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Research trends in U.S. national parks, the world's "living laboratories"

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Abstract

U.S. national parks are essential public assets for preserving natural and cultural resources and for decades have provided natural laboratories for scholarly research. However, park research, and how it may be biased, has not been inventoried at a national scale. Such a synthesis is crucial for assessing research needs and planning for the future. Here, we present the first comprehensive summary of national park research using nearly 7,000 peer-reviewed research articles published since 1970. We report when and where these studies occurred, what academic disciplines were most represented, and who funded the research. Our findings show that publication rates increased rapidly during the 1990s and 2000s, but since about 2013 have declined. Over half of the studies occurred in five parks, with Yellowstone representing over a third of all studies, followed by Everglades, Great Smoky Mountains, Glacier, and Yosemite. Nearly half of the studies occurred in the Northwestern Forested Mountains ecoregion. The life sciences, particularly ecological studies, contributed the majority of park research, although the earth sciences dominated several arid ecoregions of the West. Federal agencies funded the largest proportion of research, followed by U.S. universities, non-profit organizations, federal programs (mainly the National Science Foundation), state agencies, and private industry. Over a quarter of the research was supported by international sources. Recent declines in scholarly output suggest that national park research directions and funding opportunities should be examined.

KEYWORDS

land management, natural and cultural resources, parks and protected areas, public land, research funding

1 | INTRODUCTION

Parks and protected areas are unique public resources that serve a multitude of societal needs. Historically, parks and protected areas were created primarily to conserve valued species and landscapes, and conservation continues to be a core mission of many parks around the world (Watson, Dudley, Segan, & Hockings, 2014). Parks also serve as reservoirs of ecosystem services (Palomo, Martín-López, Potschin, Haines-Young, & Montes, 2013; Postel & Thompson Jr., 2005; Soares-Filho et al., 2010), as test sites for developing climate change mitigation and adaptation plans (Gonzalez, Neilson, Lenihan, & Drapek, 2010; Rehfeldt, Ferguson, & Crookston, 2009; Westerling, Turner, Smithwick, Romme, & Ryan, 2011), as sources of aesthetic and artistic inspiration (e.g., Nancarrow, 2006; Vaughn & Lovett, 2019), and as vital connection points between people and nature (Floyd, 2001; Leaman, 2013). For these reasons, among many others, parks have been valuable sites for both basic and applied scholarly research, ranging from long-term studies of environmental change (e.g., Roland, Stehn, Schmidt, & Houseman, 2016) to archeological and paleontological discoveries (e.g., Thomas et al., 2020) to advances in economic valuation of non-market goods (e.g., Haefele, Loomis, & Bilmes, 2016).

Research in national parks has a long history. In the 1890s, for example, Henry Cowles conducted the first field studies of plant succession—one of the central concepts in ecology—at what is now Indiana Dunes National Park (Cowles, 1899). Experiments conducted by Dan Simberloff at Everglades National Park in the 1960s tested MacArthur and Wilson's island biogeography models and remain widely influential in ecology and conservation biology (Simberloff, 1969; Simberloff & Wilson, 1969). In the 1970s, Rowland Tabor and Wallace Cady showed the relationship between topography, rock distribution, and subduction zones in Olympic Mountains National Park at a time when the idea of plate tectonics was relatively new (Tabor & Cady, 1978). Monica Turner's research on wildfire in Yellowstone National Park in the 1990s was among the first to examine ecosystems over large extents and is seminal to the field of landscape ecology (Turner, Hargrove, Gardner, & Romme, 1994). Also at Yellowstone in the 1990s, Robert Smith and Lawrence Braile proposed that the Snake River Plain is part of a continuum related to the North American plate moving over a fixed mantle hotspot, and that volcanism at Yellowstone is related to the passage of the continent over a conduit of ascending magma (Smith & Braile, 1994). This hypothesis has many derivative consequences for the topography, geologic hazards, mineral resource distribution, and even the flora and fauna of the Yellowstone region. In the 2000s, community science BioBlitz events in national parks, wherein families, students, and the public join National Park Service (NPS) staff to conduct intensive field studies, have informed and inspired engagement, outreach, and inventory methods worldwide (Francis, Easterday, Scheckeland, & Beissinger, 2017).

Despite these important discoveries and scientific advances, there has not been a systematic review of research conducted in national parks. Independent reviews of research in national parks have been published periodically since the 1960s but have often focused on single issues of concern, such as wildlife management (e.g., Leopold, 1963; Mech & Barber, 2002). Much that has been written about NPS research has been limited in scope to compilations and case studies, as exemplified by the title of the 1989 review, *National Parks: from vignettes to a global view* (Bishop et al., 1989). NPS has a broad mission of conserving national parks for future generations and has traditionally valued national park research in several broad categories: inventories of resources for protection, management, and monitoring; studies that can guide understanding of natural dynamics and processes from individuals to ecosystems; assessments of threats; and evaluations of management responses (NRC, 1992). More recent efforts have broadened this scope to consider the relationships between people and parks, the use of community science for research, and the special needs and potential of "blue" (ocean) parks (Beissinger & Ackerly, 2017). Historic support for and interest in scientific research within NPS has ranged from encouraging to hostile (reviewed in Parsons, 2004). The establishment of Research Learning Centers starting in 2001 publicly signaled that the agency welcomed park-based research by non-NPS scholars, recognized that NPS relies on science to inform management and outreach activities, and stated a new vision of "parks for science and science for parks" (NPS, 2016). Presidential administrations and Congressional mandates may affect access to parks and support for research, yet U.S. national parks contain unparalleled natural, cultural, and historic resources and therefore remain extraordinary places to conduct research.

Over a century ago, Grinnell and Storer (1916) warned that the national parks would "probably be the only areas remaining unspoiled for scientific study". As land use intensifies and climate change continues, U.S. national parks may be more important than ever for both basic and applied research. However, a nationwide synthesis of trends in national park research, and potential biases in that research, has never existed, despite the need for such a synthesis to assess needs and guide future decisions. In this study, we asked three questions to understand recent research trends in U.S. national parks, using nearly 7,000 peer-reviewed research articles published since 1970: (a) When and where has scholarly research taken place in national parks? (b) Which academic disciplines and sub-fields are most and least represented? and (c) Who is funding the research? This first nationwide synthesis of scholarly trends and biases in U.S. national park research can inform the scope and direction of the second century of park science and management.

2 | METHODS

We used the Web of Science database to collect peer-reviewed journal articles regarding 59 national parks published between 1970 and 2018. There are very few indexed publications pre-1970 and about half of the national parks were established after 1970, which provides a suitable cutoff to examine recent trends. We excluded three very recently established parks—Gateway Arch National Park (2018), Indiana Dunes National Park (2019), and White Sands National Park (2019)—because any research conducted at these locations is unlikely to be linked to the name of the national park. In addition to the national parks, the NPS manages another 360 units across 18 other designations, including national historical parks and battlefields, national seashores, and national recreation areas. Here we turn our attention to designated national parks and the "park research" discussed herein refers explicitly to research conducted at national parks rather than the national parks system overall.

We used the name of each park as the search term and restricted the search to journal articles published in English as of December 2018. We manually evaluated each article found and excluded articles that did not explicitly study a national park (e.g., park name only appeared in references cited). To assess disciplinary trends, we noted the academic sub-field associated with each article in the Web of Science database. We aggregated the sub-field of each article to its broader academic field and discipline, as defined by the National Academies of Sciences, Engineering, and Medicine (NASEM, 2006; Table A1). Next, we manually sorted into categories the sources of funding identified by Web of Science for each article. We first noted whether the origin was U.S. domestic or international, and we categorized the source of domestic funding as one of seven types: federal agency (e.g., United States Geological Survey), federal program (e.g., the National Science Foundation), state agency (e.g., North Carolina Department of Transportation), university institution (e.g., North Carolina State University), park-affiliated non-profit (e.g., Friends of Saguaro National Park), other non-profit (e.g., The Nature Conservancy), and private industry (e.g., ExxonMobil).

We also documented each park's ecoregion (Level I; US EPA, 2016) to assess geographical differences in the quantity and type of research conducted in U.S. national parks. Where park boundaries overlapped two ecoregions, the associated publications were attributed to both ecoregions. Finally, we created two indices of research representativeness to indicate which parks and ecoregions have been most studied and least studied. Our park representativeness (Park Rep) index normalized the number of publications in each park by the number and area of parks in each ecoregion: that is, for each park, we divided its number of publications by the number of parks in the ecoregion, then multiplied that value by the total park area within the ecoregion. The ecoregion representativeness (Ecoregion Rep) index normalized publications by ecoregion area: that is, for each ecoregion, we divided its number of publications by ecoregion area.

3 | RESULTS

Our Web of Science search for research conducted in U.S. national parks found 6,965 peer-reviewed, published articles between 1970 and 2018. The rate of publication increased slowly between 1970 and 1990, when there was a marked increase in the output of scholarly work. The highest number of publications (418) occurred in 2013, followed by a steady decline through 2018 (296 publications; Figure 1). Five of the 59 national parks accounted for 60% of the 6,965 studies. Yellowstone accounted for 36.2% of studies (Figure 1), followed by Everglades (6.8%), Great Smoky Mountains (6.2%), Glacier (5.6%), and Yosemite (5.3%; Figure 1, Table A2). The "big five" parks were all established prior to 1950 and in general, more peer-reviewed research has been conducted at older parks (Table A2). However, some parks established >100 years ago, such as Crater Lake, Mesa Verde, and Wind Cave have relatively few publications, while others established within the past 50 years, such as Canyonlands, have amassed a higher number of publications (Table A2).

Across academic disciplines, the life sciences dominated national parks research (60% of total publications; Figure 1), followed by the physical sciences and mathematics (25%), social and behavioral sciences (8%), engineering (3%), arts and humanities (<1%), and other (education and multidisciplinary research; 3%). The field of ecology and evolutionary biology was most commonly studied (31% of total publications), followed by earth sciences (22%), animal sciences (7%), plant sciences (6%), and forestry and forest sciences (5%; Table A1).

Ecology and evolution represented the largest proportion of studies in eight of the 12 ecoregions (Figure 2). Earth sciences represented the largest proportion of publications in the other four ecoregions, all of which occurred west of the Great Plains (Figure 2). Plant sciences is one the top four most commonly studied fields in the Great Plains and other eastern ecoregions, whereas forestry and forest sciences is one of the most commonly studied fields in the conterminous United States west of the Great Plains, except in the Northwestern Forested Mountains and the Southern Semi-Arid Highlands.

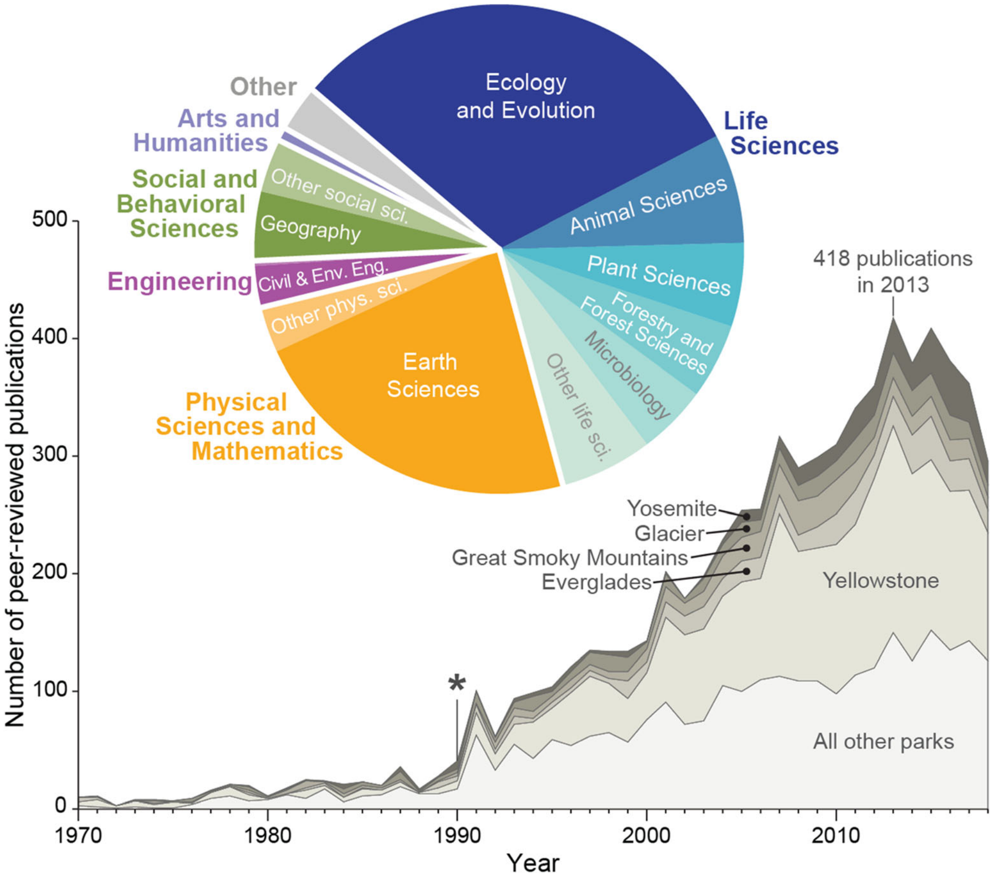

FIGURE 1 Annual publications reporting research conducted in U.S. national parks (1970–2018). Filled areas in the graph indicate the number of publications for the five most researched national parks (Yellowstone, Everglades, Great Smoky Mountains, Glacier, and Yosemite) and all other parks. Stacked areas sum to the total number of publications per year (max = 418 in 2013). Starting in 1990 (denoted by *), there was a marked increase in the output of scholarly work. The pie chart indicates the representation of academic sub-fields and disciplines across all 6,965 studies

Over half of the studies (51%) were conducted in Northwestern Forested Mountains parks, followed by North American Deserts (17%), Eastern Temperate Forest (10%), Tropical Wet Forest (7%), and Marine West Coast Forest (6%). Two ecoregions accounted for less than 1% of the studies (Southern Semi-Arid Highlands and Great Plains; Figure 2; Table 1). Publication rates in the most studied ecoregions generally increased through time, but started to decline or experienced no growth since approximately 2013 (Figure A1).

Our measure of park representativeness, which normalizes each park's publications by the number and area of parks in each ecoregion, shows that some parks have been studied disproportionately more than others (Table A2). For example, Everglades (Tropical Wet Forests) is extremely well represented in the literature, followed by Channel Islands (Mediterranean California), Great Smoky Mountains (Eastern Temperate Forests), and Guadalupe Mountains (Temperate Sierras). Parks with the lowest number of publications relative to the number and area of parks in their ecoregion include Black Canyon of the Gunison (North American Desert), North Cascades (Northwestern Forested Mountains), and Lake Clark (Marine West Coast Forest). Our measure of regional representativeness, which normalizes publications by ecoregion area, shows that Tropical Wet Forests are very well represented in the literature, followed by Northwestern Forested Mountains, and Marine West Coast Forest. The Great Plains, Tundra, Eastern Temperate Forests, and Taiga have very few publications relative to their area (Table 1).

Our Web of Science search for research funding in U.S. national parks found 6,236 unique instances of funding; where a study listed more than one source of funding, each was counted as a funding instance. In total, 44% (3,040) of papers listed at least one funder through Web of Science; 31% listed multiple funders (71% of papers that reported funders). Of the 6,236 unique funding instances identified, 75% came from domestic funders and 25% came from international organizations, institutions, or government agencies (Figure 3). Among domestic funders, federal agencies (e.g., US Forest Service, US Fish and Wildlife, NPS) accounted for 26% of funding instances, while federal grants (e.g., National Science Foundation) accounted for 8.4%. Universities and research institutions associated with universities represented 17.5% of funding instances. Combined, non-profit organizations contributed to 22% of domestic funding instances, and of those instances, 21% came from park-associated non-profits (e.g., Friends of Saguaro National Park). We were unable to categorize 93 (1.5%) funding instances with the information provided.

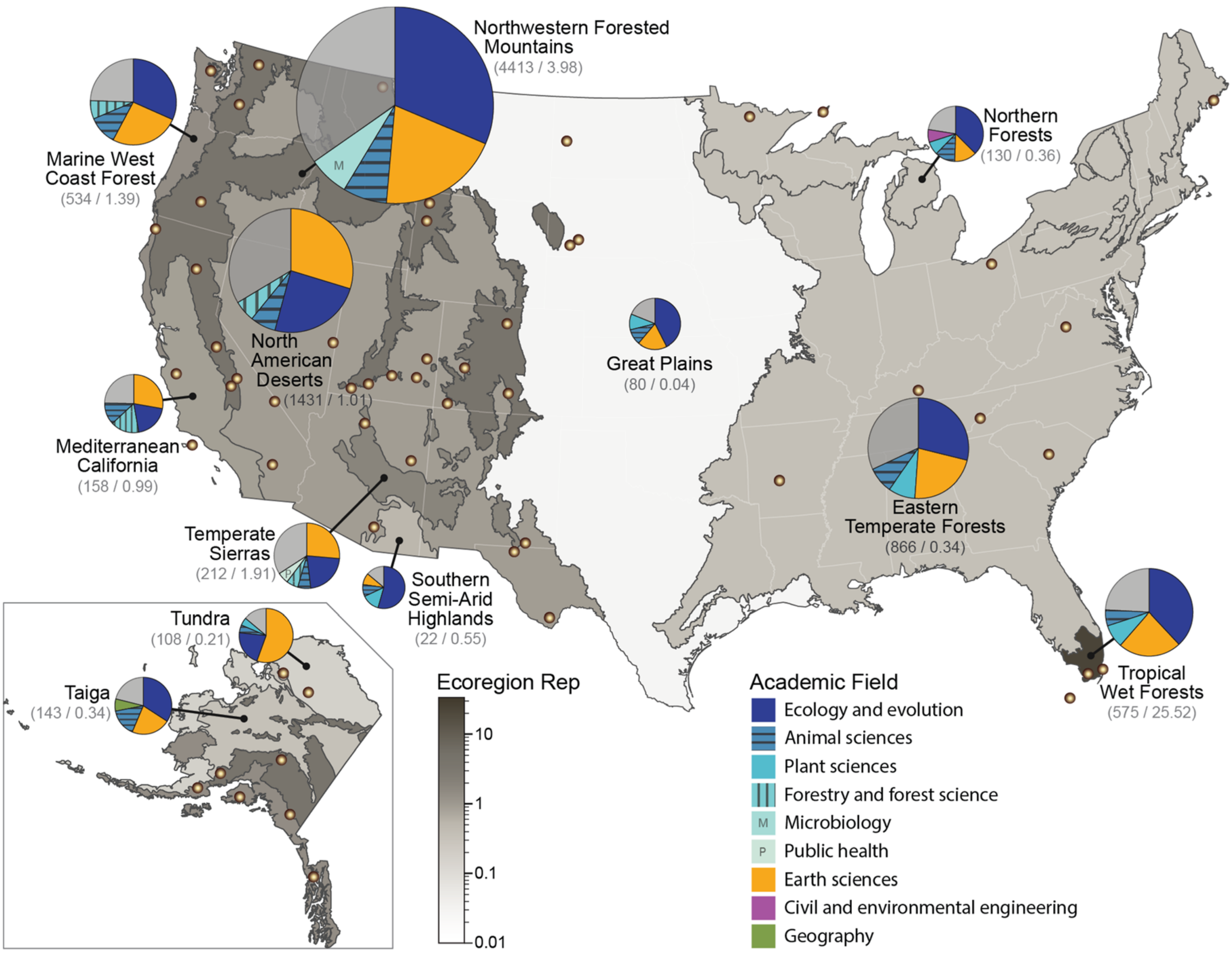

FIGURE 2 Research disciplinary focus by ecoregion (EPA Level 1). Pie charts indicate the four most commonly studied academic fields (five if there was a tie) plus all others (gray). Numbers in parentheses indicate the (1) total number of studies in the ecoregion and (2) the ecoregion representativeness value. Map shading indicates ecoregion representativeness (Ecoregion Rep), an index that normalizes publications by ecoregion area. NB: U.S. EPA ecoregions cover the continental U.S., excluding Hawaii, American Samoa, and the U.S. Virgin Islands

4 | DISCUSSION

We found that research in national parks increased rapidly during the 1990s and 2000s, a trend that broadly mirrors some research policy changes and priorities within NPS. In 1992, for example, the National Research Council called for an explicit research mission within NPS and recommended the appointment of a chief scientist (NRC, 1992). Cooperative Ecosystem Studies Units (CESUs) began forming in 1999 to expand science in national parks by leveraging a large network of university collaborators, and in 2000 NPS established the Inventory and Monitoring (I&M) Program for long-term ecological monitoring within national park sites. With programs at 280 parks (NPS I&M, 2020), the I&M Program represents most of the science capacity within NPS (Beissinger & Ackerly, 2017).

Our analysis also revealed that studies in ecology and evolutionary biology contribute the most scholarly research related to national parks. Given NPS objectives and programs (such as I&M) and the fact that national parks are large, relatively intact natural areas, this finding is not surprising. The possibility exists, however, that research in the social sciences and humanities at national parks may expand. The NPS Social Science Division and the Climate Change Response Program were both established in 2010, signaling new agency recognition of the importance of human dimensions. Among researchers, there is also growing interest in studying ecosystem services, the relationships between people and

TABLE 1 Bioregional characteristics of publications reporting research in U.S. national parks 1970–2018

	Number of papers[a]	Number of parks	Park area (km^2)	Total area (km^2)	Ecoregion Rep[b]
Eastern Temperate Forests	866	8	3,552.8	2,521,769.2	0.34
Great Plains	80	3	1,273.7	2,239,327.8	0.04
Marine West Coast Forest	534	10	60,943.4	383,771.7	1.39
Mediterranean California	158	2	517.2	159,962.2	0.99
North American Deserts	1,431	22	30,021.1	1,411,982.5	1.01
Northern Forests	130	2	1,486.9	365,637.2	0.36
Northwestern Forested Mountains	4,413	21	83,601.8	1,109,527.4	3.98
Southern Semi-Arid Highlands	22	1	171.4	39,649.7	0.55
Taiga	143	4	10,288.3	416,238.4	0.34
Temperate Sierras	212	3	706.8	110,909.7	1.91
Tropical Wet Forests	575	3	3,821.2	22,533.4	25.52
Tundra	108	5	41,497.5	521,324.4	0.21

[a]Where park boundaries overlapped two ecoregions, publications were attributed to both.
[b]Ecoregion Representativeness (Ecoregion Rep) is calculated as the number of papers per ecoregion divided by total ecoregion area. Ecoregion Rep numbers have been multiplied by 1,000 for readability.

nature, and engaging people in parks (DeFries, 2017), which may shape future national parks research. These disciplinary trends may differ across other National Park holdings. For example, historical and archaeological research may be much more prevalent at National Historic Parks and National Historic Battlefields than ecological studies. Future work that examines research across the NPS's 423 holdings could shed additional light on both research trends overall and on the impacts of NPS-wide programs and research initiatives. Both disciplinary trends and the overall number of publications may be affected by the proliferation of new journals and increased opportunities for researchers to publish over time. The increase in opportunities to share national parks research makes the decline in peer-reviewed publications since 2013 even more noteworthy.

One potential limitation of our analysis is the use of Web of Science disciplinary designations to categorize research focus. These disciplinary designations are based on the field and subfield to which each peer-reviewed journal is assigned. As scholarship grows increasingly inter- and transdisciplinary and field/sub-field designations shift, split, and merge, these designations may not always represent the "most correct" taxonomy. For example, in the life sciences, some designations are by biological taxa (e.g., mycology, ornithology), while others are categorized by approach or application (e.g., biological conservation, horticulture). Categorizing the interdisciplinary field of geography is also problematic; geography is classified by the National Academies of Sciences, Engineering, and Medicine (NASEM, 2006) under "social and behavioral studies" and here accounts for 56% of publications within that academic discipline, but we noted a considerable number of physical geography

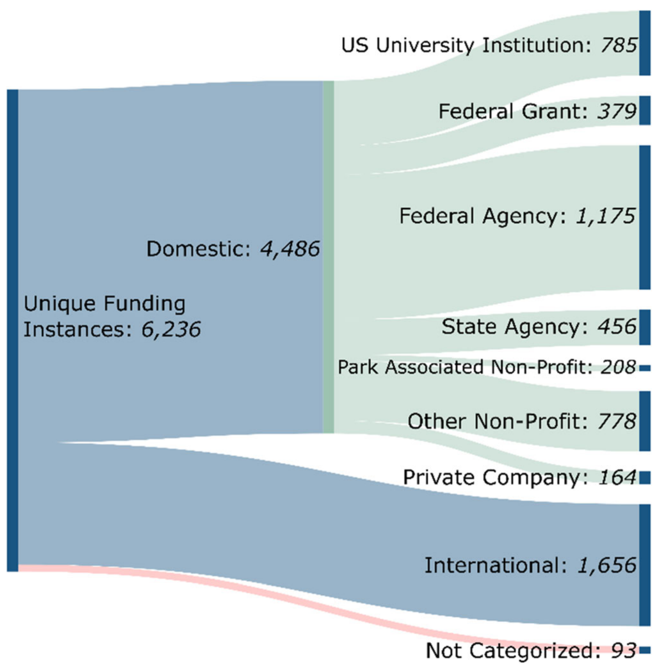

FIGURE 3 Sources of funding that supported research in U.S. national parks (1970–2018). Where multiple sources of funding were reported in a publication, all were included as unique funding instances. Only funders listed through the Web of Science are included

papers that might be better classified within the geosciences. By using the Web of Science designations for geography, we may have overestimated research in the social and behavioral sciences (8% of publications). If so, the dearth of national park research in the social and behavioral sciences becomes even more stark and may more closely approximate the proportion of research in the arts and humanities (<1% of publications).

We recognize that a great deal of relevant research conducted at national parks is not published in peer-reviewed journals and that Web of Science databases do not contain all relevant peer-reviewed research. In addition, Web of Science searches may more accurately report scientific output for Natural Sciences, Engineering, and Biomedical Research than for Social Sciences and Arts and Humanities, where publishing books is more frequent and important for a researcher's career than publishing articles (Mongeon & Paul-Hus, 2016). Still, we believe that the results reported here using our reproducible methods are broadly representative of overall trends in park research. NPS' Natural Resource Report Series (NRRS), which publishes reports of "high-priority, current natural resource management information", and Cultural Landscape Reports (CLR), which are "the primary reports that document the history, significance and treatment of a cultural landscape", document management, treatment and history across NPS-managed units. These reports broadly mirror our findings of the indexed, peer-reviewed literature (Figure A2), with a low and steady publication rate between 1990 (start of the NRRS) and 2003 that then increased rapidly between 2004 and 2018. Similarly, in the same time period there were 1,910 natural resource reports and 316 cultural landscape reports, echoing the predominance of natural science disciplines over the humanities and social sciences reported in this study.

Between 1970 and 2018, the five most studied national parks were Yellowstone, Everglades, Great Smoky Mountains, Glacier, and Yosemite. These parks also see the greatest number of annual visitors (Table A2). Future work that examines what is driving the patterns of research activity could inform efforts to boost research activity in understudied parks and ecoregions. Proximity to R1 (doctoral university with very high research activity) and R2 (doctoral university with high research activity) research institutions does not appear related to research productivity: Biscayne, Cuyahoga Valley, and Saguaro National Parks are <10 km from research universities, but together have less than 100 publications (Table A2). Likewise, 32 research universities are within a "day's drive" (350 km) of Shenandoah National Park, but there are a modest 125 publications from Shenandoah compared to 434 from nearby Great Smoky Mountains National Park. For some researchers, longitudinal research questions, and the need for repeat measurements, make it necessary to return to the same park (e.g., Turner, Romme, Gardner, & Hargrove, 1997). The differing research outputs among parks suggest that a complex suite of drivers influence national parks research, even as large numbers of national parks remain poorly studied. Researchers with adequate funding support can travel to their choice of research destinations, but what is it about those destinations that is particularly appealing from a research perspective—biophysical features, opportunities for longitudinal studies (legacy effects), park size, facilities and/or logistical considerations, others? At the same time, many researchers struggle to secure adequate research funding, but perhaps are not taking advantage of nearby (i.e., more affordable and/or accessible) research opportunities in national parks. Untangling these drivers of research in national parks could help administrators at both national parks and research institutions identify and address barriers to research in understudied parks and ecoregions.

Our analysis detected a notable decline in published national park research after 2013, and we speculate that this trend may be related in part to funding. Investment in basic science has remained fairly flat for the past decade, and a growing proportion of funding for the basic sciences now comes from the private sector, primarily the pharmaceutical industry (NCSES, 2019). In 2013, for the first time, U.S. government investment in the basic sciences fell below 50% of total spending on basic research (Mervis, 2017). The lag between project funding and publication date may further suggest that the decline in published research will continue into the future. Proportionally, funding of basic research is decreasing, as funding of applied research increases (NCSES, 2019). Assuming that research productivity in national parks is related to funding, and that much of the research done at national parks can be considered "basic" (e.g., most "ecology and evolutionary biology" studies), these overall trends in research funding could explain the recent decline (2013–2018) in research productivity. Some academic fields studied in national parks mirror the increase in funding for applied research. For example, 65% of the research in microbiology in the national parks was published between 2008 and 2018. To better leverage funding opportunities from industry, NPS could promote those disciplines that are suitable for applied research funding. The funding information obtained through Web of Science does not indicate funding level or amount (nor is that information commonly reported in published papers) and our analysis reports all funding instances equally. However, grants from park-associated nonprofits, for example, are likely smaller than those from NSF or private companies. A deeper exploration of funding levels is necessary to support efforts that aim to increase research productivity by strategically leveraging different funding sources or targeting new funders.

We found that 25% of funding instances were from international sources (universities, organizations, and government agencies), indicating considerable international interest in research opportunities in U.S. national parks. This interest exemplifies the idea that national parks are the world's living laboratories. Overall, international research productivity is growing, with China in particular showing exponential growth in research productivity (Leydesdorff & Wagner, 2009). While the U.S. leads in terms of total spending, South Korea, Japan, Finland, Switzerland, Austria, Sweden, Denmark, and Germany devote a larger share of their gross domestic product (GDP) to research and development; these countries also all have higher numbers of researchers per capita than the United States (UNESCO UIS, 2020). The extent to which funding and research capacity from these nations will extend to the science done at U.S. national parks is unknown. What NPS, university consortia, and U.S. government agencies do to either promote or hinder international research collaborations could impact the next chapter of national parks research.

Information on funding instances to-date may also offer a window to future opportunities. For example, we found that non-profit organizations contribute 16% of all funding instances, suggesting ample room for new partnerships. This information could be used by non-profits to consider pivoting efforts and resource allocation to take advantage of the charismatic draw of natural parks to donors. Park-associated non-profits in particular could look at their contributions to national park research (3% of all instances) and decide to amplify fundraising efforts or to consider targeting their contributions to disciplines in the social sciences or humanities for which there is less peer-reviewed literature. Similarly, those sitting on the research or philanthropic boards of private companies (3% of funding instances) could see untapped opportunities to boost their image by supporting research in national parks. Funder information could bring to light potential partnerships and collaborations where interests overlap. Our open-source data repository (github.com/ncsu-landchangelab/research-trends-national-parks) allows those interested to take a closer look at the organizations funding research at specific parks.

Future research and needs assessments will also benefit from improved tracking and archiving of national park research studies. Prior to performing our review using Web of Science, we explored NPS's Integrated Resource Management Applications (IRMA) portal, which is a web-based "one-stop" for data and information related to NPS natural and cultural resources and houses documents, reports, publications, data sets, and park species lists. We found that the main repository for the agency is little used and infrequently updated. For example, for Congaree National Park, only eight peer-reviewed publications that met our search criteria were uploaded to IRMA (with the most recent published in 1997), but Web of Science yielded 18 publications for Congaree. By working directly with the Chief of Resource Stewardship and Science at Congaree and examining the park archives, we were able to identify 48 peer-reviewed publications that stem from work at Congaree. Some of these articles did not appear in any database search, but did fit our criteria (peer-reviewed publication of work conducted at the park). Comprehensively surveying park research at Congaree required the assistance and input of someone deeply involved in that park, but this level of effort is not currently sustainable for NPS staff or for researchers seeking park-related information. Research conducted in U.S. national parks is valued worldwide, and maintaining a comprehensive record of that work is in the world's collective interest. We call on NPS leadership to provide the time and resources needed for park staff to collect, organize, and share the scholarly research conducted in their parks. Chief Resource Officers (or equivalent) at each park are likely best suited to monitor and update the scholarly effort related to their parks, especially if that research is connected to a park-issued research permit, and we therefore suggest that they be supported to make inventories of park research publicly available. These efforts could also largely clear up the primary concerns with the use of non-peer-reviewed publications (the "gray literature") - quality, discovery, access and archiving (Corlett, 2011), allowing for more comprehensive future work.

Our analysis illustrates several key points. First, following a marked increase in the output of scholarly work starting in 1990, there has been a steady decline since 2013. The majority of publications come from five large, iconic parks and focus on ecology and other life sciences. Second, regional representativeness is very skewed, with some large, heterogeneous ecoregions having only a handful of national-park associated publications. And third, even as U.S. funding for basic research stagnates, support for applied research and interest from international funders offers new opportunities. A comprehensive understanding of disciplinary, regional, and funding trends in national parks research is essential to support future work, address research gaps and biases, and determine funding priorities. As land use intensifies and climate change continues, Grinnell & Storer's, 1916 warning that national parks may be the only unspoiled areas remaining for scientific study looms large. This analysis can support NPS personnel, researchers, and other decision-makers as they assess needs and guide the direction of the second century of park science and management.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Jelena Vukomanovic conceived the study. Jelena Vukomanovic and Joshua Randall contributed to study design. Joshua Randall performed the analysis and drafted figures. Jelena Vukomanovic wrote the manuscript.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available at github.com/ncsu-landchangelab/research-trends-national-parks.

ETHICS STATEMENT

No ethics approval was required for this research.

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APPENDIX

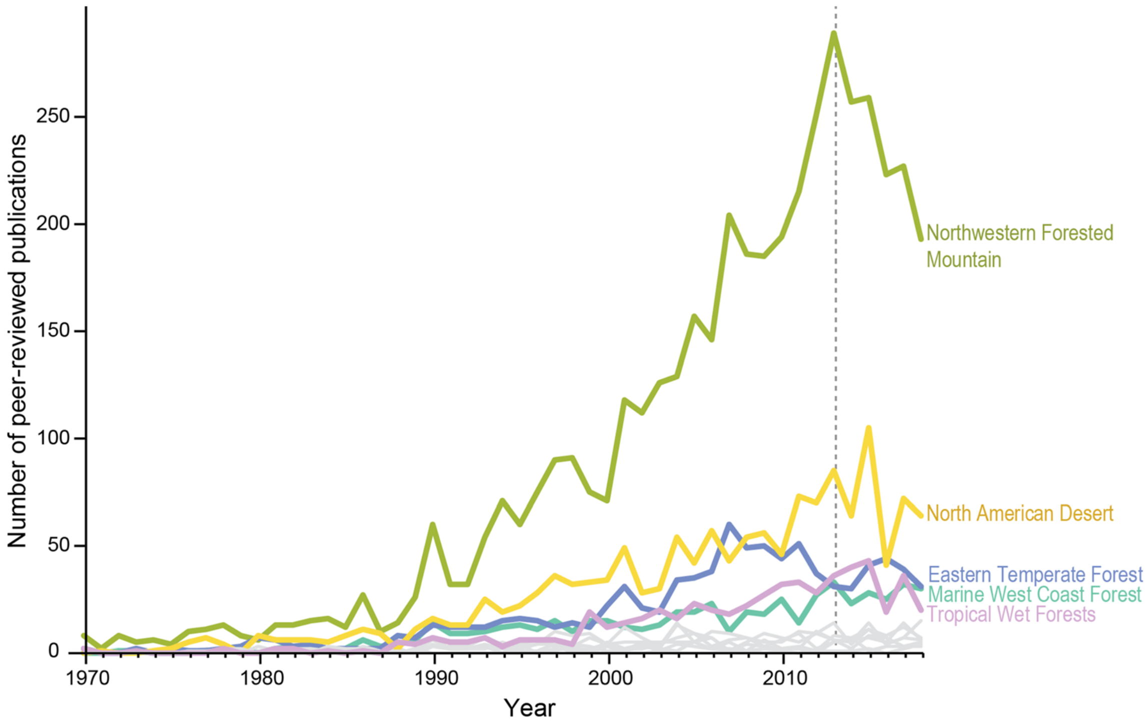

FIGURE A1 Publications by ecoregion over time. The five ecoregions with the most peer-reviewed publications (Northwestern Forested Mountains, North American Deserts, Eastern Temperate Forests, Marine West Coast Forest, and Tropical Wet Forests) are highlighted

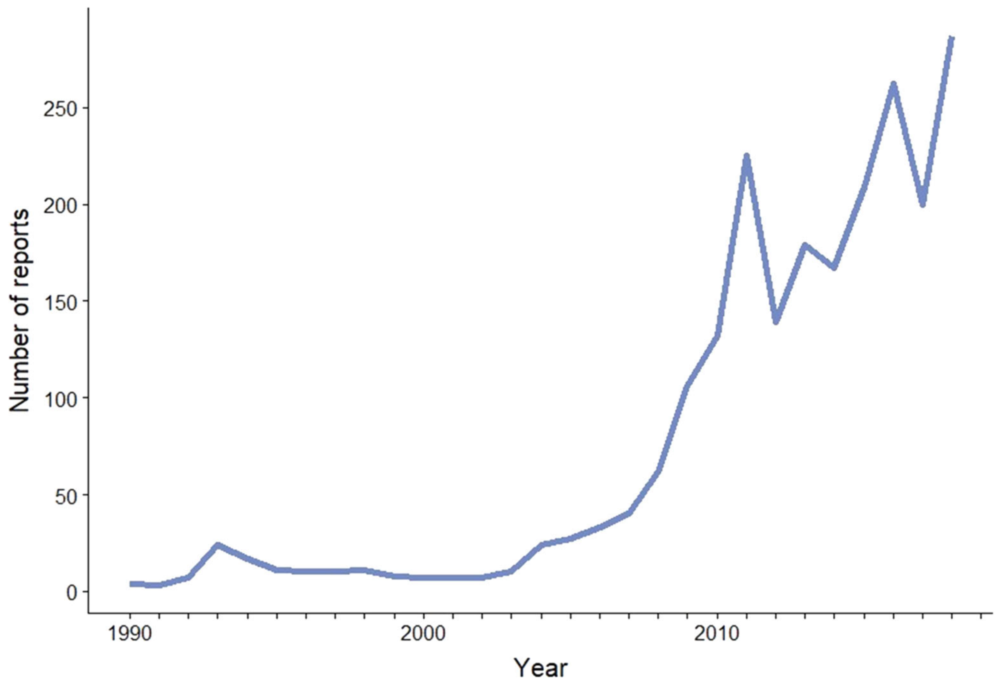

FIGURE A2 National Park Service Natural Resource Reports (total = 1,910) and Cultural Landscape Reports (total = 316) published from 1990 to 2010.
Source: NPS Integrated Resource Management Applications (IRMA) Data Store

TABLE A1 The disciplinary focus of peer-reviewed journal articles containing national park research. The academic sub-fields (right column) were designated in the Web of Science database. We aggregated the sub-field of each article to its broader academic field (middle column) and discipline (left column), as defined by the National Academies of Sciences, Engineering, and Medicine (NASEM, 2006). Numbers in brackets indicate tallies

Life Sciences (4,147)	Biochemistry, Biophysics, and Structural Biology (85)	Biochemical Research Methods (4); Biochemistry & Molecular Biology (75); Biophysics (6)
	Cell and Developmental Biology (3)	Anatomy & Morphology (3)
	Ecology and Evolutionary Biology (2,166)	Evolutionary Biology (16); Ecology (1389); Mycology (51); Limnology (26); Biodiversity Conservation (580); Marine & Freshwater Biology (104)
	Public Health (70)	Medicine, General & Internal (7); Medicine, Legal (1); Emergency Medicine (4); Public, Environmental & Occupational Health (57); Reproductive Biology (1)
	Genetics and Genomics (9)	Genetics & Heredity (8); Mathematical & Computational Biology (1)
	Immunology and Infectious Disease (16)	Parasitology (7); Immunology (9)
	Biology/Integrated Biology/ Integrated Biomedical Sciences (103)	Biology (103)
	Microbiology (320)	Microbiology (171); Virology (13); Biotechnology & Applied Microbiology (136)
	Pharmacology, Toxicology and Environmental Health (1)	Pharmacology & Pharmacy (1)
	Physiology (3)	Endocrinology & Metabolism (1); Physiology (2)
	Animal Sciences (503)	Fisheries (89); Zoology (281); Agriculture, Dairy & Animal Science (21); Veterinary Sciences (46); Ornithology (66)
	Entomology (134)	Entomology (134)
	Forestry and Forest Sciences (346)	Forestry (346)
	Nutrition (2)	Nutrition & Dietetics (2)
	Plant Sciences (386)	Agronomy (32); Agricultural Engineering (8); Horticulture (1); Plant Sciences (332); Agriculture, Multidisciplinary (13)
Physical Sciences & Mathematics (1,766)	Statistics and Probability, Mathematics, and Applied Mathematics (5)	Mathematics (1); Mathematics, Applied (2); Statistics & Probability (2)
	Chemistry (31)	Chemistry, Analytical (14); Chemistry, Inorganic & Nuclear (4); Chemistry, Multidisciplinary (10); Chemistry, Physical (3)
	Computer Sciences (51)	Computer Science, Hardware & Architecture (1); Computer Science, Information Systems (3); Computer Science, Interdisciplinary Applications (9); Computer Science, Software Engineering (1); Robotics (2); Remote Sensing (35)
	Earth Sciences (1,555)	Geology (124); Mineralogy (2); Geosciences, Multidisciplinary (353); Paleontology (35); Water Resources (34); Soil Science (48); Geochemistry & Geophysics (215); Environmental Sciences (744)
	Oceanography and Atmospheric Sciences and Meteorology (88)	Oceanography (7); Meteorology & Atmospheric Sciences (81)
	Physics (36)	Physics, Condensed Matter (1); Physics, Fluids & Plasmas (4); Optics (4); Astronomy & Astrophysics (20); Acoustics (5); Microscopy (2)

TABLE A1 (Continued)

Engineering (215)	Chemical Engineering (17)	Engineering, Chemical (7); Engineering, Petroleum (1); Energy & Fuels (9)
	Civil and Environmental Engineering (191)	Engineering, Civil (56); Engineering, Environmental (107); Engineering, Geological (9); Architecture (14); Green & Sustainable Science & Technology (5)
	Electrical and Computer Engineering (4)	Engineering, Electrical & Electronic (4)
	Materials Science and Engineering (1)	Materials Science, Characterization & Testing (1)
	Operations Research, Systems Engineering and Industrial Engineering (2)	Engineering, Industrial (2)
Social & Behavioral Sciences (561)	Hospitality, Leisure, Sport & Tourism (67)	Hospitality, Leisure, Sport & Tourism (67)
	Behavioral Sciences (42)	Behavioral Sciences (42)
	Anthropology (40)	Anthropology (25); Archaeology (15)
	Communication (4)	Communication (4)
	Economics (13)	Economics (11); Agricultural Economics & Policy (2)
	Geography (316)	Geography (53); Geography, Physical (262); Area Studies (1)
	Political Science (4)	Political Science (4)
	Public Affairs, Public Policy and Public Administration (13)	Public Administration (3); Planning & Development (4); Management (2); Law (1); Business (3)
	Psychology (15)	Psychology, Biological (9); Psychology, Experimental (5); Psychology, Social (1);
	Sociology (47)	Sociology (2); Demography (1); Environmental Studies (43); Social Issues (1)
Arts & Humanities (61)	History (53)	History (52); History & Philosophy Of Science (1)
	Philosophy (4)	Philosophy (1); Ethics (3);
	Religion (1)	Religion (1)
	Performing Arts (3)	Music (2); Theater (1)
Other (214)	Education (11)	Education & Educational Research (10); Education, Scientific Disciplines (1)
	Multidisciplinary (203)	Multidisciplinary Sciences (183); Social Sciences, Interdisciplinary (7); Humanities, Multidisciplinary (13)

TABLE A2 Characteristics of U.S. national parks that have been the location of peer-reviewed published research 1970–2018

National Park	Number of papers	Park Rep[a]	EPA Ecoregion I	Area of park (km^2)	Year founded	Annual visitors (2017)	Number R1 or R2 Inst.[b] w/in 350 km
Acadia	116	4.08	Eastern Temperate Forest	192.8	1919	3,509	15
Arches	41	0.06	North American Desert	309.0	1971	1,539	2
Badlands	27	7.07	Great Plains	988.6	1978	1,054	1
Big Bend	164	0.25	North American Desert	3,242.2	1944	440	0
Biscayne	66	5.76	Tropical Wet Forests	699.8	1980	447	7
Black Canyon of the Gunnison	7	0.01	North American Desert	123.0	1999	307	7
Bryce canyon	22	0.03	North American Desert	145.0	1928	2,572	4
Canyonlands	103	0.16	North American Desert	1,366.2	1964	742	2
Capitol Reef	19	0.03	North American Desert	979.0	1971	1,150	3
Carlsbad Caverns	21	9.90	Temperate Sierras	189.3	1930	520	3
Channel Islands	31	29.97	Mediterranean California	1,009.1	1980	384	10
Congaree	18	0.63	Eastern Temperate Forest	89.8	2003	160	15
Crater Lake	33	0.02	Northwestern Forested Mountain	741.5	1902	712	3
Cuyahoga Valley	9	0.32	Eastern Temperate Forest	133.5	2000	2,227	22
Death Valley	50	0.08	North American Desert	13,759.3	1994	1,295	13
Denali	127	0.21	Marine West Coast Forest	24,398.2	1917	643	1
Dry Tortugas	34	2.97	Tropical Wet Forests	261.8	1992	54	4
Everglades	475	41.44	Tropical Wet Forests	6,105.0	1947	1,019	7
Gates of the Arctic	13	0.06	Tundra	34,398.3	1980	11	1
Glacier	390	0.22	Northwestern Forested Mountain	4,101.8	1910	3,306	4
Glacier Bay	67	0.11	Marine West Coast Forest	13,274.5	1980	547	0
Grand Canyon	169	0.26	North American Desert	4,926.7	1919	6,254	3
Grand Teton	91	0.05	Northwestern Forested Mountain	1,254.5	1929	3,317	3
Great Basin	19	0.03	North American Desert	312.3	1986	168	3
Great Sand Dunes	16	0.02	North American Desert	433.0	2004	487	7
Great Smoky Mountains	434	15.27	Eastern Temperate Forest	2,110.4	1934	11,339	19
Guadalupe Mountains	22	10.38	Temperate Sierras	349.7	1966	225	3
Hot Springs	8	0.28	Eastern Temperate Forest	22.5	1921	1,562	5
Isle Royale	68	2.39	Eastern temperate Forest	2,314.0	1940	28	1
Joshua Tree	44	0.07	North American Desert	3,213.2	1994	2,854	11
Katmai	78	0.13	Marine West Coast Forest	16,551.6	1980	38	0
Kenai Fjords	15	0.02	Marine West Coast Forest	2,456.4	1980	304	0
Kings Canyon	31	0.02	Northwestern Forested Mountain	1869.2	1940	693	15
Kobuk Valley	3	0.07	Taiga	7,082.0	1980	16	0
Lake Clark	9	0.01	Marine West Coast Forest	16,369.5	1980	23	0

TABLE A2 (Continued)

National Park	Number of papers	Park Rep[a]	EPA Ecoregion I	Area of park (km^2)	Year founded	Annual visitors (2017)	Number R1 or R2 Inst.[b] w/in 350 km
Lassen Volcanic	60	0.03	Northwestern Forested Mountain	430.5	1916	507	4
Mammoth Cave	39	1.37	Eastern Temperate Forest	213.8	1941	588	12
Mesa Verde	27	0.04	North American Desert	210.7	1906	614	1
Mount Rainier	61	0.03	Northwestern Forested Mountain	953.5	1899	1,416	6
North Cascades	21	0.01	Northwestern Forested Mountain	2,768.0	1968	30	4
Olympic	131	0.21	Marine West Coast Forest	3,731.2	1938	3,402	3
Petrified Forest	48	0.07	North American Desert	378.5	1962	628	4
Pinnacles	3	2.90	Mediterranean California	107.7	2013	233	7
Redwood	32	0.05	Marine West Coast Forest	438.7	1968	445	3
Rocky Mountain	282	0.16	Northwestern Forested Mountain	1,075.5	1915	4,437	7
Saguaro	22	0.03	North American Desert	370.1	1994	965	4
Sequoia	93	0.05	Northwestern Forested Mountain	1,635.2	1890	1,291	15
Shenandoah	125	4.40	Eastern Temperate Forest	794.4	1935	1,459	33
Theodore Roosevelt	26	6.80	Great Plains	285.1	1978	708	0
Voyageurs	62	2.18	Eastern Temperate Forest	882.4	1975	237	3
Wind Cave	32	0.02	Northwestern Forested Mountain	114.5	1903	620	1
Wrangell—St. Elias	22	0.04	Marine West Coast Forest	53,369.9	1980	68	1
Yellowstone	2,519	1.43	Northwestern Forested Mountain	8,991.2	1872	4,117	3
Yosemite	372	0.21	Northwestern Forested Mountain	3,026.9	1890	4,337	8
Zion	46	0.07	North American Desert	593.2	1919	4,505	3

[a]Park Representativeness (Park Rep) index normalized the number of publications in each park by the number of area of parks in each ecoregion—that is., for each park, we divided its number of publications by the number of parks in the ecoregion, then multiplied that value by the total park area within the ecoregion. Park Rep numbers have been multiplied by 1,000 for readability.

[b]R1 (doctoral university with very high research activity) and R2 (doctoral university with high research activity) institutions.