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REVIEW

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Climate-change vulnerability assessments of natural resources in U.S. National Parks

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Abstract

Climate change poses significant challenges to protected area management globally. Anticipatory climate adaptation planning relies on vulnerability assessments that identify parks and resources at risk from climate change and associated vulnerability drivers. However, there is currently little understanding of where and how protected area assessments have been conducted and what assessment approaches best inform park management. To address this knowledge gap, we systematically evaluated climate-change vulnerability assessments of natural resources in U.S. National Parks. We categorized the spatial scale, resources, methods, and handling of uncertainty for each assessment and mapped which parks have assessments and for what resources. We found that a few broad-scale assessments provide baseline information—primarily regarding physical climate change exposure—for all parks and can support regional to national decisions. However, finer-scale assessments are required to inform decisions for individual or small groups of parks. Only 10% of parks had park-specific assessments describing key climate impacts and identifying priority resource vulnerabilities, and 37% lacked any regional or park-specific assessments. We identify assessment approaches that match the scale and objectives of different protected area management decisions and recommend a multi-scaled approach to implementing assessments to meet the information needs of a large, protected area network like the National Park system.

KEYWORDS

biodiversity conservation, climate change, climate change adaptation, climate change vulnerability assessment, National Parks, natural resource management, protected areas

1 | INTRODUCTION

Protected area networks are a central component of nature conservation strategies globally. Yet climate change has significant implications for the effectiveness and management of the areas that make up these networks (Elsen et al., 2020; Hannah et al., 2007; Hoffmann et al., 2019). Warming temperatures and changing precipitation patterns are driving shifts in species distributions, changes in phenology, altered behavior, and altered interspecific interactions

(IPCC, 2014). In the United States, National Parks are disproportionately exposed to climate change (Gonzalez et al., 2018) and are already experiencing significant changes in fire regimes, biological composition, and coastlines (Gonzalez, 2017; Hameed et al., 2013; Pendleton et al., 2010). Many parks have the potential to provide critical climate-change refugia (Michalak et al., 2018) and yet face climate impacts that could potentially transform vegetation, species composition, and disturbance regimes (Scriven et al., 2015; Van Dusen et al., 2020; Wu et al., 2018; Zomer et al., 2015). These transformative changes have profound implications for protected area management (Schuurman et al., 2020).

Climate-change vulnerability assessments (hereafter "assessments") evaluate the degree to which a system or a component of that system is likely to be adversely affected by changes in climate and are a critical first step toward adapting protected area management to address climate-change impacts (Cross et al., 2012). Climate-change vulnerability is often viewed as a function of three elements—exposure, sensitivity, and adaptive capacity (Glick et al., 2011). Exposure is the extent to which a target experiences physical climatic changes (e.g., temperature, precipitation, and so on) or changes in a climate-driven process or disturbance (e.g., sea-level rise, fire, and flooding); sensitivity is the target's response (positive or negative) to changes in climatic conditions; and adaptive capacity is the ability of the system to adapt to climate change (Dawson et al., 2011). Adaptive capacity can include both landscape characteristics (extrinsic adaptive capacity) or characteristics inherent to the target (intrinsic adaptive capacity) that facilitate or impede the target's response to negative impacts of climate change (Beever et al., 2016).

General guidance exists for assessing climate-change vulnerability for species and ecological systems (Dawson et al., 2011; Glick et al., 2011) and approaches to species vulnerability assessment have been extensively reviewed (Foden et al., 2018; Pacifici et al., 2015). Despite these recommendations, we lack a systematic understanding of how vulnerability assessments have been implemented to inform protected area (hereafter "parks") management. Compared with evaluating vulnerability for individual species or ecosystems, evaluating climate-change vulnerability for a system of parks raises additional considerations. Park system managers need vulnerability assessments to inform decisions at multiple spatial and temporal scales including prioritizing regions or parks based on their vulnerabilities, informing long-term park planning, and making immediate resource management decisions for specific species or ecosystems. Fundamental characteristics of assessment design, such as spatial scale and/or conceptual scope (i.e., how many, and which resources or impacts are evaluated), ultimately affect which management decisions an assessment can adequately inform. Defining the scope of an assessment is challenging because park vulnerability can arise from characteristics of the park itself (e.g., biophysical characteristics of the park site), the cumulative vulnerability of the resources within the park, and primary threats originating from outside park boundaries. These considerations raise questions about which resources, impacts, and spatial scales to target. Finally, decisions to implement assessments must be strategic given the large scope of information needs, limited resources for conducting assessments, and the time-sensitive nature of decision-making.

To understand how climate-change vulnerability has been assessed for a protected area network, we performed a systematic review of assessments for natural resources in U.S. National Parks. The U.S. National Park system includes hundreds of protected areas, many of which have been the focus of vulnerability assessments conducted both by the National Park Service (NPS) and independent researchers. This review provides insights into how to design and implement assessments for a large protected area system managed at multiple scales. We structured our review around the three central components of vulnerability—exposure, sensitivity, and adaptive capacity. In addition, we identified common approaches, methods, and resource targets and evaluated to what extent, and how, the assessments incorporated best practices from the literature. We discuss the benefits, limitations, and applications of different approaches, and outline recommendations to help managers determine and commission vulnerability assessments that are best suited to inform protected area management decisions at local to national scales.

2 | METHODS

We systematically searched for vulnerability assessments conducted for natural resources in U.S. National Parks using Web of Science, Google Scholar, and NPS document databases in January and February 2019. Our search used a named list of all parks on the NPS Inventory and Monitoring (I&M) list (N = 289 park units, hereafter referred to as "parks") as these parks were identified by the NPS as having "significant" natural resources (NPS, 1999). Our search terms included park name, "climate," and "change." We also searched more generally for "national park" AND "climate" AND "change." Finally, we included any additional assessments in Gonzalez (2017).

We used the following criteria to identify climate-change vulnerability assessments specific to national parks. We retained all documents that explicitly claimed to evaluate climate-change vulnerability for a park or park resource regardless of method or format, even when the study evaluated only a single component of vulnerability (e.g., exposure). We refer to these as "explicit" assessments. We identified additional "implicit" assessments that assessed climate-change vulnerability for a park or park resource but did not use the term "climate-change vulnerability." To qualify, implicit assessments needed to estimate potential changes in future resource condition due to climate change, either quantitatively or qualitatively, and link that evaluation to resource condition within park boundaries. By necessity, we excluded studies such as regional or national assessments that did not explicitly evaluate National Parks, internal NPS documents that were not publicly available, and analyses that did not evaluate potential changes to resource levels or condition within named parks. Consequently, this review does not represent all the vulnerability information available to park managers.

Assessments are differentiated by key decisions defining conceptual scope, or how many and which resource targets were evaluated, spatial scale of the assessment, and analysis approach. For each assessment, we identified the primary assessment target, or the object whose vulnerability was being assessed (Table S2). For example, Catano et al. (2015) evaluated the vulnerability of seven species groups in Everglades National Park using four contrasting future climate and sea-level rise projections. In this case, the species groups were the primary target. For each assessment, we recorded key characteristics, including which vulnerability components were addressed (i.e., exposure, sensitivity, and adaptive capacity; Table S3), the types of evidence used (Table S4), and whether and how uncertainty was addressed (Table S5) (Dawson et al., 2011; Glick et al., 2011; Pacifici et al., 2015).

Finally, we documented the parks evaluated in each assessment, and defined the spatial scale of assessments based on the number of parks included. Each study was reviewed by one of eight evaluators. We assessed inter-reviewer reliability by having all reviewers assess a common set of five assessments. In addition, a single reviewer conducted a final review of all assessments to ensure consistency.

3 | RESULTS

Our initial search returned 282 documents. From these, we identified 40 assessments that explicitly claimed to evaluate climate-change vulnerability of natural resources within one or more National Parks, and 47 that implicitly evaluated vulnerability without using the term "vulnerability" (Table S1). The following results apply to the 87 explicit and implicit assessments. These 87 assessments were published between 1991 and 2019 with most assessments (70%) published between 2008 and 2016.

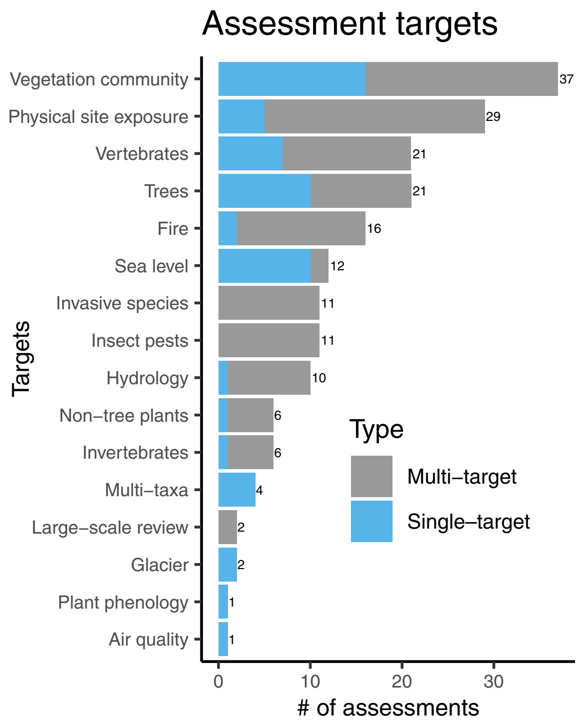

FIGURE 1 Number of assessments that evaluated the vulnerability of targets listed as part of a multi-target assessment (gray) or single-target assessment (blue). Totals for assessment types combined are shown. Two "large-scale reviews" summarized vulnerabilities for all, or large portions of the park system as opposed to evaluating individual parks or targets.

Here we first describe the most common vulnerability targets. Then we summarize whether and how the assessments evaluated physical climate-change exposure, exposure to climate-driven disturbances, resource sensitivity, and adaptive capacity, approaches to evaluating uncertainty, and the spatial scale and distribution of assessments.

3.1 | Assessment targets

Although the conceptual scope of assessments varied widely, the assessments could be distinguished by the number and types of targets evaluated. Broadly speaking, assessments either evaluated the vulnerability of the park itself (25%), the vulnerability of individual resources (e.g., habitats, species, glaciers, etc.) within the park (51%), or both (23%). The final two assessments reviewed vulnerabilities for the park system as a whole (Gonzalez, 2017) and for western parks (Saunders et al., 2007). Park-focused

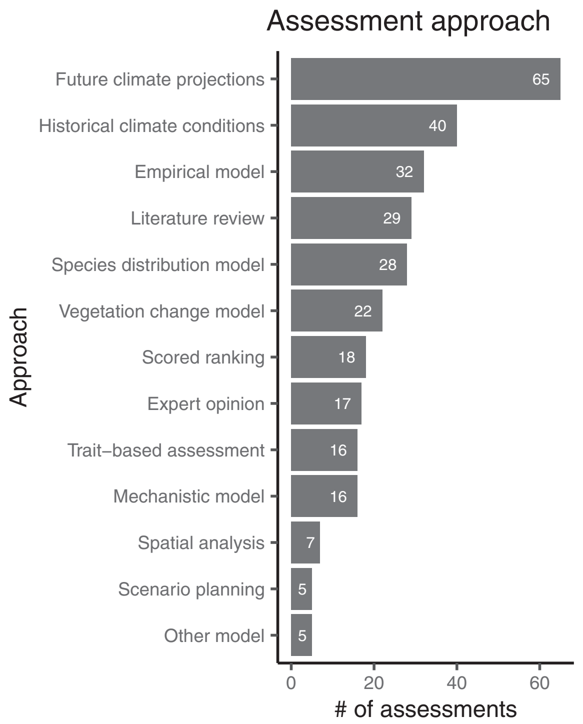

FIGURE 2 Assessment approaches used to evaluate climate-change vulnerability, exposure, or impact. A single assessment could use more than one approach.

assessments evaluated vulnerability of the site based on one or more of the following: (1) climatic changes projected for the park and surrounding landscape, (2) impacts from climate-influenced disturbances (e.g., sea-level rise, fire, or hydrology), and (3) landscape characteristics affecting extrinsic adaptive capacity. Examples of landscape characteristics include topography, which influences climatic velocity and refugia potential (Carroll et al., 2017), and human development and landscape modification which can impede species range shifts (McGuire et al., 2016). By contrast, resource-focused assessments evaluated the vulnerability of species, vegetation communities, and/or habitats within parks. These resource-focused assessments also incorporated information about projected changes in physical climate and disturbance regimes, but only as they related to the assessment target.

Most assessments (70%) had a single primary target or type of target (i.e., the resource or location for which vulnerability is being evaluated) including vegetation or habitats, plant species, animal species, or sea-level (Figure 1). Relatively few assessments had multiple primary targets (28%), and these were all park focused. Nearly all multi-target assessments summarized physical climate exposure of the park site and potential impacts to vegetation communities. In addition, many multi-target assessments addressed impacts from climate-driven changes to physical processes and disturbances (e.g., sea-level rise, fire, or hydrology). We identified 13 "comprehensive" multi-target assessments that summarized historical and/or projected future climatic changes and then evaluated the implications of those changes across a range of physical processes (e.g., fire or sea-level rise) and resource targets including habitats, vegetation types, and species.

3.2 | Physical climate-change exposure

Nearly all assessments evaluated the potential exposure of the primary target to physical climate-change (81%). Most assessments quantified exposure using projections of future climatic conditions (Figure 2). Other approaches to evaluating exposure included examining historical changes in climatic conditions or modeling potential impacts against predetermined benchmarks. For example, Monahan and Fisichelli (2014) evaluated historical temperature trends and found that recent mean and extreme temperatures in parks tended to be at the extreme warm end of their historical temperature range. Davis et al. (2001) reconstructed climatic conditions over the last 10,000 years for six parks in the Great Lakes region and provided evidence that a lake effect reduced climate change exposure for most of these parks. Nungesser et al. (2015) identified the potential for accelerated loss of tree islands and peat moss in Everglades National Park based on modeled hydrological changes resulting from a 1.5°C temperature increase and 10% decrease in precipitation.

3.3 | Exposure to climate-driven disturbances

Over half the assessments evaluated exposure to a climate-driven disturbance such as sea-level rise, fire, and/or altered hydrology. Evaluation of exposure to changes in fire and hydrology were mostly secondary studies of existing literature, but a small number of primary analyses used either mechanistic or statistical models to project quantitative changes. For example, Westerling et al. (2011) projected increased fire frequency and severity for the Greater Yellowstone Ecosystem using results from the variable infiltration capacity hydrologic model and logistic regression. Using the Hydrologiska Byråns Vattenbalansavdelning hydrologic model, Crossman et al. (2013) determined that changes in precipitation could increase flood frequency and magnitude on the Toklat river in Denali National Park.

Specialized quantitative models were commonly used to evaluate potential sea-level rise impacts. Murdukhayeva et al. (2013) found that priority resource sites are highly vulnerable to inundation from sea-level rise and storm surges in Assateague Island National Seashore based on three modeling approaches (modified bathtub, SLOSH, and SLAMM). In addition, eight assessments evaluated sea-level rise vulnerability using the Coastal Vulnerability Index (CVI), which classifies shorelines based on local topography, geomorphology, historical sea-level change, and tidal characteristics. Using this approach, Pendleton et al. (2010) compared sea-level rise vulnerability for 22 coastal parks nationwide. They identified parks along the Atlantic and Gulf Coast as most vulnerable, Pacific, oceanic island and Great Lakes parks were moderately vulnerable, and coastal Alaskan parks were least vulnerable.

3.4 | Resource sensitivity and vulnerability

Most assessments implicitly considered the sensitivity of resources by either qualitatively or quantitatively evaluating potential responses of the target (e.g., species, vegetation system, etc.) to climate-change impacts. The most common two approaches to evaluating target sensitivity were quantitative models and systematic vulnerability indices. Often, these approaches integrate exposure and sensitivity as opposed to evaluating sensitivity in isolation.

Quantitative models were commonly used to project changes in species habitat suitability and/or vegetation changes, but several modeled wildlife populations. For example, Fisichelli et al. (2014) used the USFS Tree Atlas (Iverson et al., 2008) to evaluate projected habitat suitability change for 134 tree species in 121 parks in the eastern United States, finding that 22%–77% of tree species with ranges currently overlapping target parks were projected to shift substantially, with northern parks experiencing greater change. An additional 16 assessments used mechanistic or process-based models such as the MC1 dynamic global vegetation model. King et al. (2013) used MC1 to model potential fire and vegetation changes in Wind Cave National Park. They found that the frequency of high fire danger could increase from 12 days (currently) to between 20 and 100 days per year by the end of the century with significant implications for the distribution of forest and grassland vegetation. Hall and Fagre (2003) developed a simulation model to compare the extent of glacier retreat in the Blackfoot–Jackson Glacier Basin of Glacier National Park under two climate change scenarios.

Another common approach was to conduct trait-based assessments of species or habitats. Several assessments used the NatureServe Climate-Change Vulnerability Index (Young et al., 2015), to evaluate species (e.g., Bruno et al., 2012) or habitats (e.g., Comer et al., 2012). Amberg et al. (2012) similarly used a systematic trait-based approach to evaluate species and habitats in Badlands National Park. They identified black-footed ferrets (*Mustela nigripes*), bighorn sheep (*Ovis canadensis*), mule deer (*Odocoileus hemionus*), herpetofauna, and grassland bird species as particularly vulnerable due to higher physiological sensitivity to temperature, disease susceptibility, and/or dependence on vulnerable habitats. Two assessments paired trait-based evaluations with habitat suitability projections (Barrows et al., 2014; Bruno et al., 2012). Barrows et al. (2014) applied both a trait-based scoring system and habitat suitability modeling for a suite of species in Joshua Tree National Park. The two approaches largely agreed on which species were most vulnerable, for example the desert tortoise (*Gopherus agassizii*) and single-leaf pinyon pine (*Pinus monophylla*). However, several species, such as chuckwallas (*Sauromalus ater*) and California junipers (*Juniperus californica*), were identified as resilient based on habitat suitability modeling, but likely vulnerable based on the trait-based approach, highlighting the benefit of using multiple approaches.

Seven assessments evaluated the target's response to historical fluctuations in climatic conditions to provide insight into how the target might respond to future climatic changes. For example, Wang, Hobbs, Singer, et al. (2002) analyzed the historical influence of climate on elk (*Cervus canadensis*) populations and suggested that warmer, wetter, winters could double the elk population of Rocky Mountain National Park.

Lastly, 17 assessments qualitatively described potential resource vulnerability based on the literature and/or expert opinion. For example, Raymond et al. (2014) conducted an in-depth synthesis of current literature and data on potential vegetation change in North Cascades and Mount Rainier National Parks identifying key climate sensitivities such as reduced tree vigor and increased susceptibility to insect pathogens. This synthetic approach allowed the authors to integrate evidence from empirical research, mechanistic vegetation models, statistical plant species distribution models, and projected changes in relevant climate variables such as climatic moisture deficit.

3.5 | Adaptive capacity

Fewer studies addressed adaptive capacity than other components of vulnerability, either directly (23%) or indirectly (37%). Most of these studies evaluated intrinsic adaptive capacity—the inherent ability of a species or system to adapt to climate change—with species' range shifts most frequently cited as a potential adaptive response to climate change (e.g., Hansen & Phillips, 2015). Others identified species traits that enhance or detract from adaptive capacity such as dispersal ability (e.g., Hameed et al., 2013), ability to adapt to temperature changes (Clark et al., 2017), reproductive rates (Ulrey et al., 2016), or how species may alter diet in response to climate impacts (Wang, Hobbs, Singer, et al., 2002).

Some studies evaluated extrinsic adaptive capacity—factors external to the organism or system that affect its ability to adapt. The most common measures of external adaptive capacity were evaluations of potential barriers to migration, such as roads or urban areas. Nielsen and Dudley (2013) evaluated sea-level rise impacts on salt marshes in and around Acadia National Park. They identified 41 potential barriers to migrations for the 110 salt marshes evaluated in the analysis. Stroh et al. (2016) quantified levels of landscape modification (i.e., development) and elevational range for 60 parks in the Midwest as potential constraints on adaptive capacity leading the authors to identify Indiana Dunes and Illinois and Michigan Canal as highly vulnerable. Both are in the heart of the Chicago Wilderness region.

3.6 | Uncertainty

Nearly all the assessments explicitly addressed uncertainties about future climatic conditions (88%). Of the 65 assessments that used climate projections, 59 used at least two different climate futures or otherwise provided a range for potential future climatic changes (i.e., multiple global climate models (GCMs), emissions scenarios, or predefined climate benchmarks). Beyond using a variety of climate projections, many assessments incorporated methods to account for uncertainty in other aspects of the assessment, such as the understanding (or lack thereof) of species traits, interactions, or other important variables. The most common approach was for experts to assign confidence values to vulnerability information. Qualitative assessments identified knowledge gaps and uncertainties.

Five assessments used a formal scenario-planning process to address uncertainty. For example, Symstad et al. (2017) used scenario planning to identify divergent but plausible future soil moisture and flooding regimes and then evaluate management actions for targets such as bison and native vegetation within these scenarios. Since the time of this review, scenario planning has been implemented in Devil's Tower National Monument (Schuurman et al., 2019) and Wind Cave National Park (Runyon et al., 2021) and is increasingly used by NPS as a core strategy for evaluating climate-change vulnerability (Miller et al., 2022).

Assessments also addressed uncertainty by employing multiple approaches to evaluating vulnerability (Dawson et al., 2011; Michalak et al., 2017). Most commonly, assessments presented more than one line of evidence to evaluate vulnerability. Twelve assessments evaluated resource vulnerability using both quantitative resource modeling and a trait-based approach. Finally, nine assessments conducted secondary research using existing data and literature spanning multiple vulnerability assessment approaches. Six of these secondary-research assessments reviewed evidence from future climate projections, quantitative resource models, trait-based assessments, and historical climate trends.

4 | SPATIAL SCALE AND DISTRIBUTION OF ASSESSMENTS

Assessments varied widely in spatial scale. Overall, five broadscale assessments were essentially national in scope, 27 evaluated multiple parks within the same geographic area, and 55 evaluated a single park. The five broadest-scale quantitative assessments evaluated large numbers of parks spanning the United States. As a result of these assessments, all parks ($N = 289$) were included in at least one evaluation. These broadscale assessments primarily evaluated climate-change exposure (e.g., Gonzalez et al., 2018; Monahan & Fisichelli, 2014) with the exception of one study that estimated potential air quality impacts from climate change (Val Martin et al., 2015).

We reviewed 27 assessments that evaluated more than one park within a specific geographic area (median = 4, maximum = 121 parks). Collectively, these multi-park assessments covered 60% of parks. The remaining 55 assessments evaluated a single park, but because some assessments targeted the same park, only 29 (10%) parks were included in single park assessments. In total, multi-park and single park assessments covered 63% of parks.

Assessments of habitat, vegetation, or plants are available for nearly 60% of all parks (169 parks), although most of these are from a single study that modeled habitat suitability projections for trees in 118 eastern parks (Fisichelli et al., 2014). An additional 51 parks (17%) have assessments for at least one animal. Assessments of climate-driven disturbances were conducted for 18% of parks, most commonly sea-level rise (29 parks), insect-pest risk (7), fire (25), and altered hydrology (13).

Comprehensive assessments that evaluated physical climatic changes, climate-driven disturbance impacts, potential habitat/vegetation changes, and animal species vulnerability, have been completed for 26 parks. In addition, all four of these topics have been evaluated for Everglades National Park, albeit in separate assessments. Parks with comprehensive assessments are primarily

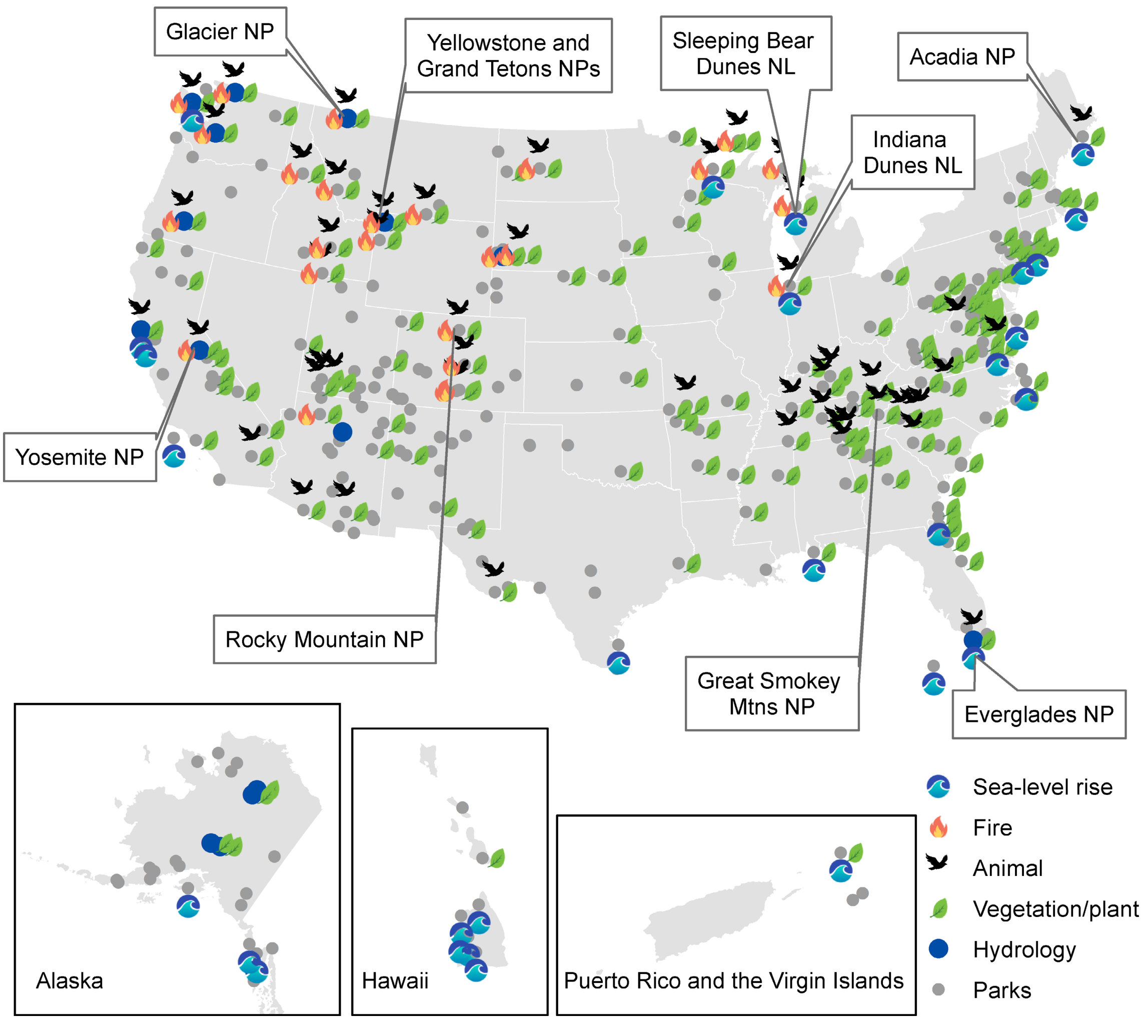

FIGURE 3 Map showing which natural resource national parks ($n = 289$) had assessments addressing each subject matter area. Physical climate exposure has been evaluated for all parks. Parks with the most assessments are labeled.

located in the western United States and in the Great Lakes region with only three such parks (Acadia, Everglades National Parks, and Colonial National Historical Park) in the eastern United States (Figure 3).

5 | DISCUSSION

Substantial effort has been put into developing vulnerability assessments for natural resources in National Parks. However, to date, implementation has not been coordinated, resulting in an uneven distribution of assessments across parks. Of the assessments we reviewed, four evaluated all parks, but were either very general (Gonzalez, 2017), or focused on a small number of exposure indicators (Hansen et al., 2014; Monahan & Fisichelli, 2014). Beyond these broad-scale assessments, regional, multi-park assessments, and single-park assessments collectively evaluated 63% of parks, but most of these assessments focus on a single assessment target or type of target (e.g., species, physical process, or habitat). Comprehensive assessments that provide a detailed evaluation of key climate impacts and priority resources were only available for 26 parks (9%). Additional broad-scale (Gonzalez et al., 2018; Wu et al., 2018) and comprehensive assessments have occurred since this review (Powell et al., 2018; Schuurman et al., 2019; Thoman & Walsh, 2019). In addition, many states and regions have comprehensive assessments that can be used by park managers in lieu of a park-specific assessment (Colorado Natural Heritage Program [CNHP], 2015). However, even with these additions, the need for vulnerability information across the NPS is substantial even though the agency has traditionally been a leader in climate change adaptation planning among federal agencies (Archie et al., 2012).

Ultimately, the information needs of protected area decision-makers will require climate-change vulnerability assessments that use a variety of approaches and that are conducted at a range of scales. We loosely organize

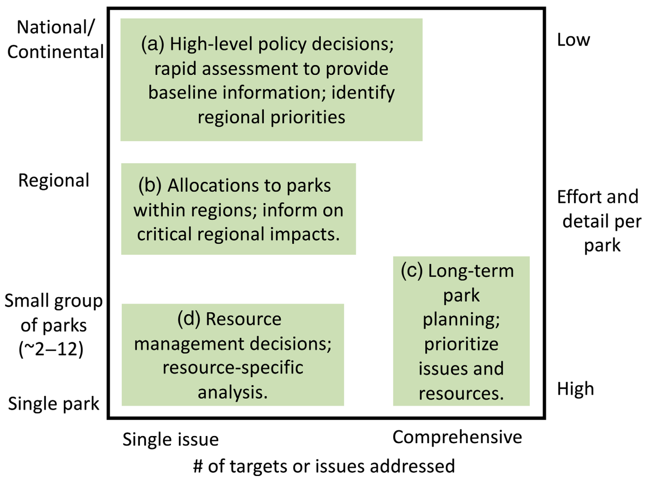

FIGURE 4 Trade-offs between spatial scale (left y-axis), number of issues or targets addressed (x-axis), and level of detail per park (right y-axis) constrain climate-change vulnerability assessment design. Common assessment approaches included (a) broad-scale assessments that use vulnerability indicators to evaluate many parks simultaneously, (b) single issue regional assessments of critical vulnerability impacts such as sea-level rise or fire, (c) comprehensive assessments evaluating key climate impacts and resources for a park/s, and (d) resource-specific assessments that evaluate a single resource within a single or small group of parks. Park management decisions are made at a variety of spatial scales. Vulnerability assessments will be most informative if they are designed to match the scale and scope of management decisions.

assessments into four common approaches based on their spatial scale, conceptual scope, and level of effort per park (Figure 4). For each approach, we discuss the policy and management decisions the assessments best inform, the analytical approaches commonly used, and the strengths and limitations of these design choices, and summarize these points in Table 1.

At broad spatial scales (Figure 4a), most assessments we reviewed were quantitative spatial analyses, although two studies conducted literature reviews of general climate vulnerabilities relevant to National Parks (Gonzalez, 2017; Saunders et al., 2007). Quantitative broad-scale assessments (i.e., those covering many parks over a large area) can efficiently evaluate numerous parks simultaneously but are limited to attributes that can be consistently measured for a large extent, across diverse regions. These include climate-change exposure (Gonzalez et al., 2018), landscape characteristics influencing adaptive capacity (Hansen et al., 2014; Stroh et al., 2016), and aggregated metrics based on species distribution models (Fisichelli et al., 2014; Wu et al., 2018). These broad-scale assessments can be useful for system-wide strategic planning, and they provide a common baseline of climate vulnerability information. They inform resource managers of impending changes, can initiate discussions that build institutional capacity, and motivate anticipatory management. When used for screening, they can identify threats, resources, or geographies that merit more detailed assessments. However, broad-scale assessments are generally unable to incorporate detailed local data and thus are poorly suited to informing site-scale decisions.

When key climate impacts arise from a common threat like fire or sea-level rise, regional-scale assessments can offer substantial efficiencies of scale and effectively support both park-specific and broader-scale planning (Figure 4b). We identified 27 regional, multi-park assessments that collectively addressed 310 parks compared to 55 single-park assessments that collectively addressed 29 parks (some parks had multiple assessments). For example, regional assessments of sea-level rise impacts were conducted for five parks in Hawaii (Marrack & O'Grady, 2014) and for 22 parks spread across the United States (Pendleton et al., 2010) and more recently, Caffrey et al. (2018) modeled sea-level rise for 118 coastal parks. Similarly, regional assessments can evaluate vulnerability for regionally significant vegetation types, such as the assessment of Mojave and Sonoran Desert habitats (Comer et al., 2012), or evaluate species turnover, loss, or gain within parks using species distribution models (e.g., Burns et al., 2003; Zolkos et al., 2015).

Assessments that address a single park or small groups of parks can devote more attention and detail to conditions within individual parks (Figure 4c,d). At the single-park to small-group (i.e., ~2–12 parks) scale, common approaches were literature reviews, quantitative modeling, and species trait-based assessments. In this group, trade-offs between the scope, or number of topics or resources evaluated, and types of evidence used (i.e., secondary versus primary research) were often evident. However, these trade-offs can be offset when park managers and partners are willing to commit substantial time and effort to do so (e.g., Runyon et al., 2021; Schuurman et al., 2019).

Secondary research assessments that relied on existing literature and data were a common approach with many benefits. Using existing information allows for a comprehensive approach identifying key climate impacts, summarizing what is known about potentially transformational processes (e.g., fire or flooding), clarifying priority resources (vegetation types or priority species), and/or identifying knowledge or data gaps. These types of assessments can inform natural resource management throughout a region by providing the broad context for climate change and are well suited to regional collaborative planning efforts (Miller et al., 2022). Secondary assessments can incorporate evidence from multiple sources, such as reviewing results from different modeling

TABLE 1 Summary of characteristics, benefits and applications, and limitations for select common assessment types as structured in Figure 4.

Assessment scale and approach	Common indicators or assessment targets	Benefits and applications	Limitations	Example assessments
National quantitative (Figure 4a)	Physical climate change, landscape characteristics, vegetation change, species distribution models.	Rapid evaluation of multiple parks, consistent metrics to compare vulnerability. Useful for national and regional planning and prioritizing.	Generally limited to large-extent data, often remotely sensed or from databases of observations (e.g., invasive species, breeding birds). May inadequately represent regional and local characteristics.	(Hansen et al., 2014; Stroh et al., 2016)
National qualitative (Figure 4a)	Any target.	Identify and summarize known or potential vulnerabilities. Identify existing literature, data, and relevant resources.	Low level of per-park information. No consistent comparison across parks.	(Gonzalez, 2011; Saunders et al., 2007)
Regional, single issue, quantitative modeling (Figure 4b)	Climate-driven disturbances with regional characteristics (e.g., sea-level rise, fire, drought). Regional vegetation or species range shift trends and data.	Focus assessments in priority regions (e.g., sea-level rise in southeastern U.S.). Accounts for regionally specific conditions (e.g., regional fire regimes and management approaches).	Appropriate for phenomena that span a relatively large spatial extent and can be assessed remotely.	(Fisichelli et al., 2014 [tree species composition], Marrack & O'Grady, 2014 [sea-level rise, HI parks])
Regional, trait-based (Figure 4b)	Species, ecosystems, coastal vulnerability.	Applies an existing framework to evaluate multiple species, habitats, or sites based on existing literature or commonly available data. Allows for the ranking of relative vulnerability.	Relies on existing literature and data. Ranks may differ depending on approach. Do not provide quantitative estimates of change or degree of impact.	(Barrows et al., 2014; Comer et al., 2012)
Single or small group of parks—comprehensive (Figure 4c)	All or most high priority issues, impacts, and/or resources.	Highlights priorities, incorporates multiple assessment approaches, compare results from existing studies, incorporates local/regional nuance.	Depending on level of detail, can be resource intensive to implement.	(Halofsky et al., 2019; Raymond et al., 2014; Schuurman et al., 2019)
Single or small group of parks—single issue (Figure 4c)	Any vulnerability target. Often individual species, glacier, or sea-level rise of individual park.	In-depth assessment of local resource/s using custom models. Best for high-priority resources with significant management implications.	The narrow scope of the assessment that limits their applicability. Conducting detailed assessments of all resources is not practical.	(Brown et al., 2010 [Glaciers]; Nungesser et al., 2015 [Everglades ecosystem])

approaches, paleoclimatic information, and/or empirical studies of trait-based sensitivities. Evaluating a broad range of information can identify scientific consensus and uncertainties and has been highly recommended to hedge against the limitations of any single assessment method (Dawson et al., 2011; Rowland et al., 2011). For example, Ashton (2010) synthesized existing literature and model projections for key issues including physical climatic changes, fire, insect pests, and individual vegetation communities for 12 parks in the Rocky Mountain and Upper Columbia Basin region.

Limitations of secondary research assessments are their reliance on existing information and focus on broad trends in climate vulnerabilities, which may not be sufficient to inform management decisions that require detailed information. Some assessments that primarily reviewed existing data and literature also incorporated new modeling (e.g., Halofsky et al., 2019) or implemented a scenario planning framework to expand analytical capacity and provide context for strategic decision-making (e.g., Runyon et al., 2021). Although these approaches require intensive effort, they foster engagement and trust from managers which greatly facilitates implementation (Miller et al., 2022).

At the single-park to small-group scale, systematic assessment approaches were used to compare vulnerability of species, habitats, or vegetation types. Two common approaches were trait-based indices, like the NatureServe Climate-Change Vulnerability Index (CCVI; Young et al., 2015), and species distribution models. Both can be implemented relatively quickly, yet each has their own strengths and limitations. Trait-based indices are helpful for guiding assessments based primarily on literature reviews by highlighting characteristics contributing to vulnerability. These indices can broadly categorize or rank species or habitat vulnerability, but results can vary depending on which method is used (Lankford et al., 2014) and are rarely spatially explicit. Species habitat suitability and/or distribution models are spatially explicit but often fail to account for important behavioral and ecological species traits (Franklin, 2010), although recent methodological advances partially address these limitations (Iverson et al., 2019). Considering both habitat suitability projections and trait-based assessments will provide a more complete understanding of potential vulnerability than either approach alone.

Narrowing the scope of an assessment to a single species, habitat, or process can facilitate the application of more detailed models and analyses (Figure 4d). Such models can be useful for understanding changes in fire, hydrology, or vegetation, which can have cascading ecological impacts on a range of targets. Several assessments developed mechanistic models to evaluate hydrologic changes in Everglades National Park (Nungesser et al., 2015; van der Valk et al., 2015), and mechanistic vegetation models were frequently used to evaluate interactions among fire, management strategies, and vegetation (Clark et al., 2017; Flatley & Fulé, 2016; Panek et al., 2009). Some species-specific assessments used mechanistic population models, as did Wang, Hobbs, Giesen, et al. (2002) for the white-tailed ptarmigan in Rocky Mountain National Park. Mechanistic models can account for important drivers missed by simpler correlative species distribution models. However, more complex models have their own limitations as they often incorporate highly uncertain parameters or simplify complex phenomena (Fisher et al., 2010), again highlighting the importance of pairing different modeling or assessment techniques (Kearney & Porter, 2009). Given limited resources for conducting assessments, detailed modeling will likely be reserved for high priority targets identified by prior rapid assessments.

Given these trade-offs, vulnerability assessments will be most successful if they are intentionally designed to inform specific management decisions. For large, protected area networks like the U.S. National Park System, we recommend implementing a multi-scaled approach. Large-scale network-wide assessments can evaluate climate-change exposure, landscape and topographic characteristics, and some resource modeling approaches such as species or vegetation turnover. These assessments provide indicators of vulnerability, identify regional trends, and inform prioritization efforts for more detailed assessments. At a regional or local scale, holistic assessments that synthesize existing information provide the broad context for regional climate change including identifying key climate impacts, potential vulnerabilities for priority resource classes, and evaluating impacts based on multiple lines of evidence. Finally, priority resources identified as potentially vulnerable in rapid assessments are candidates for detailed evaluation to inform specific management questions. A strategic and systematic approach will ensure that vulnerability assessments can be efficiently and effectively implemented across even large, protected areas networks.

AUTHOR CONTRIBUTIONS

John E. Gross and Joshua J. Lawler conceived of the project. Julia L. Michalak, Joshua J. Lawler, Michelle C. Agne, Robert L. Emmet, Hsin-Wu Hsu, and Vivian Griffey designed the analysis. Julia L. Michalak, MCA, Robert L. Emmet, Hsin-Wu Hsu, and Vivian Griffey conducted the analysis. Julia L. Michalak and John E. Gross reviewed and revised the analysis. Julia L. Michalak, Joshua J. Lawler, Michelle C. Agne, Robert L. Emmet, Hsin-Wu Hsu, and Vivian Griffey wrote the article.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data are available on request from the author.

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