Received: 8 March 2024 | Accepted: 5 November 2024

DOI: 10.1111/1365-2664.14835

Journal of Applied Ecology | BRITISH ECOLOGICAL SOCIETY

PRACTITIONER'S PERSPECTIVE

Unusual success, future uncertainty, and science needs for adaptive management of invasive plants in a US national park

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Funding information
Schoodic Institute at Acadia National Park; Ocean Ledges Fund at the Maine Community Foundation; Maine Timberlands Charitable Trust; Friends of Acadia

Handling Editor: Rafael Zenni

Abstract

1. Invasive plants threaten natural areas, yet Acadia National Park, Maine, USA has been successful in managing invasive plant populations for over three decades. However, rapid environmental change and increasing pressure from encroaching invasive plants may adversely affect the success of ongoing management.
2. This article presents an overview of invasive plant management in Acadia National Park, highlighting lessons learned in over 30 years of active management. Acadia provides a valuable case study for other protected areas, sharing many features with protected areas globally. We offer recommendations for protected area managers in the face of rapid environmental change.
3. Deliberate and continuous management actions by park resource staff starting in the late 1980s and expanding in the mid-2000s have resulted in extremely low incidence of invasion within Acadia. This success has resulted from effort centred around a science-based and adaptive approach to management, early detection, and rapid response. Strong partnerships have ensured the continuation of this work.
4. Park staff continue to reduce invasive species populations to <1% cover, monitor managed areas to track treatment success, and re-treat upon reinvasion. However, total eradication is rare and continued management of new and re-invasions is expensive and challenging. Maintaining effective invasive plant management is likely to become more difficult as climate change interacts with other stressors in protected areas.
5. *Synthesis and applications*: Responding to these changes requires articulating desired and realistic future conditions for resources in protected areas, then using actions such as invasive plant removal and native plant revegetation to achieve goals. Long-term management through a flexible experimental approach is critical to successful invasive plant management. Both Western and Indigenous science are needed to inform responses to the multiple and interacting global change stressors, and management is needed to advance scientific understanding of ecosystem and species responses to change.

KEYWORDS
Acadia National Park, adaptive management, Friends of Acadia, Indigenous science, invasive plant management, invasive species, *Lythrum salicaria*, rapid environmental change

1 | INTRODUCTION

Many protected areas were specifically created to provide habitat for the abundant and often unique biodiversity found within their borders. Invasive species are a major concern for native biodiversity and ecosystem function in many protected areas globally (Simberloff et al., 2013). Despite heightened attention to this issue, translocation of non-native species by humans continues to increase along with the impacts from these species (Seebens et al., 2017). Invasive plants impact native ecosystems in myriad ways, including by reducing the abundance, growth, reproduction, and diversity of native species (Simberloff et al., 2013), and by initiating cascading effects that alter nutrient cycling, ecosystem productivity, ecosystem services, and human well-being (Pejchar & Mooney, 2009). Invasive plants also negatively impact viewscapes and visitor experiences (Belote et al., 2010). The impacts and ecologies of invasive species are heterogeneous, requiring nuanced management approaches for each species and invaded system (Simberloff et al., 2013).

Managing invasive species comprises a substantial proportion of the resource management activities and costs in protected areas internationally (Diagne et al., 2020; Foxcroft et al., 2013), and is one of the few interventions that occurs within Category I protected areas (strict nature reserves and wilderness areas), or those afforded the highest levels of protection. Managing invasive species also complicates managers' ability to maintain ecological integrity in protected areas as ecosystems and climates change (Crausbay et al., 2022). For example, the presence of invasive plants might prevent native species from warmer climates from establishing and facilitating desired transitions in ecosystems as temperatures warm. As managers juggle multiple conservation priorities, assessing past efforts and future needs for the management of invasive species is critical.

Here we explore the success of invasive plant species management via multiple metrics (species, sites, time, and herbicide) in Acadia National Park—located on the coast of Maine, USA—relative to other units managed by the US National Park Service (NPS) in the northeastern United States (US) and to other protected areas worldwide. In contrast to all other national parks in the region and many protected areas globally, Acadia has less than 1% cover of invasive plants and is maintaining consistently low abundances of invasive plants (Miller et al., 2021). Part of this management success is due to Acadia's relative isolation, northern location, and coastal influence (Figure 1), where a cooler climate and rural landscape have meant fewer introductions. However, Acadia's ambitious 35-year effort to inventory and manage select invasive plants within the park's boundaries has also played a key role. In this article, we examine the history of invasive plant management in Acadia National Park, review lessons learned from this long-term effort, provide management recommendations, and identify scientific needs for protected area managers in an era of rapid change.

2 | ACADIA IN AN INTERNATIONAL AND REGIONAL CONTEXT

Acadia National Park shares several features with other protected areas around the world that make it a relevant case study. Specifically, the colonial history and expansion of homes, businesses, and tourism around Acadia have contributed to the establishment and spread of invasive species, which is one of the park's top management priorities. Acadia is managed by a federal land management agency (NPS) with a mission to protect natural and cultural resources and provide educational visitor experiences. The agency has limited resources and works with local communities and partner organizations to achieve its mission. These characteristics are common to many protected areas and strongly influence strategies for managing invasive plants. We believe that lessons gained from managing invasive plants in this context can inform managers responsible for other protected areas globally.

The land we now call Acadia National Park is a part of the homeland of the Wabanaki Nations (Maliseet, Micmac, Passamaquoddy, and Penobscot), where for 12,000 years Wabanaki people have hunted, fished, gathered, and stewarded the land. Between the 1500s and 1800s, Wabanaki people were displaced and most of the land that is now in the park was privately owned and managed as homesteads, gardens, woodlots, and pastures. Many of these parcels had been planted with invasive plants prior to NPS involvement. Acadia was established in 1916, with new parcels having been added since then. After transferring to federal protection most areas have reverted to forest. These characteristics make parklands especially vulnerable to the impacts of invasive plants.

The NPS has long recognized the threat posed by invasive species to the mission of the agency and to NPS units. In 1988, NPS Management Policies directed managers to prevent introductions of invasive species, stating that management would be undertaken when park resources or public health is threatened, and when control is 'prudent and feasible'. A study of 39 national parks in the northeastern US from 2007 to 2018 found that 92% of the parks had invasive plant species present in more than half of the study plots, and 80% of the parks were experiencing increases in abundance of at least one invasive plant species (Miller et al., 2021). Invasive plants have similarly increased in abundance in 31% of protected areas globally over the past 30 years, according to a resurvey of 21 parks.

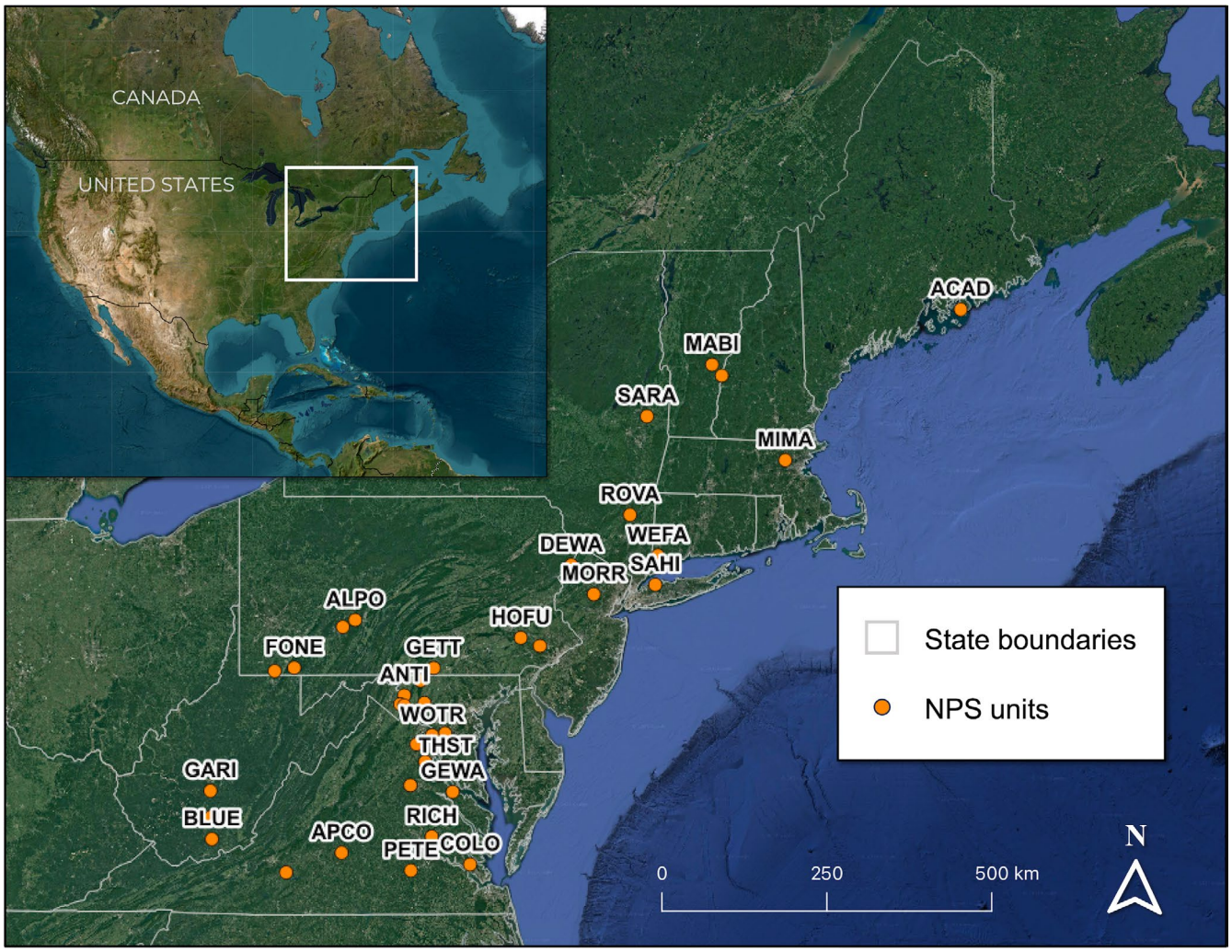

FIGURE 1 Map of the northeastern US national park units (NPS units) as reference for the location of Acadia National Park (ACAD), the most north and east unit. For a full list of the park codes included on this map, see Table S1 in Supporting Information.

3 | THE HISTORY OF INVASIVE PLANT MANAGEMENT IN ACADIA

The NPS has managed invasive plants in Acadia National Park continuously since 1988 (Figure 2). Following a field survey of non-native flora in 1986, NPS natural resource staff identified 12 of the ~289 non-native plant species on the park's flora inventory as species of management concern based on the best available science (e.g. literature, life histories, and discussions with other managers). Of these, purple loosestrife (*Lythrum salicaria*) was identified as the most threatening to Acadia's resources based on the impact of the species in other protected areas. This species is an herbaceous wetland plant that reproduces both by seed and root fragments, thrives in disturbance, and was commonly used in ornamental gardens at the time. NPS managers determined that management was 'prudent and feasible' in accordance with the management policies, and used a science-based, integrated management approach when developing the purple loosestrife management plan. The plan established management goals, action thresholds, quantitative monitoring methods, and management actions including prevention and early detection, education, and herbicide treatments. In 1996, park managers invited subject experts to review the management program. They confirmed that efforts had achieved NPS goals of preventing invasion of wetlands that had been free of purple loosestrife, and that extant populations of purple loosestrife were being managed below ecological impact thresholds (Hiebert, 1997).

Resource managers at Acadia started to target other invasive plant species in the early 2000s, as funding and staff allowed. Expanding the program required a detailed assessment of the distribution and abundance of invasive plants in the park to understand the full scope of the issue (Figure 3). Acadia staff developed integrated management plans for the most threatening invasive plants based on the best available science (Weber & Rooney, 2007), and began to actively manage several species including: garlic mustard (*Alliaria petiolata*), honeysuckle shrubs (*Lonicera morrowii*, *L. tatarica*, *and L. x bella*), and giant hogweed (*Heracleum mantegazzianum*).

Expanded invasive plant management required larger investments of funds and staff time—a seasonal crew of 3–6 people—embedding

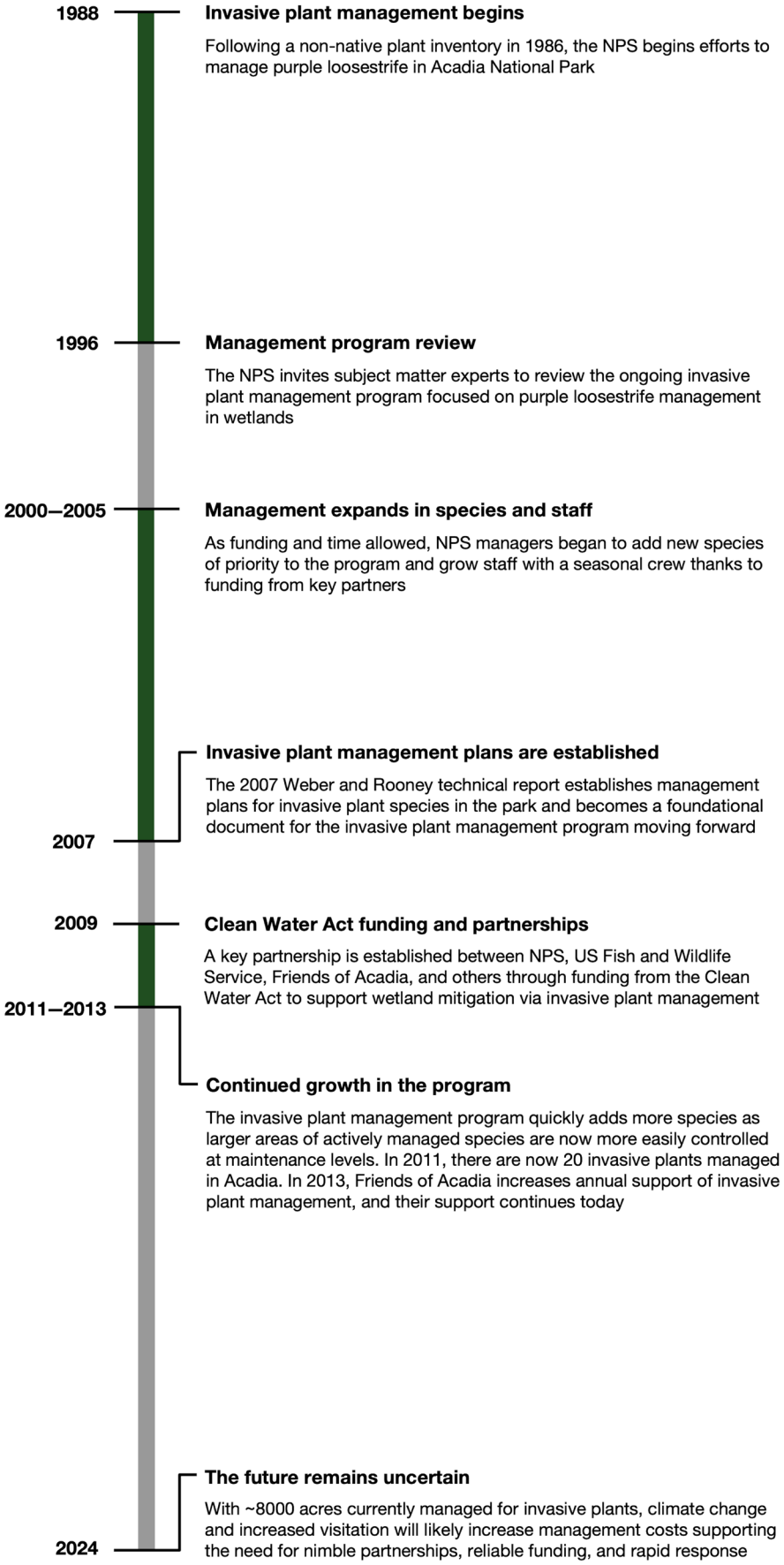

FIGURE 2 Timeline of the history of how the invasive plant management program developed in Acadia National Park from 1988 to 2024.

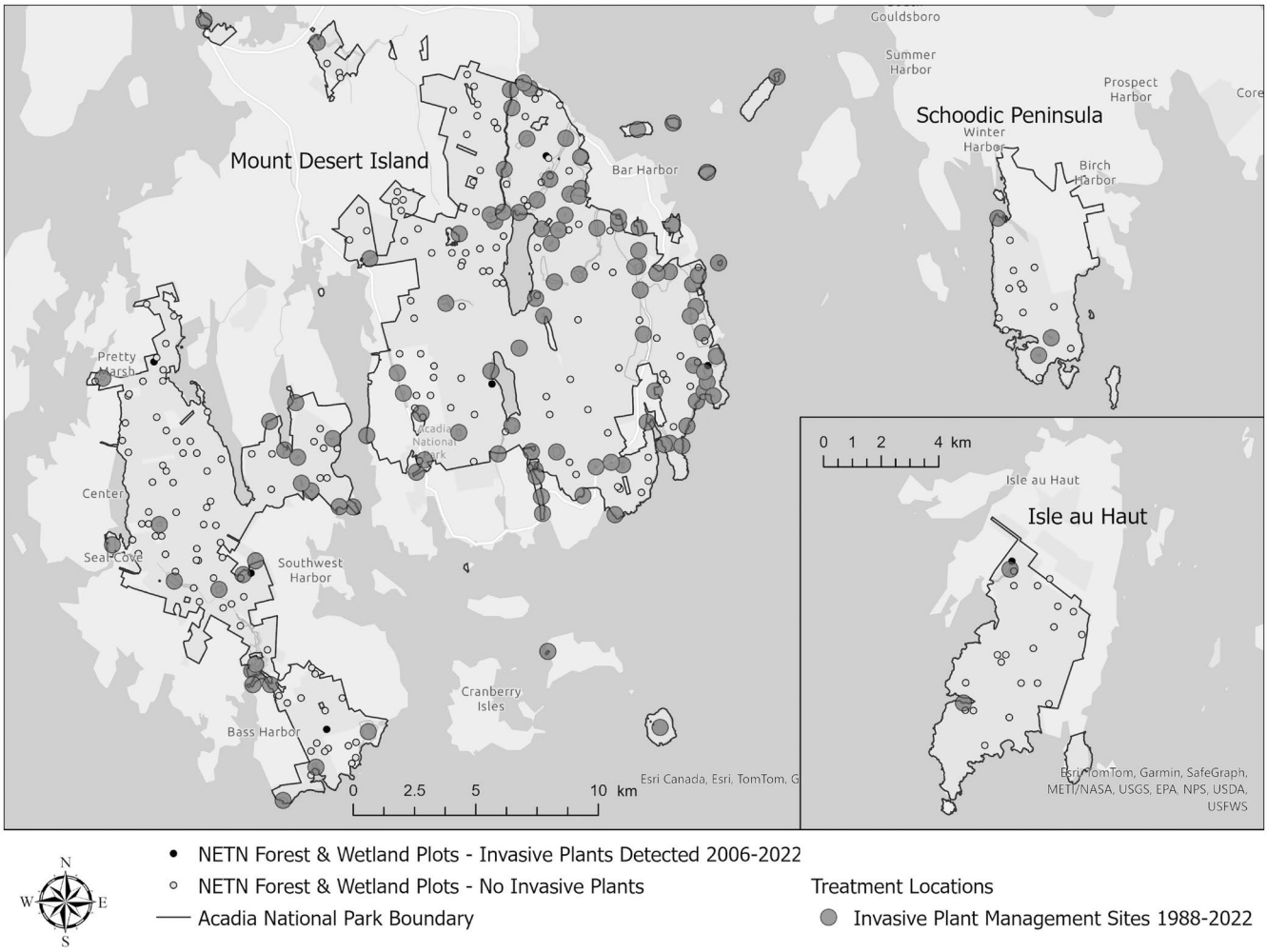

FIGURE 3 Approximately 63% of monitoring plots contain invasive plants, but only 5% of forest plots contain invasive plants compared with 58% of wetland plots. The highest concentrations of non-native plants occur adjacent to developed areas, and intact forests have the fewest invasive species. This map shows the invasive plant management sites (1988–2022), and forest and wetland vegetation monitoring plots (2006–2022) with and without invasive plant species in Acadia National Park, Maine.

one of the largest sustained natural resource management programs Acadia had taken to date. High quality inventory and monitoring data that identified the extent of the threat and past program successes, in addition to support from park partner organizations, such as Friends of Acadia, played crucial roles in the decision of park leaders to expand the program. With the lack of base funding from the park for invasive species management, Friends of Acadia's philanthropic commitment was critical to long-term success.

In 2009, a key partnership was established between the NPS, US Fish and Wildlife Service, Friends of Acadia, and other partners that provided multi-year funding from wetland enforcement actions under the Clean Water Act to support wetland mitigation through invasive plant management. Acadia staff launched an intensive campaign to: (1) control and reduce the extent of cover and abundance of select invasive species, (2) reduce the sources of these species, and (3) detect new occurrences of these species early during their establishment (early detection/rapid response) following established methods (Weber & Rooney, 2007). Management actions followed evidence-based methods with the least potential environmental damage (e.g. mechanical removal, careful herbicide application using species-specific protocols). Park staff reduced populations to <1% cover to suppress the species to what were considered maintenance levels, monitored managed areas to assess treatment success, and re-treated upon reinvasion (Weber & Rooney, 2007). For example, managers reduced the infested area of *Lonicera* spp. on Bar Island, Maine from 7.6% to 0.2% between 2015 and 2017 and have maintained <1% cover. Managers use GPS/GNSS and observational surveys to inform annual assessments of invasive species management plans and prioritize these maintenance efforts.

By 2011, park staff was managing 20 invasive species including high-priority infestations of glossy buckthorn (*Frangula alnus*), Japanese barberry (*Berberis thunbergii*), Asiatic bittersweet (*Celastrus orbiculatus*), and Japanese knotweed (*Fallopia japonica*). These species have spread widely across other protected areas in the northeastern US (Miller et al., 2021), and their ecological impact was well documented in the literature (Weber & Rooney, 2007). Managers

prioritized removing these shrubs, vines, and herbaceous invasive plants because they (1) most threatened the park's resources, (2) management was feasible with existing methods, and (3) abundance and distribution were known. As reproductive stems were eliminated from large, previously unmanaged stands of invasive plants, management teams were able to treat smaller infestations, adding to the total sites managed each year (Figure 4).

Management teams have since shifted from time-consuming initial treatments to surveying for new infestations and working to maintain low densities at management sites (Figure 4). Because of the abundance of invasive plant populations in neighbouring areas outside of park boundaries, which continue to disperse seeds into the park, eradication was never a feasible goal. Intensive invasive plant management in Acadia has resulted in low population levels of target invasive species. For example, after 35 years of management, purple loosestrife is still found in the park, albeit at very low levels with less than 162 m^2 managed each year in the last decade. Over the decades, Acadia has managed invasive plants spread across 7930 acres or roughly 17% of the park. Reducing infestations that have mature plants and established seed banks to maintenance levels required years and even decades of effort (see Figures S1 and S2).

4 | LESSONS LEARNED AND RECOMMENDATIONS FOR OTHER PROTECTED AREAS

Many other protected areas in the northeast have not had this level of management effort or success (Miller et al., 2021). In many cases, this is because of insufficient staff and financial resources, competing priorities, higher levels of plant invasions, and factors such as overabundant deer or non-native earthworms that enhance plant invasions (Fisichelli & Miller, 2018). Long-term forest health monitoring in the region has shown that invasive plant cover and frequency increased in nearly all parks over the past 12 years, and that 92% of parks have invasive plants present in at least half of forest health monitoring plots (Miller et al., 2021). Resurvey data and manager interviews show that threats from invasive plants continue to grow in protected areas globally, although aggressive management has been successful in some cases (Shackleton et al., 2020). In contrast, Acadia has invasive species present in less than 1% of forest health monitoring plots (Figure 3), and abundance has remained consistently low over the past 12 years (Miller et al., 2021). From this long-term effort, we've

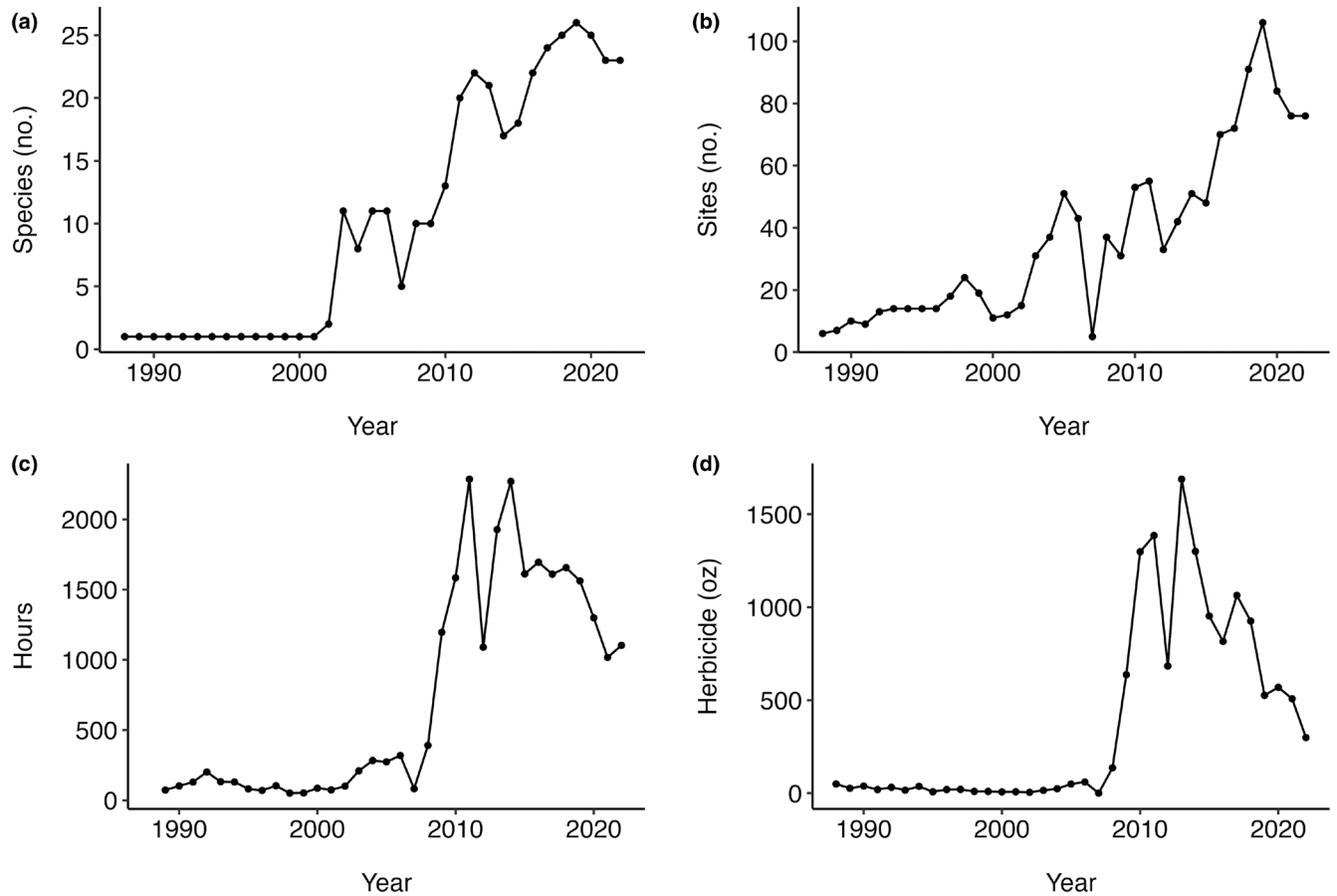

FIGURE 4 The (a) number of species and (b) number of sites managed, (c) hours of work, and (d) herbicide concentrate used during invasive plant management have increased overtime. More recently, however, time spent managing invasive species has decreased as populations are being maintained at low densities, as has the amount of herbicide concentrate used. Hours of work were not recorded in 1988.

identified the following as critical components of successful invasive plant management.

4.1 | Commit for the long-term

Successful invasive plant management in Acadia National Park shows that consistent, long-term investment in science-based, integrated management approaches (as well as associated management plans and monitoring) can allow protected area managers to suppress invasive plant populations to maintenance levels. This approach can work even as climate conditions change, new invasive species arrive, and funding and staffing resources change, as demonstrated in Acadia and in other protected areas that have successfully managed invasive plant populations (Shackleton et al., 2020).

Similarly, past invasive plant management success is not necessarily an indicator of future performance, especially given the many ongoing changes and stressors to ecosystems. In Acadia non-native plants comprise 25% of the vascular plant species (McDonough MacKenzie et al., 2019), and tree habitat suitability by 2100 is projected to undergo major change for 57% of tree species modelled for the region (Iverson et al., 2019), and mammalian herbivores, earthworms, and other factors are further exacerbating changes (Fisichelli & Miller, 2018). As conditions continue to change, interactions among disturbances are likely to release limiting resources (i.e., light at the forest floor) and foster invasive plants (Bradley et al., 2010). Similar changes are creating challenges for invasive plant management across protected areas worldwide (Shackleton et al., 2020).

Some of these changes are likely to be large-scale and abrupt. A recent forest disturbance scenario planning workshop in Acadia identified future interactions among windstorms, drought, fire, insect pests, diseases, and invasive plants as major threats to the forests of the park. Many of these scenarios have played out at other NPS units, and these disturbances are expected to increase in intensity and frequency (Miller et al., 2023). Forests in the park are also maturing and transitioning to stages where disturbances can quickly open canopy space and increase light availability at the forest floor, conditions favourable for invasive plants. If invasive plants establish and dominate following disturbances that open gaps or larger areas of forest, they may prevent regeneration by native tree species (Miller et al., 2023) or species and genotypes from southern locations from establishing. Managers must ask whether current management strategies will continue to be effective as conditions change and disturbances become more frequent. Thus, flexibility and rapid response alongside a dedicated long-term effort are critical for successful invasive plant management.

4.2 | Gather evidence of effectiveness

Evidence of the impacts of invasive plants on native ecosystems can help managers acquire the support and resources necessary for management. Thorough monitoring can then inform management practices and justify sustained funding and effort. These types of evidence are limited in protected areas globally and should be a priority (Foxcroft et al., 2013; Shackleton et al., 2020). In the northeastern US, recent evidence shows that increasing densities of invasive plants are outcompeting native forest regeneration, severely degrading ecological integrity, and reducing the capacity of ecosystems to recover after disturbances or adapt to climate change (Miller et al., 2023). In response, the NPS is increasing investments in managing invasive plants in northeastern units, following the models established at Acadia National Park and other areas with successful invasive plant management.

Conducting consistent and thorough monitoring is difficult, however, because parks tend to prioritize funds and staff time for eradication efforts. In Acadia, monitoring of purple loosestrife documented the success of early management efforts (in the 1980s and 1990s, Figure 2), and provided crucial evidence to help convince park leadership to increase investment in invasive plant management. Monitoring glossy buckthorn treatments helped managers determine the effectiveness of mechanical and chemical control methods of the species. Since 2016, managers have established monitoring plots before treatments to document the effectiveness of treatments and to identify re-invasions. These examples show the importance of gathering evidence of the effectiveness of invasive plant management.

4.3 | Set clear, achievable goals and learn as you go

Resource managers need information and tools to navigate future uncertainty. Scenario planning can help managers assess a range of plausible futures, but it can be difficult to connect scenarios to natural resource management decisions, such as how to adjust invasive management practices. It is crucial that managers set clear and achievable management goals and establish frameworks for making decisions. Clear goals allow park managers to measure success, prioritize limited resources, and know when to act. Decision-making frameworks, in turn, help scientists and managers work together to prioritize specific actions. For example, the resist-accept-direct framework, used by NPS and many other agencies around the world, provides a relatively straightforward way for scientists, managers, and policy makers to discuss and make climate change adaptation decisions whether to resist changes, accept those taking place, or direct them to a different trajectory (Crausbay et al., 2022).

We also encourage managers to integrate science and management and test different approaches as they manage. Integrating science and management more closely than is typical in adaptive management frameworks can greatly speed learning (Nadeau et al., 2024). For example, managers in Acadia are considering planting native species after the removal of invasive plants, particularly species that might shade invasive plants and reduce the rate of reinvasion. It is possible that this strategy could also be used to

assist the colonization of species or genotypes from southern locations, which have longer leaf-on seasons and might be expected to colonize on their own if not for obstacles created by humans like urban areas and roads (Miller & McGill, 2018). Many invasive plant species in the northeastern US are successful in part because they have longer leaf-on seasons than native plants in the region (Fridley et al., 2023). However, it is unclear which individual species, genotypes, or assemblages to use when planting after invasive plant removal. Thus, managers and scientists at Acadia are explicitly testing different planting strategies as they implement their management actions.

4.4 | Form partnerships and co-create

Other NPS units in the northeast region of the US face many challenges related to managing invasive plants. They tend to have warmer climates, richer soils, more intense human disturbance histories, higher deer browse pressure, and greater presence of non-native earthworm disturbance in forest plots (Fisichelli & Miller, 2018). They also tend to have fewer staff and resources to dedicate to invasive plant management. These challenges are like those faced in protected areas globally, particularly the lack of or difficulties in sustaining funding, use of appropriate management techniques, and support of neighbouring communities (Foxcroft et al., 2013; Shackleton et al., 2020).

Increased communication across protected areas globally and partnerships among government agencies, academic institutions, nongovernmental organizations, and funders can help address these problems and speed up the pace of learning. In Acadia, these types of partnerships have been essential in increasing the capacity (e.g. funds, staff, science, and management expertise) to sustain effective invasive species management. Improvements in communication across protected areas could increase success by sharing lessons as they are learned, including lessons that may be slow to be published in the peer-review literature.

The NPS is also now required by policy to include Indigenous knowledge alongside Western science in decision-making. Working with Indigenous scientists and knowledge holders will bring new perspectives and evidence to what has previously been planned and decision-making processes dominated by Western science. In Acadia National Park, this process is starting through the restoration of traditional Indigenous plant gathering by Wabanaki people, which has been absent from the landscape since the park's inception. Plant gathering restores critical cultural practices and benefits many native plant species (Greenlaw, 2023). Park managers, Indigenous scientists, plant gatherers, and Western scientists are now working together to address many of the challenges posed previously—how to identify desired conditions, assess risk, learn, and make management decisions. Specifically, they are addressing these challenges as they relate to restoring ecosystems and plant communities following the management of invasive plants. This work is still early in its development, but it will be a critical part of managing invasive plants in Acadia. Much more work is needed to incorporate Indigenous science into the management of other protected areas in the US, but these partnerships are crucial for the successful management of protected areas on a global scale.

5 | CONCLUSIONS

The success of invasive plant management in Acadia National Park has resulted from a long-term effort with unique partnerships that rely on a science-based and adaptive approach to management, early detection, and rapid response. However, park staff continue to reduce invasive species populations, monitor managed areas, and re-treat upon reinvasion. Rapid environmental change may adversely affect the success of ongoing stewardship activities in protected areas globally, thus implementing and maintaining effective invasive plant management is likely to become more difficult. Responding to these changes requires articulating desired but realistic future conditions for resources in protected areas, then acting (e.g. invasive plant removal, native plant revegetation) to achieve these goals. Therefore, continuous management through a flexible experimental approach will be critical to successful invasive plant management in the future. Science, both Western and Indigenous, is needed to inform responses to the multiple and interacting global change stressors, and management is needed to advance scientific understanding of ecosystem and species responses to change.

AUTHOR CONTRIBUTIONS

Nicholas A. Fisichelli, Jesse S. Wheeler, and Abraham J. Miller-Rushing conceived the idea of this manuscript; Kyle A. Lima, Nicholas A. Fisichelli, and Jesse S. Wheeler analysed the data; Kyle A. Lima, Nicholas A. Fisichelli, Jesse S. Wheeler, Abraham J. Miller-Rushing, and Judith Hazen Connery wrote of the manuscript. All authors contributed equally to the manuscript and gave final approval for publication.

ACKNOWLEDGEMENTS

We thank the US National Park Service, Maine Timberlands Charitable Trust, Ocean Ledges Fund at the Maine Community Foundation, Schoodic Institute, and Friends of Acadia for funding this work. We also thank the many people who have contributed to invasive plant management in the park. Additionally, we thank David Manski, Linda Gregory, Geneva Langley, Aleta McKeage, Frank Archuleta, and Tony Tocci for their critical roles in the history of invasive plant management in Acadia National Park. The findings and conclusions presented in this article are those of the authors and do not necessarily reflect those of the US Government or the US Department of the Interior.

CONFLICT OF INTEREST STATEMENT

We declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data are available from the US National Park Service DataStore, Integrated Resource Management Applications (IRMA): https://doi.org/10.57830/2306778 (Lima et al., 2024).

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Table S1. Table of the National Park Units and their park codes included in Figure 1 of the main manuscript.

Figure S1. The hours of work spent on the management of nine invasive plant species in Acadia National Park (1989–2022); hours of work were not recorded in 1988.

Figure S2. Herbicide (in ounces of concentrate) used for management across nine invasive plant species in Acadia National Park (1988–2022) varies greatly by species.

How to cite this article: Lima, K. A., Wheeler, J. S., Hazen Connery, J., Miller-Rushing, A. J., & Fisichelli, N. A. (2025). Unusual success, future uncertainty, and science needs for adaptive management of invasive plants in a US national park. *Journal of Applied Ecology*, *62*, 9–18. https://doi.org/10.1111/1365-2664.14835