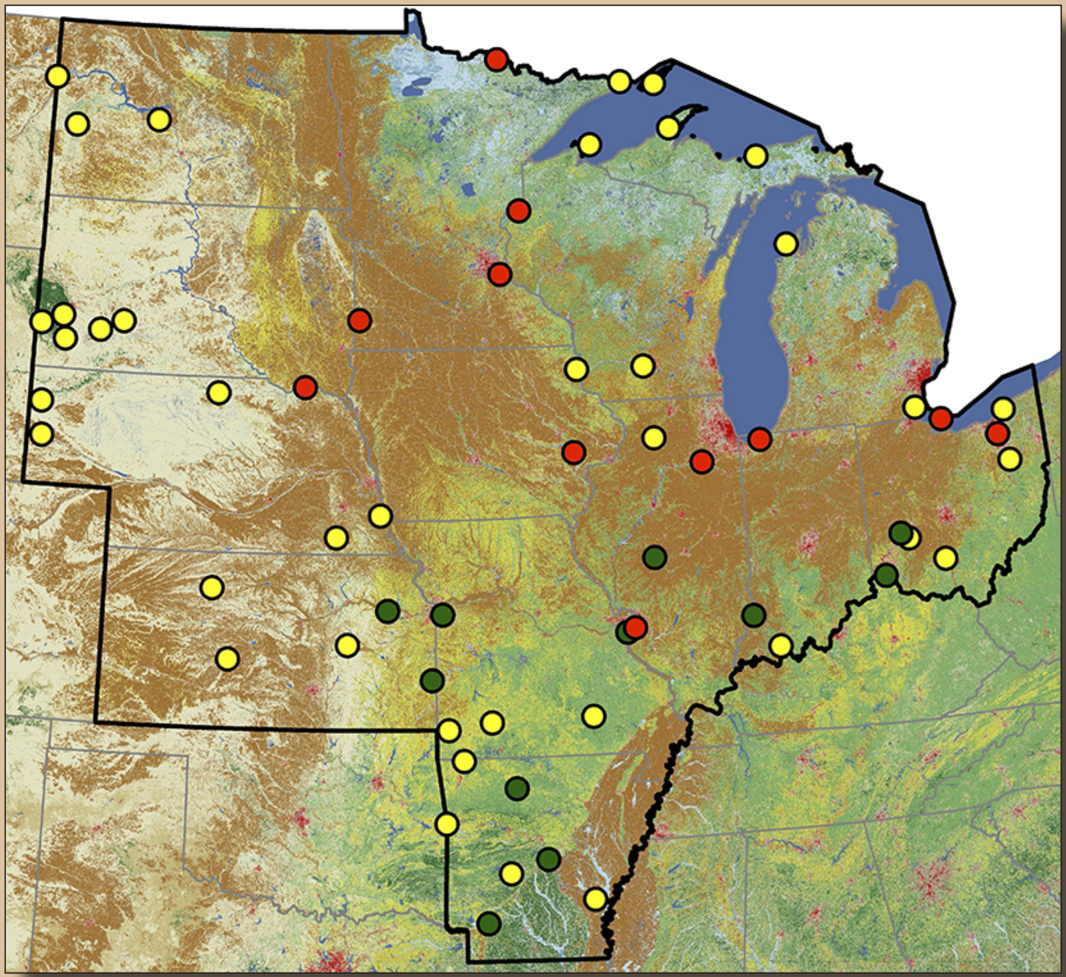
Prepared in cooperation with the National Park Service

Vulnerabilities of National Parks in the American Midwest to Climate and Land Use Changes



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Cover. Simplified map showing locations of national parks ranked high (red circles), medium (yellow circles), or low (green circles) relative to all American Midwestern national parks for vulnerability to a suite of climate and land use stressors (see fig. 3, p. 15).

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Vulnerabilities of National Parks in the American Midwest to Climate and Land Use Changes

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Abstract

Many national parks in the American Midwest are surrounded by agricultural or urban areas or are in highly fragmented or rapidly changing landscapes. An environmental stressor is a physical, chemical, or biological condition that affects the functioning or productivity of species or ecosystems. Climate change is just one of many stressors on park natural resources; others include urbanization, land use change, air and water pollution, and so on. Understanding and comparing the relative vulnerability of a suite of parks to projected climate and land use changes is important for region-wide planning. A vulnerability assessment of 60 units in the 13-state U.S. National Park Service Midwestern administrative region to climate and land use change used existing data from multiple sources. Assessment included three components: individual park exposure (5 metrics), sensitivity (5 metrics), and constraints to adaptive capacity (8 metrics) under 2 future climate scenarios. The three components were combined into an overall vulnerability score. Metrics were measures of existing or projected conditions within park boundaries, within 10-kilometer buffers surrounding parks, and within ecoregions that contain or intersect them. Data were normalized within the range of values for all assessed parks, resulting in high, medium, and low relative rankings for exposure, sensitivity, constraints to adaptive capacity, and overall vulnerability. Results are consistent with assessments regarding patterns and rates of climate change nationwide but provide greater detail and relative risk for Midwestern parks. Park overall relative vulnerability did not differ between climate scenarios. Rankings for exposure, sensitivity, and constraints to adaptive capacity varied geographically and indicate regional conservation planning opportunities. The most important stressors for the most vulnerable Midwestern parks are those related to sensitivity (intrinsic characteristics of the park) and constraints on adaptive capacity (characteristics of the surrounding landscape) rather than exposure to external forces, including climate change. Output will allow individual park managers to understand which metrics weigh most heavily in the overall vulnerability of their park and can be used for region-wide responses and resource allocation for adaptation efforts.

Introduction

Climate change is causing shifts in the geographic ranges, distributions, and phenologies of many species at faster rates than previously reported (Chen and others, 2011); these shifts have been documented on every continent and across most major taxa (Walther and others, 2002; Parmesan, 2006; Bellard and others, 2012). An environmental stressor is a physical, chemical, or biological condition that affects the functioning or productivity of species or ecosystems. In addition to climate changes, documented changes in land use and increases in invasive species are projected to continue and synergistically affect ecosystem function and biodiversity in national parks (Hansen and others, 2014). Nearly all U.S. national parks protecting natural resources have reported recent climates that are warmer than their historical range of variability (Monahan and Fisichelli, 2014). Parks and protected areas have fairly static boundaries; therefore, adaptation to potential future conditions is becoming an important emphasis for resource managers (Baron and others, 2009; Staudinger and others, 2012).

Globally, various biomes are more or less human-modified and are expected to respond differently to climate change (Millennium Ecosystem Assessment, 2005). Human modification of the landscape has been shown to affect the vulnerability and resiliency of ecosystems to climate change at the biome level (Gonzalez and others, 2010; Watson and others, 2013; Brown and others, 2014; Eigenbrod and others, 2014); in this study, we assessed the relative importance of climate and land use change stressors at a finer ecoregional scale within a few biomes in the American Midwest. Ecoregions are defined by similarities in geology, vegetation, climate, and soils. The United States Environmental Protection Agency (2011) employs a four-level, hierarchical classification system that subdivides nested ecoregions. The finest of these, Level IV, incorporates land use practices, and was used to summarize climate and land cover data in our study. The American Midwest is more variable than other U.S. regions in annual temperature and precipitation (Walther and others, 2002) and is particularly vulnerable because of the combined rates of climate and land use change (Orodonez and others, 2014) and its highly modified landscape (Watson and others, 2013). A study of 501 U.S. wildlife refuges determined that climate change vulnerability varied within and among biomes, with many of the most vulnerable refuges located in Midwestern biomes (Magness and others, 2011).

Like many wildlife refuges, most Midwest national parks are relatively small islands of mostly undeveloped land embedded in a matrix of intensive agriculture or urbanizing areas or adjacent to highly fragmented or rapidly changing landscapes; some parks are very small developed sites in urban areas. Within a regional context, Midwest park managers and policy makers need to understand the relative vulnerability of parks within their jurisdiction to climate change and other stressors to prioritize actions, allocate resources, and develop adaptation strategies. These decisions could be greatly informed by vulnerability assessments that consider and integrate resource sensitivities and adaptive capacities of parks along with climate change exposure (Monahan and Fisichelli, 2014). Managers need information regarding relative vulnerability of parks in the Midwest in order to prioritize regional actions related to park vulnerability. In other words, information is needed on more than the absolute values of park exposure to stressors, but also the range and relative rankings of Midwest parks to those stressors. In particular, by understanding the amount of deviation (percent change) from conditions for which parks have been managed for the past several decades or more, Midwest parks can be compared to each other and ranked according to which parks are projected to have the greatest relative vulnerability.

We conducted a relative vulnerability assessment of 60 units in the (U.S.) National Park Service Midwestern administrative region under two climate change scenarios: the middle-emissions A1B scenario and the high-emissions A2 scenario of the Intergovernmental Panel on Climate Change (Intergovernmental Panel on Climate Change, 2007a). Vulnerability analyses using a high greenhouse gas emissions scenario such as A2 explore impacts of continued dependence on fossil fuels; analyses using middle emissions scenarios such as A1B explore impacts that will require adaptation even without mitigation strategies in place (Hayhoe, 2013). Our study focused on vulnerability of natural resources, yet the National Park Service manages some parks that protect both natural and cultural resources; for example, historical battlefields or very small units such as the former homes of U.S. Presidents. All these parks face multiple stressors, including climate change, land use change, habitat fragmentation, and nearby human population growth. We included natural and cultural resource parks in the study, but 14 small parks with greater than 90 percent of their footprints identified as developed in the 2011 land cover data set (Jin and others, 2013) were treated differently. These 14 parks were not assessed for metrics relating solely to natural resource vulnerability.

Purpose and Scope

The purpose of this report is present results and rankings from a vulnerability assessment of 60 units in the National Park Service Midwest Administrative Region to multiple stressors under two future climate scenarios for the period 2080-2099. Parks included in the study are located in the states of Arkansas, Illinois, Indiana, Iowa, Kansas, Michigan, Minnesota, Missouri, Nebraska, North Dakota, Ohio, South Dakota, and Wisconsin.

Methods

Vulnerability Metrics

Vulnerability to climate change (and other stressors) has three components: exposure, sensitivity and adaptive capacity (Intergovernmental Panel on Climate Change, 2007a). Using data from multiple sources, we selected a total of 18 metrics at three scales (within park boundaries, within 10-km buffers surrounding them, and within the ecoregions that contain them) to calculate exposure (five metrics), sensitivity (five metrics), and constraints on adaptive capacity (eight metrics, table 1). We did not assess certain metrics for 14 parks whose footprints are greater than 90 percent developed, because those metrics relate to habitat or connectivity for biological resources; these include two sensitivity metrics and all of the constraints on adaptive capacity metrics indicated in table 1. Individual metric descriptions and calculations are detailed below, in sections describing the vulnerability components of exposure, sensitivity and constraints to adaptive capacity. For all calculations based on area, we measured area using an Albers conical equal area projection in ArcMap 10.1 (Esri, 1999–2012). For all metrics, a relative value on a scale of 0 to 1 was calculated from the range of observed values for all parks. Higher values indicate greater exposure, sensitivity, or constraint on adaptive capacity and are assumed to increase vulnerability.

Table 1. Metrics and sources for data used to calculate vulnerability components of exposure, sensitivity and constraints on adaptive capacity.

[GCM, global climate model]

Metric	Source
Exposure	
Ecoregional percent change from 1960–1990 for mean annual (1) temperature, (2) precipitation, and (3) moisture deficit (2 climate scenarios)	Ensemble means of 8 GCMs calculated under A1B and A2 scenarios (Girvetz and others, 2009)
Recent land use change within 10 kilometer buffer from 2006 to 2011	2006–2011 land cover change dataset (Jin and others, 2013)
Projected housing density change within 10 kilometer buffer (2 climate scenarios)	Integrated climate and land use scenarios calculated under A1B and A2 scenarios (U.S. Environmental Protection Agency, 2014)
Sensitivity	
Number of federally threatened, endangered, or candidate species in park	National Park Service internal data
Threatened or endangered species designated critical habitat in park	Environmental Conservation Online System (U.S. Fish and Wildlife Service, 2014)
Park proximity to biome boundaries	U.S. Environmental Protection Agency Ecoregion Level I (U.S. Environmental Protection Agency, 2011)
Limited topographic relief within park[1]	National Elevation Dataset (Gesch, 2007)
Degree of human modification within park[1]	*H*, degree of human modification (Theobald, 2013)
Constraints on Adaptive Capacity[1]	
Degree of human modification within (1) 10 kilometer buffer and (2) Level IV Ecoregion(s) containing park	*H*, degree of human modification (Theobald, 2013)
Percent unprotected areas within (1) 10 kilometer buffer and (2) Level IV Ecoregion(s) containing park	Protected areas database (U.S. Geological Survey Gap Analysis Program, 2012)
Limited topographic relief within (1) 10 kilometer buffer and (2) Level IV Ecoregion(s) containing park	National Elevation Dataset (Gesch, 2007)
Dissimilarity of land cover (1) inside park compared to 10 kilometer buffer and (2) inside buffer compared to Level IV Ecoregion(s)	2011 National Land Cover Data (Jin and others, 2013)

[1]Not calculated for parks with footprint greater than 90 percent developed.

Exposure

Exposure is a measure of the degree, magnitude, or rate of change a park is likely to experience (Glick and others, 2011); we selected metrics for projected future changes in climate and housing density, and for observed changes in land cover from 2006 to 2011 (table 1). Exposure metrics were measured in terms of percent change because we were interested in relative change, not absolute change, and deviation from conditions for which parks have managed for decades. For example, a small change in absolute precipitation in an area that typically receives very little precipitation can have quite a large effect on species adapted to the baseline conditions (Sala and Lauenroth, 1982). Exposure was calculated under two climate change scenarios (A1B and A2, Intergovernmental Panel on Climate Change, 2007b).

Climate Change

We acquired 4-km gridded reference period (1960–90) climate data from the Climate Wizard tool (Girvetz and others, 2009; climatewizard.org), which uses Parameter-elevation Regressions on Independent Slopes Model (PRISM) mapping system for downscaled historical climate data. We also acquired projected future climate data for late century (2080–99) percent change in annual temperature (degrees Celsius [°C]), precipitation (in millimeters [mm]), and moisture deficit (mm). Climatic moisture deficit measures the difference between precipitation and potential evapotranspiration (PET); stress occurs when there is greater evaporative demand than precipitation. Moisture deficit is calculated as PET minus precipitation (equal to zero if precipitation is greater than PET) and summed for all months for given time period (Wolock and McCabe, 1999). We used two future climate scenarios: A1B and A2 (Intergovernmental Panel on Climate Change, 2007a). The A1B scenario is a mid-emissions scenario, projecting a future with very rapid economic growth, a global population peak in mid-century followed by a subsequent decline, and rapid introduction of new and more efficient technologies. The A2 scenario is a high-emissions scenario with continuous increases in global population along with fragmented and slower technological changes in fuel sources and efficiencies (Intergovernmental Panel on Climate Change, 2007a). These data are from the World Climate Research Programme's Coupled Model Intercomparison Project phase 3 (CMIP3) multimodel dataset (Maurer and others, 2007). Although newer CMIP5 models and Representative Concentration Pathways (RCPs) are now available, they are similar to the CMIP3 models and scenarios (Knutti and Sedláček, 2013); we used the CMIP3 models and scenarios for comparison to other climate change vulnerability analyses conducted between 2008 and 2014.

Using the Climate Wizard Custom Analysis Tool (Girvetz and others, 2009), we acquired the ensemble mean of eight CMIP3 global climate models (GCMs) considered by Hayhoe (2013) as suitable for use as input in ecological studies to assess regional climate change impacts in the United States: CGCM3.1 T47, CNRM-CM3, ECHAM5/MPI-OM, ECHO-G, GFDL CM2.1, CCSM3, UKMO-HadCM3, and PCM (for model descriptions, see Intergovernmental Panel on Climate Change, 2007b). Improved projections by an ensemble of GCMs compared to any individual model have resulted in widespread use of ensemble means in climate change projection (Bader and others, 2008); use of an ensemble result is recommended for ecological studies to achieve consensus estimates of the mean and range of climate future climate (Mote and others, 2011).

Mean percent change in climate variables was calculated for each Level IV Ecoregion (U.S. Environmental Protection Agency, 2011). For parks that intersect more than one ecoregion, mean percent change among ecoregions was calculated. Relative climate change exposure was calculated as follows:

$$\frac{mean\ \%change\ within\ ecoregion(s) - minimum\ mean\ \%change\ among\ ecoregions}{maximum\ mean\ \%change\ among\ ecoregions - minimum\ mean\ \%change\ among\ ecoregions} \quad (1)$$

Higher values indicate greater exposure to climate change within the ecoregion(s) for each park.

Surrounding Land Use Change

Intensification of land use and increasing human population density in the surrounding landscape are primary causes of habitat degradation within protected areas (Wittemyer and others, 2008); recent land use change surrounding national parks is expected to continue into the next century (Hansen and others, 2014). We calculated recent land use change for each park buffer using 2011 National Land Cover Data (NLCD; Jin and others, 2013). This dataset includes a grid indicating which pixels have changed in their land use classification between 2006 and 2011. We calculated land use change relative exposure for park buffers as follows:

$$1 - \frac{unchanged\ buffer\ area}{total\ buffer\ area} \quad (2)$$

Higher scores indicate greater exposure to recent land use change.

Housing Density Change

Urbanization can substantially affect weather and climate, increasing air temperatures and changing the location and amounts of precipitation (Brown and others, 2014) and is a primary concern in landscapes surrounding national parks (Hansen and others, 2014). We estimated changes in housing density from 2010 to 2080 using housing density projections from the Environmental Protection Agency Integrated Climate and Land Use Scenarios (U.S. Environmental Protection Agency, 2014). Mean housing density for each time period (2010 and 2080) and emissions scenario (A1B and A2) was calculated for each park buffer using zonal statistics in ArcGIS. Mean housing density was used to calculate the projected percent change in buffer mean housing density between the two time periods. A relative housing density change exposure score was calculated as follows:

$$\frac{mean\ \%change\ within\ buffer - minimum\ mean\ \%change\ among\ buffers}{maximum\ mean\ \%change\ among\ buffers - minimum\ mean\ \%change\ among\ buffers} \quad (3)$$

Higher scores indicate greater exposure to projected housing density changes.

Sensitivity

Sensitivity is a measure of intrinsic properties that affect tolerance to stressors (Glick and others, 2011). Five metrics were selected that describe biological, geographic, physical, and human-caused conditions that can increase or decrease parks' sensitivity to climate change (table 1).

Endangered Species and Critical Habitat

Every U.S. national park reports yearly on the status and trends of current, historic, and extirpated threatened, endangered, and candidate species within their borders; definitions of endangered, threatened, and candidate species are found in the Endangered Species Act of 1973 (16 U.S.C. 1531–1544). We acquired a comprehensive list of species monitored in each of the Midwestern parks from the National Park Service and assigned each park a score reflecting the number of threatened, endangered, and candidate species present in the park in 2013 or known from historical records. Relative sensitivity based on endangered species was calculated as follows:

$$\frac{number\ of\ species\ for\ park}{maximum\ number\ of\ species\ recorded\ at\ any\ park} \tag{4}$$

We acquired shapefiles for all critical habitat designations in the Midwest from the Environmental Conservation Online System (U.S. Fish and Wildlife Service, 2014) and we assigned a relative sensitivity score of 1 to a park if it contained designated critical habitat and a 0 if it did not.

Proximity to Biome Edges

A biome is the largest global unit of ecological classification; they are characterized by similar major vegetation types and life forms, and their distribution is primarily controlled by climate (Woodward and others, 2004). Various biomes have exhibited different rates of climate change (Millennium Ecosystem Assessment, 2005; Loarie and others, 2009), and their boundaries are expected to shift with future climate conditions (Gonzalez and others, 2010). Parks closest to biome edges are therefore situated in ecological tension zones and are more inherently sensitive to climate change than parks far from biome edges. Level I Ecoregions wholly contain the Level IV Ecoregions used in our analyses and correspond with North American biomes (U.S. Environmental Protection Agency, 2010). We defined proximity to biome as the distance (km) from the park boundary to the closest Level I Ecoregion boundary, including any Great Lake shoreline. We calculated the relative sensitivity metric as follows:

$$1 - \frac{distance\ from\ park\ to\ nearest\ biome\ boundary}{maximum\ distance\ from\ any\ park\ to\ its\ nearest\ biome\ boundary} \tag{5}$$

Closer proximity reflects greater relative sensitivity.

Topographic Limitation within Park Boundaries

Species respond to spatially heterogeneous climates rather than broader averages (Walther and others, 2002). Greater topographic range and relief provide opportunities for landscape diversity, providing site resilience to climate change (Anderson and others, 2014) and microclimatic differences to support potential climatic refugia (Dobrowski, 2011). Climate change velocities have been observed to be highest in regions with little topographic relief (Ordonez and others, 2014), and species in flat landscapes must disperse farther than those in regions with high topographic relief to keep pace with changing climates (Intergovernmental Panel on Climate Change, 2014a). We obtained 100-m raster elevation data from the National Elevation Dataset (Gesch, 2007). For each cell in the study area, we calculated the range of elevation within a 300-m x 300-m window using focal statistics in ArcMap 10.1 (Esri, 1999–2012). We then used zonal statistics to calculate the mean elevation range within each park (unit). The relative elevation limitation score was calculated as follows:

$$1 - \frac{mean\ range\ within\ unit - minimum\ mean\ range\ among\ units}{maximum\ mean\ range\ among\ units - minimum\ mean\ range\ among\ units} \tag{6}$$

Parks with larger values for internal elevation limitation are therefore more sensitive to climate change; 14 parks whose footprint is greater than 90 percent developed did not have this metric included in their sensitivity score, because this metric relates to biological resource vulnerability.

Landscape Modification within Park Boundaries

Human modification of natural systems has been shown to increase vulnerability to climate change for ecoregions (Watson and others, 2013) and parks (Hansen and others, 2014). Modified landscape within park boundaries restricts internal ecological flows, increasing sensitivity to climate change; landscape modification within buffers and ecoregions restricts potential flows between the park and its surrounding landscape, increasing constraints on adaptive capacity. We used the degree of human modification, H (Theobald, 2013), to calculate landscape modification. This metric was developed specifically as a quantitative measure of ecological integrity suitable for comparing broad units at landscape scales and incorporates stressors such as land use, land cover, and presence, use, and distance from roads (Theobald, 2013). Data are 270-m grid cells with values between 1 and 0 indicating the level of multiple human modifications to land cover. We calculated landscape modification as the mean H value for all cells in each park using the zonal statistics tool in ArcMap 10.1 (Esri, 1999–2012). The relative landscape modification score was calculated as follows:

$$\frac{\mathit{mean\ H\ within\ unit} - \mathit{minimum\ mean\ H\ among\ units}}{\mathit{maximum\ mean\ H\ among\ units} - \mathit{minimum\ mean\ H\ among\ units}} \tag{7}$$

Higher scores indicate greater barriers to ecological flows and organism movement. Fourteen parks whose footprint is greater than 90 percent developed did not have this metric included in their sensitivity score.

Constraints on Adaptive Capacity

Adaptive capacity is the ability of a system to adjust to, moderate, or cope with climate change (Intergovernmental Panel on Climate Change, 2007a). The characteristics of the surrounding landscape influence the adaptive capacity of each park; in our vulnerability formula, we used the reciprocal of eight metrics (table 1) that increase adaptive capacity and call them “constraints on adaptive capacity.” Constraints on adaptive capacity quantify a potential inability to adjust to climate change and other stressors; therefore, higher scores for each metric examined represent increased vulnerability. Fourteen parks whose footprint is greater than 90 percent developed were not assessed for constraints on adaptive capacity, as this component relates only to biological resources.

Topographic Limitation within Buffers and Ecoregions

As described above for “Topographic Limitation within Park Boundaries,” we calculated the range of elevation within a 300-m x 300-m window using focal statistics in ArcMap 10.1 (Esri, 1999–2012) and used zonal statistics to calculate the mean elevation range and relative elevation limitation for each buffer and Level IV Ecoregion. Buffers and ecoregions with larger values for elevation limitation are assumed to reduce park adaptive capacity.

Landscape Modification within Buffers and Ecoregions

As described above for “Landscape Modification within Park Boundaries,” landscape modification was calculated as the mean H value (Theobald, 2013) for all cells in each buffer and Level IV Ecoregion using the zonal statistics tool in ArcMap 10.1 (Esri, 1999–2012), as well as the relative landscape modification score for each buffer and ecoregion.

Unprotected Areas

Parks exist in a context of larger ecosystems, and the important role of protected areas in lands surrounding parks in maintaining ecological flows and biodiversity has long been recognized (Hansen and others, 2011). We used the Protected Areas Database (U.S. Geological Survey Gap Analysis Program, 2012) to identify parcels of land in GAP status codes 1 and 2, which are managed for different levels of biodiversity protection, and no extractive uses (Gergely and McKerrow, 2013). We calculated percent unprotected area as 1- [percent area classified as protected] within the 10-km buffer surrounding each park and within the Level IV Ecoregion containing the park (mean percentage if park is in more than one ecoregion).

Land Cover Dissimilarity

Habitat intactness as measured by percent area in natural vegetation has been associated with decreased ecosystem vulnerability to climate change (Watson and others 2013; Eigenbrod and others, 2015). For a park, greater similarity of land cover within its boundaries and surrounding landscape reflects a greater abundance of nearby habitat suitable for park organisms, which increases adaptive capacity. We used 2011 NLCD (Jin and others, 2013) to calculate land cover similarity between each park and its buffer and ecoregion(s). The percent area in each land cover class was estimated for each park, buffer, and ecoregion using the Tabulate Area function in the Spatial Analyst Tools of ArcMap 10.1 (Esri 1999–2012). We calculated percent similarity of each park to its buffer and ecoregion by summing the lower of the percentage values for each shared land cover class (Renkonen, 1938; as cited in Wolda, 1981). For parks that intersect more than one ecoregion, we calculated an area-weighted mean percent similarity value between the park and its ecoregions. The relative land cover dissimilarity score for each park buffer and Level IV ecoregion was calculated as follows:

$$1-\frac{\%\mathit{similarity\ to\ park}-\mathit{minimum}\ \%\mathit{similarity\ among\ parks}}{\mathit{maximum}\ \%\mathit{similarity\ to\ park}-\mathit{minimum}\ \%\mathit{similarity\ among\ parks}} \tag{8}$$

Greater dissimilarity yields higher scores, indicating greater constraints on adaptive capacity provided by the surrounding landscape.

Vulnerability Calculations

For each park, we calculated exposure, sensitivity, and constraints on adaptive capacity scores as the mean value of each component's individual metrics. We calculated two exposure scores for each park: one for each of the two climate scenarios (A1B and A2, Intergovernmental Panel on Climate Change, 2007a). To calculate overall vulnerability, we averaged exposure, sensitivity, and constraints on adaptive capacity scores for each park (just exposure and sensitivity for 14 developed parks). We then classified parks as high, medium, or low for each component (A1B exposure, A2 exposure, sensitivity, adaptive constraint) and for A1B vulnerability, and A2 vulnerability. Classification was made by assigning parks with scores within one standard deviation of the group mean as "medium;" parks with scores greater than one standard deviation above the mean were classified as "high," and parks with scores more than one standard deviation below the mean were classified as "low." We examined correlations among the scores for exposure, sensitivity, constraints to adaptive capacity, and overall vulnerability to determine which components were most strongly associated with overall vulnerability. We also examined correlations among the constituent metrics of each vulnerability component to determine which metrics are most strongly associated with the resulting component score.

Results

Climate Change Exposure

Climate parameters consist of three of the five exposure metrics and we present them individually to set the context for overall relative exposure, sensitivity, constraints on adaptive capacity and vulnerability. Geographic patterns of the relative exposure of parks to future climate using A1B scenarios compared to A2 scenarios were more variable for precipitation (fig. 1, *A* and *B*) than for temperature (fig. 1, *C* and *D*). Southernmost parks tended to rank low for percent annual precipitation and temperature changes under both emissions scenarios. Parks in the extreme northwest and northeast parts of the region ranked high for percent annual precipitation change for the A1B scenario; whereas for the A2 scenario, mid-latitude parks ranked high for percent annual precipitation change. For relative percent annual temperature change, northernmost parks ranked high and southernmost parks ranked low under both scenarios. In both A1B and A2 scenarios, northernmost parks ranked high for relative change in moisture deficit. There were more parks classified as low for relative percent moisture deficit change in the A2 scenario because of the increased data spread; these parks were in the westernmost part of the region (fig. 1, *E* and *F*).

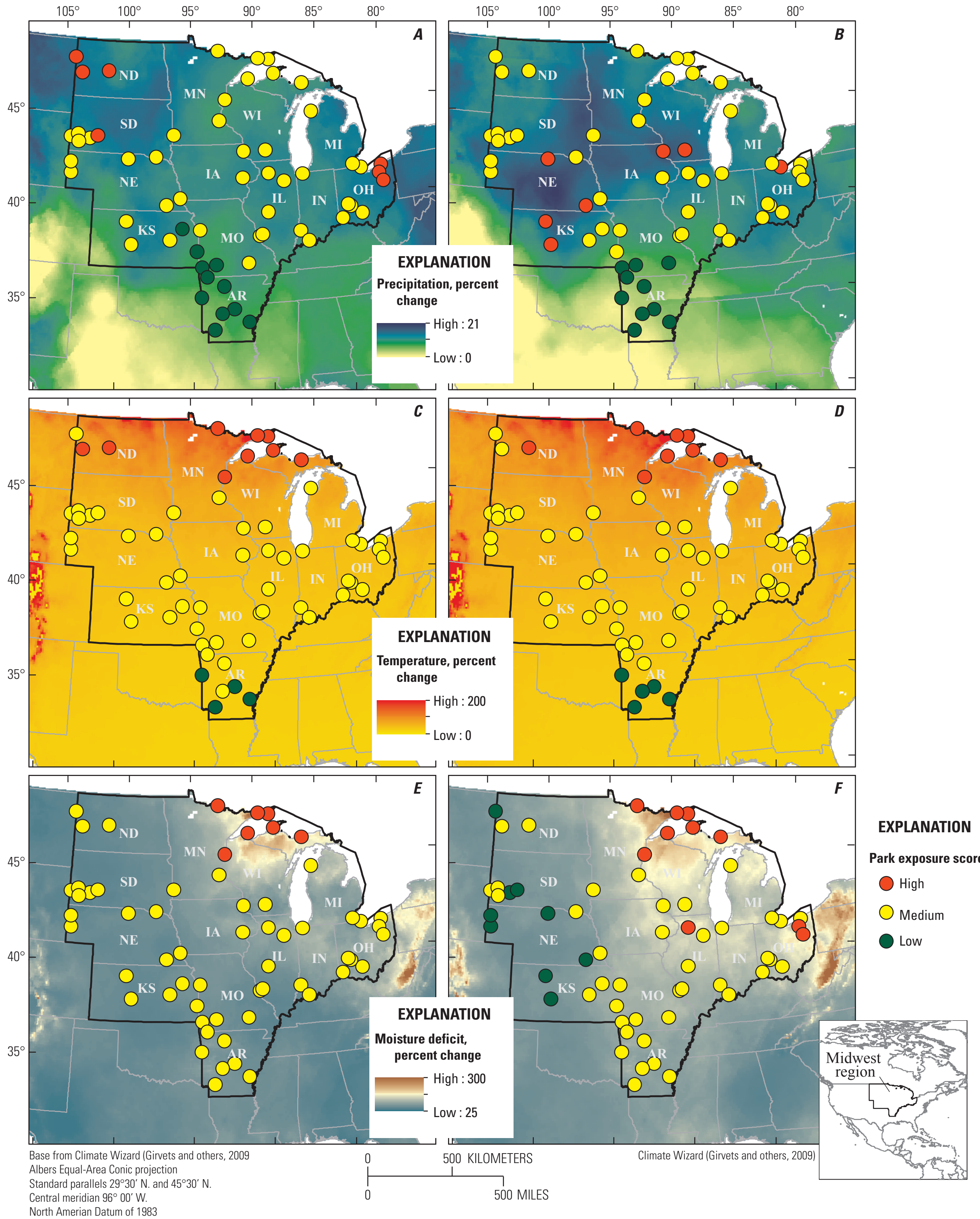

Figure 1. Relative exposure of national parks in the American Midwest to projected percent change in *A* and *B*, precipitation; *C* and *D*, temperature; and *E* and *F*, moisture deficit for 2080–99 relative to 1960–90 for the A1B and A2 emissions scenarios (Intergovernmental Panel on Climate Change, 2007a).

Park Relative Exposure, Sensitivity, Constraints on Adaptive Capacity, and Overall Vulnerability

Parks ranged in size from less than 0.01 square kilometers (km^2) to greater than 2,200 km^2 and from less than 1 percent developed to 100 percent developed, including 14 units with a footprint greater than 90 percent developed (table 2). Mean normalized scores for exposure, sensitivity, adaptive constraint, and overall vulnerability for each climate scenario are shown in table 2. Overall relative vulnerability scores and rankings were nearly identical for A1B and A2 scenarios; the same 11 parks ranked high in both scenarios, and 10 of the 11 parks ranked low in the A1B scenario were also ranked low in A2 scenario (table 2). Raw and normalized scores for each park for every metric used to calculate table 2 values are given in the appendix.

Of the four most vulnerable parks, Indiana Dunes, Illinois and Michigan Canal, Voyageurs, and Pipestone (INDU, ILMI, VOYA, and PIPE), three ranked high for both sensitivity and adaptive constraint; VOYA had high exposure and high sensitivity. Indiana Dunes protects natural resources, and Illinois and Michigan Canal protects cultural and natural resources in a rapidly urbanizing and agricultural landscapes; Pipestone protects cultural and natural resources in an agricultural matrix, and Voyageurs protects natural resources in a fairly intact forested landscape. Nine of the 11 most vulnerable parks had high sensitivity or constraints on adaptive capacity scores or both; only 3 had high exposure scores (table 2).

All but one park with a low A1B vulnerability ranking were small units greater than 90 percent developed and lacking sensitive species (table 2). One undeveloped park, Buffalo National River (BUFF), received a low vulnerability ranking, and it ranked low for both climate scenarios. The least vulnerable undeveloped parks were those with the lowest constraints on adaptive capacity (table 2) for both climate scenarios, typically because of high topographic relief of ecoregion and buffer, high similarity of land cover between park and buffer, and buffer and ecoregion, and low human modification of surrounding ecoregions.

Landscape patterns of high, medium, and low rankings for exposure, sensitivity, and constraints on adaptive capacity become apparent when displayed over spatial gradients of various vulnerability metrics (fig. 2). For example, projected changes in precipitation increase roughly from south to north, and this is reflected in the exposure rankings of the park units (fig. 2*A*). Park sensitivity, which was calculated on metrics measured within park boundaries and therefore too small to be apparent at regional scales, is nevertheless somewhat correlated with regional topographic relief, as within-park topographic relief was one of the five sensitivity metrics (fig. 2*B*). Parks that had the highest constraints on adaptive capacity (lowest adaptive capacity) lie near urban centers or within the most intensively modified agricultural areas (fig. 2*C*).

The Pearson correlation values (r) between the three vulnerability components and overall vulnerability scores, as well as correlations of individual metrics with their vulnerability component score are shown in table 3. This value ranges from –1 to 1 and estimates linear correlation between two variables where 1 indicates complete positive correlation, 0 indicates no correlation, and −1 indicates complete negative correlation. Correlation between overall vulnerability scores for parks in A1B and A2 scenarios was very strong ($r = 0.99$), indicating that parks scoring high (or low) for vulnerability for the A1 scenario also scored high (or low) for the A2 scenario. Vulnerability was strongly correlated with sensitivity ($r \geq 0.83$) and moderately correlated with constraints on adaptive capacity ($r \geq 0.66$) and exposure ($r \geq 0.50$) for both climate scenarios. The stronger correlations of sensitivity and constraints on adaptive capacity with overall vulnerability indicate that metrics other than projected changes in climate contribute more to relative vulnerability of these Midwestern Parks. Within the exposure component, temperature and moisture deficit changes were both strongly correlated ($r \geq 0.75$) with overall exposure score for the park. Within the sensitivity component, the presence of critical habitat was moderately correlated ($r = 0.59$) with the overall component score; the other metrics had only weak or no correlation. Nearly all of the metrics comprising the constraint on adaptive capacity component were strongly ($r \geq 0.76$) or moderately ($r \geq 0.59$) correlated with the component score (table 3).

A geographic display of overall relative vulnerability rankings for all parks is shown with 2011 land cover in figure 3. All but one of the parks with low vulnerability are more than 90 percent developed (table 2); the one low-vulnerability undeveloped park, Buffalo National River (BUFF), is in a relatively intact forested landscape in a region of high topographic relief. All but one of the parks with high vulnerability are undeveloped parks near urban centers or in highly agricultural, relatively flat landscapes in the central part of the region. Voyageurs National Park (VOYA), an undeveloped park in an intact lake and forest landscape, received its high vulnerability ranking from a combination of high exposure and sensitivity metrics (table 2).

Table 2. Area, percent of park footprint developed, and mean normalized scores for metrics comprising relative exposure, sensitivity, constraints on adaptive capacity, and overall vulnerability for national parks in the American Midwest under the A1B and A2 climate scenarios (Intergovernmental Panel on Climate Change, 2007a).

[The table is sorted according to A1B vulnerability and cells are shaded according to relative rankings of high (red) medium (yellow) and low (green) within each column]

Park code	Park unit names	Area, in square kilometers	Percent developed	Exposure		Sensitivity	Constraints on adaptive capacity	Vulnerability	
				A1B	A2			A1B	A2
INDU	Indiana Dunes National Lakeshore, Indiana	64	13	0.34	0.39	0.72	0.79	0.62	0.63
ILMI	Illinois and Michigan Canal National Heritage Corridor, Illinois	1,474	36	0.32	0.35	0.72	0.75	0.60	0.60
VOYA	Voyageurs National Park, Minnesota	829	0	0.68	0.67	0.60	0.50	0.59	0.59
PIPE	Pipestone National Monument, Minnesota	1	11	0.26	0.29	0.64	0.82	0.57	0.58
MISS	Mississippi National River and Recreation Area, Minnesota	218	32	0.38	0.46	0.60	0.72	0.57	0.59
MNRR	Missouri National Recreational River, Nebraska	279	2	0.23	0.24	0.67	0.73	0.54	0.55
SACN	Saint Croix National Scenic Riverway, Wisconsin	395	6	0.43	0.50	0.60	0.57	0.53	0.56
CUVA	Cuyahoga Valley National Park, Ohio	135	15	0.38	0.35	0.47	0.74	0.53	0.52
PEVI	Perry's Victory and International Peace Memorial, Ohio	0	42	0.24	0.29	0.50	0.82	0.52	0.54
JEFF	Jefferson National Expansion Memorial, Missouri	1	77	0.28	0.30	0.54	0.73	0.52	0.52
HEHO	Herbert Hoover National Historic Site, Iowa	1	30	0.24	0.29	0.56	0.75	0.52	0.53
KEWE	Keweenaw National Historical Park, Wisconsin	8	56	0.47	0.47	0.51	0.52	0.50	0.50
GRPO	Grand Portage National Monument, Minnesota	3	3	0.56	0.57	0.45	0.48	0.49	0.50
SLBE	Sleeping Bear Dunes National Lakeshore, Michigan	284	4	0.34	0.32	0.53	0.60	0.49	0.49
KNRI	Knife River Indian Villages National Historic Site, North Dakota	7	8	0.31	0.26	0.53	0.63	0.49	0.47
APIS	Apostle Islands National Lakeshore, Wisconsin	278	0	0.43	0.43	0.45	0.58	0.49	0.49
FOUS	Fort Union Trading Post National Historic Site, North Dakota	2	5	0.28	0.23	0.60	0.57	0.48	0.47
FOSM	Fort Smith National Historic Site, Arkansas	0	81	0.11	0.10	0.53	0.77	0.47	0.46
CHYO	Charles Young Buffalo Soldiers National Monument, Ohio	0	15	0.26	0.28	0.44	0.69	0.47	0.47
IATR	Ice Age National Scenic Trail, Wisconsin	1	1	0.48	0.49	0.32	0.59	0.46	0.47
LECL	Lewis and Clark National Historic Trail, Nebraska	0	36	0.17	0.21	0.40	0.79	0.45	0.47
WICR	Wilson's Creek National Battlefield, Missouri	10	6	0.21	0.26	0.44	0.69	0.45	0.46
HOME	Homestead National Monument, Nebraska	1	15	0.18	0.24	0.36	0.78	0.44	0.46
ISRO	Isle Royale National Park, Wisconsin	2,225	0	0.39	0.39	0.40	0.51	0.43	0.43
MIMI	Minuteman Missile National Historic Site, South Dakota	0	9	0.26	0.22	0.49	0.55	0.43	0.42
PIRO	Pictured Rocks National Lakeshore, Michigan	298	1	0.44	0.39	0.46	0.38	0.43	0.41
LIBO	Lincoln Boyhood National Memorial, Indiana	1	5	0.16	0.19	0.33	0.76	0.42	0.43

Table 2. Area, percent of park footprint developed, and mean normalized scores for metrics comprising relative exposure, sensitivity, constraints on adaptive capacity, and overall vulnerability for national parks in the American Midwest under the A1B and A2 climate scenarios (Intergovernmental Panel on Climate Change, 2007a).—Continued

[The table is sorted according to A1B vulnerability and cells are shaded according to relative rankings of high (red) medium (yellow) and low (green) within each column]

Park code	Park unit names	Area, in square kilometers	Percent developed	Exposure		Sensitivity	Constraints on adaptive capacity	Vulnerability	
				A1B	A2			A1B	A2
EFMO	Effigy Mounds National Monument, Iowa	10	2	0.26	0.35	0.46	0.54	0.42	0.45
PERI	Pea Ridge National Military Park, Akansas	17	6	0.28	0.33	0.42	0.55	0.41	0.43
HOCU	Hopewell Culture National Historical Park, Ohio	7	7	0.26	0.26	0.39	0.57	0.41	0.41
BADL	Badlands National Park, South Dakota	982	1	0.21	0.21	0.47	0.55	0.41	0.41
SCBL	Scotts Bluff National Monument, Nebraska	13	5	0.20	0.23	0.39	0.62	0.40	0.41
GWCA	George Washington Carver National Monument, Missouri	1	6	0.10	0.13	0.48	0.63	0.40	0.41
NICO	Nicodemus National Historic Site, Kansas	0	41	0.15	0.22	0.34	0.70	0.40	0.42
FOLS	Fort Larned National Historic Site, Kansas	3	13	0.15	0.23	0.35	0.64	0.38	0.40
TAPR	Tallgrass Prairie National Preserve, Kansas	44	4	0.16	0.18	0.40	0.56	0.37	0.38
AGFO	Agate Fossil Beds National Monument, Nebraska	12	3	0.17	0.23	0.41	0.51	0.36	0.38
NIOB	Niobrara National Scenic River, Nebraska	118	2	0.20	0.23	0.35	0.52	0.36	0.37
ARPO	Arkansas Post National Memorial, Arkansas	3	10	0.09	0.07	0.33	0.65	0.36	0.35
JECA	Jewel Cave National Monument, South Dakota	5	6	0.39	0.42	0.35	0.33	0.36	0.37
THRO	Theodore Roosevelt National Park, North Dakota	285	1	0.27	0.20	0.30	0.46	0.34	0.32
JAGA	James A. Garfield National Historic Site, Ohio	0	100	0.36	0.33	0.33	[a]	0.34	0.33
WICA	Wind Cave National Park, South Dakota	137	2	0.25	0.27	0.40	0.34	0.33	0.34
FILA	First Ladies National Historic Site, Ohio	0	100	0.36	0.34	0.27	a	0.32	0.30
MORU	Mount Rushmore National Memorial, South Dakota	5	10	0.38	0.42	0.35	0.19	0.31	0.32
HOSP	Hot Springs National Park, Arkansas	22	7	0.20	0.20	0.27	0.43	0.30	0.30
RIRA	River Raisin National Battlefield Park, Michigan	0	92	0.26	0.30	0.33	[a]	0.30	0.32
OZAR	Ozark National Scenic Riverways, Missouri	333	4	0.16	0.15	0.38	0.34	0.29	0.29
RRBH	Ronald Reagan Boyhood Home National Historic Site, Illinois	0	100	0.27	0.31	0.29	[a]	0.28	0.30
BUFF	Buffalo National River, Arkansas	379	3	0.11	0.12	0.37	0.33	0.27	0.27
LIHO	Lincoln Home National Historic Site, Illinois	0	100	0.28	0.31	0.23	[a]	0.26	0.27
HSTR	Harry S Truman National Historic Site, Missouri	0	100	0.25	0.32	0.26	[a]	0.25	0.29
ULSG	Ulysses S. Grant National Historic Site, Missouri	0	100	0.19	0.24	0.30	[a]	0.24	0.27
DAAV	Dayton Aviation Heritage National Historical Park, Ohio	0	99	0.29	0.31	0.19	[a]	0.24	0.25

Table 2. Area, percent of park footprint developed, and mean normalized scores for metrics comprising relative exposure, sensitivity, constraints on adaptive capacity, and overall vulnerability for national parks in the American Midwest under the A1B and A2 climate scenarios (Intergovernmental Panel on Climate Change, 2007a).—Continued

[The table is sorted according to A1B vulnerability and cells are shaded according to relative rankings of high (red) medium (yellow) and low (green) within each column]

Park code	Park unit names	Area, in square kilometers	Percent developed	Exposure		Sensitivity	Constraints on adaptive capacity	Vulnerability	
				A1B	A2			A1B	A2
WICL	President William Jefferson Clinton Birthplace Home National Historic Site, Arkansas	0	100	0.23	0.21	0.23	[a]	0.23	0.22
FOSC	Fort Scott National Historic Site, Kansas	0	97	0.11	0.17	0.29	[a]	0.20	0.23
BRVB	Brown v. Board of Education National Historic Site, Kansas	0	100	0.14	0.19	0.20	[a]	0.17	0.19
WIHO	William Howard Taft National Historic Site, Ohio	0	100	0.20	0.22	0.12	[a]	0.16	0.17
CHSC	Little Rock Central High School National Historic Site, Arkansas	0	100	0.16	0.13	0.13	[a]	0.14	0.13
GERO	George Rogers Clark National Historical Park, Indiana	0	93	0.14	0.15	0.12	[a]	0.13	0.14

[a]Not calculated for parks with footprint greater than 90 percent developed

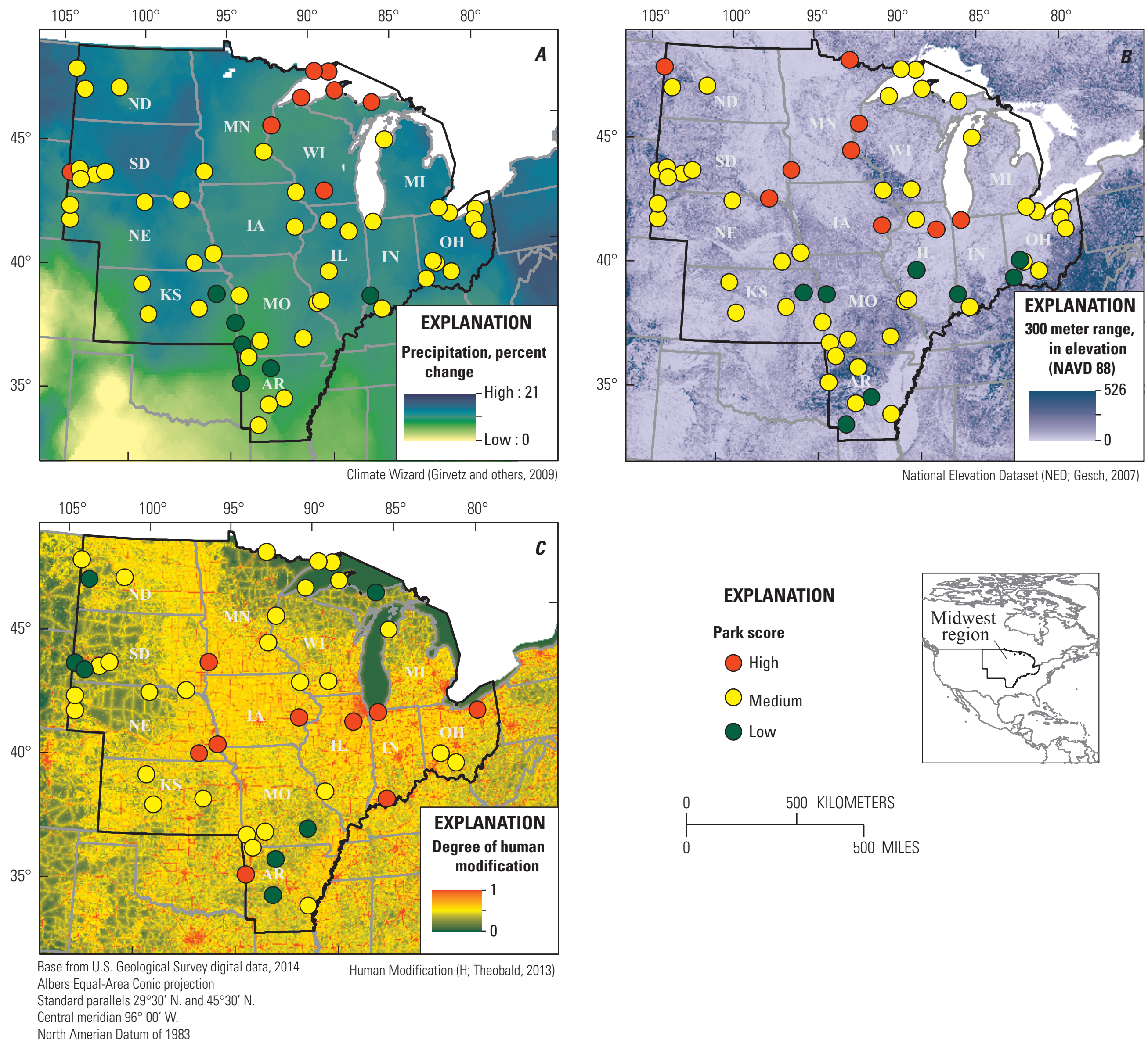

Figure 2. High, medium, and low rankings of Midwest national park units for *A*, relative exposure displayed over projected percent precipitation change for 2080–99 compared to 1960–90 (Girvetz and others, 2009); *B*, relative sensitivity displayed over elevation range (Gesch, 2007); and *C*, relative constraints on adaptive capacity displayed over human landscape modification (H; Theobald, 2013). Fourteen parks whose footprints are greater than 90 percent developed are not shown in panel *C*.

Table 3. Pearson correlations (*r*) of vulnerability components with overall vulnerability scores under the A1B and A2 climate scenarios (Intergovernmental Panel on Climate Change, 2007) and correlations of component scores with their constituent metrics.

[–, not applicable]

Vulnerability components	A1B overall vulnerability	A2 overall vulnerability
A1B overall vulnerability	–	0.99
A2 overall vulnerability	0.99	–
A1B exposure score	0.50	–
A2 exposure score	–	0.52
Sensitivity score	0.84	0.83
Constraints on adaptive capacity score	0.66	0.69

Exposure metrics	A1B exposure	A2 exposure
Percent temperature change	0.83	0.79
Percent moisture deficit change	0.76	0.75
Buffer land cover change 2006–2011	0.44	0.43
Percent precipitation change	0.39	0.44
Buffer housing density change	0.20	0.22

Sensitivity metrics	Sensitivity score
Endangered species critical habitat in park	0.59
Elevation limitation within park[1]	0.48
Threatened and endangered species in park	0.36
Park distance to biome edge	0.34
Landscape modification within park[1]	0.15

Constraints on adaptive capacity metrics[1]	Constraints on adaptive capacity score
Landscape modification of ecoregions	0.78
Topographic limitation of ecoregions	0.77
Topographic limitation of buffer	0.76
Percent unprotected buffer area	0.64
Land cover dissimilarity between park and buffer	0.64
Land cover dissimilarity between park and ecoregion	0.61
Landscape modification of buffer	0.59
Percent unprotected ecoregion area	0.51

[1]Not calculated for parks with footprint greater than 90 percent developed.

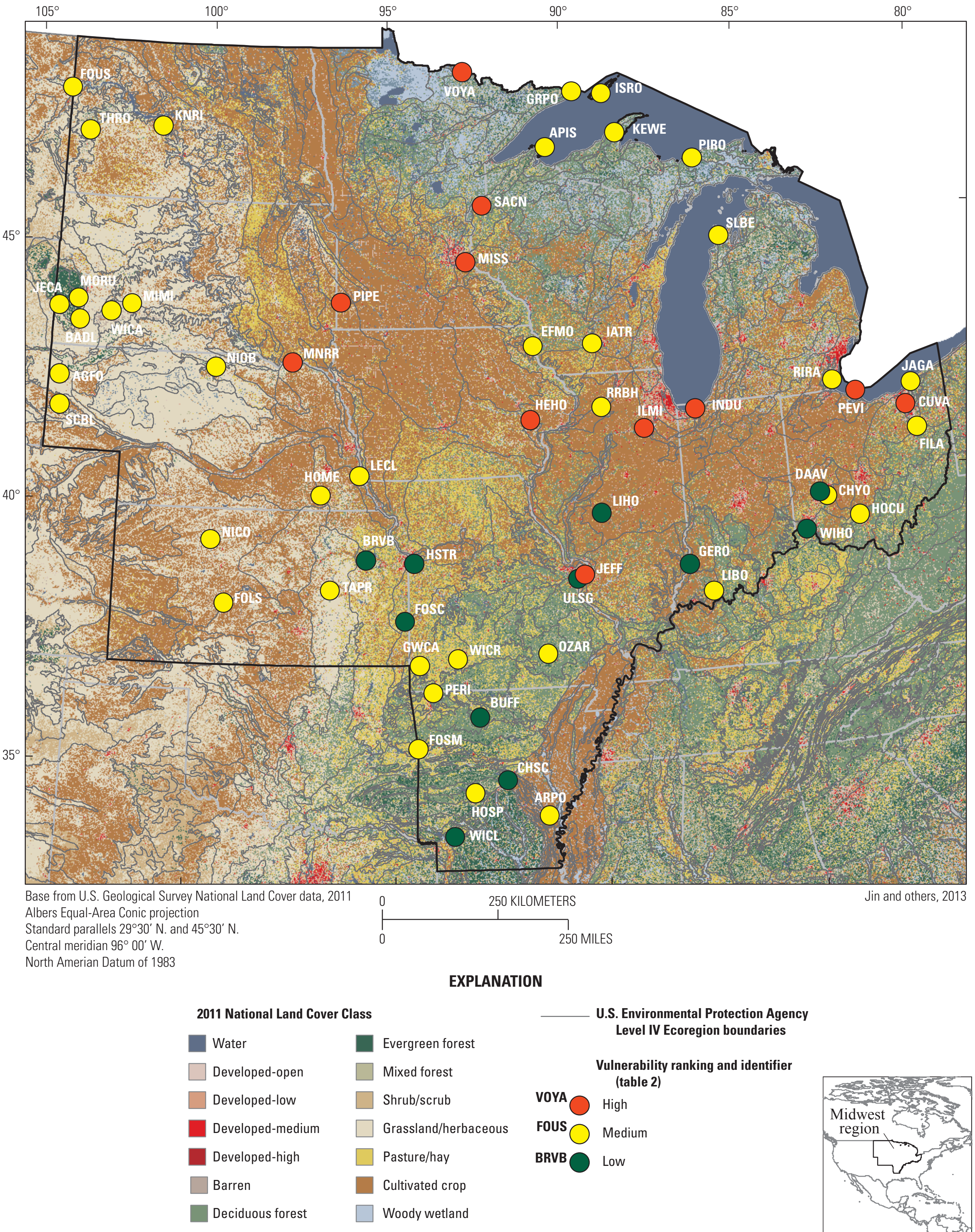

Figure 3. Relative vulnerability rankings of American Midwest national park units for A1B emissions scenarios (Intergovernmental Panel on Climate Change, 2007a) displayed over 2011 land cover and Ecoregion Level IV boundaries (U.S. Environmental Protection Agency, 2011). Park codes, names, and scores are shown in table 2.

Discussion

Human modification of the landscape has been shown to affect the vulnerability and resiliency of ecosystems and protected areas to climate change at the biome level (Gonzalez and others, 2010; Magness and others, 2011; Watson and others, 2013; Brown and others 2014; Eigenbrod and others, 2015); here, we assessed the relative importance of climate and land use stressors at a finer ecoregional scale within a few biomes in the American Midwest. Midwestern national parks are exposed to multiple stressors that differentially affect the vulnerability of the natural and cultural resources they protect. In this study, factors other than climate change played a large role in differentiating parks from each other in terms of the stressors for each park. The most important stressors for the most vulnerable Midwestern parks are more often those related to sensitivity (intrinsic characteristics of the park) and constraints on adaptive capacity (characteristics of the surrounding landscape) rather than exposure to external forces, including climate change. This does not mean that climate change is not an important factor in the future health and resiliency of Midwestern parks, but rather, that management for climate change effects should include other landscape characteristics that affect vulnerability. For example, landscape modification of the ecoregion(s) containing the park and percent of buffer in unprotected status are the two metrics most easily managed by human intervention and most highly correlated with constraints to adaptive capacity (table 3). This highlights the importance of preserving or restoring existing patches of native land cover within Midwest ecoregions that contain national parks. In these highly-modified landscapes, small patches are all that remain to serve as refugia for species because large patches of wilderness no longer exist (Eigenbrod and others, 2014).

The capacities of ecosystems to adapt to climate change can be improved by reducing other stressors to which they are exposed, and regional approaches to adaptation and conservation planning are preferable to exclusively national policies (Intergovernmental Panel on Climate Change, 2014b). Unlike global climate, land use change can be influenced by broad and fine scale management strategies (Ordonez and others, 2014), providing local and regional solutions to help ameliorate global-scale stressors. A high priority for regional conservation strategies includes coordinating reserve planning to improve landscape connectivity; a network of connected habitats provides more resilience than any reserve or protected area alone (Heller and Zavaleta, 2009), and integrating parks and protected areas within a larger landscape is more effective than managing them as islands (Willis and Bhagwat, 2009). Other approaches that are best applied in a region-wide manner include conserving the distribution of regional geophysical and topographic properties, current and historical climatic refugia, and ecosystem processes and disturbance regimes (Groves and others, 2012).

A region-wide response to improving adaptive capacities of Midwestern parks extends well beyond the jurisdiction and control of the National Park Service. Regional conservation planning to help mitigate combined effects of climate and land use change will require multiple partners working together to identify the most appropriate and achievable approaches for various Midwest ecoregions. Existing Midwest efforts to develop regional conservation strategies include those by Chicago Wilderness and by several U.S. Department of the Interior Landscape Conservation Cooperatives. Chicago Wilderness is an alliance of more 300 local, state and federal agencies, conservation organizations, municipalities, corporations, and other groups working in a four state area around an urban core to restore and preserve ecosystems (Chicago Wilderness, 2014). The two park units ranked most vulnerable in this study, Indiana Dunes (INDU) and Illinois and Michigan Canal (ILMI), are in the heart of the Chicago Wilderness region. The Landscape Conservation Cooperatives (LCC's) work with a wide variety of federal, state, and local governments and nongovernmental organizations to develop landscape-level conservation objectives based on the best available science (Jacobson and Robertson, 2012). The 60 Midwest parks assessed in this study are distributed across 6 different LCC's that may or may not include the entire ecoregion(s) in which a given park resides. Consequently, although regional networks are in place to begin to address landscape-level approaches to ameliorating effects of climate change, the Midwest region of the National Park Service has more than a one-half-dozen multi-partner networks with which to work to assure that the needs of Midwest national parks are being addressed, a logistically very difficult and time-consuming endeavor. However, to that end, our study provides insight into the relative importance of a suite of climatic and non-climatic stressors affecting individual parks throughout the administrative jurisdiction of the National Park Service Midwest Region.

Summary

Midwestern national parks are surrounded by agricultural or urban areas or are in highly fragmented or rapidly changing landscapes, and climate change is just one of many stressors on their natural resources. An assessment of 60 Midwestern national parks estimated vulnerability components of exposure (5 metrics), sensitivity (5 metrics), and constraints to adaptive capacity (8 metrics) under 2 future climate scenarios. Overall vulnerability was calculated from the three component scores. Metrics were measures of existing or projected conditions within park boundaries, within 10-kilometer buffers surrounding parks, and within ecoregions that contain or intersect them. Data were normalized within the range of values for all assessed parks, resulting in high, medium, and low relative rankings for exposure, sensitivity, constraints to adaptive capacity, and overall vulnerability. Results are consistent with assessments regarding patterns and rates of climate change nationwide but provide greater detail and relative risk for Midwestern parks. Park overall relative vulnerability did not differ between climate scenarios. Rankings for exposure, sensitivity, and constraints to adaptive capacity varied geographically and indicate regional conservation planning opportunities. The most important stressors for the most vulnerable Midwestern parks are those related to sensitivity (intrinsic characteristics of the park) and constraints on adaptive capacity (characteristics of the surrounding landscape) rather than exposure to external forces, including climate change. Understanding relative vulnerability of a suite of parks to climate and land use changes is important for region-wide planning. Output will allow individual park managers to understand which metrics weigh most heavily in the overall vulnerability of their park and can be used for region-wide responses and resource allocation for adaptation efforts.

References Cited

Anderson, M.G., Clark, M., and Sheldon, A.O., 2014, Estimating climate resilience for conservation across geophysical settings: Conservation Biology, v. 28, no. 4, p. 959–970.

Bader, D., Covey, C., Gutowski, W., Held, I., Kunkel, K., Miller, R., Tokmakian, R., and Zhang, M., 2008, Climate models—An assessment of strengths and limitations, *in* Department of Energy Office of Biological and Environmental Research, Synthesis and Assessment Product 3.1 Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research: Washington, D.C., U.S. Department of Energy, p. 124.

Baron, J., Gunderson, L., Allen, C., Fleishman, E., McKenzie, D., Meyerson, L., Oropeza, J., and Stephenson, N., 2009, Options for national parks and reserves for adapting to climate change: Environmental Management, v. 44, no. 6, p. 1033–1042.

Bellard, C., Bertelsmeier, C., Leadley, P., Thuiller, W., and Courchamp, F., 2012, Impacts of climate change on the future of biodiversity: Ecology Letters, v. 15, no. 4, p. 365–377.

Brown, D., Polsky, C., Bolstad, P., Brody, S., Hulse, D., Kroh, R., Loveland, T., and Thomson, A., 2014, Land use and land cover change, *in* J. M. Melillo, T.C.R., Yohe, G.W., eds., The Third National Climate Assessment: Washington, D.C., U.S. Global Change Research Program, p. 318–332.

Chen, I.-C., Hill, J.K., Ohlemüller, R., Roy, D.B., and Thomas, C.D., 2011, Rapid range shifts of species associated with high levels of climate warming: Science, v. 333, no. 6045, p. 1024–1026.

Chicago Wilderness, [2014], Chicago Wilderness: About Us Web page, accessed September 16, 2014, at http://www.chicagowilderness.org/.

Dobrowski, S.Z., 2011, A climatic basis for microrefugia—The influence of terrain on climate: Global Change Biology, v. 17, no. 2, p. 1022–1035.

Eigenbrod, F., Gonzalez, P., Dash, J., and Steyl, I., 2015, Vulnerability of ecosystems to climate change moderated by habitat intactness: Global Change Biology, v. 21, no. 1, p. 275–286.

Esri (Environmental Systems Resource Institute), 1999–2012, ArcMap 10.1: Redlands, California, Esri.

Gergely, K., and McKerrow, A., 2013, PAD-US—National inventory of protected areas: U.S. Geological Survey Fact Sheet 2013–3086, p. 1.

Gesch, D.B., 2007, The National Elevation Dataset, *in* Maine, D., ed., Digital Elevation Model Technologies and Applications—The DEM Users Manual (2d ed.): Bethesda, Maryland, American Society for Photogrammetry and Remote Sensing, p. 99–118.

Girvetz, E.H., Zganjar, C., Raber, G.T., Maurer, E.P., Kareiva, P., and Lawler, J.J., 2009, Applied climate-change analysis—The climate wizard tool: Plos One, v. 4, no. 12. Accessed July 17, 2014 at http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0008320.

Glick, P., Stein, B.A., and Edelson, N.A., 2011, Scanning the conservation horizon—A guide to climate change vulnerability assessment: Washington, D.C., National Wildlife Federation, p. 168.

Gonzalez, P., Neilson, R.P., Lenihan, J.M., and Drapek, R.J., 2010, Global patterns in the vulnerability of ecosystems to vegetation shifts due to climate change: Global Ecology and Biogeography, v. 19, no. 6, p. 755–768.

Groves, C.R., Game, E.T., Anderson, M.G., Cross, M., Enquist, C., Ferdana, Z., Girvetz, E., Gondor, A., Hall, K.R., and Higgins, J., 2012, Incorporating climate change into systematic conservation planning: Biodiversity and Conservation, v. 21, no. 7, p. 1651–1671.

Hansen, A.J., Davis, C.R., Piekielek, N., Gross, J., Theobald, D.M., Goetz, S., Melton, F., and DeFries, R., 2011, Delineating the ecosystems containing protected areas for monitoring and management: Bioscience, v. 61, no. 5, p. 363–373.

Hansen, A.J., Piekielek, N., Davis, C., Haas, J., Theobald, D.M., Gross, J.E., Monahan, W.B., Olliff, T., and Running, S.W., 2014, Exposure of U. S. National Parks to land use and climate change 1900-2100: Ecological Applications, v. 24, no. 3, p. 484–502.

Hayhoe, K., 2013, Development and dissemination of a high-resolution national climate change dataset: Final Report for United States Geological Survey, 497 p.

Heller, N.E., and Zavaleta, E.S., 2009, Biodiversity management in the face of climate change: A review of 22 years of recommendations: Biological Conservation, v. 142, no. 1, p. 14–32.

Intergovernmental Panel on Climate Change (IPPC), 2007a, Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II: Cambridge, United Kingdom and New York, N.Y., USA, Cambridge University Press.

Intergovernmental Panel on Climate Change, 2007b, Climate change 2007: The physical science basis. Contribution of Working Group I Cambridge, United Kingdom and New York, N.Y., USA, Cambridge University Press, 333 p.

Intergovernmental Panel on Climate Change, 2014a, Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II: Cambridge, United Kingdom and New York, N.Y., USA, Cambridge University Press, 1132 p.

Intergovernmental Panel on Climate Change, 2014b, Climate Change 2014: Impacts, adaptation, and vulnerability, part B—Regional Aspects: Contribution of Working Group II Cambridge, United Kingdom and New York, N.Y., USA, Cambridge University Press, 688 p.

Jacobson, C., and Robertson, A.L., 2012, Landscape conservation cooperatives—Bridging entities to facilitate adaptive co-governance of social–ecological systems: Human Dimensions of Wildlife, v. 17, no. 5, p. 333–343.

Jin, S., Yang, L., Danielson, P., Homer, C., Fry, J., and Xian, G., 2013, A comprehensive change detection method for updating the National Land Cover Database to circa 2011: Remote Sensing of Environment, v. 132, p. 159–175.

Knutti, R., and Sedláček, J., 2013, Robustness and uncertainties in the new CMIP5 climate model projections: Nature Climate Change, v. 3, no. 4, p. 369–373.

Loarie, S.R., Duffy, P.B., Hamilton, H., Asner, G.P., Field, C.B., and Ackerly, D.D., 2009, The velocity of climate change: Nature, v. 462, no. 7276, p. 1052–U1111.

Magness, D.R., Morton, J.M., Huettmann, F., Chapin, F.S., III, and McGuire, A.D., 2011, A climate-change adaptation framework to reduce continental-scale vulnerability across conservation reserves: Ecosphere, v. 2, no. 10. Accessed August 14, 2012 at http://onlinelibrary.wiley.com/doi/10.1890/ES11-00200.1/full.

Maurer, E.P., Brekke, L., Pruitt, T., and Duffy, P.B., 2007, Fine-resolution climate projections enhance regional climate change impact studies: Eos, Transactions American Geophysical Union, v. 88, no. 47, p. 504–504.

Millennium Ecosystem Assessment, 2005, Ecosystems and human well-being: Washington, D.C., Island Press, v. 5, 155 p.

Monahan, W.B., and Fisichelli, N.A., 2014, Climate exposure of US National Parks in a new era of change: Plos One, v. 9, no. 7. Accessed September 10, 2014 at http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0101302.

Mote, P., Brekke, L., Duffy, P.B., and Maurer, E., 2011, Guidelines for constructing climate scenarios: Eos, Transactions American Geophysical Union, v. 92, no. 31, p. 257–258.

Ordonez, A., Martinuzzi, S., Radelo, V.C., and Williams, J.W., 2014, Combined speeds of climate and land use change of the conterminous US until 2050: Nature Climate Change, v. 4, no. 9, p. 811–816.

Parmesan, C., 2006, Ecological and evolutionary responses to recent climate change: Annual Review of Ecology Evolution and Systematics, p. 637–669.

Renkonen, O., 1938, Statisch-ökologische Untersuchungen über die terrestrische Käferwelt der finnischen Bruchmoore: Annales Zoologici Societatis Zoologicae-Botanicae Fennicae Vanamo, v. 6, p. 1–231.

Sala, O.E., and Lauenroth, W.K., 1982, Small rainfall events: An ecological role in semiarid regions: Oecologia, v. 53, no. 3, p. 301–304.

Staudinger, M.D., Grimm, N.B., Staudt, A., Carter, S.L., Chapin, F.S., Kareiva, P., Ruckelshaus, M., and Stein, B.A., 2012, Impacts of climate change on biodiversity, ecosystems, and ecosystem services: Washington, D.C., United States Global Change Research Program, Technical Input to the 2013 National Climate Assessment. Cooperative Report to the 2013 National Climate Assessment, p. 296.

Theobald, D.M., 2013, A general model to quantify ecological integrity for landscape assessments and US application: Landscape Ecology, v. 28, no. 10, p. 1859–1874.

U.S. Environmental Protection Agency, 2010, Level I Ecoregions: National Health and Environmental Effects Research Laboratory.

U.S. Environmental Protection Agency, 2011, Level III and IV ecoregions of the conterminous United States: National Health and Environmental Effects Research Laboratory.

U.S. Environmental Protection Agency, 2014, Integrated Climate and Land Use Scenarios (ICLUS) Tools and Datasets (Version 1.3 & 1.3.1 ed.): Washington, D.C., U.S. Environmental Protection Agency, v. EPA/600/R-09/143F.

U.S. Fish and Wildlife Service, [2014], ECOS Environmental Conservation Online System: Critical Habitat Portal Web page, accessed August 8, 2014 at http://crithab.fws.gov/ecp/report/table/critical-habitat.html.

U.S. Geological Survey, Gap Analysis Program, 2012, Protected Areas Database of the United States (PADUS) version 1.3—Combined feature class. [Also available at http://gapanalysis.usgs.gov/padus/data/.]

Walther, G.R., Post, E., Convey, P., Menzel, A., Parmesan, C., Beebee, T.J.C., Fromentin, J.M., Hoegh-Guldberg, O., and Bairlein, F., 2002, Ecological responses to recent climate change: Nature, v. 416, no. 6879, p. 389–395.

Watson, J.E.M., Iwamura, T., and Butt, N., 2013, Mapping vulnerability and conservation adaptation strategies under climate change: Nature Climate Change, v. 3, no. 11, p. 989–994.

Willis, K.J., and Bhagwat, S.A., 2009, Biodiversity and climate change: Science, v. 326, no. 5954, p. 806–807.

Wittemyer, G., Elsen, P., Bean, W.T., Burton, A.C.O., and Brashares, J.S., 2008, Accelerated human population growth at protected area edges: Science, v. 321, no. 5885, p. 123–126.

Wolda, H., 1981, Similarity indices, sample size and diversity: Oecologia, v. 50, no. 3, p. 296–302.

Wolock, D.M., and McCabe, G.J., 1999, Explaining spatial variability in mean annual runoff in the conterminous United States: Climate Research, v. 11, no. 2, p. 149–159.

Woodward, F.I., Lomas, M.R., and Kelly, C.K., 2004, Global climate and the distribution of plant biomes: Philosophical Transactions of the Royal Society of London Series B-Biological Sciences, v. 359, no. 1450, p. 1465–1476.

Appendix 1. Table containing raw and normalized scores used to calculate vulnerability of 60 American Midwestern national parks to projected climate and land use changes for 2080–2099

An Excel table is provided at http://dx.doi.org/10.5066/F78913XX giving raw and relative (normalized) data for all metrics used to measure exposure, sensitivity, constraints on adaptive capacity, and vulnerability for 60 units in the U.S. National Park Service Midwest administrative region.

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