Invasive Species Policy Must Embrace a Changing Climate

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With increasing impacts of climate change observed across ecosystems, there is an urgent need to consider climate change in all future environmental policy. But existing policy and management might be slow to respond to this challenge, leading to missed opportunities to incorporate climate change into practice. Furthermore, invasive species threats continue to rise and interact with climate change—exacerbating negative impacts. Enabling natural resource managers and individuals to be proactive about climate-driven invasive species threats creates a win–win for conservation. Recommendations include expanding opportunities for information sharing across borders, supporting proactive screening and regulation of high-risk species on the horizon, and incentivizing individual actions that reduce ecological impacts. In addition, invasive species risk should be considered when crafting climate mitigation and adaptation policy to reduce compounding stressors on ecosystems. As we develop much-needed tools to reduce harm, policy and management must consider the combined threats of invasions and climate change.

Keywords: adaptation, climate change, invasive species, policy, regulation

Globally, temperatures have already risen by 1 degrees Celsius, straining a natural resource management landscape that is already at capacity. As the Intergovernmental Panel on Climate Change reports made clear, the time to act on climate change is now (IPCC 2022). This urgency demands that we support new policies that incorporate climate change as well as build climate considerations into current practice. One area that must become more "climate smart" is invasive species policy and management. Opportunities to incorporate climate change into invasive species policy exist across jurisdictions, including at federal, state, and local levels. By failing to incorporate climate change into invasive species policy, we miss an opportunity to be proactive about future threats.

Interactions between climate change and invasive species are numerous and well documented (Dukes and Mooney 1999, Hellmann et al. 2008, Walther et al. 2009). They include shifting ranges of invasive species (Allen and Bradley 2016), altered efficacy of invasive species treatment (Ziska et al. 2004, Waryszak et al. 2018), new direct pathways of species introduction (Hellmann et al. 2008), and increased "weediness" or other negative impacts of previously benign species populations (tables 1a and 1b; Spear et al. 2021). At the same time, invasive species inhibit effective climate change adaptation by increasing ecosystem stress (Vilà et al. 2011, Gallardo et al. 2016), worsening declines in native species biodiversity and survival (Bradley et al. 2019, Lopez et al. 2022), and reducing carbon sequestration (tables 1a and 1b; Lovett et al. 2016, Quirion et al. 2021).

Natural resource managers are particularly concerned about interactions between climate change and invasions. Invasive species are a top concern for managers focused on climate change adaptation (Ernest Johnson 2018, Peters et al. 2018, 2020), whereas climate change is a top concern for managers focused on invasive species (Beaury et al. 2020). Federal and state invasive species policies enable and support invasive species management from local to national levels. In many cases, climate-smart invasive species management can be accomplished within the framework of existing invasive species policy, whereas other changes will require new policy initiatives. Given the many ways that climate change will affect invasions, there is a clear need for environmental policy and management that considers both of these global changes.

Crafting climate-smart invasive species policy

The most effective and resource-efficient way to avoid the negative impacts of invasive species is to prevent them from being introduced in the first place (Keller et al. 2007). However, invasive species policy and management primarily focuses on invasives that are already widespread (Beaury et al. 2021a). With many new invaders likely to emerge with climate change, expanding our capacity to proactively identify and prevent climate-driven invasions creates an opportunity for a rare win for invasive species management.

Sharing information across climate gradients. Invasions span political boundaries, but invasive species management is

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Table 1a. Interactions between invasive species and climate change that compound harm to ecosystems in which climate change exacerbates invasions or invasive species impacts.

Interaction	Definition	Examples	Potential solution	References
Range-shifting species	Species track changing climate conditions and move to new areas where they have negative impacts	*Aedes* mosquitoes,kudzu (*Pueraria montana*) vine, hemlock wooly adelgid	• Proactive policies that address likely future invasive species • Collaboration across borders to identify likely rangeshifters	Mosquitoes: Rochlin and colleagues (2013); kudzu: Coiner and colleagues (2018); HWA: Lombardo and Elkinton (2017)
Changes in phenology	Some nonnative species will be able to shift the timing of seasonal events to track a changing climate in ways that increase their ecological impacts	Scale insect pests; Eurasian watermilfoil.	• Monitoring to identify newly impactful species • Proactive management earlier in the season	Scale insects: Frank and Just (2020); Eurasian watermilfoil: Patrick and colleagues (2012); meta-analysis: Stuble and colleagues (2021)
Sleeper species or populations	Established species may become invasive if climate change removes abiotic constraints	Acorn barnacle (*Austrominius modestus*)	• Evaluate established nonnative species to identify taxa known to be invasive elsewhere	Witte and colleagues (2010), Spear and colleagues (2021)
Decreased management efficacy	Climate change decreases the efficacy of management strategies to reduce invasive species impacts	Decreased herbicide effectiveness on Canada thistle (*Cirsium arvense*)	• More research and data sharing on management options • Flexibility for adaptive management	Ziska and colleagues (2004), Waryszak and colleagues (2018)
New sources of invaders	New introduction pathways are opening up	Melting sea ice may allow species to colonize new areas through newly formed shipping routes.	• Horizon scanning and proactive regulation • Increased screening capacity focusing on repeat offenders	Pyke and colleagues (2008), Roy and colleagues (2014), McKeon and colleagues (2016)

Table 1b. Interactions between invasive species and climate change that compound harm to ecosystems in which invasions exacerbate climate change or climate change impacts.

Interaction	Definition	Examples	Potential solution	References
Changing disturbance regimes	Invasive species increase fire frequency	Invasive grasses lead to more frequent fires, which increase emissions and reduce carbon storage.	• Including invasive species management in fire management	Balch and colleagues (2013), Fusco and colleagues (2019), Nagy and colleagues (2021)
Decreased resistance or resilience	Invasive species and climate change interact to reduce native species' survival and diversity	Weakened trees from pests or pathogens can be more susceptible to disturbance events (e.g., windthrow)	• Horizon scanning for forest pests and pathogens	Papaik and colleagues (2005), Lopez and colleagues (2022)
Decreased carbon storage	Invasive species directly or indirectly lead to reduced biomass carbon storage	Cheatgrass increases fire frequency and carbon loss; Forest pests cause tree die-off	• Horizon scanning for forest pests and pathogens • Increased screening capacity	Nagy and colleagues (2021), Quirion and colleagues (2021)
Decreased ecosystem services	Invasive plants can reduce floodplain effectiveness for mitigating flood events	Invasive shrub *Amorpha fruticosa* increases flooding	• Floodplain restoration where climate change is expected to increase flood events	Kiss and colleagues (2019)

strongly influenced by the policies of the country, state, or province. A management focus within political boundaries tends to lead to few connections and conversations across political borders. If we want to be proactive about identifying and preventing the invasives that are coming next, it is essential that we learn from colleagues working in different political jurisdictions in warmer regions. For example, a survey of priority species for invasive species managers in the eastern United States (Beaury et al. 2020) showed that managers across the region are dealing with similar species (figure 1a) and would likely benefit from information sharing. In the context of climate change, species that are actively managed to the south are emerging in the north, as has been illustrated for stiltgrass (*Microstegium vimineum*; figure 1b).

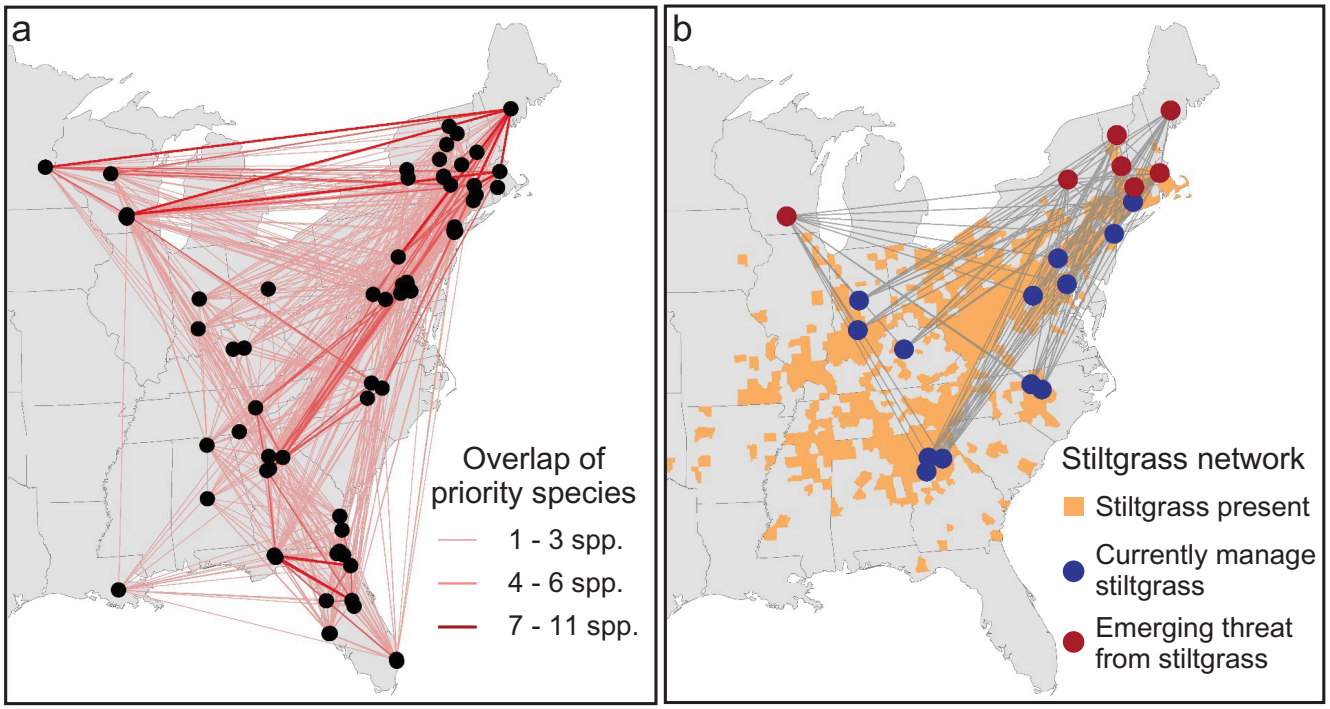

Figure 1. Invasive species managers across the eastern United States are managing similar high priority species across a range of climate conditions. Source: The data are from Beaury and colleagues (2020). (a) For 83 survey respondents who reported priority invasive species that they are currently managing, line thickness indicates amount of overlap. (b) For the range-shifting invasive plant stiltgrass (*Microstegium vimineum*), there are clear opportunities for information sharing across a gradient of stage of invasion. The points in the south represent managers who identified stiltgrass as a current management concern and points in the north represent managers who identified stiltgrass as an emerging concern with climate change.

Sharing information about best management practices across climatic gradients will be critical for addressing range-shifting invaders early—when treatment is most feasible and cost-effective (Westbrooks 2004). Unfortunately, there are few mechanisms for sharing information across political borders (Reaser et al. 2020), which results in redundant and inefficient risk assessment (Buerger et al. 2016, Bradley et al. 2022) or, in the worst case, no risk assessment at all (Early et al. 2016). In the United States, this lack of coordination highlights a strong need for federal leadership to build accessible repositories for data sharing and tools to support decision-making by practitioners.

First, federal agencies could conduct or fund assessments of future invasion risk that can be shared across jurisdictions. For example, the range shift listing tool (www.eddmaps.org/rangeshiftlisting) allows users to identify invasive plants in the United States that could expand into their state by mid-century on the basis of species distribution models (Allen and Bradley 2016). However, this type of information is lacking for most other invasive taxa and needs support for regular updates as new species emerge and new distribution data are collected. Expanding existing invasive species modeling platforms, such as the US Geological Survey's INHABIT tool (Engelstad et al. 2022) to incorporate climate change projections would support proactive management. Second, federal agencies could support and expand repositories for sharing data and expertise so that managers can easily access information about new and emerging species (Reaser et al. 2020). For example, because of limited state resources, completed invasive species risk assessments are rarely available on public websites. The lack of access to this information makes it more challenging to proactively identify emerging, high-risk species. Expanding online databases of invasive species risk assessments, such as New York state's Invasive Species Information database (http://nyis.info/non-native-animal-assessments, http://nyis.info/non-native-plant-assessments), the US Department of Agriculture's Noxious Weeds Program, and the US Fish and Wildlife's Ecological Risk Screening Summaries would support science-driven best practices at all levels of invasive species management.

Federal support for data sharing and the creation of decision support tools is particularly important because of large discrepancies in state capacity to address invasive species. To follow the above example of risk assessment capacity, some states have support to both conduct and host risk assessments (including New York's Invasive Species Information database or the nongovernmental organization–supported PlantRight Plant Risk Evaluator tool in California). Other states have policies aimed at preventing the introduction of high-risk invasive species but have not created a

standard risk assessment process (including Idaho, Kansas, and Tennessee). Still other states have no policy to prohibit the sale and distribution of high-risk invasives (including Louisiana, New Jersey, and Rhode Island). This patchwork of state regulation leads to wasted resources and ineffective prevention and management. Coordination and support at the federal level could lead to more cohesive and proactive management strategies at state and local levels.

Horizon scanning and incentivizing pest-free trade. Preventing the unintentional introductions of invasive species requires a focus on introduction pathways. With new and more direct ports of entry emerging as sea ice melts and new pests establishing more readily as the climate warms (Hellmann et al. 2008), increased inspection, cleaning, and quarantine measures are needed (Lovett et al. 2016). At the national level, the volume of trade greatly exceeds inspection capacity (McCullough et al. 2006), but there are ways to optimize the inspection process while also minimizing costs (Chen et al. 2018). For example, inspections can be targeted on the basis of a risk-based approach, in which lots assigned a high level of risk (on the basis of their history of accidentally importing pests) are inspected more frequently. This shifts resources to focus on known bad actors and incentivizes compliance with pest management protocols to reduce the likelihood of inspection (Chen et al. 2018).

Pairing optimized inspection with an expanded list of high-risk species to look for, particularly those from warmer climates, would also make border inspection more effective and proactive. Border control agencies (such as the Animal and Plant Health Inspection Service in the United States) must have the capacity and authority to conduct horizon scans and identify pests that will soon threaten natural and agricultural resources because of climate change (Pyke et al. 2008). For example, analyses for Great Britain (Roy et al. 2014), the Netherlands (Matthews et al. 2014), Ireland (Lucy et al. 2020), and the state of Florida (Kendig et al. 2022) have all used panels of experts to evaluate risk from species not yet present in the region but known to be invasive elsewhere. Criteria such as the likelihood that the species will be introduced, the likelihood that it will establish in either current or future climate conditions, and the likelihood that it will have a negative impact can all be included to identify high-risk species. These species can then be added to watch lists for border inspection, increasing the likelihood that warm-adapted invasives are stopped before they are introduced. As with risk assessments for existing invasives, the results of horizon scans for novel species should be coordinated, supported, and shared at the federal level.

Making regulations more proactive. One of the only existing policy mechanisms for preventing the intentional introduction of invasive species is through regulatory lists that prohibit species introductions across international or state borders (e.g., as ornamental plants or exotic pets). These regulatory lists are typically informed by risk assessments that identify high-risk potentially invasive species. Unfortunately, few existing risk assessments explicitly consider how climate change could alter risk (Roy et al. 2018), and regulatory bodies rarely have the extra capacity needed to proactively evaluate range-shifting invasive species; most have yet to evaluate and regulate existing species (Bradley et al. 2022).

Preventing the intentional introductions of invasive species will require a renewed focus on consistent, climate-smart regulation to limit the sale of invasive ornamental plants, pets, and the pests or diseases they carry. US federal regulations use horizon scanning to prevent introductions across international borders, prioritizing prevention of agricultural pests and species injurious to wildlife. Federally regulated species include a number of species that are not yet present in the United States. For example, Beaury and colleagues (2021a) reported that 42% of federal noxious weeds are not present in the United States. Within the United States, state regulations aim to prevent the spread of existing invasive species that are intentionally introduced, primarily invasive plants and seeds, and regulations often include both agricultural "weeds" and invasives affecting natural resources. Optimal state regulations would also focus on preventing the introduction of high-risk species—especially new species emerging with climate change.

Unfortunately, state invasive plant regulations are highly inconsistent across state borders and tend to focus on species that are already widespread (Lakoba et al. 2020, Beaury et al. 2021a). Risk assessments used to inform regulation require a more proactive definition of invasion risk (Roy et al. 2018), including species likely to expand their ranges with climate change (e.g., Allen and Bradley 2016), as well as "sleeper" populations that could increase in population density with climate change (Spear et al. 2021). Fortunately, the language in existing risk assessments is often focused on the "potential" of species to establish and have impacts, which could be interpreted in the context of climate change without the need for a lengthy overhaul of state risk assessment and regulatory processes (Bradley et al. 2022). Even so, states are often hesitant to overwhelm regulatory lists with watch list species given uncertainty in the timeline of when they might arrive. Flexibility in risk assessment language and requirements to regularly update risk assessments are needed to keep existing regulations up to date and responsive to new threats from climate change.

Supporting climate-smart ecological restoration. Finally, ecological restoration is critical for effective, long-term invasive species management. Invasive species management typically focuses on invasive species treatment and removal rather than restoring ecosystem function (Zavaleta et al. 2001, Barney and Tekiela 2020). Native plant diversity can provide resistance to invasion (Levine et al. 2004, Beaury et al. 2019) and resilience to climate-driven disturbance (Millar et al. 2007) but building long-term resistance to invasion will require the use of climate-adapted native species. Expanding funding for invasive species restoration projects

and enabling practitioners to experiment with climate-smart species selection would provide critical information for best practices for adapting ecosystems to climate change. For example, the Seedlot Selection Tool can be used in the western United States, Canada, and Mexico by forest managers to match seed collections with a known provenance to restoration sites based on projected climates (https://seedlotselectiontool.org/sst). In the eastern United States, Tug Hill State Forest, in New York, planted native, warm-adapted trees in a forest restoration project—an example of the type of experimentation needed to reduce invasions and build climate-adapted ecosystems. Expanding the ranges of native species is much less likely to cause harm than the introduction and movement of nonnative species (Simberloff et al. 2012). Nonetheless, adding any novel species to intact native communities carries some risk (Wallingford et al. 2020). Therefore, combining invasive species treatment with climate-smart restoration is a win–win approach for building climate resilience—simultaneously creating the experiments we need to understand climate resilience while reducing the risk of harming intact ecological communities.

Climate policy must not exacerbate invasions

Climate change mitigation requires a broad suite of strategies, including some that have the potential to introduce or spread invasive species. Biofuels, cultivation of insects as a less carbon-intensive protein source, nonnative tree plantations, and afforestation (both managed and unmanaged) to enhance carbon sequestration could all create negative ecological impacts if invasion science is not considered. The cultivation of new biofuels often targets fast growing species that are tolerant of a broad range of growing conditions. Unfortunately, these traits are also associated with invasive species (Barney and DiTomaso 2008). The invasion risks from candidate biofuel species need to be carefully considered before planting occurs to avoid introducing high-risk species, such as *Arundo donax*, that go on to become invasive (Pyke et al. 2008). Similarly, insect protein as an alternative to livestock could create new invasions unless appropriate risk assessments and quarantines are implemented (Bang and Courchamp 2021). Calls to increase carbon storage by planting trees require a careful assessment of risk of tree invasion (figure 2). Invasive pines are an infamous example of a nonnative tree introduction that have negatively affected ecosystems in the southern hemisphere and in some cases led to water scarcity (Pyke et al. 2008, Nuñez et al. 2021).

People as part of the solution

The problems associated with invasive species and climate change stem from human actions at the individual, institutional, and societal levels. Just as incentives for both individual and industrial actions to reduce greenhouse gas emissions are critical for mitigating climate change, similar incentives that support ecological adaptation and reduce the spread of invasives could promote "climate-smart" decisions by individual landowners, natural resource managers, and the nursery plant and pet trade industries. Integrating invasive species and climate change policy will be most effective with public support and within a societal framework that provides a foundation for individual people and institutions to undertake this grand challenge. Solutions can be focused in two areas: expanding public awareness and incentivizing climate smart invasive species actions at the individual and institutional levels (figure 2) and connecting research, management, and policy across climate change and invasive species silos and geographic boundaries (figure 1).

Expanding public awareness and incentivizing climate-smart action. Creating a solution that involves the public will require increasing education about the problems caused by invasive species and climate change and providing people with incentives to act in ways that reduce harm. One way that individuals and institutions can reduce invasive species introduction and spread is through climate-smart gardening and landscaping that focuses on native plants (figure 2). Currently, the vast majority of plants available to gardeners and landscapers are nonnative (Harris et al. 2009, Bayón and Vilà 2019). Not only do nonnative landscaping plants provide few ecological benefits (Tallamy et al. 2021), they are also an estimated 40 times more likely than native plants to become invasive (Simberloff et al. 2012) and many are preadapted to warmer climates (Van der Veken et al. 2008). Widespread use of nonnative plants in landscaping increases invasion risk with climate change (Bradley et al. 2012, Fusco et al. 2018).

The ornamental plant trade already expands the ranges of plants poleward, giving predominantly nonnative species a strong advantage with climate warming (Van der Veken et al. 2008). Even well-known invasive plants remain widely available for sale as ornamentals (Beaury et al. 2021b), and the intersection of ornamental plant sales and shifting risk with climate change is likely to create future invasions. For example, *Nandina domestica* (sacred bamboo) is currently available for sale across the east coast of the United States despite being invasive in the southeast. Ongoing nursery sales in the northeast are establishing populations that are likely to become invasive with climate warming (figure 3). Expanding education on these topics to nursery and landscaping professionals could shift the industry toward less harmful practices that focus on native plants. At the local scale, University cooperative extension programs commonly engage with nursery plant growers and retailers. Rather than spending research effort supporting the sale of known invasive plants (e.g., reducing the fecundity of invasive *Berberis thunbergii* cultivars; Brand and Durocher 2022), extension programs could instead support the sale of native alternatives (e.g., UConn Extension's Native Plant and Sustainable Landscaping Guide; Wallace and Siegel-Miles 2021). Climate change could be incorporated through work that identifies range-shifting invasive plants to avoid while promoting native plants likely to survive in warmer conditions (e.g., Allen et al. 2022).

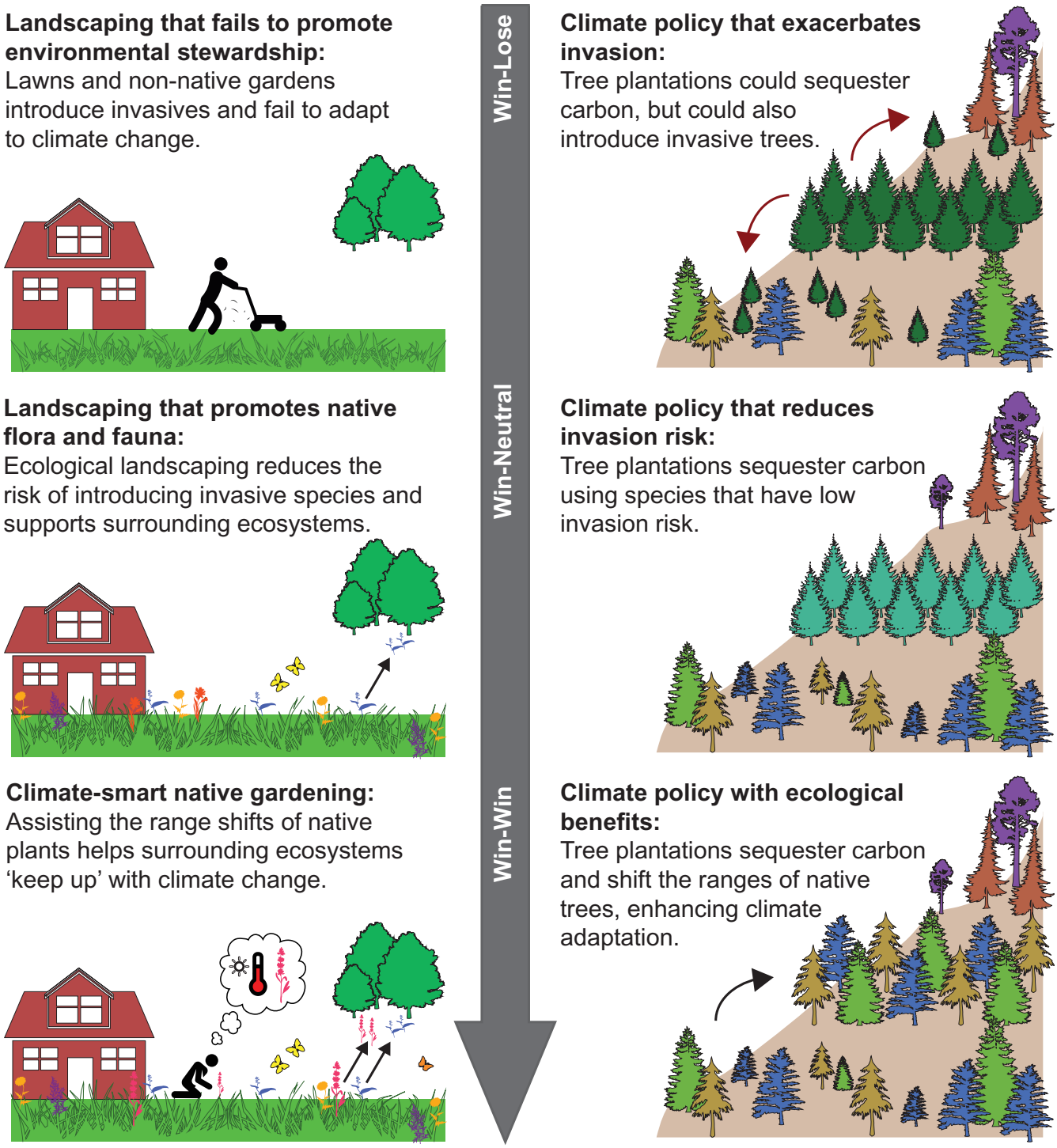

Figure 2. By integrating knowledge about invasion and climate adaptation science, we avoid addressing one problem at the expense of another and work toward win–win environmental solutions.

Another opportunity for the education of both nursery professionals and the public is through labeling of nursery stock. People cannot be part of the solution if they do not know which plants are potentially harmful. Currently, the requirements for plant labeling in the United States vary by state and are only applied to state-regulated species (which, as was discussed above, are ineffective at consistently regulating invasives; Beaury et al. 2021a). To create a single consistent set of invasive plants for labeling purposes, federal groups such as the National Invasive Species Council could instead look to known sources of globally invasive plants, such as the CABI invasive species compendium

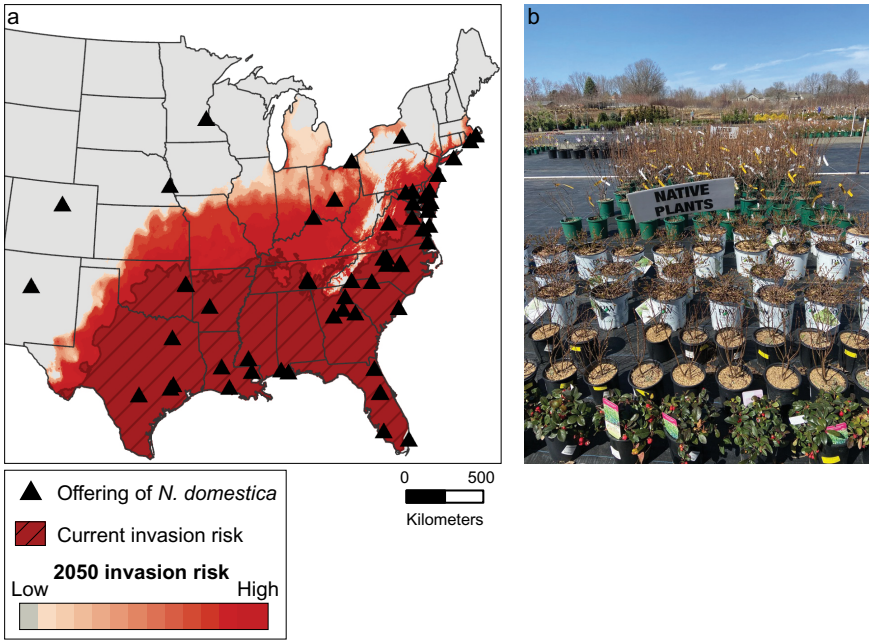

Figure 3. The ornamental plant trade facilitates the introduction and establishment of species likely to become invasive with climate change. (a) Sacred bamboo (*Nandina domestica*) is widely available for sale across the east coast of the United States. Source: The data are from Beaury and colleagues (2021b). The species already poses high invasion risk in the southeast (the hashed areas) and invasion risk is projected to expand into the mid-Atlantic by 2050 with climate warming. Source: The data are from Allen and Bradley (2016). (b) Reducing the sale of problematic species and encouraging native alternatives would help to stop invasions before they start.

(www.cabi.org/ISC) or the Global Plant Invaders database (Laginhas and Bradley 2022). This practice would make it easier for voluntary labeling practices to include all potentially invasive plants and would provide a single, standardized source for the industry to use rather than changing labeling for each state. A single source would also encourage the ornamental plant industry to move away from known invasive plants. For native plants, climate-smart labeling that includes current and projected plant hardiness zone maps could help the public choose warm-adapted species for planting (Yue et al. 2011), facilitating the movement of native plants in response to climate change and leading to more ecological landscaping (figure 2). Collectively, these approaches would provide the information that consumers need to avoid introducing current or future invasives and instead focus on species that can provide ecosystem services—potentially increasing resilience of flora and fauna to climate change.

Some people and industries may need additional incentives before becoming part of the solution. Financial incentives, such as tax breaks for ecological landscaping, and changing social norms, such as popularizing biodiverse and low-maintenance pollinator meadows over resource-intensive grass lawns, would have the double advantage of reducing future invasions while helping native species shift their ranges to match climate change (figure 2). The recent popularity of pollinator gardens is an example of a bottom-up change that has increased demand for native plants and incentivized nurseries to carry more native stock. With climate change, we have an opportunity to bring new native plants to gardeners, proactively avoiding invasions while supporting the climate-driven migration of native plants (e.g., Bradley et al. 2020). Individuals, nongovernmental organizations, and local governments can prioritize climate-smart native plant nurseries for landscaping—supporting these industries with our dollars (e.g., PlantRight in California, https://plantright.org/approach).

Another way to educate the public about the benefits of planting native would be to focus on native plantings on state and federal lands. For example, a recent bill proposed in the US House of Representatives would require native plants in National Park Service landscaping (H.R. 6024: Native Plant Species Pilot Program Act of 2020). This type of initiative could provide more opportunities for education on the benefits of planting native and the range of available species that could be selected for home gardens and institutional landscaping. This approach could also be adopted by town or municipal governments aiming to reduce their environmental impact and promote ecological landscaping.

The approaches for public education and awareness about invasive animals will differ from those about plants because they have different pathways of introduction. The pet trade is one major introduction pathway for some animal taxa; therefore, education could include resources that explain the ecological consequences of releasing pets (Lockwood et al. 2019). Important information for prospective pet owners includes the ecology and life span of the species and avenues for pet return rather than release. Similarly, incentives for breeding (not poaching) of pets with low invasion risk would reduce the invasion risk from released pets (Lockwood et al. 2019).

Connecting research with policy and management. Finally, building connections to share our best science and practice is critical to solving environmental crises. Invasive species management and climate adaptation science both suffer from a knowing–doing gap such that manager needs are not addressed by science and relevant science does not always reach managers (Matzek et al. 2014, Morelli et al. 2021). Closing this gap will require rethinking how we connect

research, practice, and policy. Translational science (Enquist et al. 2017, Morelli et al. 2021) provides a framework for producing more actionable outcomes by incorporating decision-makers into the research process. Successful translational research often hinges on organizations and individuals who identify stakeholders needs, facilitate conversations, increase collaboration, and translate knowledge (Guston 2001). Supporting these entities, termed *boundary spanners*, *bridging organizations*, or *climate adaptation services*, will be critical for integrating climate change into invasive species research, policy, and practice.

Conclusions

Climate change requires us to make decisions in the present about how best to preserve ecosystems of the future. Although climate change will exacerbate threats from invasive species, several avenues exist for adjusting management and incentivizing "climate-smart" actions that will proactively reduce future invasion risk and impacts. Some advances will require reframing our approach to invasive species policy and management (e.g., shifting from reactive to proactive management). But other changes can be achieved within existing frameworks and with minimal expense (e.g., facilitating information exchange, incorporating climate change into invasion risk assessments). Invasive species managers are already thinking ahead about emerging species and better ways to control them. Framing policy and management in the context of climate change requires some shifts in thinking but is readily achievable and defends future ecosystems against these combined threats.

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