Conservation Letters

WILEY

Conservation Letters
A journal of the Society for Conservation Biology
Open Access

LETTER OPEN ACCESS

Relative Vulnerability of US National Parks to Cumulative and Transformational Climate Impacts

Julia L. Michalak[1,2] | Caitlin E. Littlefield[3] | John E. Gross[4] | Tina G. Mozelewski[3] | Joshua J. Lawler[2]

[1]Washington Department of Fish and Wildlife, Olympia, Washington, USA | [2]School of Environment and Forest Sciences, University of Washington, Seattle, Washington, USA | [3]Conservation Science Partners, Truckee, California, USA | [4]Climate Change Response Program, National Park Service, Fort Collins, Colorado, USA

Correspondence: Julia L. Michalak (Julia.Michalak@dfw.wa.gov)

Received: 6 December 2023 | **Revised:** 11 December 2025 | **Accepted:** 27 December 2025

ABSTRACT

National Parks are under threat from multiple interacting climatic changes, which have already triggered transformations in these protected landscapes. We conducted a multidimensional analysis of climate-change vulnerability for National Parks to identify which parks are most at risk of climate-change impacts and therefore in the greatest need of targeted climate-change vulnerability assessment and planning. We identified 174 (67%) parks as most exposed to one or more potentially transformative climate impacts including fire, drought, sea-level rise, and forest pests and diseases. Cumulative vulnerability across multiple dimensions was the highest for parks in the Midwest and eastern United States due to high physical exposures, the exacerbation of existing stressors, and high surrounding land-use intensity. Western parks exhibited lower cumulative vulnerability due to less intense land use and topography that may provide climatic refugia. However, western parks tended to be most exposed to multiple transformative impacts. These widespread, diverse threats highlight not only the need for coordinated evaluation of vulnerabilities from multiple perspectives, but also the need for park managers to evaluate and plan for potentially irreversible ecological changes to the landscapes and resources that parks are intended to preserve.

1 | Introduction

National Parks in the United States protect some of the world's most unique and valued species, ecosystems, geologic features, and cultural sites. Yet, anthropogenic climate change poses a significant threat to the resources and values protected by the US National Park Service (NPS) (Gonzalez 2017). Over the last 100 years, National Park units (hereafter "parks") have experienced a disproportionate degree of warming and precipitation change relative to the United States in general, and these trends are projected to continue (Gonzalez et al. 2018). In addition to exposure to simple physical climatic changes (e.g., changes in temperature), parks face multiple cascading impacts that are amplified by climate change, including extreme weather events, forest insect outbreaks, more frequent and severe wildfire, and other novel disturbance regimes that occur both individually and simultaneously (Ridder et al. 2022; Abatzoglou and Williams 2016; Turner et al. 2016). Such disturbances and stressors may trigger irreversible ecological transformations in parks (Holsinger et al. 2019; Crausbay et al. 2022), creating an imperative need for park managers to evaluate and strategically plan for potentially transformational impacts (Schuurman et al. 2022).

Accordingly, the NPS has engaged in numerous efforts to evaluate climate-change vulnerability as a foundational step to developing robust climate-adaptation plans (Peek et al. 2022; Miller et al. 2022). These include broad-scale and park-specific analyses evaluating physical exposure of parks (Hansen et al. 2014; Gonzalez et al. 2018; Runyon et al. 2024), sea-level rise (Caffrey et al. 2018), and species loss and turnover (Fisichelli et al. 2013; Guay et al.

2016; Wu et al. 2018). Despite these concerted efforts, most parks lack comprehensive climate-change vulnerability assessments that evaluate multiple dimensions of vulnerability, in part due to gaps in spatial data. Specifically, Michalak et al. (2022) found that although a few limited regional assessments have been done, only 10% of the parks had park-specific assessments and 37% had no assessments whatsoever. For individual parks, the likelihood of climate impacts and potential transformational changes therefore remains uncertain. Determining where more in-depth, park-specific assessments are warranted is essential for allocating resources to parks where climate-adaptation planning is most urgently needed.

Climate-change vulnerability is generally defined as the intersection of exposure, sensitivity, and adaptive capacity.[1] Climate-change exposure is the intensity of changes a location (e.g., a park) may experience (Dawson et al. 2011; NPS 2021b). This includes changes in the climate itself (e.g., temperature, precipitation) as well as changes in climate-exacerbated disturbances (e.g., fire, drought, and sea-level rise). Sensitivity is the extent to which a location or resource is affected or existing stressors are amplified by climatic changes, whether adversely or beneficially (NPS 2021b). Imperiled species, for instance, may be further threatened if climatic changes make conditions more conducive for invasive species (Finch et al. 2021; Bradley et al. 2024). Likewise, ambient air pollution within parks may be exacerbated by wildfire smoke (Kalashnikov et al. 2022). Finally, adaptive capacity is the ability of a system to adapt to climate-change impacts (NPS 2021b). Landscape characteristics may confer or reduce adaptive capacity if those characteristics facilitate or impede the ability of a species or ecosystems to adapt (Beever et al. 2016). Examples include the permeability of the surrounding landscape for species movements, which may be compromised by intensive land-use (McGuire et al. 2016), as well as environmental diversity, which includes topographic, edaphic, and vegetation diversity. Such diversity may create climate-change refugia (Carroll et al. 2017) or otherwise afford a range of conditions for ecological and evolutionary processes and for community reshuffling (Lawler et al. 2015). Our goals were to identify high-priority threats, determine parks and resources most at risk, and inform strategies to meet NPS-wide needs for vulnerability assessments of parks and their resources. To do so, we used 45 spatial data layers to develop relative indicators for multiple dimensions of all three components of climate vulnerability for parks in the conterminous United States. Using these indicators, we calculated a cumulative vulnerability score to identify the most vulnerable parks nationally and within selected ecoregions. In addition, we identified parks relatively more at risk to transformational impacts from fire, drought, sea-level rise, and forest pests and diseases. The results of this assessment were designed to inform prioritization efforts, resource allocation, and guide the design and application of adaptation strategies for groups of parks facing similar threats.

2 | Methods

We evaluated the relative vulnerability of all parks in the continental United States designated as "natural resource parks" and serviced by the NPS Inventory and Monitoring Division (n = 259 park units; island parks and Alaska were omitted due to insufficient data availability). We iteratively solicited feedback from experts at the NPS to refine a suite of vulnerability factors relevant to terrestrial natural resources in parks, primarily plant and animal species and ecosystem functions, including a specific set of climate metrics. In addition, many of these factors were previously used in summaries of climate-change impacts to parks (Hansen et al. 2014; Morgan et al. 2016; NPS 2016; Rockman et al. 2016; Gonzalez 2017; USGCRP 2023).

For each vulnerability factor, we identified spatial datasets with consistent information across the study region that could be evaluated at individual park locations and in the surrounding landscapes. With NPS expert feedback, we identified data for 45 indicators collectively representing 21 more general vulnerability factors across all three vulnerability components (Figure 1), the details of which are given in the Supporting Information (sections *Conceptualizing Vulnerability* and *Indicator Details*). The indicators are intended to provide information on the relative vulnerability of each park compared to other parks.

For gridded spatial datasets, we calculated the mean indicator values for all cells within a park boundary plus a 30-km or 60-km buffer surrounding the park to account for the potential influence of the broader landscape context on the park. Buffer size was informed by the spatial resolution of the indicator datasets. We standardized each indicator using a min-max (0-1) approach to identify parks that scored relatively highest for each indicator regardless of the range of values for any individual indicator. We then aggregated indicators that characterized the same attribute (e.g., temperature, precipitation) into vulnerability factors to avoid overrepresentation of attributes for which there were multiple indicators. All indicators were weighted equally within these factors. We then calculated cumulative scores for each vulnerability component (i.e., exposure, sensitivity, and adaptive capacity, Figure 1) and a total cumulative vulnerability score by adding exposure and sensitivity, and subtracting the value of adaptive capacity (Equation 1 in Supporting Information):

$$\text{Cumulative vulnerability score} = \text{Exposure} + \text{Sensitivity} - \text{AdaptiveCapacity}$$

We then ranked all parks by their cumulative score to calculate a multidimensional metric of relative vulnerability. We highlighted parks that scored at or above the 75th percentile nationally as parks with the highest multidimensional vulnerability scores. We conducted a comparable ranking and categorization of parks by ecoregional group (Supporting Information section *Ecoregional Analysis*).

We weighted all indicators, factors, and vulnerability components equally when computing scores, but we recognize that some vulnerability factors have an outsized potential to affect and even transform ecosystems (Turner et al. 2016; Anderegg et al. 2022). Thus, we identified four vulnerability factors with the potential to trigger transformational change—namely fire (Coop et al. 2020), drought (Hammond et al. 2022), pests and diseases (Perovich and Sibold 2016), and sea-level rise (Caffrey et al. 2018). We analyzed these individually, drawing on the literature and NPS experts to identify thresholds associated with transformational change. For drought and forest pests and disease, we retained

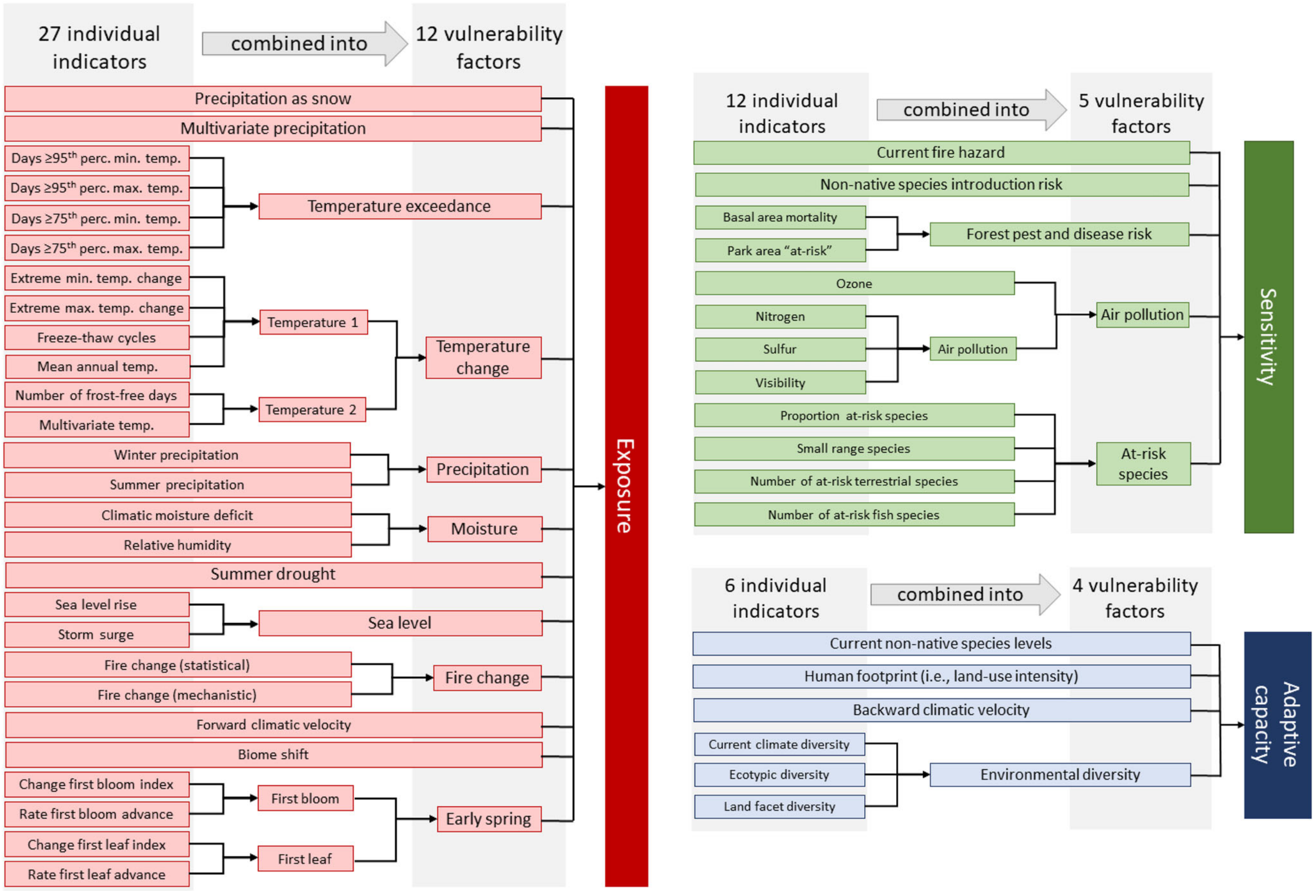

FIGURE 1 | Indicators combined into vulnerability factors underpinning exposure (left panel; see Table S1), sensitivity (upper right panel; see Table S2), and adaptive capacity (lower right panel; see Table S3). A full description of all indicators including their derivation, resolution and extent, and relevant projection information (e.g., GCMs, emissions scenarios) is given in the Supporting Information section entitled *Indicator Details*.

the 80th percentile as the threshold, based on a desire to balance greater selectivity with the right-skewed distribution of the data. For the other factors, we identified absolute thresholds that if exceeded, would flag the park as having high vulnerability to those specific factors (expert-informed thresholds are described in Supporting Information section *Transformational Factors*). Although freshwater flooding was highlighted by NPS experts as also possibly transformative, the required data were unavailable. We identified parks most at risk for each of these four factors (Table S4) and considered those parks high priorities for more detailed vulnerability analysis and planning regardless of how that park scored with respect to other vulnerability factors.

3 | Results

Our analyses identified 200 parks (77%) as most vulnerable to climate change, based on relative scores for either cumulative vulnerability or for at least one potentially transformational factor. These parks may be considered priorities for more in-depth evaluation and climate adaptation planning that considers potential transformation. These included 65 parks (25%) with the highest cumulative vulnerability scores nationally, 68 parks (26%) with high cumulative vulnerability per ecoregion, and 174 parks (67%) most at risk of transformational impacts (i.e., fire, drought, pests and diseases, and/or sea-level rise). Of the parks most at risk of transformation, one-third ($n = 57$) were also in the top quartile of vulnerability nationally and/or regionally (Table 1).

3.1 | Patterns in Exposure, Sensitivity, and Adaptive Capacity

Geographic patterns in the components of vulnerability emerged that contributed to but were not always apparent in patterns of cumulative vulnerability (described below). Parks most exposed to climate change were in the Midwest due to large projected changes in physical climate metrics (i.e., temperature, precipitation, moisture, and snow), as well as in the Southwest where drought frequency and fire hazard are both anticipated to increase (Figure 2). Sensitivity was the highest for parks in the Mid-Atlantic and Southeast due to the combination of higher air pollution levels, non-native species invasion risk, and high levels of forest pests and diseases. Several parks in California had high sensitivity scores due to high numbers of at-risk species. Parks with the highest adaptive capacity scores were predominantly in the western United States, especially in areas with complex topography and/or minimal human modification and land use (i.e., low human footprint).

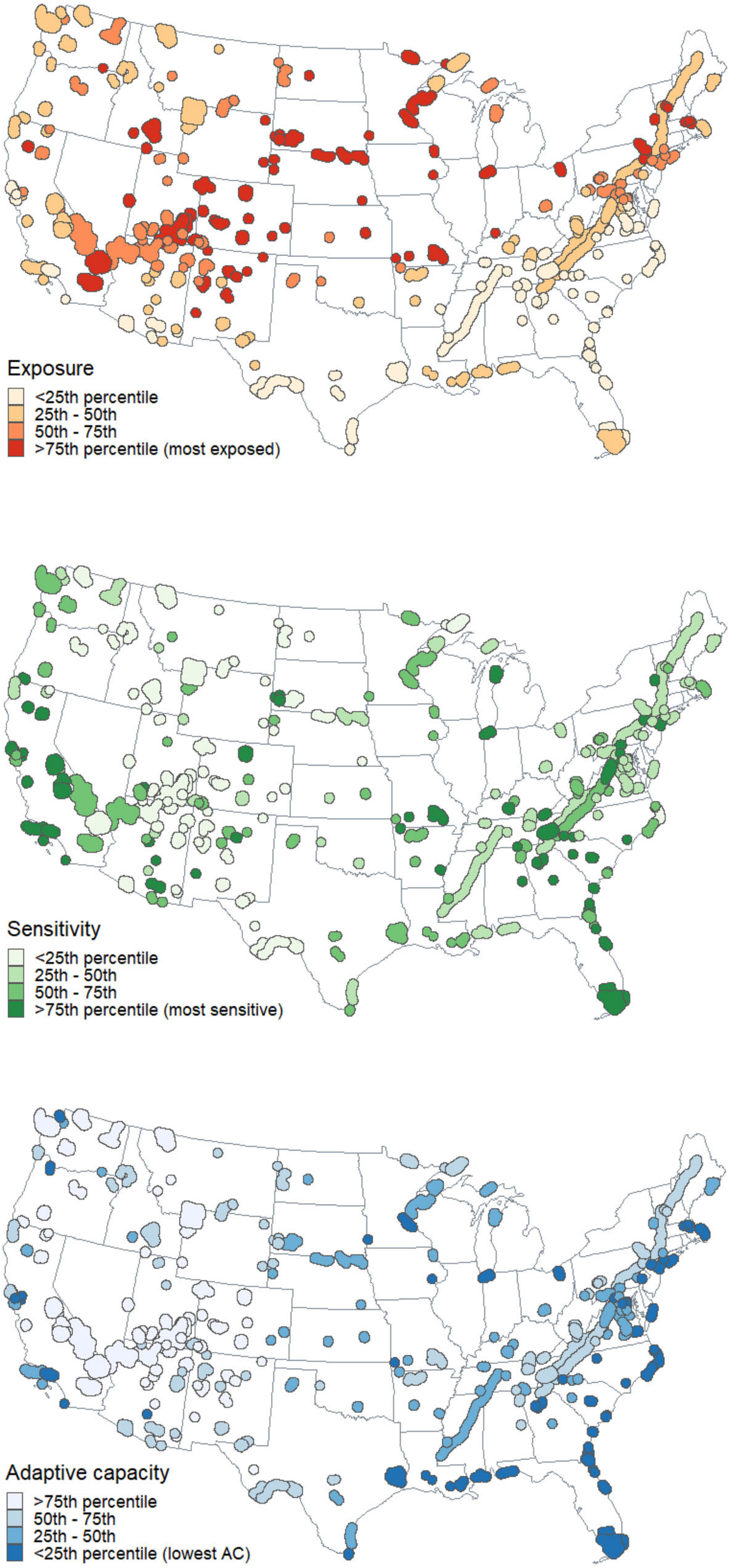

FIGURE 2 | Quartile of total scores for indicators related to exposure (top), sensitivity (middle), and adaptive capacity (bottom). Parks with the highest exposure and sensitivity and the lowest adaptive capacity are considered most vulnerable.

TABLE 1 | Number and percent of parks in the continental United States that scored high for each transformational vulnerability factor, and how many of those parks also scored in the top quartile for cumulative vulnerability at the national or regional scale.

High impact vulnerability	Number of parks	Percentage of parks	Number of parks with national vulnerability scores in top quartile	Number of parks with regional vulnerability scores in top quartile[a]
High current fire hazard	73	28	11	21
High future fire hazard	98	38	41	22
Summer drought	66	25	8	17
Forest pest and disease	92	36	28	25
Sea-level rise	28	11	9	10
Storm surge inundation	19	7	5	6
At least one of the above	174	67	40	47

[a]Summary ecoregional results are given in the SI and are fully presented in the associated report (*Michalak* et al. 2021).

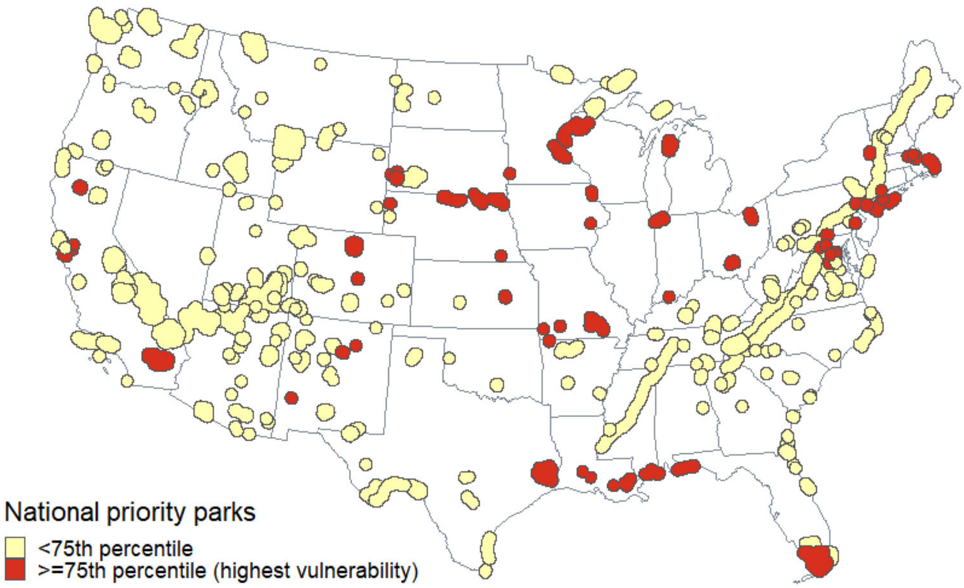

FIGURE 3 | Priority parks at the national scale, which were identified as those ranking at or above the 75th percentile in total cumulative vulnerability scores. Ecoregional results are given in the Supporting Information.

3.2 | Regional Patterns in Total Cumulative Vulnerability

Parks with the highest cumulative vulnerability scores were in the Midwest, in and near Washington, DC, and along the Gulf Coast of the southeast (Figure 3). For many of these parks, vulnerability stemmed from high levels of human development, poor air quality, high proportions of non-native species, and low environmental diversity, which is considered an indicator of climate-change resilience. Parks in the Great Plains scored very high for climate-change exposure, in part because the low topographical relief of the region contributes to high climate velocity—the rate a species must move to keep pace with the same climatic conditions—and the region lacks landscape features (e.g., higher elevations, north-facing slopes) that confer adaptive capacity (e.g., by providing climatic refugia). Human footprint scores were lower in the Great Plains relative to parks in the East but high relative to parks in the West. Indeed, lower vulnerability scores for parks in the west were largely due to low levels of human modification as well as high levels of environmental diversity. However, many western parks scored very high for one or more potentially transformational impacts.

3.3 | High-Impact, Transformational Vulnerabilities

One hundred and seventy-four parks (67%) scored high for at least one potentially transformational impact: fire, drought, forest pests and diseases, and/or sea-level rise (Table 1). (What constitutes a high score was based on literature- or expert-informed thresholds—e.g., the percentage of park area inundated during storm surge—that are given in Supporting Information section *Transformational Factors*.) Many western parks scored high for multiple, interacting, transformational threats despite relatively low cumulative vulnerability scores (Figure 4).

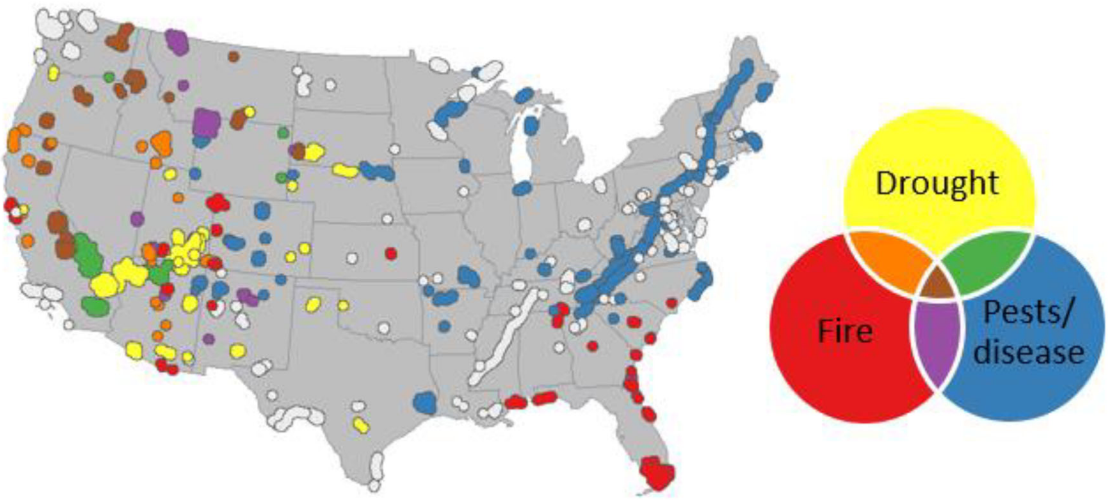

FIGURE 4 | Parks most at risk of potentially transformational impacts associated with fire, drought, and/or forest pest or disease. Parks that exceeded thresholds (Table S4) were deemed most vulnerable to these high-impact, transformational vulnerabilities. Parks in light gray did not exceed any thresholds for these transformational impacts.

Parks that scored high for forest pest and disease indicators were concentrated in the mountainous West and the Northeast. Parks poised to be most affected by fire were concentrated in the West and Southeast. Projected increases in the frequency of moderate or severe summer droughts were the highest in the West. Thirteen parks in the West scored high for a "trifecta" of fire, drought, and forest pests and disease, with potentially transformational consequences (Figure 4). Parks along the Atlantic and Gulf Coasts scored the highest for vulnerability to sea-level rise and/or storm surge, and 15 parks in the Southeast scored high for both sea-level rise (sea-level rise and/or storm surge) and fire.

4 | Discussion

Vulnerability to climate-change arises from factors associated with exposure, sensitivity, and adaptive capacity. Most previous analyses have evaluated individual vulnerability factors for individual National Parks (reviewed by Gonzalez et al. 2018), but this is the first evaluation of vulnerability that examined a broad range of interacting factors for US national parks at large. By including indicators of all three components of vulnerability, we identified new patterns in park vulnerability and uncovered potentially at-risk parks and regions that were previously overlooked. For example, an analysis that relied primarily on climate-change velocity as an indicator of vulnerability categorized much of the western United States as having relatively low vulnerability (Belote et al. 2017), whereas other assessments identified western parks as highly exposed to temperature increases (Hansen et al. 2014; Monahan and Fisichelli 2014). By integrating a robust suite of indicators, our analyses provide a more complete picture of climate-change vulnerability and the aspects of climate change that place parks at risk.

The broad geographic patterns in vulnerability that emerged from our analysis can be attributed in part to underlying landscape patterns also noted in other regional, national, continental, and even global studies (e.g., Batllori et al. 2017; Parks et al. 2023). Many parks across the West are highly exposed to physical climatic changes, as found in previous analyses (e.g., Hansen et al. 2014; Gonzalez et al. 2018; Hoffman and Beierkuhnlein 2020; Tercek et al. 2023). However, the relatively high degree of adaptive capacity in some parks contributed to lower overall vulnerability scores in our analyses. For example, the topographic complexity of many western parks creates substantial climatic gradients (Krosby et al. 2018), reduces climatic velocities (Hamann et al. 2015), and may provide climate-change refugia (Carroll et al. 2017; Hoylman et al. 2019). These attributes may enable some species to access and persist in suitable climatic conditions more easily. By contrast, relatively flat and topographically homogenous parks like those in the Midwest have lower degrees of environmental diversity—and therefore adaptive capacity, also identified in Stroh et al. (2016)—and experience high climatic velocities (Batllori et al. 2017).

Further, the human footprint across much of the western landscape is relatively low compared to other regions, which means species may more easily access suitable conditions without having to traverse areas of intensive human land use (McGuire et al. 2016; Parks et al. 2020). However, high, localized rates of land use change projected in the West may increasingly reduce landscape permeability, thereby undermining this adaptive capacity (Oakleaf et al. 2024). Many parks in the eastern United States are already embedded in highly modified landscapes crossed with transportation corridors that may impede movement of native species while exacerbating ongoing invasions of non-native species and pathogens that may already be aided by climatic changes (Fisichelli et al. 2014; Lovett et al. 2016). These geographic patterns underscore the importance of evaluating adaptive capacity because analyses that examine only elements of climate-change exposure may inadvertently identify areas as highly vulnerable when, in fact, high (or low) degrees of adaptive capacity may offset (or exacerbate) the detrimental effects of exposure elements. Our analyses thus build upon the foundation of prior studies that examine only exposure and lend a more nuanced lens to patterns of vulnerability.

Despite the adaptive capacity conferred by landscape patterns (e.g., from environmental diversity), our results identified many western parks as being some of the most exposed to multiple transformative and interacting impacts—namely, fire, drought, and forest insects and diseases—as consistently documented elsewhere (e.g., Turner et al. 2016; Anderegg et al. 2022). Post-fire forest recovery failure has been documented across the West (Coop et al. 2020), enduring drought has triggered ecosystem state changes and community collapse (Hammond et al. 2022), and forest pests and diseases have killed vast areas of trees and shifted forest composition (Perovich and Sibold 2016) as in Rocky Mountain and Yellowstone National Parks. Furthermore, each of these disturbances and impacts—among others—may amplify one another (Robbins et al. 2022; Wayman and Safford 2021). For example, wildfires in Bandelier National Monument have exacerbated the risk of debris flows (Touma et al. 2022), and invasive grasses may increase fine-fuel loads, potentially altering fire regimes and increasing fire occurrence in Mojave National Preserve (Fusco et al. 2019). The result of these compounding disturbances may be rapid, dramatic, and irreversible transformation of western park ecosystems (Turner et al. 2020).

The potential for transformation is also relevant for parks far from western forests: the vast majority (n = 47) of the parks along the Atlantic and Gulf coasts face substantial inundation from sea-level rise (≥5%) or storm surge (≥20%). Coastal inundation puts mangroves, salt marsh, and coastal forest ecosystems at risk (Saintilan et al. 2020; Smart et al. 2020), while coastal development inhibits inland migration of these systems (Leo et al. 2019). We identified 15 parks facing these compounding and novel impacts that, to our knowledge, have not yet been systematically identified in this way. Our analysis lacked data to evaluate projected changes in the frequency and severity of hurricanes and freshwater flooding that would exacerbate coastal inundation impacts (USGCRP 2023).

To avoid potentially catastrophic changes from transformative climate-change impacts, park managers will need to adopt strategies that facilitate adaptation to the considerable changes that the parks may experience. Some of these strategies will focus on resisting change, while others will allow changes to unfold, and still others will attempt to direct changes in ways that may achieve preferred—even if different—conditions. To that end, the US National Park Service has adopted a new management paradigm: the resist-accept-direct framework that directly confronts the inevitability of transformative impacts (Schuurman et al. 2022). For highly valued, irreplaceable park resources, resisting change may be a preferred pathway in the near-term to prevent or delay impacts. But as climate change progresses, strategies will likely need to shift toward accepting and directing change, especially when managers have little leverage for controlling system dynamics (Siegel et al. 2024). Species range shifts may change management goals and conservation targets altogether (Parks et al. 2023), increasing the need for actions that facilitate species movement through the landscapes between parks or that promote fire, drought, or climatic refugia (Meddens et al. 2018; Michalak et al. 2018).

Managing a large, multifaceted public lands agency, like the NPS, requires information at multiple scales. Broad-scale studies such as the one described here can inform the efficient allocation of funding and capacity nationally and regionally. Knowing which parks are likely to be most vulnerable to a specific threat allows managers to design and apply strategies appropriate to those parks in those regions (see the Table of Park Scores in the Supplemental Information). Such knowledge could also help foster collaborations between managers of different parks within and across regions that may result in efficiencies in the design and execution of more detailed vulnerability assessments; shared learning; and pooled resources for coordinated, landscape-scale efforts. The results of this analysis can inform regional and national prioritizations of candidate parks for such in-depth vulnerability assessments, identify vulnerabilities warranting finer scale or more localized study, and suggest areas of transformation for which climate change adaptation actions might be targeted. Collectively, these results can highlight the individual and shared vulnerabilities faced by park managers and regional decision-makers, enabling more targeted allocation of resources and encouraging boundary-spanning collaboration which are critical to effective climate change adaptation planning and implementation. Large-scale spatial analyses generally cannot account for regional or local conditions. In addition, our approach evaluated the relative vulnerability among parks as opposed to empirically establishing vulnerability levels. Although broad-scale, systematic studies of climate change vulnerability have inherent limitations, such analyses are needed to direct resources to parks and locations with the greatest need for climate change vulnerability resources. Such assessments are complementary to rather than replacements for fine-scaled assessments of individual parks.

Although the precise consequences of the changes parks will experience remain difficult to predict, it is clear that the goal of conserving parks as a "*vignette of primitive America*" (Leopold et al. 1963) is incompatible with the trajectories of change that are underway. Rather, park managers are now challenged to steward resources "for continuous change that is not yet fully understood" (Colwell et al. 2014). A comprehensive assessment of parks' climate-change vulnerability, as we have undertaken here, is one important step toward building that understanding.

Acknowledgments

We are grateful to the following individuals who supported various aspects of project design, development, and administration: Cat Hawkins-Hoffman, Gregor Schuurman, Amanda Babson, Rebecca Beavers, Rob Young, David Lawrence, Marcy Rockman, Pei-lin Wu, and Melanie Wood. The National Park Service funded this effort (Cooperative Agreement P21AC10645).

Conflicts of Interest

The authors declare no conflicts of interest.

Funding

This work was funded by the National Park Service.

Data Availability Statement

The data that support the findings of this study are archived with Open Science Foundation (https://doi.org/10.17605/OSF.IO/R8PTQ).

Note

[1] Our conception of vulnerability follows the definition advanced in the fourth assessment of the Intergovernmental Panel on Climate Change (IPCC): "Vulnerability is a function of the character, magnitude and rate of climate change and the variation to which a system is exposed, its sensitivity and its adaptive capacity" (IPCC 2007). Even as subsequent IPCC reports (e.g., IPCC 2014, IPCC 2022) offer an alternative definition centered on sensitivity and adaptive capacity and as critiques over vulnerability assessment approaches have arisen (Ford et al. 2018), the former definition remains widely adopted within the conservation and natural resource communities (Glick et al. 2011; Foden et al. 2019) and is codified in the official NPS planning approach (NPS 2021).

References

Abatzoglou, J. T., and A. P. Williams. 2016. "Impact of Anthropogenic Climate Change on Wildfire Across Western US Forests." *Proceedings of the National Academy of Sciences* 113, no. 42: 11770–11775.

Anderegg, W. R., O. S. Chegwidden, G. Badgley, et al. 2022. "Future Climate Risks From Stress, Insects and Fire Across US Forests." *Ecology Letters* 25, no. 6: 1510–1520.

Batllori, E., M. A. Parisien, S. A. Parks, M. A. Moritz, and C. Miller. 2017. "Potential Relocation of Climatic Environments Suggests High Rates of Climate Displacement Within the North American Protection Network." *Global Change Biology* 23, no. 8: 3219–3230.

Beever, E. A., J. O'Leary, C. Mengelt, et al. 2016. "Improving Conservation Outcomes With a New Paradigm for Understanding Species' Fundamental and Realized Adaptive Capacity." *Conservation Letters* 9: 131–137.

Belote, R. T., M. S. Dietz, P. S. McKinley, et al. 2017. "Mapping Conservation Strategies Under a Changing Climate." *Bioscience* 67: 494–497.

Bradley, B. A., E. M. Beaury, B. Gallardo, et al. 2024. "Observed and Potential Range Shifts of Native and Nonnative Species with Climate Change." *Annual Review of Ecology, Evolution, and Systematics* 55: 23–40.

Caffrey, M. A., R. L. Beavers, and C. H. Hoffman. 2018. *Sea Level Rise and Storm Surge Projections for the National Park Service*. Natural Resource Report NPS/NRS/NRR—2018/1648. National Parks Service.

Carroll, C., D. R. Roberts, J. L. Michalak, et al. 2017. "Scale-Dependent Complementarity of Climatic Velocity and Environmental Diversity for Identifying Priority Areas for Conservation Under Climate Change." *Global Change Biology* 23: 4508–4520.

Colwell, R., S. Avery, J. Berger, et al. 2014. "Revisiting Leopold: Resource Stewardship in the National Parks." *Parks* 20: 15–24.

Coop, J. D., S. A. Parks, C. S. Stevens-Rumann, et al. 2020. "Wildfire-Driven Forest Conversion in Western North American Landscapes." *Bioscience* 70: 659–673.

Crausbay, S. D., H. R. Sofaer, A. E. Cravens, et al. 2022. "A Science Agenda to Inform Natural Resource Management Decisions in an Era of Ecological Transformation." *Bioscience* 72, no. 1: 71–90.

United States Global Change Research Program. 2023. *Fifth National Climate Assessment*. Edited by A. R. Crimmins, C. W. Avery, D. R. Easterling, K. E. Kunkel, B. C. Stewart, and T. K. Maycock. U.S. Global Change Research Program. https://doi.org/10.7930/NCA5.2023.

Dawson, T. P., S. T. Jackson, J. I. House, I. C. Prentice, and G. M. Mace. 2011. "Beyond Predictions: Biodiversity Conservation in a Changing Climate." *Science* 332, no. 6025: 53–58.

Finch, D. M., J. L. Butler, J. B. Runyon, et al. 2021. *Effects of Climate Change on Invasive Species. Page Invasive Species in Forests and Rangelands of the United States: A Comprehensive Science Synthesis for the United States Forest Sector*. Springer. https://doi.org/10.1007/978-3-030-45367-1.

Fisichelli, N. A., M. Peters, L. Iverson, S. Matthews, and C. Hawkins-Hoffman. 2013. *Climate Change and Forests of the Acadia National Park Region: Projected Changes in Habitat Suitability for 83 Tree Species*. Natural Resource Report NPS/ACAD/NRR 2013/733, Open-File Report. National Park Service.

Fisichelli, N. A., S. R. Abella, M. Peters, and F. J. Krist. 2014. "Climate, Trees, Pests, and Weeds: Change, Uncertainty, and Biotic Stressors in Eastern U.S. national Park Forests." *Forest Ecology and Management* 327: 31–39.

Foden, W. B., B. E. Young, H. R. Akçakaya, et al. 2019. "Climate Change Vulnerability Assessment of Species." *Wiley Interdisciplinary Reviews: Climate Change* 10, no. 1: e551.

Ford, J. D., T. Pearce, G. McDowell, L. Berrang-Ford, J. S. Sayles, and E. Belfer. 2018. "Vulnerability and Its Discontents: The Past, Present, and Future of Climate Change Vulnerability Research." *Climatic Change* 151: 189–203.

Fusco, E. J., J. T. Finn, J. K. Balch, R. C. Nagy, and B. A. Bradley. 2019. "Invasive Grasses Increase Fire Occurrence and Frequency Across US Ecoregions." *Proceedings of the National Academy of Sciences* 116, no. 47: 23594–23599.

Glick, P., B. A. Stein, andN. A. Edelson, eds. 2011. *Scanning the Conservation Horizon: A Guide to Climate Change Vulnerability Assessment*. National Wildlife Federation.

Gonzalez, P. 2017. "Climate Change Trends, Impacts, and Vulnerabilities in US National Parks." *Science, Conservation, and National Parks*, edited by S. R. Beissinger, D. D. Ackerly, H. Doremus, and G.E. Machlis. University of Chicago Press.

Gonzalez, P., F. Wang, M. Notaro, D. J. Vimont, and J. W. Williams. 2018. "Disproportionate Magnitude of Climate Change in United States National Parks." *Environmental Research Letters* 13: 104001.

Guay, K., P. Jantz, J. E. Gross, B. M. Rogers, and S. J. Goetz. 2016. "Historical and Projected Climates as a Basis for Climate Change Exposure and Adaptation Potential Across the Appalachian Landscape Conservation Cooperative." *Climate Change in Wildlands: Pioneering Approaches to Science and Management*, edited by A. J. Hansen, D. M. Theobald, W. B. Monahan, and S. T. Olliff, 78–94. Island Press.

Hamann, A., D. R. Roberts, Q. E. Barber, C. Carroll, and S. E. Nielsen. 2015. "Velocity of Climate Change Algorithms for Guiding Conservation and Management." *Global Change Biology* 21: 997–1004.

Hammond, W. M., A. P. Williams, J. T. Abatzoglou, et al. 2022. "Global Field Observations of Tree Die-off Reveal Hotter-Drought Fingerprint for Earth's Forests." *Nature Communications* 13, no. 1: 1–11.

Hansen, A. J., N. B. Piekielek, C. Davis, et al. 2014. "Exposure of US National Parks to Land Use and Climate Change 1900–2100." *Ecological Applications* 24: 484–502.

Hoffmann, S., and C. Beierkuhnlein. 2020. "Climate Change Exposure and Vulnerability of the Global Protected Area Estate From an International Perspective." *Diversity and Distributions* 26, no. 11: 1496–1509.

Holsinger, L., S. A. Parks, M. A. Parisien, C. Miller, E. Batllori, and M. A. Moritz. 2019. "Climate Change Likely to Reshape Vegetation in North America's Largest Protected Areas." *Conservation Science and Practice* 1, no. 7: e50.

Hoylman, Z. H., K. G. Jencso, J. Hu, et al. 2019. "The Topographic Signature of Ecosystem Climate Sensitivity in the Western United States." *Geophysical Research Letters* 46, no. 24: 14508–14520.

Intergovernmental Panel on Climate Change. 2007. "Climate Change 2007: Impacts, Adaptation and Vulnerability." In *Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.

Intergovernmental Panel on Climate Change. 2014. "Climate Change 2014: Impacts, Adaptation, and Vulnerability." *Contributions of Working Group II to the Fifth Assessment Report*. Cambridge University Press.

Intergovernmental Panel on Climate Change. 2022. "Climate Change 2022: Impacts, Adaptation, and Vulnerability." *Contributions of Working Group II to the Sixth Assessment Report*. Cambridge University Press.

Kalashnikov, D. A., J. L. Schnell, J. T. Abatzoglou, D. L. Swain, and D. Singh. 2022. "Increasing Co-Occurrence of Fine Particulate Matter and Ground-Level Ozone Extremes in the Western United States." *Science Advances* 8, no. 1: eabi9386.

Krosby, M., D. M. Theobald, R. Norheim, and B. H. McRae. 2018. "Identifying Riparian Climate Corridors to Inform Climate Adaptation Planning." *PLoS ONE* 13: e0205156. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6235256/.

Lawler, J. J., D. D. Ackerly, C. M. Albano, et al. 2015. "The Theory Behind, and the Challenges of, Conserving Nature's Stage in a Time of Rapid Change." *Conservation Biology* 29, no. 3: 618–629.

Leo, K. L., C. L. Gillies, J. A. Fitzsimons, L. Z. Hale, and M. W. Beck. 2019. "Coastal Habitat Squeeze: A Review of Adaptation Solutions for Saltmarsh, Mangrove and Beach Habitats." *Ocean & Coastal Management* 175: 180–190.

Leopold, A. S., S. A. Cain, C. M. Cottom, I. N. Gabrielson, and J. T. Kimball. 1963. "Wildlife Management in the National Parks." *Transactions of the North American Wildlife and Natural Resources Conference* 28: 28–45.

Lovett, G. M., M. Weiss, A. M. Liebhold, et al. 2016. "Nonnative Forest Insects and Pathogens in the United States: Impacts and Policy Options." *Ecological Applications* 26: 1437–1455.

McGuire, J. L., J. J. Lawler, B. H. McRae, T. A. Nuñez, and D. M. Theobald. 2016. "Achieving Climate Connectivity in a Fragmented Landscape." *Proceedings of the National Academy of Sciences* 113: 7195–7200.

Meddens, A. J., C. A. Kolden, J. A. Lutz, et al. 2018. "Fire Refugia: What Are They, and Why Do They Matter for Global Change?" *Bioscience* 68, no. 12: 944–954.

Michalak, J. L., J. J. Lawler, D. R. Roberts, and C. Carroll. 2018. "Distribution and Protection of Climatic Refugia in North America." *Conservation Biology* 32: 1414–1425.

Michalak, J. L., J. J. Lawler, J. E. Gross, and C. E. Littlefield. 2021. *A Strategic Analysis of Climate Vulnerability of National Park Resources and Values*. Natural Resource Report NPS/NRSS/CCRP/NRR—2021/2293. National Park Service.

Michalak, J. L., J. J. Lawler, J. E. Gross, et al. 2022. "Climate-Change Vulnerability Assessments of Natural Resources in U.S. National Parks." *Conservation Science and Practice* 4: e12703.

Miller, B. W., G. W. Schuurman, A. J. Symstad, A. N. Runyon, and B. C. Robb. 2022. "Conservation Under Uncertainty: Innovations in Participatory Climate Change Scenario Planning From U.S. National Parks." *Conservation Science and Practice* 4: e12633.

Monahan, W. B., and N. A. Fisichelli. 2014. "Climate Exposure of US National Parks in a New Era of Change." *PLoS ONE* 9: e101302.

Morgan, J. A., M. Rockman, C. Smith, and A. Meadow. 2016. "Climate Change Impacts on Cultural Resources." In *Cultural Resources Partnership and Science*. National Park Service.

National Park Service. 2016. *Coastal Hazards and Climate Change Asset Vulnerability Protocol: Project Description and Methodology*. NPS 999/132623. National Park Service, Washington, D.C.

National Park Service. 2021b. *Coming to Terms With Climate Change: Working Definitions*. National Park Service, Climate Change Response Program, Fort Collins, Colorado.

Oakleaf, J., C. Kennedy, N. H. Wolff, et al. 2024. "Mapping Global Land Conversion Pressure to Support Conservation Planning." *Scientific Data* 11: 830.

Parks, S. A., C. Carroll, S. Z. Dobrowski, and B. W. Allred. 2020. "Human Land Uses Reduce Climate Connectivity Across North America." *Global Change Biology* 26, no. 5: 2944–2955.

Parks, S. A., L. M. Holsinger, J. T. Abatzoglou, C. E. Littlefield, and K. A. Zeller. 2023. "Protected Areas Not Likely to Serve as Steppingstones for Species Undergoing Climate-induced Range Shifts." *Global Change Biology* 29, no. 10: 2681–2696.

Peek, K. M., B. R. Tormey, H. L. Thompson, A. C. Ellsworth, and C. H. Hoffman, editors. 2022. *Climate Change Vulnerability Assessments in the National Park Service: an Integrated Review for Infrastructure, Natural Resources, and Cultural Resources*. National Park Service, Fort Collins, Colorado.

Perovich, C., and J. S. Sibold. 2016. "Forest Composition Change After a Mountain Pine Beetle Outbreak, Rocky Mountain National Park, CO, USA." *Forest Ecology and Management* 366: 184–192.

Ridder, N. N., A. M. Ukkola, A. J. Pitman, and S. E. Perkins-Kirkpatrick. 2022. "Increased Occurrence of High Impact Compound Events Under Climate Change." *NPJ Climate and Atmospheric Science* 5: 3. https://doi.org/10.1038/s41612-021-00224-4.

Robbins, Z. J., C. Xu, B. H. Aukema, et al. 2022. "Warming Increased Bark Beetle-induced Tree Mortality by 30% During an Extreme Drought in California." *Global change biology* 28, no. 2: 509–523.

Rockman, M., M. Morgan, S. Ziaja, et al. 2016. Cultural Resources Climate Change Strategy. National Park Service Cultural Resources, Partnerships, and Science and Climate Change Response Program, Washington, D.C.

Runyon, A. N., J. E. Gross, G. W. Schuurman, D. J. Lawrence, and J. H. Reynolds. 2024. *Methods for Assessing Climate Change Exposure for National Park Planning*. Park Resource Report PRR—2024/02, National Park Service, Fort Collins, Colorado.

Saintilan, N., N. S. Khan, E. Ashe, et al. 2020. "Thresholds of Mangrove Survival Under Rapid Sea Level Rise." *Science* 368, no. 6495: 1118–1121.

Schuurman, G. W., D. N. Cole, A. E. Cravens, et al. 2022. "Navigating Ecological Transformation: Resist–accept–direct as a Path to a New Resource Management Paradigm." *Bioscience* 72, no. 1: 16–29.

Siegel, K. J., K. C. Cavanaugh, and L. E. Dee. 2024. "Balancing Multiple Management Objectives as Climate Change Transforms Ecosystems." *Trends in Ecology & Evolution* 39, no. 4: 381–395.

Smart, L. S., P. J. Taillie, B. Poulter, et al. 2020. "Aboveground Carbon Loss Associated With the Spread of Ghost Forests as Sea Levels Rise." *Environmental research letters* 15, no. 10: 104028.

Stroh, E. D., M. Struckhoff, D. Shaver, and K. Karstensen. 2016. Vulnerabilities of national parks in the American Midwest to climate and land use changes: U.S. Geological Survey Scientific Investigations Report, 2016–5057.

Tercek, M. T., J. E. Fross, and D. P. Thoma. 2023. "Robust projections and consequences of an expanding bimodal growing season in the western United States." *Ecosphere* 14: e4530.

Touma, D., S. Stevenson, D. L. Swain, D. Singh, D. A. Kalashnikov, and X. Huang. 2022. "Climate Change Increases Risk of Extreme Rainfall Following Wildfire in the Western United States." *Science Advances* 8, no. 13: eabm0320.

Turner, M. G., W. J. Calder, G. S. Cumming, et al. 2020. "Climate Change, Ecosystems and Abrupt Change: Science Priorities." *Philosophical Transactions of the Royal Society B* 375, no. 1794:20190105.

Turner, M. G., D. C. Donato, W. D. Hansen, B. J. Harvey, W. H. Romme, and A. L. Westerling. 2016. "Climate Change and Novel Disturbance Regimes in National Park landscapes." Pages 77–101 In: *Science, Conservation, and National Parks*, edited by S. R. Beissinger, D. D. Ackerly, H. Doremus, and G. Machlis. University of Chicago Press, Chicago, IL.

Wayman, R. B., and H. D. Safford. 2021. "Recent Bark Beetle Outbreaks Influence Wildfire Severity in Mixed-conifer Forests of the Sierra Nevada, California, USA." *Ecological Applications* 31, no. 3: e02287.

Wu, J. X., C. B. Wilsey, L. Taylor, and G. W. Schuurman. 2018. "Projected Avifaunal Responses to Climate Change Across the U.S. National Park System." *PLoS ONE* 13: e0190557.

Supporting Information

Additional supporting information can be found online in the Supporting Information section.

Supplementary Materials: conl70020-sup-0001-SuppMat.docx