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PERSPECTIVES AND PARADIGMS

Understanding and managing introduction pathways into protected areas in a changing climate

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Abstract The Kunming-Montreal Global Biodiversity Framework 2030 calls for the conservation of 30% of the world's ecosystems, focusing on protecting areas vital to biodiversity, identifying and managing invasive species introduction pathways, and minimizing the impacts of climate change on biodiversity. While protected areas (PAs) have historically limited the introduction, establishment, and spread of non-native species, climate change is likely to increase their susceptibility to invasion. Yet we know little about how pathways may shift in the future, making it difficult for managers to plan appropriately. This paper explores how climate change may affect primary and secondary pathways of introduction and presents an adaptive management approach to avoid, minimize, and mitigate impacts. Climate change has influenced introduction pathways by modifying human behaviors (e.g., forced migration and shifting travel and vacation destinations), and by altering transportation routes, natural dispersal mechanisms, and the environmental conditions along these pathways and in donor and receiver regions. These changes increase the risk of non-native species introductions and their subsequent spread within PAs. Implementing climate-smart adaptive biosecurity, an iterative process that includes the incorporation of new technologies and perspectives, will become increasingly important for invasive species prevention and management of PAs as it provides flexibility in

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management response and maximizes positive outcomes when resources are limited.

Keywords Adaptive biosecurity · Alien species · Climate change · Global biodiversity framework · Human dimensions · Management prioritization · Surveillance

Introduction

Land use change, climate change, and invasive species are leading drivers of biodiversity decline worldwide (Díaz et al. 2019). The Convention on Biological Diversity established the Kunming-Montreal Global Biodiversity Framework (GBF) to address biodiversity loss and reduce pressures on vulnerable ecosystems. This framework includes Target 3, which set the goal of designating 30% of the world's terrestrial, inland waters, marine, and coastal areas as protected (CBD 2022). Currently, the World Database of Protected Areas (PAs) lists over 295,000 PAs covering approximately 16% of terrestrial environments and inland waters, and 8% of the world's oceans; a 35% increase since January 2016 (WDPA 2024).

Target 6 of the GBF aims to reduce threats to biodiversity by eliminating, minimizing, or mitigating the impacts of non-native species (synonym for alien species) in part by reducing the rates of introduction and establishment through the identification and management of introduction pathways (CBD 2022). Because PAs preserve key elements of global biodiversity, the influx of invasive species into these areas can lead to substantial biodiversity loss, especially on islands (Carneiro et al. 2024). It is particularly important to focus on PA pathways because they may experience different invasion pressures than non-protected areas by virtue of their protected status (Pickering 2010; Du et al. 2024). For instance, tourism can be concentrated in remote and scenic PAs (Pickering 2010), mercy/prayer releases may be more prevalent in undisturbed protected natural areas that are also remote (Du et al. 2024), and areas set aside for wildlife or forest protection may be more suitable for vertebrate invasive species than other PAs (Xin et al. 2024) leading to differential pathway interactions. Invasions inside areas that are protected for their landscapes and biodiversity may therefore arise from novel pathways distinct from those occurring in other areas such as urban or agricultural settings.

Climate change is expected to further impact biodiversity in PAs through melting ice caps, extreme climatic events, rising sea-levels, increased fire intensity, and changes in water availability (Ranius et al. 2023). And because the effects of climate change are unevenly distributed worldwide, some PAs will likely face more severe impacts than others (Carneiro et al. 2024). The combined effects of climate change and invasive species can complicate management planning and responses (Lopez et al. 2022). For example, climate change may influence introduction pathways, and which non-native species are introduced via these pathways (Hellman et al. 2008). Research has demonstrated that the boundaries of protected areas may limit the introduction of invasive species (Beaury et al. 2020). However, there is limited understanding of how climate change will impact the efficacy of protected area designations in reducing the introduction, establishment, and spread of invasive species (Gallardo et al. 2017).

There are many current examples of how climate change affects introduction pathways. Reviewing the details of these examples and how they manifest within PAs, can inform current and future pathway risk analyses, surveillance, and other biosecurity measures. Here, we consider how climate change facilitates non-native species introduction into PAs and discuss current and future pathway management for PAs. For the purposes of this paper, we define non-native species as those whose presence in a region outside their natural range is attributable to human activities, and invasive species as a subset of non-native species that have established, spread, and are causing negative impacts (Roy et al. 2023). While there has been considerable recent attention on managing invasive species in PAs and the effects of climate change on PAs, to our knowledge, this overview is the first to synthesize these challenges in relation to introduction pathways.

Introduction pathways, climate change, and PAs

'Introduction pathways' refer to the many ways in which non-native species are moved from one location to another (Roy et al. 2023). Focusing management efforts on high-risk introduction pathways (e.g., those that transport the largest number of species, or the most impactful species) is an efficient approach to reduce the threat posed by several invasive species at once (Hulme 2009). This strategy is particularly compelling in PAs for which logistical, financial, and staffing resources are often limited (Genovesi and Monaco 2013).

An introduction pathway includes the vector that transports the non-native species (e.g., ship hulls, horticulture, aquaculture), and the geographical route along which it travels (Hulme et al. 2008). Introductions of non-native species can be either intentional, when the species serves a specific purpose in the recipient region (e.g., biological control; Sun et al. 2022); unintentional, when a species is a contaminant or stowaway with the transport of goods and people (e.g., non-native flatworms spreading in containerized plants; Murchie and Justine 2021); or can occur when a non-native species naturally disperses through human-built corridors or from existing non-native populations (Hulme et al. 2008; Faulkner et al. 2024). Pathways can also be categorized as primary, where non-native species cross jurisdictional or biogeographic boundaries, or as secondary, where they move within these boundaries after an initial introduction (e.g., secondary dispersal) (Faulkner et al. 2020).

Climate change can affect introduction pathways in four ways. First, human responses to climate change, including changes to global trade patterns and the movement of people (where they live or travel), will likely alter the risk of introducing non-native species (Robinson et al. 2020). Second, climate change can modify human-mediated transport by creating new transport routes or altering the frequency of transport along existing routes (Chan et al. 2019). Third, natural dispersal vectors of non-native species can be altered by climate change, including extreme climatic events such as hurricanes, flooding, and wildfires (Hellmann et al. 2008). Fourth, warming temperatures, shifts in precipitation, increased disturbances, and other abiotic factors related to climate change can alter conditions along the route traveled and within receiving regions, affecting both primary introduction and secondary spread (Hellmann et al. 2008). Importantly, the effects of climate change on pathways can be compounded when they interact with other major drivers influencing introduction pathways such as increasing globalization, technological advancement, and income growth (Hulme 2009).

The following subsections describe these effects on introduction pathways within the context of PAs, using examples from specific ecosystems. However, these effects are not confined to a single ecosystem type. More examples of introduction pathways impacted by climate change are highlighted in Tables 1 and S1, with details of the applicable ecosystems, the climate change pressure affecting the pathway, and brief descriptions of scenarios where the pathway is affected.

Human responses to climate change in terrestrial ecosystems

Climate change can significantly impact land use in and around PAs and subsequently, the livelihoods of local community members who rely on those lands (Xin et al. 2024; Thomas et al. 2024). Climatic stressors may lead to the abandonment of some agricultural areas, making them susceptible to invasion, while prompting agricultural expansion into other regions (Bradley et al. 2012; Xin et al. 2024). Currently, human population density near PAs is a leading driver of non-native species introductions (Spear et al. 2013). An estimated 1.2 billion people may face climate-driven displacement by 2050, potentially relocating near PAs and increasing the risk of non-native species introductions that stem from home landscaping, agriculture, and other sources (Matthew et al. 2023). For example, in Africa, livestock are often kept near and sometimes graze within PAs. As climate change drives the movement of people and animals, it can facilitate the spread of native and non-native ticks and tick-borne diseases from domesticated to wild animals (Espinaze et al. 2018), potentially impacting wildlife in PAs. Similarly, non-native trees such as Acacia, Pinus, and Eucalyptus species are planted in buffer zones around PAs for fuelwood and other agroforestry purposes (Richardson et al. 2004; Hardy et al. 2024). Climate-driven migration and settlement near or within PAs can further facilitate the introduction and spread of these non-native agroforestry species into protected ecosystems.

Tourists may increasingly choose to visit PAs with more favorable climatic conditions, potentially increasing propagule pressure as non-native species spread unintentionally via recreational equipment, hitchhike on clothing and pets, or are transported in infested firewood (Pickering and Mount 2010; Solano

Table 1 Interactions between selected pathways of introduction and climate change. The pathway is provided with the applicable ecosystem, the related pressure from climate change, and an example of where pathways and climate change interact to impact invasions. Note that Ecos=ecosystem type and Var=variable, Ter=terrestrial, Fw=freshwater, and Mar=marine ecosystems. CC (Climate Change) type is the way climate change has affected the pathway. This table provides examples and should not be considered an exhaustive list of pathways.

Intentionally for release	Biological control	Ter Fw	Human responses Altered conditions	Warming selects for plants with faster growth and higher resistance. This can complicate classical biocontrol development, widely used in PAs (Sun et al. 2022).
	Erosion control/dune stabilization	Ter	Human responses	Non-native bamboo is used for erosion control and carbon sequestration projects in PAs in Africa, posing a threat to native ecosystems (Canavan et al. 2019; Tchamba et al. 2022).
	Fisheries in the wild	Mar Fw	Human responses Altered conditions	Warming conditions may increase pathogen and parasite virulence. This likely increases translocation of species for culinary and recreational fishing to supplement native species affected by diseases (e.g., signal crayfish in Europe) (Everard et al. 2009).
Intentionally for use in captivity/cultivation	Agriculture	Ter	Human responses Altered conditions	Warming shifts what crops and where they are grown, favouring resilient species cultivated for biomass and biofuel, raising the risk of spread into nearby PAs (Lindenmayer et al. 2012).
	Aquaculture	Mar Fw	Altered natural dispersal	Severe flooding in the Western Ghats Biodiversity Hotspot led to the escape of non-native fish species from unmanaged aquaculture and illegal farming operations into adjacent lakes and waterways (Raj et al. 2021).
	Horticulture/ ornamental	Ter Fw	Human responses	The demand for second homes near PAs drives housing growth and promotes the spread of low-maintenance, resilient ornamental plant non-native plants (Novoa et al. 2022).
Accidentally with commodity	Contaminant nursery material	Ter	Altered conditions	Tropical flatworms, introduced through nursery material, are significantly reducing earthworm populations, with changing climate conditions expected to expand their distribution (Murchie and Justine 2021).
	Parasites on animals	Var	Human responses	Increased climate change-driven movement of people and animals is facilitating the spread of ticks and tick-borne diseases. Livestock grazing in and around PAs can result in disease spillover from domesticated to wild animals (Espinaze et al. 2018).
	Timber trade	Ter	Human responses Altered conditions	Firewood can protect insects during transport, influencing pest movement under a changing climate. Campers transporting infested firewood into PAs, such as with emerald ash borer or Asian longhorn beetle, can expand forest pests' range (Solano et al. 2021).
Accidentally during transport	Angling/fishing equipment	Mar Fw	Changes in transport Altered conditions	Rising ocean temperatures increase fishing pressure on Antarctic Marine PAs and weaken environmental barriers, allowing organisms to survive transport on fishing gear (Duffy et al. 2017; Robinson et al. 2020).
	Ship/boat hull fouling	Mar Fw	Changes in transport Altered conditions	Arctic ice melt is opening new shipping routes, like the Northern Sea Route, expected to be ice-free by 2050. Increased shipping raises concerns for Marine Protected Areas by boosting survival chances for biofouling alien species (Sardain et al. 2019).
	People and their recreational equipment	Var	Human responses	Tourists choosing PAs with more favorable climates may unintentionally spread non-native species through recreational gear, clothing, or pets (Pickering and Mount 2010).
Along corridor	Interconnected waterways/ basins/seas	Mar Fw	Changes in transport Altered conditions	Increased habitat suitability of the western Mediterranean for warm-water invaders, threatening the network of marine PAs (Bianchi and Morri 2003). Rising shipping traffic in the Suez Canal is increasing non-native species introductions to the Mediterranean (Sardain et al. 2019).
Self-propelled	Post-introduction spread	Var	Altered conditions	Climate change alters habitat suitability on islands, moving non-native species to higher elevations. In Hawai'i, fire-prone invasive grasses may be moving to higher elevations faster than non-fire-adapted grasses (Angelo and Daehler 2013).

et al. 2021). Additionally, tourism-driven construction of vacation homes near PAs poses a major threat, creating introduction pathways for non-native species (de la Fuente et al. 2020; Novoa et al. 2022). Transport networks servicing these homes can act as conduits for non-native species to enter otherwise remote areas (Hulme et al. 2018). Further, the irregularity of homeowner visits permits the impacts of those ornamental plants that escape confinement and become invasive to persist unnoticed for extended periods, giving them more time to penetrate the borders of nearby PAs.

Target 8 of the GBF identifies the need to mitigate the impacts of climate change on biodiversity with an emphasis on 'nature-based' approaches but lacks guidance on the use of non-native species for this purpose (CBD 2022). This omission is significant, as using high-risk non-native species to mitigate climate change (e.g., biofuel crops) can yield short-term benefits that often overlook potential long-term consequences (Lindenmayer et al. 2012). As the impacts of climate change become more pronounced and mitigation efforts increase, the risks associated with intentional introductions of non-native species to PAs will also grow. Currently, projects utilizing climate change-mitigating plants, including bamboo, are gaining traction in vulnerable regions including Africa (Lobovikov et al. 2012). For example, in Cameroon's Mbalmayo Forest Reserve, the oldest PA in the country, livelihood improvement projects in the form of bamboo plantations have been established using a mix of native and invasive bamboo species (i.e., *Bambusa* and *Phyllostachys* spp.; Fig. 1a) (Tchamba 2022). Similar initiatives marketed as reforestation projects have been implemented across Africa (Canavan et al. 2019; Masisi et al. 2022), increasing invasion risk as non-native bamboo can spread within or into adjacent PAs.

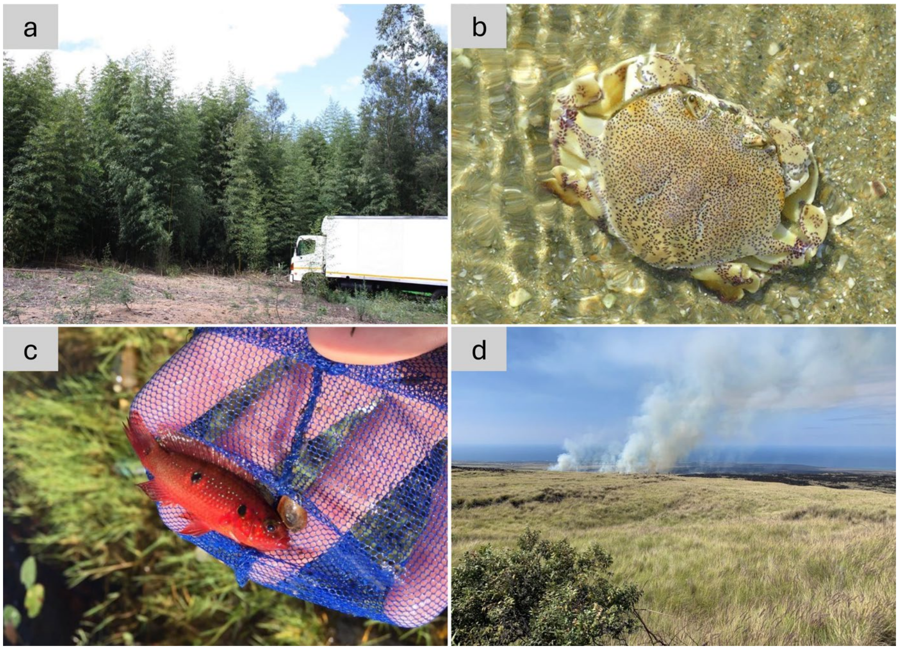

Fig. 1 Images from case studies demonstrating how climate change affects vulnerability of terrestrial, freshwater, marine, and island protected areas (PAs) to invasions: **a** Non-native bamboo species (Phyllostachys sp.) commonly used in cultivation, spreading in KwaZulu-Natal province, South Africa, **b** the Indo-Pacific moon crab (*Matuta victor*), a "Red-to-Med" invasive species first recorded in the Mediterranean Sea from Israeli coasts in 2012, **c** African jewelfish (*Hemichromis bimaculatus*) introduced through illegal aquarium dumping in Florida could threaten PAs to the north through tropicalization, **d** wildfire fueled by the range-shifting, invasive fountain grass (*Cenchrus setaceus*) in the Pu'uwa'awa'a State Forest Reserve, Hawai'i Island. Photo credits: **a** S. Canavan (Ollscoil na Gaillimhe – University of Galway), **b** Fuke, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=7259259, **c** USGS **d** E. Parsons (Pacific Islands Climate Adaptation Science Center)

Changes in transport routes and frequency in marine ecosystems

The changing climate can alter human-mediated transport by creating new introduction pathways through the opening of new shipping routes, and through changes in the frequency of transport along existing routes (Chan et al. 2019). As globalization accelerates, maritime traffic is expected to increase by up to 1200% by 2050, which when coupled with climate change, is forecast to result in a 3- to 20-fold increase in global invasion risk (Sardain et al. 2019).

The Mediterranean Sea has over a thousand designated marine PAs with varying levels of protection (MedPAN 2021). The Suez Canal is an artificial waterway that connects the Red and Mediterranean Seas. Since its construction, 384 Erythrean species (i.e. marine species that have migrated along the Suez Canal, usually from the Red Sea to the Mediterranean Sea) have been introduced including the aggressive Indo-Pacific moon crab (*Matuta victor*) (Fig. 1b; Shefer et al. 2004; Tavares et al. 2004; Galil et al. 2018). Initially, most of these invasions resulted from dispersal via natural biotic or abiotic vectors or were self-propelled (Schefer et al. 2004). However, increased shipping traffic has amplified introductions via ballast water and biofouling (Galil 2000). The movement of species into the eastern Mediterranean basin has resulted in more invasive species in the marine PAs within that region (Galil 2017). Climate change is projected to increase the suitability of the western Mediterranean for warm-water invaders, threatening the entire network of marine protected areas (Bianchi and Morri 2003). As shipping traffic rises and the canal expands to accommodate the increasing size of ships, future transport related introductions are expected (Sardain et al. 2019).

Polar regions, which are home to multiple marine PAs, are experiencing a dramatic decline in sea ice cover (Melia et al. 2016; WDPA 2024), which is opening new, shorter trans-Arctic trade routes and facilitating a prolonged shipping season, increasing the chances of unintentional species introductions (Melia et al. 2016; Chan et al. 2019). Reduced sea ice is also driving "last-chance tourism" to polar marine PAs, where visitors seek to visit destinations under threat from environmental degradation and climate change before they disappear (Chan et al. 2019). The growing cruise ship and marine expedition industry in these regions poses substantial risks as a vector of non-native species introductions (Hall 2010). While the biggest threats from tourism to the PAs in the region include further degradation of sensitive ecosystems and the introduction of non-native species to terrestrial areas, marine ecosystems could be significantly impacted by introductions through hull fouling and ballast water.

Alterations to natural dispersal pathways in freshwater ecosystems

Nearly all terrestrial PAs have freshwater resources within or adjacent to their boundaries. Climate change is expected to impact these ecosystems by altering the frequency, duration, and timing of floods and droughts, as well as by shifting seasonal water temperatures and disrupting hydrological cycles (Rahel and Olden 2008). In some cases, these changes can limit the movement of non-native species into PAs when drier conditions reduce river connectivity (Rahel and Olden 2008). In other cases, extreme weather, warmer conditions, and altered precipitation (e.g., hurricanes, flooding, precipitation pulses) can facilitate natural dispersal across PA boundaries via interconnected freshwater systems (Fobert et al. 2013). These differing effects on introduction pathways underscore the context-dependent role of climate change in shaping introduction pathways.

Extreme weather events, such as floods made more severe by climate change, create conditions where non-native species (including the parasites and diseases they may host) can escape confinement and disperse by water or by hitchhiking on other organisms moving along new or enhanced routes (Rahel and Olden 2008; Everard et al. 2009). For example, aquaculture is the fastest-growing sector of food production in the world (Ahmed et al. 2019), and many aquaculture operations exist within or close to PAs (Rico-Sánchez et al. 2020). As climate change increases the frequency and magnitude of flooding in freshwater ecosystems, the potential for non-native species to escape aquaculture facilities and move into PAs increases (Raj et al. 2021). These species may also move through previously isolated drainages, reaching PAs that were previously inaccessible to them (Fobert et al. 2013). Such was the case in the Western Ghats Biodiversity Hotspot, a UNESCO World Heritage Site, where severe flooding in 2018 and 2019 led to the escape of at least ten non-native fish species into adjacent lakes and waterways from illegal farming operations and stocked reservoirs (Raj et al. 2021). Illegal aquarium dumps including fish, snails, and plants can also spread via floodwaters to enter PAs (Nico et al. 2019). For example, African jewelfish (*Hemichromis bimaculatus*; Fig. 1c), an omnivorous fish first introduced to Florida (United States) in 1965, has expanded its range along interconnected waterways. It is now abundant in Everglades National Park and has spread via flood water connections through central Florida into various disconnected drainages, including the Lake Okeechobee Sanctuary and Indian River Lagoon Preserve State Park (Nico et al. 2019; Pfingsten et al. 2023). As climate change increases the frequency and severity of flooding events, we can expect increased movement of invasive species into PAs.

Altered conditions facilitate range shifts and expansions into islands PAs

Climate-induced changes in environmental suitability will interact with the previous three effects on pathways, creating new opportunities for the establishment and spread of non-native species worldwide. Additionally, with climate change, non-native species are likely to expand their ranges more rapidly than native species due to their broader climatic tolerances, giving them a clear advantage in a shifting climate (Bradley et al. 2024). While these effects will impact PAs across all ecosystem types, island PAs, which protect a disproportionate share of global biodiversity, face greater invasion risk and higher vulnerability compared to continental areas (Russell and Kueffer 2019).

The extremely remote, strictly protected sub-Antarctic Prince Edward Islands are shielded from the introduction of non-native species through stringent biosecurity measures (Fernandez Winzer et al. 2023), while the islands' harsh climate can prevent their establishment (Duffy et al. 2017). The islands' climate, however, is changing (le Roux and McGeogh 2008) and the arrival and establishment of new non-native species is expected to increase as existing climatic barriers weaken (Duffy et al. 2017).

On mountainous islands, climate change is expected to alter the suitability of conditions, causing invasive species limited by unsuitable temperatures to shift towards higher elevations as they follow their climate niches upslope (Rubenstein et al. 2023). While this phenomenon is widespread globally (Rubenstein et al. 2023), it is especially troubling on islands because of the high vulnerability of endemic species to extinction (Fernández-Palacios et al. 2021). Climate-induced elevational shifts have been projected for a variety of non-native species on islands, including mosquitoes (Benning et al. 2002) and plants (Angelo and Daehler 2013). The potential for range-shifting non-native species is concerning for managers in Hawaiʻi, where PAs protecting the most intact native ecosystems are located primarily at higher elevations (Yeung et al. 2019). Invasive grasses are among the most troublesome species expanding their ranges on islands, as they fuel destructive wildfires that lead to the loss of human life and property, and the degradation of important ecosystems (Fig. 1d; D'Antonio and Vitousek 1992; Parsons and Martin 2023). At Hawaiʻi Volcanoes National Park, invasive fire-prone grasses may be shifting to higher elevations by a greater amount than non-fire-adapted invasive grasses, increasing the frequency of wildfires in the park three-fold (Angelo and Daehler 2013). Importantly, wildfires also create opportunities for the spread of these grasses further into native ecosystems.

Management of introduction pathways for PAs

Effective management of non-native species in PAs is hindered by many institutional and interagency obstacles that impede coordinated responses to invasions, conflicting values and interests among stakeholders and community members, and inadequate staffing and funding for prevention and management initiatives (Genovesi and Monaco 2013). Because PAs protect areas with high biodiversity, threatened species, sensitive biomes, and other areas with important ecosystems (CBD 2022), there is a critical need for a more cost-effective and efficient approach to reducing the prevalence and impacts of invasive species, such as pathway management. Successful pathway management relies on high-quality information that is often missing in many jurisdictions and at finer spatial scales, creating critical information gaps especially relevant for PAs (Roy et al. 2023). One reason for these gaps is that pathway management is typically applied at the national level (e.g., import regulations pre-border and mandatory quarantine at the border), rather than at the scale of PAs (Faulkner et al. 2016; van Wilgen et al. 2025).

The examples included in this paper, while not exhaustive, illustrate the growing diversity of challenges faced by invasive species practitioners working in PAs in a changing climate. Uncertainty, which amplifies these challenges, surrounds both risk prediction and the potential impacts of climate change, emphasizing the need for action at finer scales where invasive species management takes place (Leung et al. 2012; Catford et al. 2022). And while invasive species practitioners working in PAs are often concerned about the effects of climate change on management efforts, they are frequently overwhelmed by managing existing invasions, leaving limited resources for proactive management (Beaury et al. 2020). To increase the effectiveness of invasive species management in this context, practitioners need a new approach that allows them to respond adaptively to the growing challenges they will face as the climate changes.

Adaptive management is a structured, iterative practice used in natural resource management that integrates lessons learned through monitoring and evaluation, to enable timely adjustments that improve management outcomes (Williams et al. 2016). Given the complexity and uncertainty associated with climate change and introduction pathways, we argue for climate-smart adaptive biosecurity as an approach to address uncertainty and mitigate harm from invasive species introduced through shifting introduction pathways (Lemic et al. 2024) (Fig. 2).

Climate-smart adaptive biosecurity

Here we highlight how pathway management in PAs can be improved using a suite of tools (Fig. 2a; Table S2), and by considering the impacts of climate change on pathways.

Integrating climate change into proven prioritization methods, such as horizon scanning for invasion threats and site prioritization schemes, can help

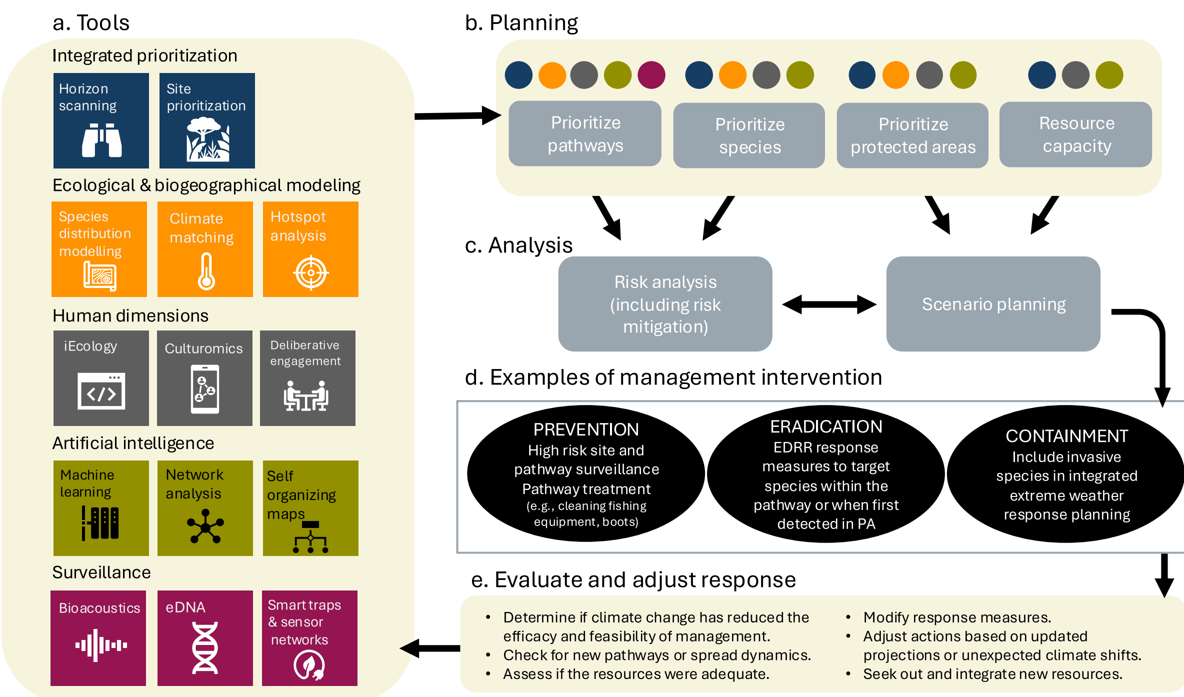

Fig. 2 A conceptual diagram for an adaptive approach for managing potential invasive species threats and their pathways for introduction in present and future climate conditions. This is an iterative approach that benefits from the utilization of new technologies and processes, and their contributions to biosecurity. Descriptions of the tools included in section (a.) can be found in Table S2

improve our ability to identify and rank threats for future climate conditions. For example, high-volume introduction pathways can be identified and ranked for different climate scenarios, and PAs can be prioritized by their susceptibility to invasion, conservation value, and vulnerability to extreme weather events (Colberg et al. 2024). These findings can then be used to guide invasive species policy and regulation (e.g., injurious listing), pathway surveillance, and other precautionary management strategies. Furthermore, horizon scans are relatively inexpensive, can be conducted at the PA level, and can be updated at regular intervals to incorporate new information and innovations (e.g., emerging research and improved models) as a part of the adaptive biosecurity process. By integrating climate-informed prioritization across these areas, we can enhance efficiency in resource allocation for management in a changing climate.

Ecological and biogeographical modeling has become increasingly popular in conservation for developing climate-adaptation strategies (Klausmeyer and Shaw 2009), spatial planning for species conservation (Mukherjee et al. 2021), and invasive species management (Wang et al. 2017). Species distribution models (SDMs), climate matching, and hotspot analyses are valuable in adaptive biosecurity because these models can integrate future climate scenarios to predict how changes in temperature, precipitation, and other factors may affect the distribution and spread of invasive species (Colberg et al. 2024), enabling PAs to anticipate threats and adjust management strategies accordingly. Broadly applied in invasive species prevention and early detection and rapid response (EDRR), these models support risk assessment, surveillance, and management (Martinez et al. 2020). While initial predictive models are often developed with limited data (Hui 2023), adaptive approaches leverage data generated through management and monitoring to refine and improve model accuracy over time (Uden et al. 2015).

Since both accelerated climate change and the transport of non-native species stem from human activities, we can also improve our ability to manage and conserve PAs by incorporating human dimensions—using what is learned from social science methods that examine cultural, sociological, and economic factors—to enhance invasive species management (Shackleton et al. 2019; Pickering 2010). For example, culturomics and iEcology, which analyze data from internet sources such as search trends and social media metrics, can identify PAs that attract or are likely to attract tourists, assess trade patterns of non-native species, detect new invasions within or near PAs, and measure public support for management strategies (Jarić et al. 2020; 2021). As well, deliberative engagement, an approach that incorporates diverse stakeholder perspectives through structured decision-making, can be effective for addressing complex challenges like the combined effects of invasive species and climate change (Magness et al. 2022). This approach also addresses GBF Targets 22 and 23, which promote equitable, inclusive, and gender-responsive representation and participation in decision-making (CBD 2022).

Artificial (AI) driven modeling applies computational methods and advanced data processing to support the prevention and management of non-native species in PAs. By running multiple iterations of models, AI improves accuracy and ensures consistent results (e.g., Bagnara et al. 2022). Examples include self-organizing maps, a type of artificial neural network used to cluster high-dimensional data for identifying regions with similar invasive species assemblages, ranking invasion risks across multiple species, and simulating their potential movement into climatically suitable areas (Worner et al. 2013); machine learning techniques to analyze how environmental conditions influence the movement of non-native species (Wang 2019); and network analysis to model the transport, introduction, and spread of species in new regions (Bagnara et al. 2022). Combined, these technologies enhance risk prediction and strengthen surveillance activities.

Detecting invasive species can be challenging within vectors and along pathways, or when they are first introduced to a receiver region, especially when populations are small, the species is difficult to detect, or the area is difficult to access. Recent advancements in surveillance technologies, such as bioacoustics (Chhaya et al. 2021), eDNA metabarcoding (Pascher et al. 2022; Clarke et al. 2023), and wireless sensor networks (Liakos et al. 2021), are helping address these challenges. These innovations improve the likelihood and efficiency of detecting invasive species while also enhancing the speed and accuracy of their identification. These tools have minimal impacts on native ecosystems compared to traditional methods, offering significant benefits for PA management.

Additionally, data collected by these tools can support the adaptive component of climate-smart biosecurity. For example, eDNA sampling in remote areas can provide occurrence data to help develop more precise and accurate SDMs (e.g., Muha et al. 2017), while machine learning algorithms can process information from smart sensors to improve the sensors' ability to accurately distinguish species (Gonzáles-Pérez et al. 2022).

These tools contribute to the 'planning' portion of the framework, which involves generating prioritized lists of species, pathways, and protected areas, as well as assessing resource capacity (Fig. 2b). This information is then incorporated into the 'analysis' stage, which includes risk analysis and scenario planning (Fig. 2c). Risk analysis involves detailed risk determination and how best to mitigate or manage the risks identified (Lieurance et al. 2024). Scenario planning, increasingly used by climate adaptation specialists (Roura-Pascual et al. 2024), helps managers prepare for uncertainties associated with future climate change, including the varied impacts of different climate scenarios on invasive species (Lawrence et al. 2021). Together, these methods inform the selection of appropriate management interventions (Fig. 2d). For example, during a 2023 a workshop in Hawaiʻi, managers of a forested protected area in North Kona and group participants explored the possible effects of two climate change scenarios (a low and high emissions scenario) on a prioritized list of high-risk invasive species and identified species-specific management interventions for each scenario (E. Parsons, unpublished results). Once the management intervention has been implemented, an evaluation and adjustment phase can help assess successes and failures, identify resource gaps, and adjustments for the next iteration of the management cycle (Fig. 2e).

Meeting target 6 in a changing climate

GBF Target 6 calls for reducing the impacts of invasive species on biodiversity and ecosystem services by identifying and managing introduction pathways and preventing the introduction of priority (e.g., high risk) species with a focus on high priority sites (CBD 2022). However, Target 6 does not integrate climate change into prevention recommendations. Our climate-smart approach to adaptive biosecurity employs old and new tools to analyze, assess, and prioritize management. Further, we stress building a network of interested parties including researchers, practitioners, policymakers, and Indigenous and local communities and the value of coordinated and accessible information sharing. Finally, evidence has accumulated showing that interventions targeting invasive species, PAs, and sustainable management have yielded positive outcomes and enhanced the state of biodiversity globally (Langhammer et al. 2024). We believe implementation of our climate-smart adaptive biosecurity approach can assist conservation efforts, help practitioners reach Target 6, and slow biodiversity loss in a changing climate.

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