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A multi-scale assessment of local and contextual threats to existing and potential U.S. protected areas

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ABSTRACT

Assessing threats to protected areas is a critical step to ensure effective resource conservation and to leverage future conservation actions. It is equally important to assess external and internal threats because human activities both in and around a protected area can impair the area's ecological goals or impart important ecological benefits to adjacent lands. We applied a threat framework that accounts for both local and surrounding threats to identify areas in the conterminous United States that provide or offer opportunities for ecological conservation. We find that, of the lands that are least threatened locally, 49% have some existing formal protection, but that more than 35% of the existing protected portfolio is at risk from external threats. However, over 20% of currently unprotected lands provide potential opportunities for conservation. Of the area identified with highest potential conservation opportunities, over 50% is on private lands, highlighting the need to engage owners of private land in conservation. There is greater potential for large, buffered, core conservation areas in the West, but other areas require networks of stepping-stone conservation islands. We summarize our results by ecoregions and within 40 national parks, identifying areas that are notably unthreatened (Colorado Plateau and Northwestern Glaciated Plains ecoregions and Great Basin and Canyonlands parks) versus those that may require more intense management actions (Eastern Great Lakes and Hudson Lowlands and Southeastern Wisconsin Till Plains ecoregions and Cuyahoga Valley and Great Smoky Mountains parks). Finally, we discuss how the approach could be applied and improved for finer-grained, local assessments.

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1. Introduction

Lands that are protected with formal, permanent protection from conversion of natural land cover and managed in whole or in part for conservation purposes (Jennings, 2000) provide valuable ecosystem services and habitat (Millennium Ecosystem Assessment, 2003; UNEP, 2003) and serve as critical leverage points for future conservation actions (Margules and Pressey, 2000). The current system of protected areas is important but not sufficient for biodiversity protection (Andelman and Willig, 2003; Newmark, 1985). Maintenance of natural processes within protected areas often relies on the existence of surrounding "buffer" lands (Hansen and Rotella, 2002; Wiens et al., 2002; Williams et al., 2005). Alternatively, human activities in the surrounding landscape may threaten the protected area by effectively reducing its size, disrupting ecological flows, removing crucial habitat outside of the protected area, and increasing human disturbance at the boundary edge (Hansen and DeFries, 2007; Noss and Harris, 1986; Parks and Harcourt, 2002). Further, future conservation options may be limited by threats from the surrounding landscape (Cole and Landres, 1996; McDonald et al., 2008; USGAO, 1994).

Assessing the number and intensity of threats to an area is recognized as a critical component in measuring protected area effectiveness (Ervin, 2003; Hockings, 2003; Margules and Pressey, 2000; Parrish et al., 2003; Salafsky and Margoluis, 1999) and in conservation prioritization frameworks (e.g., Abbitt et al., 2000; Murdoch et al., 2007; Wilson et al., 2006). Here, we define threats as human activities that may cause the destruction or impairment of ecological resources or processes (after Salafsky et al., 2008), and we ground our discussion of threats on a comprehensive list of threats to protected areas, the Conservation Measures Partnership, developed by a consortium of non-governmental organizations, led by the International Union for Conservation of Nature (IUCN, 2006; Table 1).

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Table 1
Threats to protected areas as identified by the Conservation Measures Partnership (IUCN, 2006), and the factors used in this study as proxy measures for the threats: development (*D*), agriculture (*F*), accessibility (*A*), and resource extraction (*E*).

Conservation Measures Partnership Level 1 Threat Classification (Level 2 detail examples; IUCN, 2006)	Proxy threat factors (*D*, *F*, *A*, *E*)
1. Residential & commercial development (housing & urban areas, commercial areas)	*D*
2. Agriculture & aquaculture (non-timber crops, livestock ranching)	*F*
3. Energy production & mining (oil and gas drilling, mining and quarrying)	*E*
4. Transportation & service corridors (roads & railroads, utility and service lines)	*A*
5. Biological resource use (hunting & collecting terrestrial animals)	*A*
6. Human intrusions & disturbance (recreational activities, work activities)	*A*
7. Natural system modifications (fire suppression, ecosystem modifications)	*D*, *F*
8. Invasive & other problematic species & genes (invasive non-native species, introduced genetic material)	*A*
9. Pollution (urban, industrial, and agricultural effluents, air-borne pollutants)	*D*, *F*, *A*, *E*
10. Geological events (volcanoes, avalanches)	Not considered
11. Climate change & severe weather (habitat shifts, droughts, flooding)	Not considered

Because threats from surrounding lands influence protected areas, effective conservation planning requires analysis of threats both within and surrounding protected lands (Reyers, 2004; Schonewald-Cox, 1988). In response, recent studies have emphasized how to better incorporate surrounding land use context into conservation planning analyses and frameworks (Cowling and Pressey, 2003; Goetz et al., 2004; Hamaide et al., 2009; Scott et al., 2004; Svancara et al., 2009; Theobald et al., 2000). The IUCN has also expanded its protected area categories to better incorporate working landscapes near protected areas (Locke and Dearden, 2005).

Assessing both local and contextual threats to protected areas provides an indirect means of estimating the conservation effectiveness of a protected area. For example, a small "island" protected area embedded within a highly modified landscape would be considerably less effective in maintaining ecosystem dynamics than a large area situated in a similar context (Hansen and DeFries, 2007; Janzen, 1983). The interaction of local and contextual systems in ecology inherently requires a multi-scale approach (Levin, 1998), particularly when trying to decipher the primary mechanisms of how human activities affect ecological patterns (O'Neill and Kahn, 2000). Although some studies have found that landscape characterization within a range of distances from protected lands are highly correlated (DeFries et al., 2005; Rivard et al., 2000), different threats operate at different scales (Schwartz, 1999), and so recent studies have considered threats at multiple extents surrounding protected areas (Joppa et al., 2008; Wiersma et al., 2004). However, focusing assessments primarily or even only on existing protected areas disregards the potential that currently unprotected areas may provide new conservation opportunities. Instead, analyzing the landscape context of threats and multiple scales throughout a study area using a moving-window analysis allows assessment of the complex interactions between local and contextual threats (e.g., Zaccarelli et al., 2008), and inherently accounts for variations in size, shape, and configuration of existing and potential protected areas.

In this paper, we frame the relationship between local threats and contextual threats at multiple scales by condensing the relationship into a tractable conceptual model that we term the "integrated threat matrix". The resulting matrix provides and effective structure to examine and communicate both existing protected area management strategies and future conservation actions. We apply the conceptual model to provide an assessment of lands in the conterminous United States (U.S.) that directly incorporates both local and contextual threats to identify lands that have the capacity or opportunity for protecting natural resources. We summarize our general findings and compare integrated threat categories within ecoregions and between unprotected and protected landscapes. To illustrate the use of our threat matrix, we provide more detailed discussion of the connection between the integrated threat matrix and potential ecological implications for terrestrial national parks, and discuss how the approach could be applied and improved for finer-grained, local assessments. Overall, we foresee direct applicability of this approach in improving and refining threat assessments and aiding land managers in conservation and restoration decisions.

2. Methods

2.1. The integrated threat matrix

We organize our analysis using a three-dimensional matrix, where a local threat index is on the *Y* axis and a contextual threat index is on the *X* axis, measured across multiple scales (*Z* axis; Fig. 1). Although the indices along each axis are continuous values, we show six primary categories in the matrix for simplicity. Placing an area in one of the matrix categories requires three steps: (1) assess local, in situ threats (*Y* axis); (2) assess nearby contextual threats (*X* and *Z* axes); (3) assess contextual threats at further distance (*X* and *Z* axes).

Comparing local and multi-scale contextual threats in the integrated threat matrix assists conservation planners in developing management strategies to increase the capacity for natural

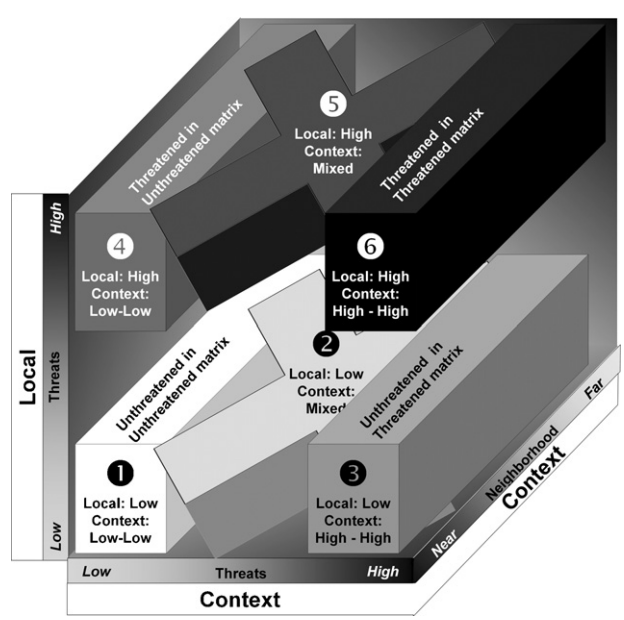

Fig. 1. (a) The integrated threat matrix as a conceptual model for comparing local threat index (*Y* axis) and contextual threat index (*X* axis) across multiple extents (*Z* axis). The conceptual model space represents a three-dimensional continuum. For summary, we grouped the matrix into six categories by comparing a given location's local threat value (low *or* high) and contextual threat value at each of two contextual distances (low *or* high at near *and* far). Generally, higher category numbers indicate increasing intensity of threats. Each successive category can be conceived as a transitional buffer between lower and higher categories. Categories suggest various conservation management actions.

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resource conservation. For example, a location with low local and low contextual threats at both near and far distances (category 1, Fig. 1) would be "unthreatened" areas in an "unthreatened" context. Protected areas in this category might be core conservation units, such as wilderness areas, and would best be managed to maintain current levels of resource conservation. Currently unprotected areas in this category might be priorities for future conservation. Alternatively, locally unthreatened areas surrounded both nearby and more distantly by threats (category 3) might be considered islands of conservation best managed as stepping-stone refuges. Lands with high local threats but embedded in an extensive unthreatened context (category 4) might be modified islands, such as a visitor center complex at the entrance to a protected area, and could be managed to contain local threats (e.g., parking lot designed to minimize runoff), or future conservation actions – interventions undertaken to achieve conservation goals (Salafsky et al., 2008) – could restore the area to core conservation land. Locally threatened lands in an extensively threatened context (category 6) could be managed to maximize conservation at finer scales (e.g., developed areas designed to provide fine-scale native plant and animal habitat) and minimize threats to neighboring areas at coarser scales (e.g., designed or managed to minimize light or air pollution).

Areas of transition where management could be targeted to ease threats from one level of intensity to the next could be identified as well. For example, lands where local threats were low but the context was mixed across distances (category 2) would serve as a buffer between categories 1 and 3, and could be managed to maintain natural process along the spectrum from conservation core to a conservation island. Lands in categories 3 and 4 would also serve as buffer between areas with low and high local threats. In general, managers could imagine increasing threat radiating out from category 1 lands as the landscape transitions along a spectrum from wilderness, to Wildland Urban Interface, to highly modified areas, with each step in category related to an increased step in disturbance intensity similar to the concentric ring buffers concept in reserve design (Batisse, 1997; Noss and Harris, 1986). In all instances, knowledge of threats would assist in targeting management actions to minimize management costs and to set more realistic conservation goals and objectives (Pressey et al., 2007).

2.2. Local threat index

To quantify the threat matrix, we use four factors that serve as surrogates for many of the Conservation Measures Partnership's identified threats (Table 1): development threats (D) based on housing densities, agricultural threats (F) based on fertilizer use, resource extraction threats (E) based on oil and gas wells and non-energy related mines, and threats related to accessibility (A) as a proxy metric for potential impacts from roads and associated human disturbance. Our surrogates include the primary threats to biodiversity and conservation (Czech et al., 2000; McKee et al., 2004; McKinney, 2002), and public land agencies have identified these factors as the most threatening to federal protected area resources (Fancy et al., 2009; USGAO, 1994). We assigned values to each of the four threat factors based on the threat intensity following other efforts to map human influence across space (e.g., Halpern et al., 2009; Sanderson et al., 2002; Theobald, 2010; Watts et al., 2007). For each of the threat factors, we calculated values for every 1-ha pixel in a grid of the conterminous U.S. using a Geographic Information System (GIS; ArcGIS v.9.3; ESRI, Redlands, CA).

To represent threats from development (D), we used housing density from the Spatially Explicit Regional Growth Model (SERGoM; Bierwagen et al., 2010; Theobald, 2005) as an indicator of the intensity of land use modification. Housing densities were calculated from US Census Bureau 2000 block level datasets (USCB, 2000), and block level housing units were spatially allocated to developable lands based on land cover, groundwater well density, and road accessibility. Because SERGoM data do not include commercial and industrial land uses and we wanted to include potential threats from these uses, we assigned lands categorized as medium and high intensity development in the 2001 National Land Cover Dataset (NLCD; Homer et al., 2004) the maximum housing density value from SERGoM within 1 km.

Table 2
Assumed average speeds of travel by road type used to calculate travel time from urban areas. Off-road travel speeds were adjusted by slope according to Tobler (1993).

Road type	Average speed (km/h)
Interstate highway	112
US Highway	88
Secondary (state and county)	64
Local	48
Four wheel drive	17
No roads (walking)	$6^{-3.5 \times \lvert \text{slope} + 0.05 \rvert}$

To represent threats associated with agriculture, we used a dasymetric mapping method (Mennis and Hultgren, 2006) to interpolate total nitrogen and phosphorous fertilizer use per county (average annual use from 1982 to 1991; NOAA, 1999) to five NLCD land cover classes (Homer et al., 2004). Classes 1 and 2 were cultivated crops and pasture, respectively, class 3 was developed open space, class 4 included developed low to high intensity, and to account for fertilizer use in tree farms, class 5 included all forest categories. Sufficient data for pesticide use were not available nationally, but we assume that fertilizer and pesticide use are correlated. We conducted the dasymetric mapping at 30-m resolution and aggregated the results using the mean to the 1-ha cell size.

To represent threats from roads and other difficult to measure human uses (e.g., recreation), we created an index of accessibility (A) by calculating travel time (minutes) from urban areas (USCB, 2000), based on anticipated travel speeds for specific road types (ESRI, 2005; Table 2). Off-road walking times were increased to reflect the slope of the terrain (Tobler, 1993). Because private lands are generally not accessible to the public, we added an additional 10% slope to all private lands before calculating travel times. We assigned lakes and reservoirs the median value of their nearest neighbors. We divided urban areas (USCB, 2000) into four categories, based roughly on quartiles (10–50 k; 50–100 k; 100–250 k; >250 k). For each city category, we calculated the median population. We then applied a standard GIS cost-distance algorithm (based on the underlying travel times as costs) from each of the four city categories. Finally, we took a weighted average of the four city category cost-distances, weighted by the median population of each category and inverted this index so that locations with the greatest travel times had the lowest threat factor value:

$$\text{Access}_i = \frac{1}{\sum_{c=1}^{4} P_{ci} * D_{ci} / \sum_{c=1}^{4} P_{ci}} \quad (1)$$

where P_{ci} and D_{ci} are the median population and cost distance, respectively, for city-size category $c = 1, \ldots, 4$ for cell i. This is a more robust estimate of threats from roads and associated accessibility (Nelson, 2008) because it differentiates the size of cities and roads and captures the topographic variability around roads as compared to simply measuring straight-line distance from roads (e.g., Riitters and Wickham, 2003; Sanderson et al., 2002; Watts et al., 2007).

Quantification of threats from extraction of natural resources (E) was hampered by sparse spatial data on extractive activities. We were unable to locate comprehensive datasets for some energy-related extraction (e.g., coal mines and uranium) or for timbering. However, because resource extraction tends to occur primarily near wildlands (Weller et al., 2002) and has substantial impacts, particularly on landscape connectivity (Berger, 2004), we used a standard

GIS point density algorithm to calculate the density (1 km radius) of oil and gas wells and for non-energy surface mines (data obtained from USGS, 1995, 2003, respectively). We used points to represent surface mines because data on actual mining footprints were unavailable.

To calculate a final, combined local threat index, we first log transformed (following Halpern et al., 2007) and rescaled each of the four threat factor values from 0 (low) to 100 (high):

$$\text{Local threat index}_i = \left(\sum_{f=1}^{4} \frac{\log_{10} TF_{fi}}{\max_{1 \le i \le n}(\log_{10} TF_f)} \right) * 100 \qquad (2)$$

where TF_{fi} is threat factor $f = 1, \ldots, 4$ for cell $i, \ldots, n$. Although it is common to convert raw values to ordinal classes (e.g., Sanderson et al., 2002; Woolmer et al., 2008), we retained the ratio values to maintain direct physical interpretation and to ensure that we did not violate the additivity axiom (e.g., a difference between 1 and 2 is the same as between 2 and 3) following the recommendations of Schultz (2001) and Hajkowicz and Collins (2007). The threat factors were correlated (Spearman Rank Correlations: $DvA = 0.47$; $DvF = 0.41$; $FvA = 0.39$; $DvE = 0.08$; $AvE = 0.06$; $FvE = 0.02$), but each represented a different aspect of potential threats. Because we wanted to show where multiple threats overlapped, we chose to retain all four threat factors. Finally, we summed the four threat factor values within each cell and again rescaled summed local threat index from 0 to 100 within Omernik level 2 ecoregions (Fig. 2a; CEC, 1997). Summing the four threat factor values avoided the need to make arbitrary threat weighting decisions and resulted in a measure of comparative combined risk for each pixel in the conterminous U.S.

2.3. Context threat index

We calculated the spatial context of threats using a standard GIS rectangular moving-window tool, assigning the median of the local threat index found in the neighborhood back to each focal cell. We used the median because it is readily calculated using standard GIS tools and is less influenced by extreme values compared to the mean. We calculated the context threat value within distances of 0.5 and 10 km from a cell (rectangular neighborhoods of 1 and 400 km^2, respectively) to represent "near" and "far" on the Z axis of the integrated threat matrix (Fig. 1), respectively. We chose these as arbitrary but sensible distances to capture both immediate and more remote threats. Additionally, the 10 km distance is commonly used (e.g., Wiersma et al., 2004; Wittemyer et al., 2008) and is approaching the computational limit for calculating a moving window median on 1-ha grid cells for the entire U.S. using standard GIS tools.

2.4. Integrated threat matrix categories

To classify cells into the six integrated threat matrix categories, we used the national median to divide the local threat index into low and high (local low $\le 32 <$ local high). We then calculated the median of the 0.5 and 10 km context threat indices associated with both the low and high local threat index to divide each of the context scales into low and high (0.5 km median associated with local low index = 24, 0.5 km median associated with local high index = 43, low 10 km median = 25, high 10 km median = 43). We used these medians as thresholds to place all lands into one of the six integrated threat categories for mapping. For example, any cell that had a local threat index ≤ 32, a 0.5 km context threat index ≤ 24, and a 10 km context threat index ≤ 25, was assigned to category 1, whereas any cell with a local threat index > 32, a 0.5 km context threat index > 43, and a 10 km context threat index ≤ 43, we placed into category 5.

2.5. Protected versus unprotected lands

We compared the integrated threat categories against protected and unprotected lands to indirectly assess the effectiveness of existing protected areas and to estimate the amount of currently unprotected land that could potentially provide conservation opportunities. We defined protected areas based on GAP (U.S. Geological Survey's Gap Analysis Program) stewardship levels. GAP stewardship level 1&2 lands are assumed to be perpetually protected from development and managed primarily for conservation purposes. GAP stewardship 3 lands are permanently protected but may be subjected to extractive uses. GAP stewardship level 4 lands (private, unprotected) have no formalized conservation protection (Jennings, 2000). We refer to level 4 lands as "unprotected" here, although many such lands may be well stewarded and have higher capacity for conservation than some lands defined as "protected".

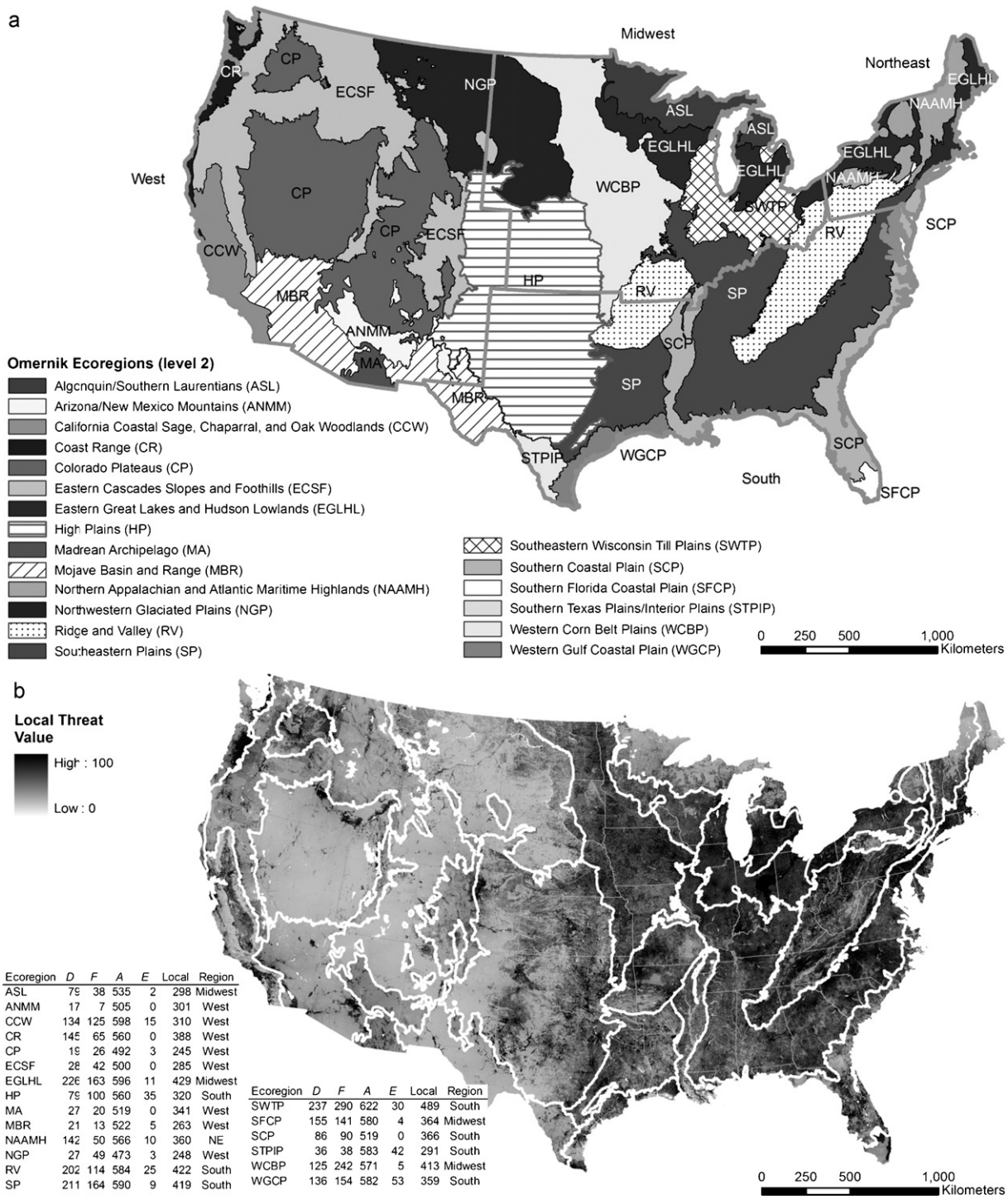
We obtained GAP stewardship level data from the Protected Area Database (PAD; CBI, 2006), which compiles spatial data from state or regional GAP projects. We updated PAD with more recent and detailed data where available, including for California (2004), New England (TNC, 2006), South Dakota (2002), and Colorado (CoMap; Theobald et al., 2007). All of these data sources included at least partial information on privately owned lands held in conservation easements and other perpetual protective covenants, and we assigned these lands a stewardship level of 3. We converted GAP stewardship level 1, 2, or 3 lands that were smaller than 10 ha to stewardship level 4 to remove noise from our analysis.

As examples of highly protected lands (GAP stewardship level 1&2), we summarized integrated threat categories for 40 predominantly terrestrial national parks in the conterminous U.S. For four pairs of parks chosen along a gradient of small to large, we provided additional analysis, comparing the average of the local threat value and the percent area in either integrated threat category 1 and 2 or 3 at multiple distances within (0.5 km increments up to 5 km) and outside of (1, 2, 3, 4, 5, 7.5, and 10 km) the park boundary.

3. Results

3.1. Local threat index

Local threat index values vary throughout the U.S., with an extensive swath of lands with relatively low index values in Nevada and along the Rocky Mountain West (Fig. 2b). The development threat factor has a particularly strong effect in the East and just inland of the West Coast. Particularly urbanized ecoregions include the Eastern Great Lakes and Hudson Lowlands (EGLHL), Ridge and Valley (RV), Southeastern Plains (SP), and the Southwestern Wisconsin Till Plains (SWTP; as illustrated by the table of mean values for each threat factor for each ecoregion shown in Fig. 2b). Agricultural threats dominate the upper Midwest, Central Valley of California, and the southeastern corner of Washington, with particularly high mean values in SWTP and Western Corn Belt Plains (WCBP) ecoregions, as well as in EGLHL, SP, and the Western Gulf Coastal Plain (WGCP). Although mean accessibility threat values are similar across ecoregions, there is significant variability within ecoregions. As expected, threats from accessibility radiate out from cities, but are particularly noticeable in areas with otherwise low threat factor values but that are near metropolitan areas, such as along the Front Range of the Rocky Mountains in Colorado and the Sierra foothills in California. Resource extraction threats are particularly noticeable in the states of Indiana, Kansas, Oklahoma, Ohio, Pennsylvania, Texas, and West Virginia, and the High Plains (HP),



Ecoregion	D	F	A	E	Local	Region
ASL	79	38	535	2	298	Midwest
ANMM	17	7	505	0	301	West
CCW	134	125	598	15	310	West
CR	145	65	560	0	388	West
CP	19	26	492	3	245	West
ECSF	28	42	500	0	285	West
EGLHL	226	163	596	11	429	Midwest
HP	79	100	560	35	320	South
MA	27	20	519	0	341	West
MBR	21	13	522	5	263	West
NAAMH	142	50	566	10	360	NE
NGP	27	49	473	3	248	West
RV	202	114	584	25	422	South
SP	211	164	590	9	419	South

Ecoregion	D	F	A	E	Local	Region
SWTP	237	290	622	30	489	South
SFCP	155	141	580	4	364	Midwest
SCP	86	90	519	0	366	South
STPIP	36	38	583	42	291	South
WCBP	125	242	571	5	413	Midwest
WGCP	136	154	582	53	359	South

Fig. 2. (a) Omernik level 2 ecoregions as used in this analysis and their abbreviations. Census region boundaries (West, Midwest, South, Northeast) are shown in grey for reference. (b) The local threat value calculated as the sum of four threat factor values (*D* – development, *F* – agriculture, *A* – accessibility, *E* – resource extraction), rescaled within the Omernik level 2 ecoregions. Local threat index values ranged from a minimum of 0 (lighter areas, lowest threat) to a maximum of 100 (darker areas, highest threat). Ecoregion boundaries are shown in white and state boundaries are shown in grey for reference. Mean values for the four threat factors and the local threat value are shown for each ecoregion (with census region listed based on majority of ecoregion).

RV, SWTP, Southern Texas Plains/Interior Plains (STPIP), and WGCP ecoregions.

Because we rescaled the local threat index by ecoregion, each ecoregion is mapped as having a high local threat value in some area (Fig. 2b). But the most threatened ecoregions, based on taking the mean local threat value (see table in Fig. 2b), include EGLHL, RV, SP, SWTP, and WCBP, which are all located primarily in either the Midwest or South census regions.

3.2. Integrated threat matrix categories

Mapping integrated threat categories from the matrix follows the pattern of the local threat index values with unthreatened lands in an unthreatened context running along the Rocky Mountains and in Nevada (category 1; 22% of the U.S.; Fig. 3a). Category 6 lands (threatened in a threatened context; 17% of the U.S.) are primarily collocated with urban areas, as would be expected.

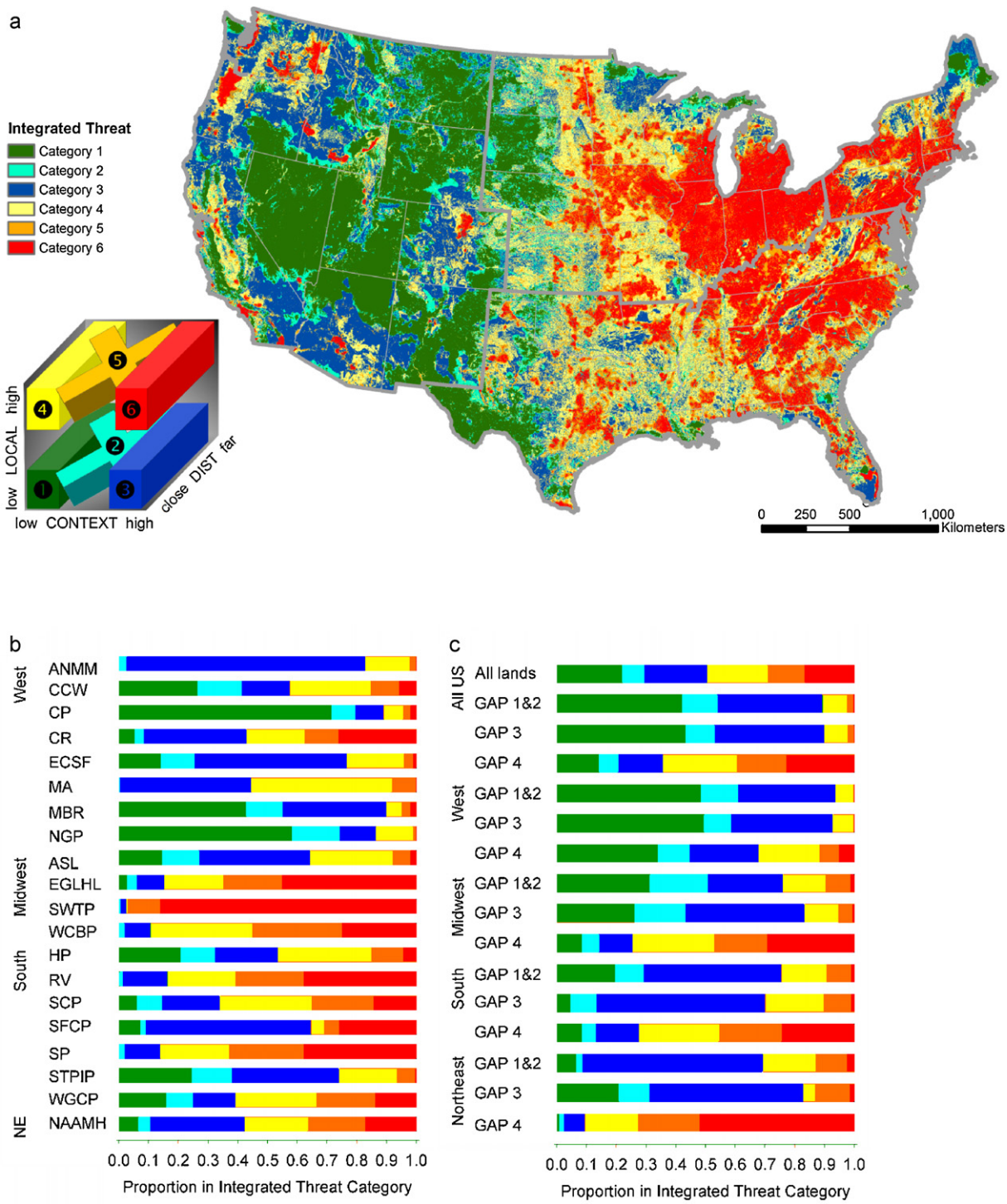


Fig. 3. (a) Integrated threat matrix categories mapped for the U.S. National parks are outlined in purple, and states (thin) and census regions (thick lines) are in grey for reference. (b) Integrated threat category summary for Omernik level 2 ecoregions, ordered alphabetically within census regions. Abbreviations are defined in Fig. 2a. (c) Integrated threat category summary for GAP stewardship levels 1&2 (permanently protected and managed primarily for conservation purposes), 3 (permanently protected with some extractive uses) and 4 (private, unprotected) for all U.S. and within census regions. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

Although results demonstrate substantial heterogeneity throughout the U.S., in general, lands in the eastern half of the U.S. are more likely to have high local threats (integrated threat categories 4–6), while western lands are more likely to have low local threats (matrix categories 1–3). This trend remains evident when summarizing by ecoregions (Fig. 3b), with western ecoregions having greater proportions of area in integrated threat categories 1–3 (0.82), while southern and Midwestern ecoregions have substantial proportions in categories 4–6 (0.81 and 0.68, respectively). The one ecoregion with the majority of its area in the Northeast (NAAMH) is about equally split between local low and local high threats (categories 1–3, 0.42; categories 4–6, 0.58). Notable ecoregions with low integrated threat include Colorado Plateaus (CP), Mojave Basin and Range (MBR), and Northwestern Glaciated Plains (NGP), while the Eastern Great Lakes and Hudson Lowlands (EGLHL), Southeastern Wisconsin Till Plains (SWTP),

Ridge and Valley (RV), and Southeastern Plains (SP) ecoregions are likely highly threatened with substantial area in categories 5 and 6. Recall that local threat index values were rescaled within each ecoregion, and thus, comparisons are relative.

3.3. Protected areas and potential conservation lands

Protected areas (GAP stewardship 1–3) have greater proportions of low local threat lands (integrated threat categories 1–3) than unprotected areas throughout the U.S. and in all regions (Fig. 3c). GAP 3 lands have nearly identical integrated threat category proportions as GAP 1&2 lands within the entire U.S. and the western and Midwestern census regions. In the South, GAP 3 lands have substantially less integrated threat category 1 (lowest threat) area than GAP 1&2 lands, while in the Northeast, the pattern is reversed. Although many of the areas considered protected have low local threat index values, many of them fall into integrated threat category 3, with high context threat value across multiple scales. About 14% and 6% of all unprotected lands in the U.S. are in integrated threat categories 1 and 2, respectively, with much of this unthreatened potential conservation area being in the West.

Summarizing results by national park (Fig. 4a), the vast majority of park area consists of integrated threat categories 1 or 2 (74%), but 21% of total park area is in category 3, suggesting that many parks are at risk from intense external threats, relative to the ecoregion in which they lie. Only 5% of total park area is in category 4, and less than 1% is in categories 5 or 6. There is only a weak relationship between park size and proportion of land in category 1 or categories 1 and 2 (logarithmic fit, $R^2 = 0.10$ and $R^2 = 0.09$, respectively, $p < 0.001$). There is, obviously, a strong relationship between size of park and area in category 1 or categories 1 and 2 (linear fit, $R^2 = 0.88$ and $R^2 = 0.91$, respectively, $p < 0.001$).

By region, parks in the Midwest are the least threatened, with the greatest proportion of category 1 lands followed by the West and South (0.86, 0.67, and 0.34, respectively). This pattern is similar when considering both category 1 and 2 lands combined (0.93, 0.79, and 0.38, respectively). But, when combining all lands in categories 1–3, the differences between regions is smaller (0.98, 0.96, and 0.85, respectively). The general patterns are not ubiquitous, however, as several parks in the West and Midwest have little category 1 or 2 land, including Crater Lake, Lassen, Mount Rainier, Rocky Mountain, Joshua Tree, and Saguaro parks in the West and Cuyahoga Valley in the Midwest. Conversely, in the South, Guadalupe Mountains and Big Bend parks have substantial proportion of their areas in categories 1 and 2.

Plotting both mean local threat value and the percentage of an area in each integrated threat category across multiple distances from a park boundary illustrates the relationship between the raw local threat index values and the categories. We provide this detail for eight parks in pairs of roughly similar sized parks (Fig. 4b–i). In most of the parks detailed, the average local threat value slowly increases approaching the park boundary; a reflection primarily of the accessibility threat factor value. Only parks that are substantially removed from urbanized areas do not show this trend (e.g., Bryce Canyon, Fig. 4c). Parks with relatively high local threat index values (relative to their ecoregion) have little or no category 1 or 2 lands at their interior, primarily having category 3 lands (e.g., Everglades, Fig. 4h) or category 3 and 4 lands (e.g., Great Smoky Mountains, Fig. 4g) within their boundaries. At the border, the local threat value increases for parks that are surrounded by external threats (e.g., Cuyahoga, Fig. 4b) or remains similar for those parks in a relatively unthreatened context (e.g., Bryce Canyon; Glacier, Fig. 4i). As local threat index values increase outside park boundaries, there is a corresponding drop in the amount of category 1,2, or 3 lands; the sharper the increase in local threats, the sharper the decline (e.g., Cuyahoga, Fig. 4b). The pattern of the integrated threat category plot shows the distribution of external threats. For example, Saguaro park has increased threats directly at its border (specifically, Tuscon, AZ), but then context slowly improves at greater distances (Fig. 4e), whereas the context surrounding the Great Smoky Mountains is continually threatened (Fig. 4g). Great Sand Dunes (Fig. 4d) has an immediate decline in category 1 and 2 lands at its border, with a continued decline at further distances because the park is surrounded by more intense agricultural use away from its boundary. Some of the uptick in the percent area in a given integrated threat category seen at greater distances is because they are being measured over larger and larger areas, but substantial changes are reflective of increased threats directly at a park's boundary.

4. Discussion

Despite much of the U.S. being locally or contextually threatened, many areas with conservation potential remain. Only 10% of each of GAP 1&2 and GAP 3 lands are considered locally threatened (categories 4–6) and less than 0.5% were in category 6 (locally and contextually threatened). Over 40% of both GAP 1&2 and GAP 3 lands are in category 1, which suggests they are relatively unthreatened lands in relatively unthreatened context (although, this does not speak to whether protected areas are ideally located for biodiversity conservation; see Scott et al., 2001). Nationally, integrated threat categories on GAP 3 lands are nearly identical to GAP 1&2 lands, and in the Northeast, GAP 3 lands may be less threatened than GAP 1&2 lands. This suggests that there is not an obvious relationship between greater protection and lower integrated threat. This would likely not be the case if threat factors better incorporated information on threats from grazing or timber harvest, among others, but those threats may be more easily reduced in the short-run with potential policy and management actions, as compared to threats from development or roads.

Western lands along the Rockies and in Nevada, and in the Colorado Plateau, Mojave Basin and Range, and Northern Glaciated Plains ecoregions likely provide the best opportunities for conserving large core areas buffered by unthreatening lands. However, these opportunities exist, to a lesser extent, throughout the rest of the country, especially in the Midwest region (which encompasses much of the Northern Glaciated Plains ecoregion). Private lands make up a substantial proportion of relatively unthreatened areas, demonstrating that a focus solely on the existing protected area portfolio would overlook substantial opportunity for conservation.

Formalized protection of most of the currently unprotected lands that are least threatened (integrated threat category 1; 14% of the U.S.) is unlikely given ownership patterns and competition for natural resources (Shafer, 1994; Margules and Pressey, 2000). This highlights the need to engage in conservation of private lands through local land trust activities as well as federal programs such as the Conservation Reserve Program (Higgins et al., 2007; Maestas et al., 2003; Theobald and Hobbs, 2002). This is particularly critical for providing buffers (lands identified here in category 2 or 3) surrounding core conservation lands (category 1). However, the map of integrated threat categories (Fig. 3a) also makes clear that the conservation approach of large cores surrounded by buffer is unviable for much of the country. Small areas of relatively unthreatened lands, whatever their context, should be considered as networks of stepping-stone conservation areas, particularly in the South and Northeast, but throughout the West and Midwest as well. Beyond conservation partnerships with private landowners, public education of those living in communities that are near small conservation areas may create an ecologically informed public, improving conservation in both protected and unprotected ecosystems (McKinney, 2002).

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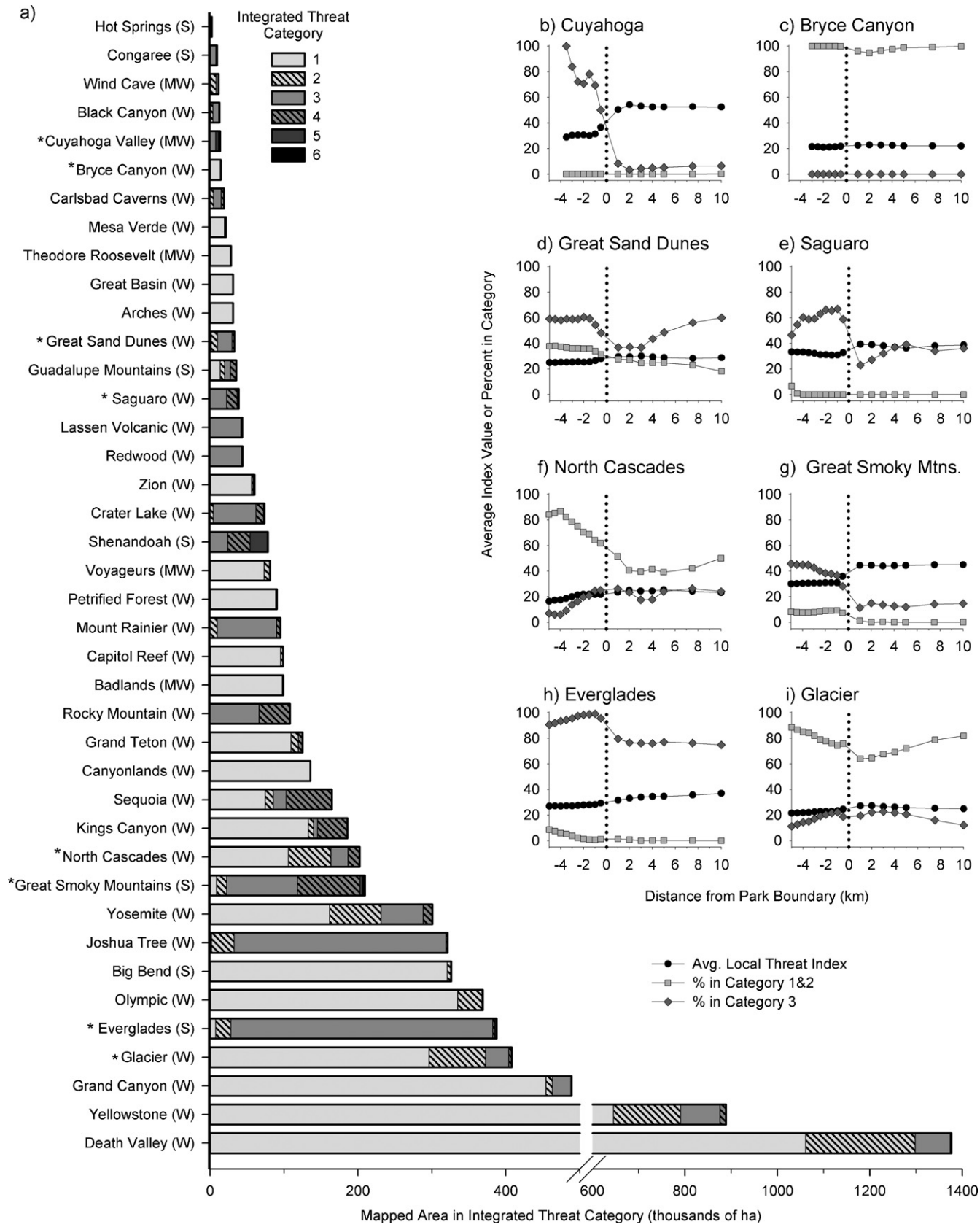

Fig. 4. (a) Integrated threat category summary for each national park ordered from smallest to largest (census region in parentheses next to park name). Asterisk next to park name denotes parks detailed in (b)–(i). (b–i) Four park pairs, based on park size, comparing average local threat index (black circles), percent in integrated threat category 1&2 (light grey squares), and percent in category 3 (dark grey diamonds) by distance from park boundary. Negative distances are within park and positive distances are outside.

Although there was no clear relationship between proportion in each integrated threat category and size of a national park, size of a reserve does matter. We suggest only lands in category 1 or 2 are potentially functional conservation areas (and perhaps only category 1 depending on the intensity of the external threats); if so, 44% of all GAP stewardship level 1 or 2 protected areas do not meet this criterion. This likely has serious implications for the effective size of conservation areas. It is questionable that the smallest parks (Fig. 4a) provide sufficient area for most dynamic processes or species requiring large-extents to meet their minimum habitat needs. Further, in our analysis, many of these small parks suffered the "double jeopardy" (Parks and Harcourt, 2002) of being embedded in a threatened context and effectively made even smaller with substantial area affected by external threats (e.g., Black Canyon [of the Gunnison], Great Sand Dunes, Saguaro, Lassen, Redwoods). Yet, the benefit of greater size is also "contingent on context" (Wiens, 2009, p. 1057) and moderate-sized (e.g., Crater Lake, Shenandoah, Mount Rainier, Rocky Mountains, Sequoia, Great Smoky Mountains) and even some of the largest parks (e.g., Joshua Tree, Everglades) were substantially at risk from external threats. In these parks, both small and large, the dynamic area is reduced, likelihood of species extinction increases from either human-caused threats or catastrophic natural disturbances, and species at the top of trophic cascades may be lost (Hansen and DeFries, 2007).

Of course, smaller protected areas are likely to be more dependent on surrounding landscape for meeting habitat needs, including population sources and migration corridors (Hansen and DeFries, 2007), and small areas situated in highly threatened contexts (here, best illustrated by small areas of integrated threat category 3 or parks like Congaree or Cuyahoga) are likely the "patches" or "islands" conceived in the patch-matrix model of landscape ecology (Forman, 1995) or the island biogeography model of metapopulation dynamics (MacArthur and Wilson, 1967). But there are more areas where this is not the case, and our results show the vast heterogeneity of integrated threat categories. Overall, context is probably more important than size, as even the largest parks illustrate varying degrees of external threat. The gradient of edge effects intruding into protected areas illustrates the importance of context most clearly, as only those parks situated at the very furthest reaches from cities showed little exposure to human impacts at their borders regardless of size (e.g., Bryce Canyon as a small but distant park indicating few edge effects, Fig. 4c, versus larger parks indicating edge effects at various depths within their boundaries: North Cascades, Fig. 4f; Glacier, Fig. 4i). Where edge effects are dominant, maximizing reserve effective area will require management to reduce threats at protected area borders (Woodroffe and Ginsberg, 1998). An important implication, therefore, is that focusing management in the surrounding landscape may have substantially greater influence on conservation targets than management within the protected area (e.g., Baeza and Estades, 2010).

Our work expands on previous threat assessments in several ways. First, we provide an improved estimate of human modification by including an accessibility index that goes beyond simple road buffers, and our development factor quantifies threat associated with a range of development density as opposed to ordinal categories. Although we relied on only four threat factors, the broad patterns of our local threat index values results are similar to "human footprint" assessments across a range of scales that rely on a greater number of inputs (e.g., Leu et al., 2008; Sanderson et al., 2002) because we capture the dominant threats (Woolmer et al., 2008). However, a non-trivial result of our work is that we map local threats with finer grain and incorporate more relevant measures (such as including a more robust estimate of threats from roads), across the entire conterminous U.S., and we do so under a method that is more accessible to land managers by requiring fewer data inputs. Second, we explicitly distinguish local from contextual threats, a critical component of conservation planning (Reyers, 2004; Schonewald-Cox, 1988). Third, we conduct threats assessment across all lands, not just outside of existing protected areas, to assess effectiveness of both existing and potential conservation lands, two key steps in systematic conservation planning (Margules and Pressey, 2000; Pressey and Bottrill, 2008). Fourth, we use a multi-scale approach, providing greater understanding of interactions between anthropogenic actions and ecological impacts (O'Neill and Kahn, 2000). We know of other multi-scale mapping exercises to map disturbances (Theobald, 2010; Wade et al., 2009; Zaccarelli et al., 2008; Zurlini et al., 2006), but placing our multi-scale analysis into the integrated threat matrix framework provides a more systematic approach for suggesting management options. For comparison, we tested using a clustering approach (k-means after Zaccarelli et al., 2008), and found that clusters represented only the diagonal of the integrated threat matrix (e.g., local-context threat value pairs such as low and low, medium and medium, high and high) as opposed to representing the full three-dimensional space. Finally, we combine all of these improvements into a parsimonious yet robust approach to provide additional insight for coarse-scale conservation planning. This is the first integrated (considering both in situ and contextual) threat assessment conducted at such a fine-grain for the entire conterminous U.S. These methods, and the results, help address critical information gaps that have been identified by the Western Governors' Association Wildlife Corridor Initiative (WGA, 2009), climate and land use change risk assessments (Glick et al., 2009), the Department of Interior's Landscape Conservation Cooperatives (NEAT, 2006), and the Bureau of Land Management's Rapid Ecological Assessment effort.

As with all broad-extent analyses, results should only be interpreted at the broad-extent, but our framework could be applied at successively finer scales for more detailed local conservation planning. An analysis applied at finer-scales (extent and grain), improved by the use of richer, more detailed data, would allow land managers and conservation planners to calibrate and apply the framework as necessary to achieve local conservation goals (Hockings, 2003). For example, both knowledge of and data for threats more directly linked to ecology or impacts to specific conservation targets are likely available locally, threat factor values could be weighted based on this knowledge, and the size of the context neighborhoods should be threat-specific (Clemens et al., 1999) or species-specific (Schwartz, 1999). Additional context neighborhoods could be incorporated, or each threat could be measured at a different, appropriate scale, and various scales should be tested to avoid inference that is merely an artifact of the scale of analysis (Li and Wu, 2004). Further, given the more site-specific threat factor values, threat value thresholds that are ecologically relevant locally could be used to divide the integrated threat matrix into any number of management-type categories (here, we use the national median to divide the integrated threat matrix into six categories, but the conceptual integrated threat matrix is a continuum, and categorization approach could be tailored to the management question). At local extents, land managers could incorporate forecasted changes in threat status to provide an important temporal aspect to the assessment. Our approach could easily be used to test various land use change scenarios or identify lands that may most readily transition from one category to another. Finally, structural connectivity measures (e.g., Urban and Keitt, 2001; Wade and Theobald, 2010) could be incorporated into the local threat index values, or for species-specific analyses, functional connectivity could be assessed (Taylor et al., 2006).

There are three likely sources of inaccuracy in our results. First, results are sensitive to errors in our threat factors data which may be substantial at the national scale. Second, the choice of threat factors chosen here are not comprehensive; threats from climate change, water resource development, off-shore activities,

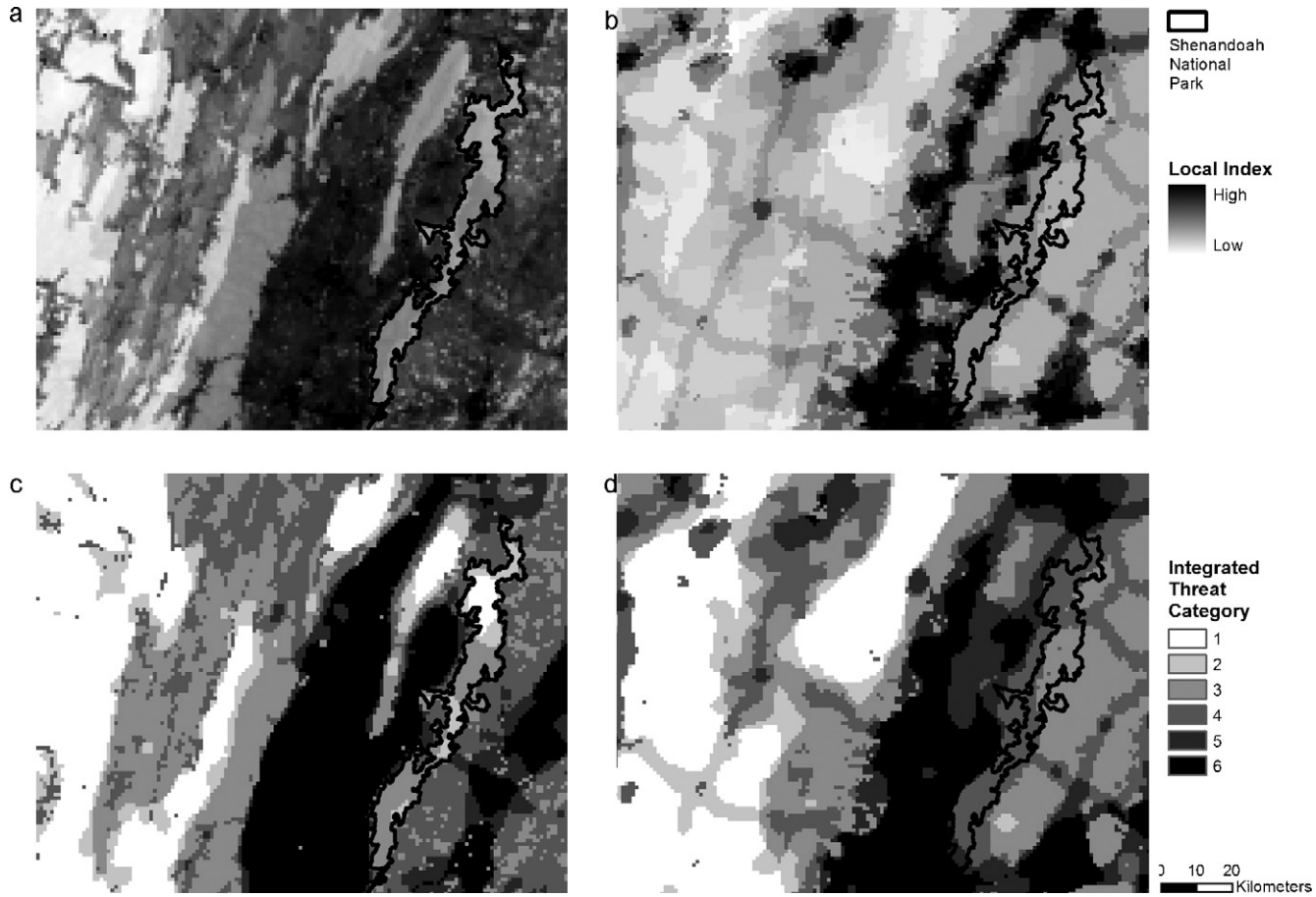

Fig. 5. (a) Local threat index (aggregated to match the 100-ha cell size of the Human Footprint data by taking the mean of the 1-ha cells in the original data) around Shenandoah National Park, compared to (b) the Human Footprint (Sanderson et al., 2002), and the results when mapping integrated threat categories based on (c) aggregated local threat index and (d) the Human Footprint. While general patterns remain, the comparison illustrates the dependency of the integrated threat categories on quantification of underlying threats.

and alternative energy development are among exceptions which might affect areas otherwise removed from threats. However, as mentioned above, threats are spatially correlated and this would likely be the case with numerous other commonly considered threats; including additional threat factors would likely only make threatened locations more threatened without changing the general patterns. Despite this, we acknowledge that our integrated threat categorization is dependent on the underlying quantification of threats. As an example, we compared resulting integrated threat categories when applying our matrix to a sub-region around Shenandoah National Park based on using the Human Footprint (Sanderson et al., 2002; Fig. 5b and d) versus using our quantification of threats (after aggregating local threat index values, using the mean, up to 100 ha cells to match the Human Footprint; Fig. 5a and c). Although general patterns remain, resulting integrated threat integrated threat categories are different. This underscores the need to follow any coarse-scale analysis with finer-scale scrutiny tied to local management needs. Third, this analysis is subject to the modifiable areal unit problem as are other GIS-based summaries (Jelinski and Wu, 1996). However, using a fine-grain (1 ha) unit of

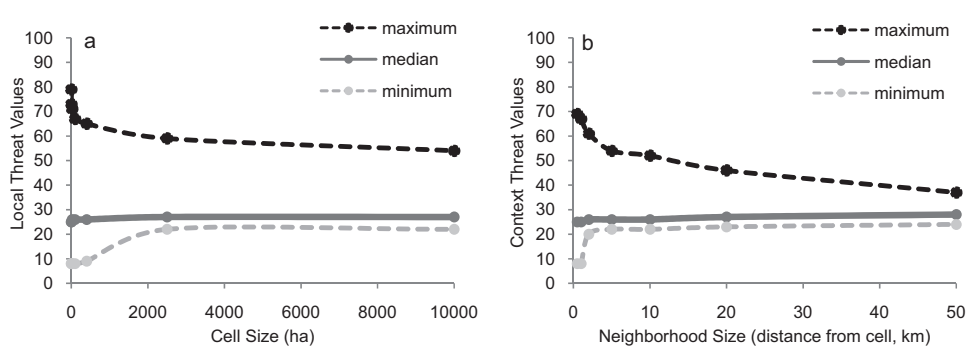

Fig. 6. (a) Maximum, median, and minimum local threat index corresponding to seven different cell sizes (original 1-ha cells, and mean aggregation of index values to 4, 25, 100, 400, 2500, and 10,000-ha cells). (b) Maximum, median, and minimum context threat index corresponding to seven different context neighborhoods (the original 0.5 and 10 km distances, and 1, 2, 5, 20, and 50 km from a cell). While the maximum and minimum index values change, the median, used for categorization in the integrated threat matrix, remains relatively constant. To show changes in minimum index values, all zero values were removed.

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analysis reduces many of these effects. Further, we used ecoregions and planning units (GAP stewardship levels) as aggregation units to maintain ecological and planning relevance. Finally, our approach appears fairly robust to the cell-size and to the size of the context extents (here 0.5 and 10 km from a cell) used for analysis. Although the maximum local threat value declined and the minimum local threat value increased when we tested seven different cell sizes (the original 1-ha cells, and 4, 25, 100, 400, 2500, and 10,000-ha cells, all created by aggregating the 1-ha cells using a mean), the median local value, which we used for integrated threat categorization, remained almost constant (Fig. 6a). Similarly, when we tested different context threat neighborhoods (0.5, 1, 2, 5, 10, 20, and 50 km from the focal cell), the median context index remained nearly constant, although the minimum and maximum index values changed relatively sharply (Fig. 6b). Thus, while there would be changes in the map of local or context threat value, the general patterns of integrated threat categorization would be largely unchanged.

Our national assessment as applied here is primarily an assessment of human modification, and a low risk from human influence is only one part of biodiversity protection (Sarkar, 1999). We conduct this analysis for the entire conterminous U.S. primarily as a first-pass assessment. For local-scale conservation planning, empirically linking spatial patterns of threats to ecological impacts would be an important extension of this analysis (Li and Wu, 2004). Here, we log transformed threat factor values based on our assumption that impacts associated with threats would likely be asymptotic. Further analysis would be required to test this assumption. However, we argue that applying our method to assess local and contextual threats at any scale can be used to extend existing approaches for risk assessment and identifying management strategies (Pressey et al., 2007) or as an improved input into other conservation planning and prioritization schemes (e.g., Davis et al., 2006; Ervin, 2003; Murdoch et al., 2007; Parrish et al., 2003; Wilson et al., 2007).

5. Conclusions

We find that 17% of the conterminous U.S. is threatened by human activities, such as housing development, agriculture, resource extraction, and transportation corridors, and those threats occur both internally and in the nearby and more distant surrounding landscape. The remainder offers potential opportunities for conservation, and over 50% of the U.S. could potentially function as core conservation areas or surrounding lands to buffer the cores from threats (integrated threat category 1 or 2). Of the lands with highest potential for resource protection (integrated threat category 1 or 2), 12% already has formal protection from substantial conversion of natural land cover (GAP stewardship level 1 or 2), while another 37% has some formal protection (GAP stewardship level 3). This leaves 51% of areas with lowest integrated threat (highest conservation potential) on private lands, illustrating the need to engage owners of private lands in conservation and stewardship. Although opportunities for adding large conservation areas to the existing protected area portfolio may remain in the West, conservation actions in other regions will likely require management of smaller stepping-stone refuges. However, expansion of the existing protected area portfolio will be difficult, and better management of the landscape adjacent to existing protected areas is imperative. Almost 50% of the most highly protected lands in the U.S. (GAP stewardship level 1&2) are likely threatened by human activities outside their borders. Our results illustrate the importance of considering multi-scale context in threats assessments for conservation planning. The integrated threat matrix provides a flexible framework that can be applied for generalized assessments or tailored to site-specific conservation planning when combined with local biodiversity information.

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