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Climate-Smart Invasive Species Management for 21st Century Global Change Challenges

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ABSTRACT

Addressing the global challenges of climate change and biotic invasions requires understanding their interactions and implications for natural resource management. To facilitate and support invasive species management in a changing climate, we review how climate change and invasions interact to impact the planning, action, and outcomes of invasive species management. Climate change is facilitating the introduction of new potential invasive species and altering pathways of introduction and spread, with implications for which species natural resource managers need to assess, monitor, and target. Climate-driven shifts in invasive species phenology require more flexible management timelines. Climate change may reduce the efficacy and feasibility of current treatment methods and make native ecosystems more vulnerable to invasion. Additionally, disturbance caused by extreme climate events can compound the spread and impacts of biological invasions, making invasive species management a necessary part of extreme event preparation and response planning. As a solution to these challenges, we propose climate-smart invasive species management, which we define as the approaches that managers and decision-makers can take to address the interactive effects of climate change and invasions. Climate-smart invasive species management includes considering potential shifts in species ranges, abundances, and impacts to inform monitoring, treatment, and policies to prevent new invasive species. Climate-smart management may also involve adjusting the timing and type of treatment to maintain efficacy, promoting resilient ecosystems through climate-smart restoration, and considering the effects of climate change when setting management goals. Explicitly considering the interactions of climate change and biological invasions within organizational decision-making and policy can lead to more effective management and promote more resilient landscapes.

1 | Introduction

The top global change challenges of climate change and invasive species (IPCC 2022; Roy et al. 2024) can interact to produce compounded ecological effects (Lopez et al. 2022). Climate change affects invasive species at every stage of invasion from introduction to spread (Hellmann et al. 2008), and invasive species can exacerbate the impacts of climate change (Bradley

et al. 2023). We define invasive species as established, non-native species with negative ecological consequences (*sensu* Roy et al. 2024), although we acknowledge species not included in this definition may also cause harm. Despite growing scientific discussion on the interactions of climate change and invasive species (Dukes and Mooney 1999; Hellmann et al. 2008; Finch et al. 2021; Ricciardi et al. 2021), the issues are usually considered separately in management. For example, the Society for

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Ecological Restoration's Principles and Standards for Ecological Restoration acknowledge both climate change and invasive species as shapers of restoration separately, not in conjunction (Gann et al. 2019). Additionally, invasive species management is an important yet still overlooked component of climate adaptation efforts and funding (e.g., Brewington, Rodgers, and Greenwood 2024), especially as biological invasions are often more detrimental to ecosystems than other forms of global change (Lopez et al. 2022). This litany of interactions creates unique and often overlapping management implications that require proactive and innovative solutions, yet invasive species management and regulation remain focused on reacting to current invasions rather than proactively preventing and halting the emerging threats of novel invasions (Early et al. 2016; Cuthbert et al. 2022).

Natural resource managers and practitioners (hereafter “managers”) report a lack of information, especially at scales relevant to management, as a key challenge to implementing more climate-smart invasive species management (Beaury et al. 2020a; Brewington et al. 2021). Indeed, few studies address the management of climate change and invasive species. A recent review found that only 4% (8/179) of papers studying the effects of climate change on invasive plants also investigated the effects of climate change on invasive plant management (Sun et al. 2021). This parallels a broader underrepresentation of applied studies and lack of focus on management priorities in the invasion ecology literature (Matzek, Pujale, and Cresci 2015). In response, the area of translational invasion ecology calls for bridging this “knowing-doing gap” (*sensu* Pfeffer and Sutton 1999), by connecting researchers and practitioners through collaborative research and knowledge coproduction (Morelli et al. 2021). While lack of funding and resources for management remain a primary challenge for traditional invasive species management, knowledge translation is an additional barrier for climate-smart invasive species management (Beaury et al. 2020a). A translational approach is needed to address the joint challenges of climate change and invasive species and requires explicitly considering the decision context in which the research results will be applied.

Differing priorities and misaligned timelines also impede the incorporation of climate change into invasive species management. For example, in the United States, most managers are highly concerned about the effects of climate change on invasive species management but believe their organizations to be less concerned, suggesting a lack of institutional priority (Beaury et al. 2020a). This disconnect might be further exacerbated by disparate timelines between climate change action and invasive species management. Climate goals are often set decades ahead of time (e.g., an 85% reduction in economy-wide greenhouse gas emissions by 2050, “New York State Climate Action Council Scoping Plan” 2022; net climate neutrality by 2050, “European Climate Law” 2021), whereas invasive species management plans are often set and reevaluated on shorter cycles (e.g., a 5-year span for the “New York State Aquatic Invasive Species Management Plan” 2015; halving the number of Red List species impacted by invasive species within 10 years, ‘EU Biodiversity Strategy for 2030’ 2020). Considering how climate change and invasive species interact can facilitate climate-smart invasive species management (Box 1) by relating the broader time frames and scales of climate change to the shorter time frames and smaller scales at which management occurs.

BOX 1 | Defining Climate-Smart Invasive Species Management.

A unifying framework for thinking about how climate change interacts with invasive species would help facilitate integration of climate change into invasive species management. In multiple disciplines, the term “climate-smart” has been adopted to describe actions that intentionally consider and act upon information on the challenges posed by climate change, to adapt and minimize risk while sustaining and enhancing the provision of goods and services. Examples include climate-smart agriculture (FAO 2010), climate-smart conservation (Stein et al. 2014), climate-smart forestry (Bowditch et al. 2020), and climate-smart pest management (Du et al. 2022). The term has similarly been used to argue for more climate-smart invasive species policy (Bradley et al. 2022, 2023), but has not been formally defined for or applied to invasive species management. Based on the interactive effects of climate change and biotic invasions and previous applications of “climate-smart”, we define “climate-smart invasive species management” as any management goal-setting, planning, or implementation that considers and aims to reduce the interactive effects of climate change and invasions.

To address the knowledge gaps preventing more proactive and climate-smart invasive species management, we divide this review into six major management challenges stemming from the interactions between climate change and biotic invasions (Figure 1; Table 1): (1) Climate-driven range shifts present new potential invasive species to evaluate, monitor, and target; (2) Newly available pathways for trade and transport create more opportunities for novel species introductions; (3) Shifting seasons and phenologies disrupt invasive species management timelines; (4) Reduced treatment efficacy and feasibility reduce the likelihood of achieving desired results; (5) Increased vulnerability of native ecosystems requires reevaluating and adjusting restoration targets; and (6) Compounding effects of extreme climate events and invasive species require integrating invasive species management into extreme event preparedness. After briefly summarizing the drivers of each management challenge, we outline invasive species management implications, options for action, and supporting policies that can account for interactions between climate change and invasions at various levels of management (Table 2), and highlight knowledge gaps impeding climate-smart invasive species management. We recognize that the feasibility of different management approaches will depend upon resource availability and local context, and thus, the examples we provide are illustrative but not exhaustive. We argue that climate-smart invasive species management is a crucial component of ecosystem management, as climate change and biological invasions create challenges for environmental and natural resource management and reduce ecosystem resilience worldwide.

1.1 | Climate-Driven Range Shifts Present New Potential Invasive Species to Evaluate, Monitor, and Target

Climate change is shifting the ranges of individual invasive species worldwide, potentially expanding the geographies of



FIGURE 1 | Climate change and invasive species interact in multiple ways, with implications for management. (A) Climate change is shifting invasive and native ranges, presenting new potential invasive species to evaluate, monitor, and target. (B) Changes in trade and transport open novel and increased pathways of introduction to monitor and regulate. (C) Shifting seasons alter invasive species' phenological timing and disrupt management timelines. (D) Higher temperatures and CO_2 concentrations and less predictable conditions reduce the efficacy and feasibility of invasive species treatment and control efforts, reducing the likelihood of achieving desired results. (E) Native species are vulnerable to the separate and combined impacts of climate change and invasive species, requiring reevaluating and adjusting restoration targets. (F) Climate-related stressors and extreme events facilitate invasive species spread and impacts, while invasive species reduce climate-regulating ecosystem services, requiring integration of invasive management into extreme event preparedness.

impact on native communities (Figure 1A; Table 1). Range models based on projected climate scenarios predict Europe, Oceania, and northeastern North America to become hot spots of invasion with climate change (Bellard et al. 2013; Allen and Bradley 2016). As temperatures increase and precipitation patterns change, terrestrial invasive species are spreading into higher latitudes (Bellard et al. 2013) and higher altitudes (Shrestha et al. 2018; Neddermeyer et al. 2023), and non-native species' rates of range expansion far exceed those of native species on land and in water (Bradley et al. 2024). Increasing minimum temperatures will likely shift or expand the ranges of previously cold-limited invasive species such as forest pest insects and pathogens (Dukes et al. 2009) and invasive fish species (McDowell et al. 2014; Mitchell et al. 2023). Beyond affecting where invasive species can exist and persist, climate change will also facilitate the naturalization of introduced but not-yet-established species (Dullinger et al. 2017; Haeuser et al. 2018) and increase the impacts of some naturalized species in their current non-native ranges enough to deem them invasive "sleepers" (Cunningham et al. 2004; Spear et al. 2021; O'Uhuru et al. 2024). The occurrence and abundance of certain invasive species may also decrease in some areas (Bellard

et al. 2013; Evans et al. 2023), potentially creating opportunities for restoration. With such climate-driven shifts in the spatial distributions and impacts of invasive species, managers will face a dynamic suite of novel species with the potential to disrupt management goals.

Adapting to a climate-linked influx of novel invasive species will require a paradigm shift from the predominant focus on managing current invasions to preventing potential future invasions, which can be facilitated through external support, boundary-spanning, and research partnerships (Beaury et al. 2020a). In the face of knowledge gaps, research can help managers proactively identify and prioritize climate-driven range-shifting species to monitor and manage (Table 2). Proactive strategies such as horizon scanning for species with high likelihood of arrival, establishment, and impact (Roy et al. 2014; Lieurance et al. 2023) and broader early detection and rapid response efforts (EDRR) (Wilson et al. 2013; Reaser et al. 2020) can become more climate-smart. For example, climate change is commonly incorporated into species distribution models to predict where species are more likely to establish and become abundant with climate change (e.g., Bezeng et al. 2017; Clarke et al. 2023).

TABLE 1 | Examples from different continents of the management challenges posed by the interactions between climate change and invasive species.

Management challenge	Region	Examples
1. Climate change-driven range shifts present new potential invasive species to evaluate, monitor, and target	Europe	Black locust (<i>Robinia pseudoacacia</i> L.) is predicted to spread earlier and farther east than previously predicted, and to increase in central and northeastern Europe with climate change (Puchałka et al. 2021). Spread of ragweed (<i>Ambrosia artemisiifolia</i> L.) with climate change is projected to increase the costs associated with allergies in central Europe (Richter et al. 2013). In Poland, climate change will increase the occurrence of high-risk invasive species, including those not regulated by the European Union or Poland itself (Solarz et al. 2023), highlighting the importance of preventative management and proactive policy to limit and control the spread of high-impact range-shifting species
	Africa	Climate change is predicted to increase the establishment and invasion of the shrub <i>Prosopis juliflora</i> (Sw.) DC. across the African continent (Sintayehu et al. 2020). Although originally introduced for environmental and economic reasons, <i>P. juliflora</i> outcompetes and suppresses native species and negatively impacts livestock in its introduced range (Hussain et al. 2021)
	Oceania	Certain invasive species and areas may decrease in priority for direct monitoring and management, whereas others may increase. The ranges of 11 non-native grass species shortlisted or listed as Weeds of National Significance or Alert List species in Australia are predicted to contract with future climate conditions (Gallagher et al. 2013). Furthermore, potential hot spots for sleeper species to establish will decline across Australia with climate change, although sleeper species potential remained high in select regions (Duursma et al. 2013). Climate change is also predicted to expand and shift the ranges of terrestrial and aquatic invasive species ranges in New Zealand, with likely impacts on native species (Macinnis-Ng et al. 2021)
2. Changes in trade and transport create novel and increased introductory pathways to monitor and regulate	Antarctica	Warmer temperatures are making Antarctica more habitable for non-native marine species while also increasing ship traffic, increasing potential for novel introductions in the region (Holland et al. 2021; McCarthy, Peck, and Aldridge 2022). Prevention could benefit from increased control measures at the point of origin, monitoring of Antarctic waters, and response plans for potential invasive species (Bergstrom 2022)
	Europe	Iceland's coastal waters already harbor non-native marine species suspected to have arrived via ship hulls and ballast water, and climate change is expected to increase the abundance of these species (Ramos Espla et al. 2020; Micael et al. 2022). Increased invasion risk with climate change is also expected of species currently in Iceland's aquarium trade (Micael, Sigurjónsdóttir, and Gíslason 2023)
	Asia	Ants sold online as pets in China pose an additional invasion risk with climate change (Wang et al. 2023). Beyond pet ants, port conditions in South Korea (and elsewhere) are predicted to become more suitable for red imported fire ants (<i>Solenopsis invicta</i> Buren) with higher temperatures under climate change (Lee et al. 2021), and increased floods may further increase fire ant dispersal upon arrival (Sung et al. 2018)
3. Shifting seasons and phenologies disrupt invasive species management timelines	Asia	In subtropical China, warming by ~2°C delayed the timing of the invasive species <i>Solidago canadensis</i> L. budding, flowering, seed-set, and dieback (Peng et al. 2018), which could impact optimal management windows
	North America	Invasive species management timelines in the Northeastern United States are shifting due to changes in invasive phenology and seasonal conditions. Woody invasive species leaf out earlier and track climate change better than native species in Massachusetts (Polgar, Gallinat, and Primack 2014), potentially advancing treatment timelines and conflicting with staff availability. In New England, frozen ground days are often required to reduce impacts of invasive treatments using heavy equipment, but are less common than in past decades and will further decrease by the end of the century (Daniel et al. 2018)

(Continues)

TABLE 1 | (Continued)

Management challenge	Region	Examples
	Europe	Longer growing seasons may increase the annual number of generations of the brown marmorated stink bug, <i>Halyomorpha halys</i> (Stål), from one generation per year to two, or even three or four in some locations (Kistner 2017). The first flowering dates of non-native plants in the British Isles responded to warming temperatures more than native species (Hulme 2011), but information on shifts in invasive phenology across Europe is scarce. However, community science initiatives such as the C.S.I. PhenoBiota project can help gather data about invasive phenology changes with climate change while also educating students and other participants (Gebeshuber et al. 2024)
4. Reduced treatment efficacy and feasibility reduce the likelihood of achieving desired results	North America	Unless managers adjust frequency and/or combine mowing with other treatments, climate change will reduce the efficacy of mowing invasive musk thistle (<i>Carduus nutans</i>), which grows more and is more likely to survive mowing in warmer temperatures (Keller and Shea 2022)
	Oceania	Higher CO ₂ concentrations can increase plant vigor and tolerance of glyphosate and other herbicides in exotic and invasive C4 grasses and woody plants (Manea, Leishman, and Downey 2011; Waryszak et al. 2018; Iqbal et al. 2021). Additionally, extreme weather events such as drought and heavy rainfall can negatively impact the outcomes of Australian environmental management, including invasive species management (Tulloch, Hagger, and Greenville 2020). Climate change is also predicted to increase costs of invasive animal control and decrease the cost-effectiveness of aquatic animal and goat control (Firn et al. 2015)
	Africa	In South Africa, increased CO ₂ may decrease the efficacy of various invasive species control methods. Glyphosate efficacy of the invasive annual <i>Parthenium hysterophorus</i> L. decreased with increasing CO ₂ levels (Cowie et al. 2020). Elevated CO ₂ also increased growth, photosynthesis, foliar C:N ratios, and water use efficiency of the invasive liana <i>Pereskia aculeata</i> Miller (Venter et al. 2022), which could make control (including biocontrol) more difficult. In other cases, invasive species may be negatively impacted by climate-related stress, which could benefit management; for example, in Tanzanian savannas, the invasive plant <i>Gutierrezia cordifolia</i> Benth. ex Oliv. can tolerate and spread with flood events due to increased leaf and seed production, but is more vulnerable to drought (Nyarobi, Ngondya, and Munishi 2022)
5. Increased vulnerability of native ecosystems requires reevaluating and adjusting restoration targets	North America	High white-tailed deer (<i>Odocoileus virginianus</i>) densities not only directly threaten native plant communities but are also associated with non-native earthworms and invasive plants (Dávalos, Nuzzo, and Blossey 2015; Golivets, Woodall, and Wallin 2019; Gorchov et al. 2021), and are predicted to withstand (Wolff et al. 2020) and even benefit from climate change (Dawe and Boutin 2016; Weiskopf, Ledee, and Thompson 2019). In such cases, deer management might be a more impactful goal than invasive species management alone
	Europe	Invasive species reduce community productivity in drought conditions, even in sites with high native species richness, suggesting a reduced ability to recover from drought due to the interaction of climate change and invasive species (Vetter et al. 2020)
	South America	More of the Amazon is predicted to transition from forest to grassland, as invasive and non-native grasses are more likely to spread and establish post-fire in a greater extent of the Amazon with climate change (De Faria et al. 2021). Given the difficulties of reverting grasslands to forestland, preventing this conversion where possible and conserving remaining forest may become increasingly important. Native grasslands such as Paraná River floodplain may also experience increased vulnerability with climate change; extreme drought and flooding events both negatively impacted the performance of the native grass <i>Panicum dichotomiflorum</i> performance without affecting the invasive grass <i>Urochloa mutica</i> , potentially shifting competitive outcomes to favor of the invasive species (Carrara et al. 2024)

(Continues)

TABLE 1 | (Continued)

Management challenge	Region	Examples
6. Compounding effects of extreme climate events and invasive species require integrating invasive management into extreme event preparedness	Oceania	In Australia, invasive grasses such as buffel grass (<i>Cenchrus ciliaris</i>) increase fuel loads (Butler and Fairfax 2003), and predicted climate-driven southward range shifts (Martin et al. 2015) will change where risk may be expected. Proactively managing invasive species that increase the risk and impacts of such extreme fire events can be part of preparation, and post-event actions to prevent new incursions can reduce the likelihood of further invasion and a repeat event (Rossiter-Rachor et al. 2023)
	Africa	Invasive species management can contribute to ecosystem resilience through extreme events, such as removal of non-native trees in South Africa increasing water security during the dry season and drought (Holden et al. 2022; Rebelo et al. 2022)
	North America	An unprecedented extreme heatwave near Southern California impacted benthic kelp forest communities, with notable and lasting increases in the populations of two invasive bryozoan species (<i>Watersipora subatra</i> and <i>Bugula neritina</i>) (Michaud, Reed, and Miller 2022)

Standardized modeling approaches (Davis et al. 2024) combined with impact assessments can identify high-risk species for EDRR (Henry and Sorte 2022; Rockwell-Postel, Laginhas, and Bradley 2020; Wallingford et al. 2020). Although climate-driven range shifts are not the only relevant factor when choosing species for risk assessment, and models inevitably contain inaccuracies and oversimplifications, their predictions can still inform proactive and precautionary management (Gordon et al. 2016; Hill et al. 2023). The results of climate-smart risk assessments can also inform the regulation of species in trade and industry (Bayón and Vilà 2019).

The utility of any assessment depends upon the quality and availability of information (Hulme 2012). Boundary-spanning initiatives, including the Regional Invasive Species and Climate Change Management Networks (riscnetwork.org) in North America and the Pacific, can help accumulate and evaluate available data to create more targeted watch lists of climate-driven range-shifting species. Multiuser databases such as iMapInvasives (imapinvasives.org), EDDmaps (eddmmaps.org), AquaNIS (<http://www.corpi.ku.lt/databases/index.php/aquanis/>), and Atlas of Living Australia (ala.org.au, Australia) can then facilitate monitoring for priority species by streamlining data collection and providing tools for data analysis (AquaNIS 2015; Wallace and Barger 2022; Finley, Dovciak, and Dean 2023).

Managers may consider not only treating and controlling current and predicted incoming invasive species found on regional and organizational watch lists, but also preemptively treating established non-native species with identified potential to become more competitive in a warmer climate (Groves 1999; Spear et al. 2021; O’Uhuru et al. 2024). Further research to identify high-risk potential sleeper species and the conditions triggering their “awakening” can support such proactive management. For example, examining whether currently established, non-native species are considered invasive in warmer geographies can provide a list of potential sleeper species for further assessment (O’Uhuru et al. 2024), and studies in urban heat islands can further augment this list (Frank and Just 2020).

Domestic trade policy can support climate-smart invasive species management by taking action to stop the sale and transport of known and potential invasive species, thereby preventing the spread of invasive species into new habitats. However, countries vary in how proactive and stringent their regulations are (Early et al. 2016; Justo-Hanani and Dayan 2021). A great number of invasive species remain available for sale in the contiguous USA through the horticultural and pet trades (Lockwood et al. 2019; Beaury, Patrick, and Bradley 2021), and the majority of state regulations are restricted to species already present and thus fail to prevent the spread of new species (Bradley et al. 2022; Pratt et al. 2024). Proactive and coordinated regulation of the sale of potential invasive species could help curb the spread of invasive species (Scott et al. 2014; Reaser et al. 2020; Bradley et al. 2022). For example, neighboring states or countries could collaborate on assessment and listing to more effectively stop the spread of new invasions by reducing redundant work and enabling resource sharing (Keller and Perrings 2011; Bradley et al. 2022).

Beyond trade, invasive species can spread via the movement and transport of equipment, vehicles, and machinery, although preventative washing and cleaning campaigns may limit this spread (e.g., the North American Invasive Species Management Association’s “WorkCleanGo” program and “Check Clean Dry” programs in the United Kingdom and New Zealand). Climate mitigation may create additional opportunities for invasive species to spread, requiring collaboration with invasive species management (Box 2). Whether through policy and research or preventative and proactive action, addressing the potential spread and impacts of climate-driven range-shifting species is part of climate-smart invasive species management.

1.2 | Changes in Trade and Transport Create Novel and Increased Introductory Pathways to Monitor and Regulate

Beyond the expansion and contraction of current invasive species’ ranges, climate change will also affect pathways of global spread and introduction through its effects on intercontinental

TABLE 2 | Options and opportunities for climate-smart invasive species management and implications for where policy and funding could support such opportunities, organized by management stages. Many options will require some investment of time, funding, or capacity, and further tailoring to fit the managing organization's values and specific context.

Management stage		Climate-smart invasive species management options	Implications for policy and funding support
1. Strategic planning	i. Mission and values	• Explicitly address the impacts and mediation of climate change in organizational mission, goals, and strategic plan. • Include invasive species management in climate change adaptation plans. • Encourage and provide staff with opportunities to learn about the interactions of climate change and invasive species.	• Enable invasive species managers to attend workshops and conferences about climate change. • Provide invasive species managers access to climate change journals and publications.
	ii. Prioritization	• Consider potential impacts of climate change on reference ecosystems, target native species, and management goals. ◦ Consider the vulnerability of target species and ecosystems to climate change and invasive species. ◦ Consider climate adaptation when setting management goals. • Incorporate predicted climate impacts on range shifts when selecting watch list invasive species. • Weigh the pros and cons of each IS under target; not always net negative	• Fund and support regional and local climate-informed horizon scans and climate vulnerability assessments that incorporate invasive species impacts. • Consider climate impacts in invasive species horizon scans and risk assessments. • Facilitate cross-border meetings between managers to discuss species of concern.
	iii. Budgeting and hiring	• Budget for increased early detection and rapid response (EDRR). ◦ Create dedicated EDRR positions. • Shift seasonal and contract-hire timelines to account for extended growing seasons. • Plan for seasonal staff shortages. • Potentially outsource labor to volunteers, school groups (depending on the task, can include various ages), or contractors. • Apply for climate adaptation funding sources. • Budget for more frequent treatments and/or alternative treatments and approaches.	• Fund invasive species management, monitoring, and EDRR. • Write MOUs and policy to allow contract hires to bridge seasonal staff shortages. • Connect management organizations to potential contractors. • Acknowledge that proactive prevention is much less effective than reactive control of invasive species.
	iv. Scheduling and timelines	• Long-term thinking (consider the scales of climate change vs. invasions). • Schedule staff and volunteer training earlier in the season to account for shifting seasons. • When possible, include contingency dates in permit applications to enable flexibility. • Plan for more frequent treatments in priority areas. • Include IS management in extreme event response plans. ◦ Involve local partners and rights holders. ◦ Include and fund EDRR and active restoration, particularly for riparian areas. ◦ Identify suppliers for post-event proactive plantings.	• Facilitate the use of emergency response and wildfire prevention funds for invasive species management. • Provide expedited funding and permit approval options for invasive species management and prevention after extreme events. • Create longer term grants and funding programs that encourage more nuanced consideration of climate change and invasive species, and allow for monitoring changes in efficacy across years. • Facilitate the use of contractors during seasonal staff shortages. • Allow flexible treatment dates in chemical permits. • Adjust timelines of funding applications and availability to allow earlier start and later end dates for seasonal staff.

(Continues)

TABLE 2 | (Continued)

Management stage	Climate-smart invasive species management options	Implications for policy and funding support
v. Partnership and collaboration	• Communicate with managers in neighboring areas about the species they manage and monitor for. • Communicate with neighboring jurisdictions to coordinate species watch lists and regulations. • Share successes and failures with colleagues and neighbors.	• Coordinate trade regulation across borders. • Create and participate in regional/subregional hubs for resource-sharing and targeted action, such as RISCC networks (riscnetwork.org) and PRISMs (https://nyis.info/prisms/).
2. Preventative action	• Understand and act to reduce co-occurring stressors. ◦ Control non-native and/or impactful herbivore populations, or fence vulnerable sites from herbivores/predators. ◦ Address hydrology issues by fixing drainage routes. ◦ Prepare and establish rapid response systems for extreme events (including wildfire, storms, and landslides). • Boost native resilience via techniques such as: ◦ Native plantings. ◦ Forestry techniques. ◦ Soil amendments/inoculum. ◦ Hydrology manipulation. • Engage in EDRR, especially of species predicted to benefit and spread with climate change. ◦ Consult climate projections to inform species watch lists for EDRR monitoring and action. ◦ Stay abreast of national EDRR framework developments. ◦ Monitor and target potential sleeper populations, especially in sensitive areas.	• Proactively regulate the sale of predicted range-shifting invasive species and potential sleeper species. • Regulate and monitor pathways of spread such as cargo ships, trains, and trucking routes, especially between climate-matched or future climate-matched areas. • Coordinate with neighboring states/countries to share resources and information for risk assessment and regulation.
3. Treatment and control	• Monitor for changes in treatment efficacy and practice adaptive management. ◦ Document phenology and compare to previous years. ◦ Record conditions during treatment. ◦ Monitor for target outcomes. ◦ Monitor for nontarget outcomes. ◦ Consider combining and adjusting treatments. • Practice climate-smart restoration. ◦ Choose species predicted to perform well with climate change when planting. ◦ Consider assisting migration of species or genotypes.	• Recommend metrics and methods to assess and evaluate treatments. • Facilitate data sharing between organizations. • Fund novel methods and climate-smart restoration approaches.
4. Education and outreach	• Include climate change in invasive species outreach and education efforts. • Collaborate with renewable energy projects and the horticulture industry to mediate novel introduction pathways. • Utilize community science to track invasive phenology and spread in a changing climate.	• Require development projects to consult invasive species experts and consider the joint effects of climate change and invasive species. • Support community science platforms.

BOX 2 | Invasive-Smart Climate Mitigation.

Efforts to reduce greenhouse gas emissions can contribute to the spread and establishment of invasive species, but “invasive-smart climate mitigation” can consider and aim to reduce these effects. For example, retaining existing tree invasions has been proposed and even incentivized as supporting an easy carbon sink despite numerous caveats (Nuñez et al. 2021). Renewable energy projects can inadvertently transport invasive propagules on equipment and materials, and create disturbances that favor invasive species (Gasparatos et al. 2017; Harrison-Atlas, Lopez, and Lantz 2022; Karban et al. 2024). Such projects can take steps to prevent and reduce the spread of invasive species by cleaning equipment, restoring native species in newly disturbed areas, and acting upon recommendations provided by invasive species experts.

Policy can facilitate invasive-smart climate mitigation by requiring renewable energy development proposals to address and act upon suggestions provided by invasive species experts in a formal review process. Biofuel projects already rely upon buffer zones, early harvest times, and risk assessments to minimize the introduction and spread of potentially invasive biofuel species (West, Matlaga, and Davis 2014; Pittman et al. 2015), and the U.S. Environmental Protection Agency maintains that current biofuel stocks are not at risk of becoming invasive (US EPA 2018). However, cultivated and proposed biofuel feedstock plants worldwide still include species with invasive tendencies and candidates for northward spread with climate change such as *Arundo donax* (Mack 2008), *Eichhornia crassipes* (Ezzariai et al. 2021), and *Miscanthus* spp. (Schnitzler and Essl 2015). The use of invasive species biomass for biofuels (Van Meerbeek et al. 2015; Bansal et al. 2019) may incentivize intentional cultivation of invasive species (Nuñez et al. 2012), increasing potential for escape and spread.

trade and transport (Figure 1B; Table 1). For example, melting sea ice is increasing the use of direct shipping routes between East Asia and the northeastern United States (Seebens et al. 2015; Nong et al. 2019), increasing connectivity, and thus, the risk of novel or repeated introductions. Although the implementation of international ballast water policy (International Maritime Organization 2004) and biofouling guidance (International Maritime Organization 2023) stand to greatly reduce unintentional introductions of aquatic invasive species via ballast water and ship hulls, invasive species can still travel intercontinentally aboard ships as goods or passengers (e.g., Tatem 2009). Wooden shipping materials can harbor non-native insects and pathogens (Lovett et al. 2016), trade goods can host invasive species, and live trade can directly spread invasive species (Liebhold et al. 2012; Pagnucco et al. 2015; Lockwood et al. 2019). Climate change is also affecting climate similarity, or climate matching, between trade partner regions, creating additional pressure on an already insufficiently regulated source of intentional and unintentional introductions (Lovett et al. 2016). For example, freshwater and terrestrial ecoregions of Europe and North America are predicted to become more similar with climate change and thus more vulnerable to invasions by species originating in either region (Hubbard,

Drake, and Mandrak 2024). Furthermore, the species in trade may shift as changing climatic conditions alter which ornamental species can survive and become in demand in a given location (Table 2). For example, with climate warming, the United States is expected to see an increased demand for warm-adapted ornamental species, which could also lead to increased introductions of novel and potentially invasive plants, pathogens, and insect pests (Bradley et al. 2012; Liebhold et al. 2012).

Preventing invasions from novel introduction pathways created by climate change will require proactive and coordinated regulation and monitoring of potential invasive species intentionally or unintentionally spread through intercontinental trade (Table 2). Proactively preventing invasions is much more cost-effective than reactively managing them after they have arrived (Keller, Lodge, and Finnoff 2007). Yet, global capacity for proactive policies to prevent novel introductions of invasive species lags behind reactive measures (Early et al. 2016), and the onus for regulation and preventative action falls more frequently on the point of arrival than the point of origin (Keller and Perrings 2011). At the point of origin, measures to prevent the export of species with the potential to be invasive elsewhere include phytosanitary standards; these might best be incentivized by importing partners (Lovett et al. 2016). The point of arrival can further prevent novel introductions through border patrol actions such as standards for the treatment of goods and materials (Haack et al. 2014), and EDRR (Lovett et al. 2016; Reaser et al. 2020). Such standards could also become more proactive by requiring that import industries evaluate new species for invasion risk before they are introduced; for example, Australia's federal government bans the import of all plant species until they have undergone formal assessment and approval rather than retroactively assessing and banning species long after they have become problematic (Black and Bartlett 2020). Understanding where future climate conditions will match the native ranges of potential invasive species can inform priority species for border control, monitoring, and EDRR (Gallardo and Aldridge 2013).

Cross-border partnerships will also play an important role in the climate-smart management of novel pathways of introduction. For example, climate similarity has increased between the Great Lakes and the native ranges of potentially invasive fish in trade (Campbell, Hubbard, and Mandrak 2022), but coordinated policies and enforcement between the United States and Canada could minimize the risk of invasions in the Great Lakes-St. Lawrence region through intercontinental trade (Pagnucco et al. 2015). Nations, states, and provinces could also collaborate on assessment and listing of potential climate-impacted invasive species in intercontinental trade to reduce redundant work and boost capacity of lower resourced areas (Early et al. 2016). Ultimately, climate-smart invasive species management will include addressing novel and climate-impacted pathways of introduction and spread.

1.3 | Shifting Seasons and Phenologies Disrupt Invasive Species Management Timelines

Climate change affects the timing of invasive species growth and reproduction, as well as seasonal weather conditions, posing challenges to management timelines and planning

(Figure 1C; Table 1). When native and non-native species differ in their phenological responsiveness to climate change, non-native species tend to be better able to shift their phenology (Zettlemoyer et al. 2022). Any change in the phenology of invasive species, whether different relative to native species or not, can affect timelines for monitoring and treatment which often depend upon leaf emergence for identification or developmental stage of both target and nontarget organisms for adequate uptake of chemical treatments (Torres et al. 2023; Buonaiuto et al. 2024). Management timelines are also challenged by increased extreme events. More frequent extreme heat events, projected to increase globally, with the most frequent occurrences in North Africa, East Asia, and North America (Suarez-Gutierrez et al. 2020), can slow down fieldwork by requiring more frequent water and rest breaks and reducing worker efficiency (Varghese et al. 2018; Birthisel, Clements, and Gallandt 2021). Extreme heat can also put outdoor workers, including invasive species professionals, technicians, and volunteers, at risk unless schedules and workloads adjust (Licker, Dahl, and Abatzoglou 2022). Other climate extremes such as extreme storm events and associated flooding and treefall hazards can limit access to field sites for monitoring and treatment, further disrupting field schedules (E. Colberg, unpublished data).

Shifting phenologies and seasonal weather conditions can shorten and reduce the predictability of time frames for invasive species treatment and control, requiring flexible and adaptive management. For example, invasive musk thistle (*Carduus nutans*) in North America grows faster and flowers earlier under warmer temperatures (Keller and Shea 2022), both advancing and potentially narrowing the optimum treatment window. Climate change is also shortening and shifting the time frames for management actions such as prescribed burning, as higher warm-season temperatures reduce the number of suitable burning days and may require a shift to more cool-season burns (Kupfer et al. 2020; Swain et al. 2023). Such changes in phenology can make it difficult to meet timelines of funding and staff availability if funding sources and organizational budget processes have deadlines that limit the ability to adjust. The ability to adapt to shifting seasonal windows is particularly limited for managers who rely upon volunteer workforces scheduled in advance, contractors juggling assignments in multiple jurisdictions, and seasonal staff for whom budgets might not allow longer appointments (Monahan et al. 2016; Sidoti et al. 2023). Nonetheless, managers can work within constraints to the best of their abilities to advance hiring and training dates and create backup plans for sudden shifts in timelines (Table 2). Volunteer forces, school collaborations, and contractors may also help bridge the gap between seasonal staff availability and altered treatment windows (Lehtiniemi, Outinen, and Puntila-Dodd 2020; Skukan et al. 2020; Encarnação, Teodósio, and Morais 2021), but are limited by whether staff can devote time and have the skills to organize and coordinate such partnerships. Organizational and funding source policies can assist by allowing for more flexible timelines in treatment, funding, and hiring, as well as by making it easier to hire temporary staff by considering contractor or other services, producing guidelines to enable effective management of temporary workers, and providing avenues to connect managers in need with appropriate staff resources.

Climate-smart management schedules proactively account for shifts in invasive species phenology by contributing to and incorporating more real-time information on local phenological changes into planning timelines. For example, managers at Midway Atoll National Wildlife Refuge used phenological data collection protocols from the USA National Phenology Network to track the phenology of the invasive plant *Verbesina encelioides* (golden crownbeard) and adjust their management schedules accordingly (Taylor et al. 2020). In other cases, researchers can create tools to facilitate decision-making in specific situations, such as the Avian Malaria Watch online tool (<http://avianmalaria.watch/>) which integrates past, current, and predicted future temperatures to provide managers in Hawai'i with current and forecast information on suitability for avian malaria transmission and mosquito vector development (Fortini, Kaiser, and LaPointe 2020). For managers whose regions fall outside the areas covered by large phenological datasets, incorporating phenological data collection into staff, volunteer, or community outreach programming could still help with planning and forecasting treatment schedules. In-house data collection may provide more relevant information than broader datasets, but comes at the cost of additional staff time to collect and analyze such data.

As climate change affects seasonal patterns of professional and recreational access to natural areas, schedules of outreach and cleaning stations will also need to shift. For example, United States boat inspection and washing stations are commonly open from the last Monday in May through the first Monday of September (Bering et al. 2013). However, warmer springs and autumns may extend recreational boating and aquatic invasive species' activity past those dates (Xia, Yan, and Wu 2013; Yue et al. 2015), and inspection protocols will need to adjust accordingly. Climate-smart invasive species management will include increasing flexibility in response to and anticipation of climate change's effects on invasive species' phenology and seasonal timing.

1.4 | Reduced Treatment Efficacy and Feasibility Reduce the Likelihood of Achieving Desired Results

Climate change is reducing the efficacy of chemical, physical, and biological invasive species control methods, highlighting the need for adaptive management and novel approaches (Figure 1D; Table 1). For example, the efficacy and reliability of herbicides and pesticides can decrease with higher CO₂ concentrations and temperatures (Matzrafi et al. 2016; Ziska 2016; Waryszak et al. 2018; Matzrafi 2019). Furthermore, increased temperatures and extreme events can increase chemical drift, volatility, and leaching, and reduce absorption and retention times (Ziska 2016), requiring increased consideration of off-target effects. Nonchemical methods of invasive species control, which can complement chemical treatments or serve as the dominant treatment, especially in lower Human Development Index countries (Weidlich et al. 2020), are also impacted by climate change. Higher CO₂ concentrations may reduce the efficacy of physical plant control methods such as tillage, flaming, mowing, and grazing (Birthisel, Clements, and Gallandt 2021). Invasive plant species may recover more quickly from mowing and grazing with higher CO₂, warmer

temperatures, increased precipitation (Ziska and Dukes 2010), and even drought (Zhai, Duell, and Zhang 2024). Additionally, biocontrol efficacy could be reduced due to phenological mismatches caused by climate change as well as climate-linked stressors on biocontrol agents (Asaro and Chamberlin 2015; Sun et al. 2020) (Table 1).

Climate change also affects the feasibility of management practice. For example, as climate change limits how often the ground freezes in colder climates (Daniel et al. 2018), the feasibility of mechanical treatments involving heavy equipment such as selective logging or wetland mowing will also decrease (Shoop 1995; Michigan Department of Environmental Quality 2014). Globally, the efficacy, feasibility, and impacts of prescribed burning may also vary with climate change and drought conditions (e.g., Bois et al. 2023) as fires in the spring and autumn become more likely to blaze out of control (Balch et al. 2017).

The efficacy and outcomes of invasive species management actions are already understudied (Gann et al. 2019), making management decisions difficult even before considering climate change. Explicit guidance for one method over another often depends upon species and context, but adaptive management can help managers make informed decisions within their own contexts (Table 2). Indeed, managers widely view adaptive management as an effective strategy to adjust to novel information and changing conditions (Dreiss et al. 2017), but implementing adaptive management is difficult when resources are devoted to management action rather than monitoring and assessment. Organizations and funding agencies can address this challenge by supporting data collection and analysis on treatment outcomes, and can further help managers recognize and adapt to climate-induced changes in treatment efficacy by allocating and allowing resources to be used for more frequent treatments, combined treatments, and alternative actions such as boosting native resilience in lieu of directly targeting invasive species (Table 2). For example, multiple rounds of mowing or grazing might counteract increased plant growth associated with higher CO₂ concentrations (Ziska and Dukes 2010; Keller and Shea 2022). However, when adjusting frequency and intensity, managers will have to balance potential gains with increased costs.

Combining control methods may improve management efficacy in a changing climate; for example, in North America, higher intensity and later mowing treatment more effectively controlled musk thistle when combined (Zhang and Shea 2012). However, combining approaches may also increase cost and effort, and some control methods can interact to reduce efficacy. For example, herbicide application or mowing before nodding thistle (*Carduus thoermeri*) senescence negatively affected its biocontrol agent, the weevil *Rhinocyllus conicus* (Tipping 1991). Allotting more resources to and structurally encouraging (through training and partnerships) adaptive management can help managers determine how climate change is affecting treatment and control in their own contexts, and also provide them with the means needed to adjust.

For invasive plants, increased temperatures might improve the efficacy of some management approaches. For example, in agricultural systems, warmer temperatures reduce weed

seed recruitment after mulching or soil solarization (Birthisel, Clements, and Gallandt 2021). Similar approaches are also used to reduce invasive plant recruitment in recently disturbed and active restoration areas (Orr, Reuter, and Murphy 2019; Scheper, Verweij, and van Kuijk 2021), and could be particularly effective for small populations at the leading edges of invasive ranges. By adjusting and adapting invasive species control and broader restoration approaches in light of potential and observed impacts of climate change, invasive species management can become more climate-smart.

1.5 | Increased Vulnerability of Native Ecosystems Requires Reevaluating and Adjusting Restoration Targets

Native species face climate-driven range shifts (Pecl et al. 2017) and potential increased vulnerability to climate change and invasive species (Rolls, Hayden, and Kahilainen 2017; Weinhäupl and Devenish-Nelson 2024), requiring managers to reevaluate the aims and methods of restoration and invasive species management (Figure 1E; Table 1). Native species and habitats can face disadvantages in a changing climate compared to invasive species (da Silva et al. 2021; Farr et al. 2021), for which performance and competitiveness are expected to benefit from increasing temperatures and CO₂ on land and in water (Sorte et al. 2013; Liu et al. 2017). For example, greater competitive ability of invasive macroalgae over native species in Hawai'i has been linked to the combined impacts of climate change and land-use change on submarine groundwater discharge, but these impacts could be minimized through forest restoration and improved wastewater management (Dulai et al. 2023). Invasive species with earlier phenology may also have competitive advantage over native species that are less able to respond to climate cues (e.g., Willis et al. 2010; Wolkovich and Cleland 2014). Climate change and invasive species can also interact to increase the vulnerability of native species, such as invasive mammal species and climate impacts jointly reducing seabird populations and thereby also decreasing coral reef health (Graham et al. 2018; Perez-Correa et al. 2020). Decreased viability of native species due to increased invasive competitiveness and climate stress could increase the costs and lower the feasibility of invasive species management and broader restoration success.

Managers will need to understand how climate change and invasions affect the vulnerability and viability of native species and ecosystems in their own jurisdictions, and then decide whether to resist, accept, or direct potential and inevitable compositional shifts (Schuurman et al. 2022). Targeted research and mapping products such as climate change vulnerability assessments can help managers determine a priori which areas will be most susceptible to the impacts of climate change and associated disturbances (Kirwan et al. 2016; Triepke, Muldavin, and Wahlberg 2019), and which areas might serve as climate change refugia (Morelli et al. 2016). Such refugia can then become conservation priorities for invasive species management. For example, eradicating invasive mammals in island ecosystems can conserve climate change refugia for native species under rising sea levels, yet funding for climate change adaptation on islands rarely supports invasive mammal eradications (Kappes et al. 2021). Invasive species can be

incorporated into climate change vulnerability assessments for a fuller understanding of all vulnerabilities (Balzotti, Kitchen, and McCarthy 2016), especially as invasive species can exacerbate or increase climate-linked stressors such as wildfire likelihood and impacts (Aslan and Dickson 2020) or decrease microclimate and snowmelt regulation from shading (Lustenhouwer, Nicoll, and Ellison 2012). Predictions of which habitats and areas will be most vulnerable to climate change and invasions can help managers reevaluate which sites and species to prioritize during monitoring, restoration, and preventative action, thereby allowing managers to maximize limited resources (Table 2).

In terrestrial ecosystems, climate-smart planting for habitat restoration shows promise as a tool for increasing native community resilience (Table 2) because native diversity is positively associated with resistance to invasions (Levine, Adler, and Yelenik 2004; Beaury et al. 2020b). Transplants started early in controlled environments such as a greenhouse or nursery may also help boost native competitive ability against invasive species (Wolkovich and Cleland 2014), especially if choosing fast-growing native species and manipulating density and spatial arrangement of plantings (Birthisel, Clements, and Gallandt 2021). However, transplant shock may increase during increased temperatures and dry periods, potentially requiring reconsidering planting schedules or using additional techniques to shade transplants or otherwise counteract water stress (Pausas et al. 2004; Logan et al. 2022). Restoration plantings can practice risk mitigation and bet hedging to reduce the chances of extreme events and climate stress preventing establishment by using a portfolio of different techniques, spreading planting efforts across multiple years, and enacting adaptive management (Svejcar, Davies, and Ritchie 2023).

As climate change alters habitat conditions, local seed sourcing may no longer be the best policy (Havens et al. 2015). Understanding the interactions and conditions predicted with climate change can enable a choice of invasion-resistant and climate-smart native plants when selecting species for restoration planting projects (Guo et al. 2018) and may help managers decide when to pursue active restoration after invasive species removal (Mostert et al. 2018). Managers can consider whether species are likely to withstand climate change when selecting native species for restoration plantings; interactive web tools can facilitate this process (St. Clair et al. 2022), although they are currently taxonomically and geographically limited. Even when desired species and provenances are decided upon, obtaining the necessary stock will still be difficult until the supply chain increases the diversity of its offerings and provides more readily accessible and clear information on provenance (Vitt et al. 2022; Clark et al. 2023). When possible, however, combining local and warm-adapted nonlocal native seeds can increase the climate resilience of planting projects (Dumroese et al. 2015; Havens et al. 2015). Assisting the migration of warm-adapted native species and genotypes to colder latitudes and altitudes could help ensure communities are able to thrive and function in the face of climate change and invasions (Dumroese et al. 2015; McKone and Hernandez 2021). Although the chances of intracontinental assisted migration and managed relocation creating novel invasions are small (Simberloff et al. 2012; Bellemare, Connolly, and Sax 2017), invasion potential should still be considered

when moving species beyond their current ranges (Mueller and Hellmann 2008; Wallingford et al. 2020). Nonetheless, the use of climate-smart seed and plant stock for ecological restoration requires further research and collaboration between researchers, practitioners, and seed sourcing entities (Vitt et al. 2022).

Although invasive species removal may be the most critical aspect of biodiversity conservation in some cases (Bissessur et al. 2023), other aspects of ecological restoration such as management actions that target native species or habitats rather than invasive populations and organisms can be a complementary and even necessary component of climate-smart invasive species management (Hess, Mesléard, and Buisson 2019; Prober et al. 2019; Robertson et al. 2020). Managers may be able to boost native community resilience to climate change and resistance to invasions by removing or reducing other environmental stressors such as intense herbivory or disturbance, but information on how to do so in different contexts is still a limitation (Brewington et al. 2021). In some cases, restoring fire to the landscape can benefit native species (Twidwell et al. 2012), although in other cases, historical fire regimes may no longer be relevant or desirable in light of invasive species and climate change (Keeley 2006; Emery, Uwimbabazi, and Flory 2011). Altering biophysical characteristics by adding mulch or biochar can also help promote native resilience to climate extremes and invasions (Prober et al. 2014). In freshwater systems, native species may benefit from site manipulations that support water flow and reduce overheating (Sorte et al. 2013), or that alter available habitat (Roche et al. 2021). In marine systems, manipulating substrate may have similar effects; for example, reducing available substrate by removing buoys or altering kelp bed composition could indirectly control an invasive bryozoan even with increasing temperatures (Denley, Metaxas, and Fennel 2019). Protecting and improving the effectiveness of existing protected areas is also an important aspect of proactive invasive species management; for example, marine and terrestrial-protected areas in Europe are predicted to have lower richness of invasive species than outside these areas, hinting at the importance of protected areas for both resistance to invasion and resilience under future climate conditions (Gallardo et al. 2017). Restoration that considers resilience to climate change and resistance to invasive species and their impacts can thus also contribute to climate-smart invasive species management.

1.6 | Compounding Effects of Extreme Climate Events and Invasive Species Require Integrating Invasive Management Into Extreme Event Preparedness

Invasive species management is a necessary part of preparation for and response to extreme weather and climate events due to the impacts of these events on invasive species and vice versa (Figure 1F; Table 1). For example, extreme climate events can increase the introduction, establishment, and spread of non-native and invasive species by transporting propagules to new areas and by decreasing biotic resistance and native competitiveness (Diez et al. 2012; Jauni, Gripenberg, and Ramula 2015). Flooding can disperse propagules, resulting in new and increased invasions after extreme precipitation and storm events (Death, Fuller, and Macklin 2015; Collieran, Lacy, and Retamal 2020;

Gui et al. 2023). Severe storms and hurricanes can also create canopy openings and increase understory density, with repercussions for native plant and animal communities (Brown, Sherry, and Harris 2011; Abella 2018). Increased disturbances from extreme storm and flood events, and associated increases in light and nutrient availability, can lend a competitive advantage to invasive over native species (Daehler 2003; Driscoll 2016), and disturbance atop environmental stress can shift the advantage to invasive species (Orbán et al. 2021). At the same time, invasive species can increase the impacts and even likelihood of extreme climate events, as in the case of invasive grass species increasing the frequency and intensity of wildfires in multiple continents (Gaertner et al. 2014; Fusco et al. 2022). Invasive species can also reduce the provision of ecosystem services that aid with climate adaptation through extreme events, such as wave attenuation (Coleman et al. 2023). Without proper precautions, management responses to extreme events can also facilitate the secondary spread of invasive species, such as soil movement and unclean equipment transfer to repair roads and other infrastructure (Thomson et al. 2021). Indeed, attempts to mitigate the effects of climate change and extreme climate events may further exacerbate invasive species spread and impacts without “invasive-smart climate mitigation” practices (Box 2).

To reduce the impacts of extreme climate events when they occur, including the potential for new and increased invasions, managers can set aside resources and create emergency response plans ahead of time to facilitate post-event monitoring and control actions (Table 2). Such plans can address early detection and rapid response as well as proactive planting to reduce (re)invasion. For example, rapid response in the form of manual removal of flood-dispersed knotweeds (*Reynoutria japonica* and related species) the first 2 years after a flood was sufficient to prevent establishment (Colleran and Goodall 2015). Alternatively, native cover crops can limit the establishment and dominance of invasive species and facilitate native establishment in newly disturbed areas with high invasive propagule pressure, such as *Bidens cernua* cover reducing invasive cattails (*Typha* spp.) during urban wetland restoration (Doherty and Zedler 2014). Native plant restoration in fertile, disturbed sites with low risk of further disturbance can favor native establishment while limiting invasion, but restoration in high stress environments could instead facilitate invasion if the microclimate conditions created by native plants subsequently benefit invasive species (Hess, Mesléard, and Buisson 2019). When native restoration is a suitable post-event action, managers will still need to know where to source appropriate quantities of native seed, seedlings, or saplings. Efforts such as the Native Seed Network (<https://appliedeco.org/nativeseednetwork/>) are striving to better connect native seed supply with restoration practitioner demand, but may require extra consideration of surges in demand due to emergency response efforts.

Flexibility is also an important component of extreme event preparedness, but increasing flexibility may not be feasible or attainable for all managers due to external barriers such as funding and regulatory timelines and restrictions (Walsh et al. 2019). Including invasive species management and ecological restoration in disaster response funds and creating expedited permit approval processes for post-disturbance preventative treatments could facilitate flexibility and enable managers

to be more proactive and responsive to the interactions of climate change and invasive species (Brewington, Rodgers, and Greenwood 2024). Governmental and municipal disaster relief efforts could also collaborate with or even create positions for invasive species experts to ensure climate-smart invasive species management is integrated into their emergency responses by including early detection, rapid response, and restoration into extreme event response plans. Supporting the inclusion of invasive species management in extreme event preparedness can thus be considered another example of climate-smart invasive species management.

2 | Conclusion

The interactions of climate change and invasive species are creating novel and additional challenges for natural resource managers. These challenges include new potential invasive species and pathways of introduction to assess, monitor, and control; increased difficulty of conducting fieldwork and obtaining desired effects with status quo control measures; and increased vulnerability of target species, ecosystems, and management goals. Climate-smart invasive species management considers and aims to reduce these interactive effects of climate change and invasions. Invasive species managers are already facing the effects of climate change on their management, but many aspects of management could better account for the interactions of climate change and invasive species. Climate adaptation planning could address the importance of invasive species management by explicitly allocating resources for invasive species management and helping invasive species managers access such resources. Considering the effects of invasive species on climate adaptation efforts could also help invasive species managers incorporate longer term thinking, as climate change adaptation often operates at longer timescales compared to invasive species management. More climate-smart invasive species management may require rethinking standard approaches to facilitate flexibility and increase effectiveness in responding to the logistical and ecological challenges posed by climate change.

Author Contributions

Eva M. Colberg: conceptualization, investigation, methodology, project administration, visualization, writing – original draft, writing – review and editing. **Toni Lyn Morelli:** conceptualization, funding acquisition, writing – review and editing. **Bethany A. Bradley:** conceptualization, funding acquisition, writing – review and editing. **Carrie J. Brown-Lima:** conceptualization, funding acquisition, writing – review and editing.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The authors have nothing to report.

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