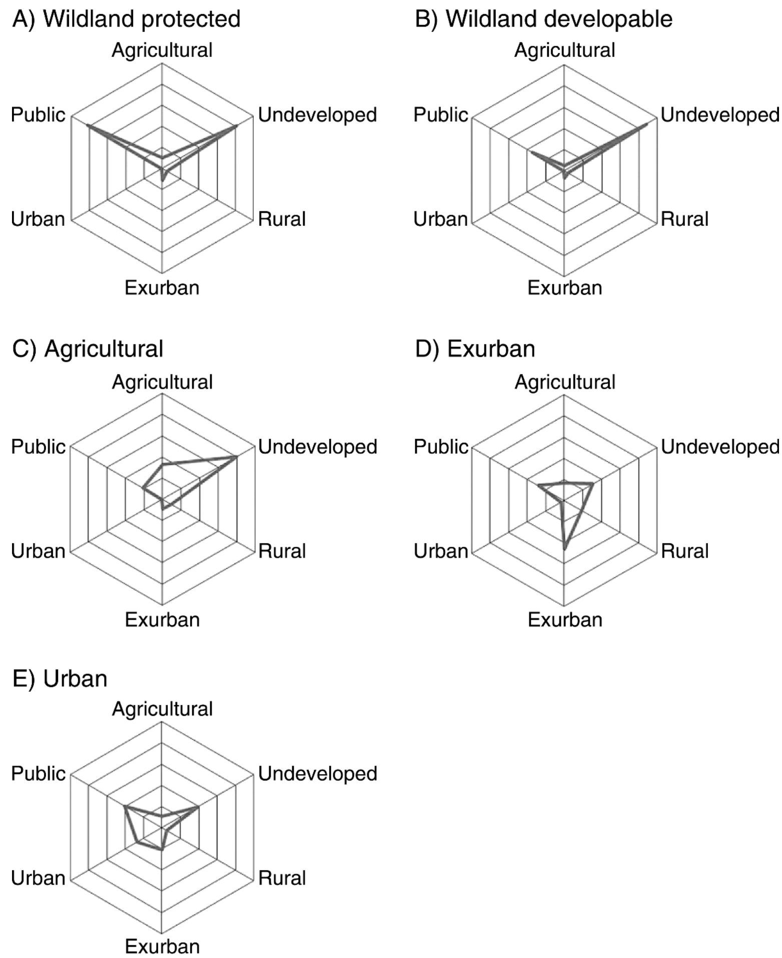

FIG. 1. Distribution of mean values for land use variables within each typological class.

(Table 6) were in the Southwest, likely because they started with very low densities. Across all PACEs, the percentage of land in agriculture remained relatively stable with a mean decrease of 2.8% (Table 6). However, some parks in the East had considerable losses in percent agriculture (i.e., Shenandoah –20%, Blue Ridge Parkway –17%, and Great Smoky Mountains –15%).

The average increase in density of housing units on private land was 17 units/km^2 (Table 7). Most of the parks in the Northeast were in the top quarter of increases, and the lowest increases were all in the Southwest. On average, PACEs lost 22% of their undeveloped private land (Table 7) to higher densities with all of the largest decreases in the Northeast. The same desert parks with the smallest increases in units also had the lowest decreases in undeveloped private land. Percent of private land in exurban housing density increased more than any other housing density class with a mean increase of 14%, and the eastern parks again having the highest increases. Suburban/urban housing increased, on average, by 3% on private land and showed much less geographical clustering (Table 7). Some parks had little to no increases in suburban/urban areas within their PACEs.

The parks were classified for each decade from 1940 to 2000 based on the rules developed during the typological classification using current development measurements. Using the 2002 county-level agriculture data and the 2001 NLCD agriculture data did not change the classification results for the current time period using the same rules. Therefore, we could substitute this agriculture data set for classifying parks across time. The amount of public land was assumed to have remained the same across this time period. Therefore, all of the parks classified in 2000 as "Wildland protected" remained within this class across all decades.

PACE typology after 1940 shifted away from Agricultural, initially toward Wildland developable (Fig. 3). Seven parks initially classified as Agricultural had shifted to Wildland developable by 1960 with one additional park changing to Exurban. Several of these parks were in the East (i.e., Blue Ridge Parkway, Great Smoky Mountains, and Shenandoah) and all eventually became Exurban. The number of Agricultural parks has

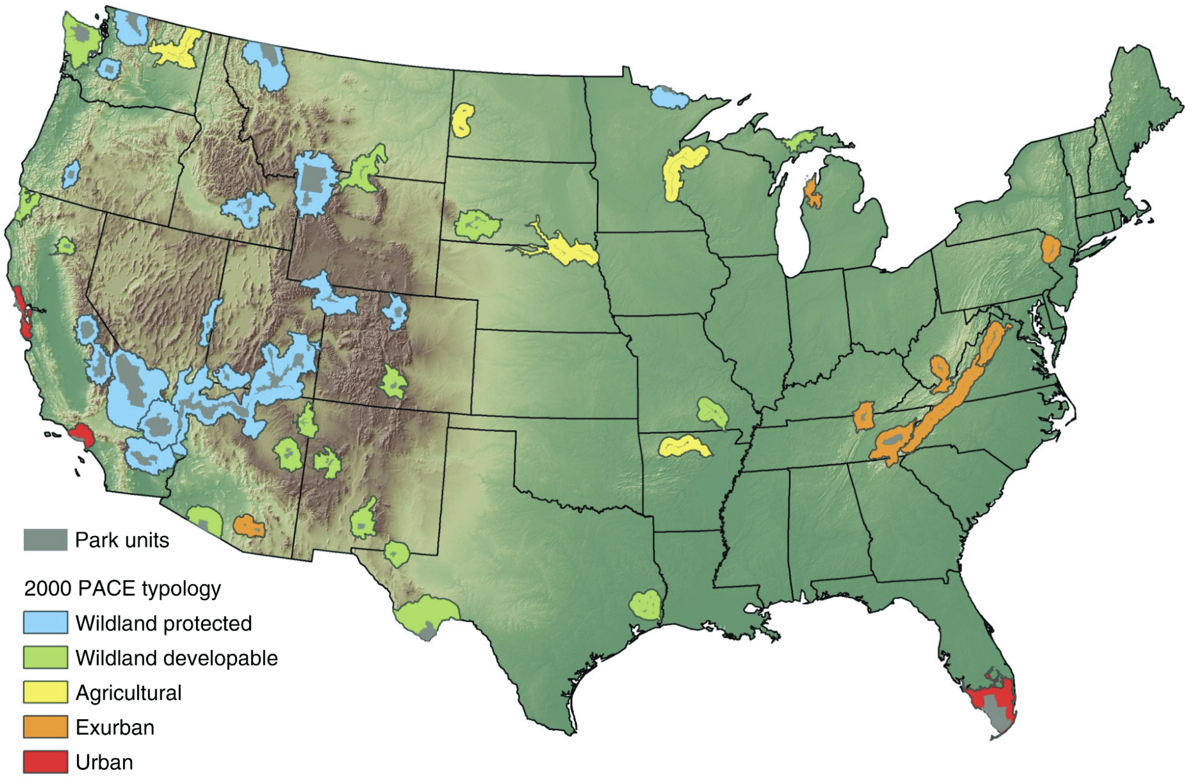

FIG. 2. Protected-area centered ecosystems (PACEs) surrounding each U.S. National Park, color-coded by typological membership. See Table 5 for a description of the categories.

since remained stable at five. After 1960, five parks shifted from Wildland developable to Exurban or Urban. Everglades/Big Cypress only recently shifted from Wildland developable to Urban between 1990 and 2000.

DISCUSSION

Our results suggest that lands around parks are experiencing more rapid changes than expected from national rates of development. For example, the national increase in population density in the United States from 1940 to 2000 was 113% (American Factfinder, U.S. Census Bureau, *available online*),[8] but the change in density in PACEs was almost double that rate, 224%. Similarly, housing density increased by 210% nationwide in the same time period, while PACE housing density increased 329%. Much of the increase in housing units has been in the form of low density (i.e., rural or exurban) development. In the United States since 1950, rural residential development was the fastest growing land use type and now covers 25% of the lower 48 states (Brown et al. 2005). On average, private land in PACEs contained a combined 24% exurban and rural housing density, and these increased by 19% from 1940 to 2000. Parks and Harcourt (2002) found a significant relationship between park area and population density in that smaller U.S. National Parks tended to have higher human densities in their surroundings. However, we had no correlation ($r = 0$) between park area and human population density across all PACEs, and no land use variables had correlations higher than 0.44 with either park area or PACE area.

The increase in population and low-density housing has been driven largely by past development patterns and the desire to live near natural amenities (Gude et al. 2006, Lepczyk et al. 2007). The presence of protected areas increases local land values by providing recreational opportunities, scenic vistas, and insurance against complete development of an area (Kramer and Doran 2010). U.S. National Parks are often located in areas of higher elevation and lower productivity (Scott et al. 2001), but many parks are surrounded by lower elevation, fertile valley bottoms coveted for agriculture. The legacy of the original agricultural development has led, more recently, to increased housing development in these areas (Gude et al. 2006). Areas that were originally coveted for proximity to water sources and fertile soils now provide aesthetic resources such as rivers and lakes and an existing transportation system in easily developable terrain.

Therefore, many parks with high amounts of adjacent private land (i.e., all classes except Wildland protected)

[8] ⟨http://factfinder2.census.gov/faces/nav/jsf/pages/index.xhtml⟩

TABLE 6. Change in population density and agricultural land from 1940 to 2000, with parks listed in decreasing order of change in population density.

Park	Change in population density		Change in area of agriculture (%)
	No. people/km^2	%	
Santa Monica Mountains	1076.8	188.1	−10.45
Point Reyes/Golden Gate	479.0	143.3	−12.63
Everglades/Big Cypress	438.3	2472.5	8.72
Saguaro	206.9	1144.5	0.00
Joshua Tree	163.5	2859.1	−1.00
Delaware Water Gap	64.3	161.4	−12.40
Rocky Mountain	52.6	387.1	−3.09
Olympic	44.3	293.7	−1.64
Death Valley	43.2	955.9	−0.39
Colorado River†	42.7	2962.1	0.28
Saint Croix	39.1	225.5	−9.97
Shenandoah	38.7	178.6	−19.98
White Sands	34.6	498.8	−0.14
Mojave	32.9	3092.2	−0.62
Mount Rainier	31.4	288.1	0.14
Yosemite/Sequoia-Kings Canyon	29.7	223.9	2.57
Great Smoky Mountains	23.6	84.5	−14.84
Blue Ridge Parkway	21.0	63.4	−17.19
Big Thicket	18.9	112.8	−0.14
Redwood	18.8	393.0	−2.03
Sleeping Bear Dunes	18.3	135.8	−14.30
Glacier	15.1	209.9	4.69
Zion	14.2	370.0	0.24
Yellowstone/Grand Teton	12.8	246.0	0.13
North Cascades	12.5	181.2	−1.71
Arches	9.7	269.8	1.57
Lake Roosevelt	6.0	70.7	0.27
Lassen Volcanic	6.0	174.2	−1.03
Dinosaur	5.2	251.7	0.68
Big South Fork	4.6	31.2	−5.53
Buffalo River	4.3	41.1	−4.66
Canyon de Chelly	3.9	326.1	−0.03
Crater Lake	2.9	190.3	−1.74
El Malpais	2.8	181.5	−1.91
Voyageurs	2.4	16.1	−2.17
Bighorn Canyon	1.6	47.2	0.95
Organ Pipe Cactus	1.5	114.4	0.36
Craters of the Moon	1.3	35.6	7.42
Badlands	1.2	72.5	−1.77
Petrified Forest	1.2	131.1	−0.30
Great Sand Dunes	1.1	31.6	0.04
Pictured Rocks	0.5	7.2	−1.53
Guadalupe Mountains	0.1	26.7	0.83
Big Bend	−0.1	−12.0	0.94
Theodore Roosevelt	−0.2	−8.4	−0.38
Ozark	−0.3	−3.5	−4.17
Missouri River	−0.6	−8.3	−3.48
Great Basin	−0.7	−24.4	0.06
New River Gorge	−6.2	−17.6	−14.82
Mean	61.7	404.4	−2.8
Median	12.5	174.2	−0.6

Note: Population is quantified within protected-area centered ecosystem and area of agriculture is measured at the county level.

† Colorado River parks are: Canyonlands, Capitol Reef, Glen Canyon, Grand Canyon, and Lake Mead.

have experienced similar trajectories in development and are moving through a series of predictable land use stages. Several parks that initially had a large amount of agricultural land in their surroundings have shifted to having a large amount of exurban or urban housing and less agriculture. Decreased areas of agriculture within PACEs are also part of a nationwide trend. From 1950 to 2000, land area in agriculture decreased from 35% to 31% in the United States (Brown et al. 2005), which is similar to the mean loss of 3% in our PACEs. Decreases were largest in the East, both nationwide (Brown et al. 2005) and within the PACEs. In the eastern U.S., the amount of forest gained from agricultural abandonment has been largely offset by forest loss to development

TABLE 7. Changes in number of housing units and in percentage area of each housing density class from 1940 to 2000, with parks are listed in decreasing order of change in density of housing units.

Park	Change in density of housing units (no./km^2)	Percentage change			
		Undeveloped area	Rural area	Exurban area	Suburban/urban area
Santa Monica Mountains	75.6	−28.7	1.9	−0.6	27.4
Everglades/Big Cypress	63.8	−32.9	2.0	10.8	20.1
Great Smoky Mountains	53.8	−75.3	10.0	62.8	2.5
Point Reyes/Golden Gate	52.1	−27.1	0.4	10.8	15.9
Delaware Water Gap	51.0	−52.1	−4.8	52.5	4.4
Saguaro	47.9	−36.6	5.5	19.0	12.2
Blue Ridge Parkway	46.4	−69.1	14.2	52.4	2.5
Shenandoah	42.3	−64.8	14.5	48.0	2.2
Sleeping Bear Dunes	37.2	−65.5	20.8	43.1	1.7
Joshua Tree	34.5	−32.2	5.4	19.7	7.1
Rocky Mountain	24.3	−33.8	7.1	24.5	2.1
New River Gorge	23.7	−49.2	21.5	26.5	1.2
Olympic	23.4	−28.1	4.0	21.4	2.7
Yosemite/Sequoia-Kings Canyon	19.8	−30.0	6.8	22.0	1.2
Big Thicket	19.7	−33.1	12.6	18.6	2.0
White Sands	19.3	−22.9	3.3	17.3	2.3
Big South Fork	19.1	−41.3	17.7	23.1	0.5
Saint Croix	13.6	−26.8	11.7	14.1	1.0
Buffalo River	13.3	−34.6	19.1	14.9	0.6
Yellowstone/Grand Teton	13.2	−24.3	9.0	14.6	0.7
Death Valley	13.0	−17.1	4.3	11.2	1.7
Mount Rainier	12.4	−15.1	2.2	11.6	1.4
Glacier	11.4	−19.7	6.1	13.1	0.5
Redwood	10.9	−14.7	3.4	10.2	1.2
North Cascades	10.7	−20.6	8.0	12.0	0.5
Voyageurs	8.7	−15.8	6.0	9.1	0.6
Zion	7.5	−11.3	3.9	6.4	1.0
Ozark	7.4	−14.8	6.2	8.2	0.4
Arches	7.3	−9.4	2.1	6.4	0.9
Mojave	7.1	−10.1	2.2	7.4	0.6
Colorado River†	6.9	−5.3	1.0	2.5	1.8
Pictured Rocks	6.3	−14.8	7.5	7.1	0.3
Lassen Volcanic	5.2	−6.2	0.8	4.8	0.6
Missouri River	5.0	−9.1	3.0	6.0	0.1
Canyon de Chelly	3.6	−7.5	3.3	4.1	0.2
Lake Roosevelt	3.4	−7.7	4.2	3.1	0.3
Dinosaur	3.2	−4.7	1.4	3.0	0.3
Great Sand Dunes	2.8	−8.2	4.9	3.3	0.1
Badlands	2.7	−4.3	1.3	2.8	0.2
El Malpais	2.3	−3.7	1.1	2.3	0.2
Crater Lake	2.2	−6.7	4.1	2.6	0.0
Craters of the Moon	1.9	−5.4	3.4	1.8	0.2
Bighorn Canyon	1.5	−3.3	1.8	1.4	0.1
Theodore Roosevelt	1.3	−3.3	1.7	1.6	0.0
Great Basin	1.2	−3.6	2.0	1.6	0.0
Petrified Forest	1.1	−2.5	1.3	1.2	0.1
Organ Pipe Cactus	0.3	−0.6	0.3	0.2	0.1
Big Bend	0.2	−0.2	0.1	0.1	0.0
Guadalupe Mountains	0.2	−0.5	0.3	0.2	0.0
Mean	17.2	−21.5	5.5	13.5	2.5
Median	10.7	−15.1	3.9	9.1	0.6

Note: All variables are based on the area of private land within the PACE.

† Colorado River parks are: Canyonlands, Capitol Reef, Glen Canyon, Grand Canyon, and Lake Mead.

over the past 30 years (Drummond and Loveland 2010). Other parks that may not have had much agriculture, but have a large amount of private land, have also shifted from relatively undeveloped to an exurban or urban setting. Shifts to exurban housing in our PACEs are similar to national trends where exurban area increased fivefold from 1950 to 2000 (Brown et al. 2005). Several authors have forecasted development trends for areas surrounding parks (Gude et al. 2007, Radeloff et al. 2010, Wade and Theobald 2010) that suggest it is likely that more parks will be shifting to exurban or urban densities.

Though development is increasing relatively rapidly on private land near parks, our results indicate that,

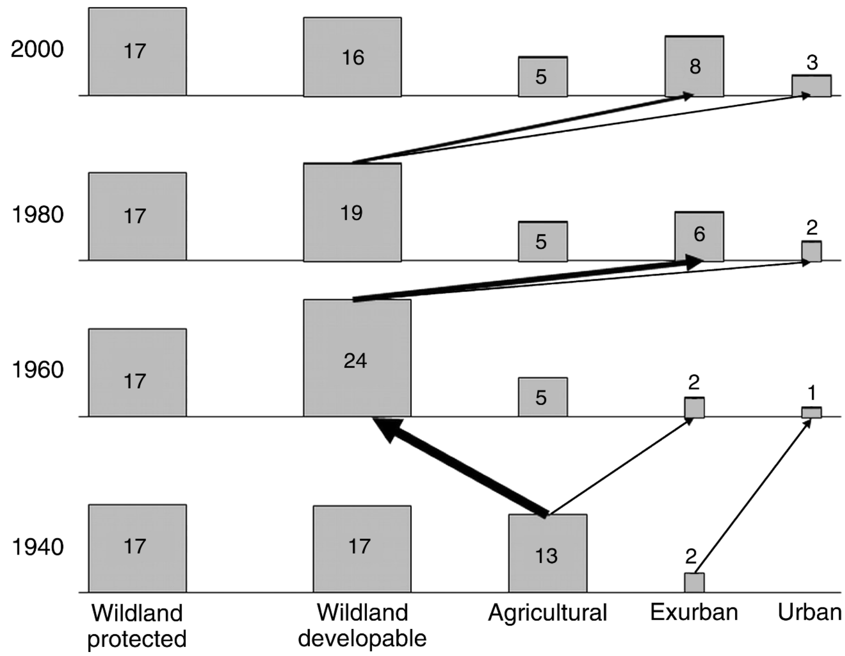

FIG. 3. Change in typology membership every 20 years from 1940 to 2000. Box size is proportional to the number of national parks in a class, and arrow width is proportional to the number of parks changing classes. The Wildland protected class does not change through time because it is based on the amount of public land within PACEs, which was assumed to remain constant.

currently, many of the largest parks within the U.S. national park system are still located within relatively undeveloped landscapes. On average, 73% of all private land within PACEs has no or very little housing (Table 3). Considering that, on average, less than half (41%) of PACE areas consist of private land (Table 2), this suggests that park surroundings are relatively unaltered. However, the amount of private land and most other land use measures are highly variable from PACE to PACE and are largely dependent on the park's geographic location. Therefore, viewing current development levels regionally or at the individual PACE level may be more revealing.

Geographic patterns in development

Parks located within the eastern United States (i.e., Big South Fork, Great Smoky Mountains, Blue Ridge Parkway, Shenandoah, New River Gorge, Delaware Water Gap, and Sleeping Bear Dunes), which were subjected to earlier settlement patterns in their surroundings, tend to be smaller and surrounded by more private land. Consequently, these PACEs also tend to have higher population and housing unit densities, more area in exurban housing, and more road cover. For example, six of the eight PACEs with >30% of their private land in exurban densities were east of the Mississippi River. Eastern parks also showed the highest rates of change for many of these same variables across time. For example, the seven PACEs with the highest losses of undeveloped private land, all with losses greater than 40%, were in the East (Table 7). This corresponds with the same parks showing the highest increases in exurban area (Table 7). The PACEs for eastern parks also had the highest decreases of agricultural land with six of the top seven losses. Some parts of the United States have seen large amounts of agricultural land converted to residential or commercial development (Brown et al. 2005) or abandoned and reverted to forest (Houghton and Hackler 2000). Other authors have shown that, even with consistent agricultural abandonment and subsequent forest regrowth, there is a steady decline in forested area of the eastern United States due to increases in land conversion to housing and resource extraction (Drummond and Loveland 2010). These results suggest that eastern parks face some of the most difficult challenges to maintaining ecosystem processes across park boundaries.

Parks in the desert Southwest mostly fall into two categories. Those located south of the Colorado River (e.g., El Malpais, Guadalupe Mountains, Great Sand Dunes, and Petrified Forest) tend to be small, remote parks with moderate to high levels of private land in their PACEs. These are the least developed parks, with high values of undeveloped private land and very low population and housing densities. Changes in most land use variables over time were also relatively low for these parks. Saguaro is an exception to these trends because it is located just outside Tucson and has experienced considerable development. Other parks in the Southwest, those located along or north of the Colorado River, have also experienced greater rates of change. They tend to be larger parks (e.g., Death Valley, Mojave, and Joshua Tree) with low proportions of private land and agriculture in their PACEs. However, they have experienced moderate increases in population and exurban housing growth in their private lands. For example, Joshua Tree lost 32% of its undeveloped private land between 1940 and 2000, mostly to exurban housing densities, which increased 20%. Mojave, the most recently established park, had the largest percentage change in population density (3093%) during this time period, mostly due to a very low population density (1.1 person/km^2) in 1940 and a moderately high increase in density (32.9 persons/km^2; Table 6).

Western mountain parks (e.g., North Cascades, Mount Rainier, Glacier, Yellowstone/Grand Teton, Rocky Mountain, and Yosemite/Sequoia-Kings Canyon) had small amounts of private land, but higher than average increases in population and housing. For example, Rocky Mountain lost 34% of its undeveloped private land to higher housing densities (i.e., 25% and 2% increases in exurban and suburban/urban densities respectively) and had a 387% increase in population density from 1940 to 2000. Yellowstone/Grand Teton lost 24% of the undeveloped private land in its PACE with an increase of 15% in exurban areas. Many western mountain parks consist of high-elevation terrain with harsh climates and can lack productive, lower elevation land often needed seasonally by ungulates and other wildlife. Therefore, maintaining connections to these lower elevation areas will be essential to park functioning (Hansen and Rotella 2002).

River parks (i.e., Buffalo, Big South Fork, New River Gorge, Ozark, Missouri, Saint Croix, and the Colorado River Parks) are also very reliant upon adjacent lands for ecological functioning, as their relatively large PACE to park ratios suggest. Development and management activities in surrounding watersheds will greatly affect the aquatic systems that these parks protect. Some of these parks have relatively high impervious surface area, making them susceptible to water pollution: Saint Croix (1.5%), Colorado River (1.5%), and New River Gorge (1.4%). Other river parks have some of the highest amounts of private land in agriculture which can affect water quantity and water quality: Missouri River 47%, Saint Croix 30%, and Buffalo River 26%. River parks are also more susceptible to invasion by exotic species because of the ease of spread along the river, which could be exacerbated by weed introductions from adjacent agricultural land.

Challenges and opportunities for each land use class

Some management challenges and opportunities will be similar across all typological classes, but some may be particularly relevant to a single class. For example, all parks have management programs to control invasive weeds. However, some groups of parks, such as parks in urban and agricultural settings, may be more susceptible to invasions by weeds because of the extent and nature of disturbance in surrounding lands. Park managers may benefit from identifying and collaborating with other parks undergoing similar changes and facing similar threats. Appendix C: Table C2 provides a list of the potential challenges and opportunities that are especially relevant to each typological class and we describe them here.

Due to their relative intactness, Wildland protected parks have the ability to maintain fully functioning food webs. The challenges are in maintaining, or potentially restoring, top predators in the face of increased development on available private lands and the resulting increases in human–wildlife conflicts (e.g., problems with garbage or pets, livestock predation, poaching). For example, the reintroduction of the gray wolf to the Yellowstone region in 1995 has been very controversial and the ecological and management implications are still being debated. Wildland protected parks also face differing management mandates on adjacent federal or state land that allow for resource extraction (e.g., logging, mining, livestock grazing). For example, Mojave and Glacier have recently had large wind energy projects proposed in their surroundings, and logging on public land surrounding Mount Rainier and Crater Lake is likely to continue. There is an opportunity for public-land managers to work together to ensure resource extraction occurs in areas that will not disrupt key ecological processes or crucial habitats (e.g., migration corridors or wintering grounds). Finally, there may be some opportunities to expand protected-area boundaries to include other adjacent federal lands deemed crucial for ecosystem intactness and/or unsustainable for resource extraction.

At this time, the Wildland developable parks have seen relatively less development in their surroundings than other classes. For many of the parks, including El Malpais, Big Bend, and Organ Pipe Cactus, this is likely due to their desert remoteness. However, other parks such as Olympic and Redwood are largely undeveloped because much of their PACE consists of private timber lands. Management of surrounding lands for rotational timber harvests may be preferable to conversion to agriculture or housing developments for maintaining ecological integrity of the parks; although rates of resource extraction on private land are largely market driven and the amount of land in mature forest at any given time can vary widely (Turner et al. 1996). Impacts on water resources and on species that require mature forests also need to be considered. There may be opportunities to purchase or swap for private land in areas identified as especially important to ecological processes, as some recent projects involving federal and private lands has shown (see The Montana Legacy Project; *available online*).[9] The implementation of conservation easements on crucial lands may also be an effective conservation tool.

[9] ⟨http://www.nature.org/wherewework/northamerica/states/montana/⟩

Parks surrounded with large amounts of agricultural land (i.e., Buffalo River, Lake Roosevelt, Missouri River, Saint Croix, and Theodore Roosevelt) have several unique challenges and opportunities. The use of fertilizers, herbicides, and insecticides on farms may pollute water and air at downstream or downwind parks. For example, agricultural runoff has been identified as a source of pollutants at several of these parks, including Saint Croix and Missouri, and at Buffalo where livestock operations were identified as a source of pollution (NPS Water Resources Division 2010; *available online*).[10] Invasive weeds respond well to nutrient enrichment of agricultural fields (Mohler 2001), and fallow or abandoned fields can become source populations for weeds that eventually make their way into adjacent protected areas. Several of these parks are also river corridors that have additional threats from non-native plants and invertebrates that spread rapidly along the river. Finally, large areas of uninterrupted agriculture can reduce connectivity among remaining patches of natural habitat, especially if suburban or exurban developments are also interspersed in the landscape. As evidenced by several parks such as Shenandoah and Delaware Water Gap, which shifted from Agricultural to Exurban classes, there is often pressure to sell marginally productive farmlands near protected areas to housing developers. However, this can also provide conservation opportunities where potentially ecologically valuable land may be purchased or placed under conservation easement and protected or restored.

Exurban and Urban parks have many similar challenges though the challenges may be more extreme in urban parks. Most urban and exurban parks have lost, or are in danger of losing, their apex predators, whether it was due to predator control efforts in the 19th and 20th centuries (e.g., eastern cougar in Great Smoky Mountains) or habitat loss today (e.g., Florida panther in Everglades/Big Cypress). Often, once these predators are removed there is an irruption of mesopredators (e.g., skunks, raccoons, opossums, coyotes) that were previously held in check by apex predators. Mesopredator releases can create additional pressure on their prey species such as birds, reptiles, and amphibians (Prugh et al. 2009) and potentially disrupt food webs. Another challenge is maintaining connectivity in the presence of increased development. For example, populations of bobcats and coyotes on separate sides of a freeway in Santa Monica Mountains were found to be genetically different from each other because of the obstacle created by the freeway (Riley et al. 2006). Many of the Exurban parks in the eastern United States have been shown to be isolated from other undeveloped land (Goetz et al. 2009). Protected areas are often popular recreation destinations for people living in nearby urban areas and recreational activities can have negative effects on vegetation and wildlife populations (Knight and Gutzwiller 1995). The often close association between housing and wildland in exurban settings also introduces the potential for wildlife interactions with pets and the diseases they can carry. Invasive species are an important concern for these parks because of the amount of disturbed area and roads that facilitate growth and transport of non-native species. Urban areas often generate large volumes of polluted runoff and smog, which can affect parks located downstream or downwind. At Great Smoky Mountains, air pollution is harming native plants, contaminating streams and soils, and hindering scenic views (NPS, Air Resources Division 2009). Parks within exurban and urban settings face the largest challenges in maintaining functioning ecosystems.

Land managers can take advantage of unique conservation opportunities in urban and exurban areas. To counteract the effects of continued development and loss of connectivity Santa Monica Mountains, in conjunction with private land conservation groups, have modeled future development scenarios to identify, and eventually purchase, vital habitat areas (Swenson and Franklin 2000). This approach may be desirable for other Urban and Exurban parks as well. Urban, and to a lesser extent Exurban, parks often have active conservation organizations within their surrounding communities that recognize the importance of maintaining the protected area and can often provide needed funding for conservation efforts outside the park.

The land use classification approach used here can be applied to protected areas globally, though the immediate threats and rates of development may be different. Many countries collect demographic and socioeconomic data that can be used in a similar way as we did here. In addition, remote-sensing data of land cover, and in some cases, land use change, are now available globally. A multivariate approach allows protected-area managers to identify similar trends and threats across their management units. The approach can provide evidence for protected-area managers and decision makers of the vulnerabilities faced by individual units, while placing them within a larger management context.

Our work shows that some protected areas are experiencing similar patterns in development on surrounding lands, and thus, may require similar management approaches. Park managers can use the specific management challenges and opportunities identified for each group to collaborate with parks with similar challenges. The results for each park also provide an overview for park managers about how severe land use changes are surrounding their park compared to other parks. If one park is known to have problems associated with outside development and another park is on the same development trajectory, then managers at that park can start planning for similar challenges. In particular, many parks are experiencing rapid increases

10 ⟨http://www.nature.nps.gov/water/horizon.cfm⟩

in exurban and urban housing densities, often at the expense of undeveloped or agricultural land. Quantifying current land use around protected areas is important for assessing vulnerability to loss of diversity, tracking trends, prioritizing research, and implementing cooperative management.

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APPENDIX A

Figure showing final park units used in analysis and table of park areas, protected-area centered ecosystem (PACE) areas, and PACE : park ratios (*Ecological Archives* A021-148-A1).

APPENDIX B

Table describing criteria used in PACE delineation and table of known impacts of land use variables on ecological systems (*Ecological Archives* A021-148-A2).

APPENDIX C

Silhouette widths and partana ratios for a selected number of clusters and a table summarizing the potential conservation challenges and opportunities for each final land use class (*Ecological Archives* A021-148-A3).