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Preemptive and proactive application of biological control for weeds: An argument for swifter action to aid conservation efforts

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HIGHLIGHTS

- Preemptive and proactive biocontrol could save money and environmental harms.
- Preemptive biocontrol focuses on implementing and investigating biocontrol before entry.
- Proactive biocontrol develops biocontrol for non-native plants with a potential of invasion.
- AI could assist with horizon scans and ID new invasion pathways.
- Collateral benefits include better investments and training opportunities.

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ABSTRACT

Invasive alien plants (IAPs) are a frequent consequence of global connectivity and present significant threats to biodiversity, amplifying impacts from global climate change and habitat loss. Integrated management efforts for landscape-level plant invasions often include some combination of mechanical, cultural, chemical, and biological control. The former three have well established protocols and development pipelines for rapid responses to new invasions. Biological control of IAPs, however, is often employed only after the invaded region has reached some arbitrary but intolerable level of negative impact that triggers efforts to develop agents to provide control. Despite mounting evidence that investments in prevention and proactive approaches to IAPs are the most cost effective, most expenditures, including those for biological control development, continue to be in the post-invasion reactive phase. We build a rationale for earlier investigation and implementation of biological control for IAPs. A potential framework for this approach would pair prioritization methods (e.g., risk assessments and horizon scanning) to identify targets with extensive literature searches for known herbivores or foreign range surveys and early host range tests. In addition, resource sharing among regions and nations with similar climates and risks would alleviate the onus of investment from any one party. Finally, investments into conservation and training opportunities between nations further incentivizes maintaining natural resources for potential biological control. By developing and implementing biological control earlier in or before the invasion process, countless impacts and costs are lessened.

1. Introduction

Despite several decades of prevention, intervention, and control, non-native invasive species continue to cause extensive damage to the environment, economy, and animal and human health globally (Fantle-Lepczyk et al., 2022; Mack and Smith, 2011; Mack et al., 2000; Schaffner et al., 2020). Most costs, which globally number in the high billions or trillions, are incurred from damage to the invaded habitats and direct losses from those damages (Fantle-Lepczyk et al., 2022; Macêdo et al., 2024). These damages are not limited to any single ecosystem or taxa

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but encompass the full range of diversity of locations, biomes and invaders – i.e., invasive non-native species are a shared global problem and require multinational, multidisciplinary approaches to improve management outcomes. As trade and travel increase, compounded by the effects of global climate change, the likelihood of lessening the frequency and impact of invasive species is low (Culliney, 2005).

Invasive species are controlled by several possible methods including chemical, mechanical, cultural, and biological control (USDA National Invasive Species Information Center, 2006). For invasive plants and insects, chemical control incurs up-front and continued costs (e.g., reapplication), and often lacks specificity, inflicting non-target damage and legacy effects in environments (Brühl and Zaller, 2021). Mechanical control can also cause non-target damage depending on the methods, and trends towards the cost-prohibitive (Culliney, 2005; Jardine and Sanchirico, 2018). Classical biological control hinges on the Enemy Release Hypothesis and relies on the introduction of specialist natural enemies to control their host through top-down effects (e.g., predation, parasitism, herbivory or disease) (Müller-Schärer and Schaffner, 2008). A significant draw back to all these strategies, but particularly chemical and biological control, is the lengthy investment in time and resources to establish safety and efficacy before utilizing them (Davis and Frisvold, 2017; Morin et al., 2009). However, the legacy effects and other damages sustained through inaction illustrate the need for intervention (Ahmed et al., 2022; Cuddington, 2011). Finally, heightened scrutiny of

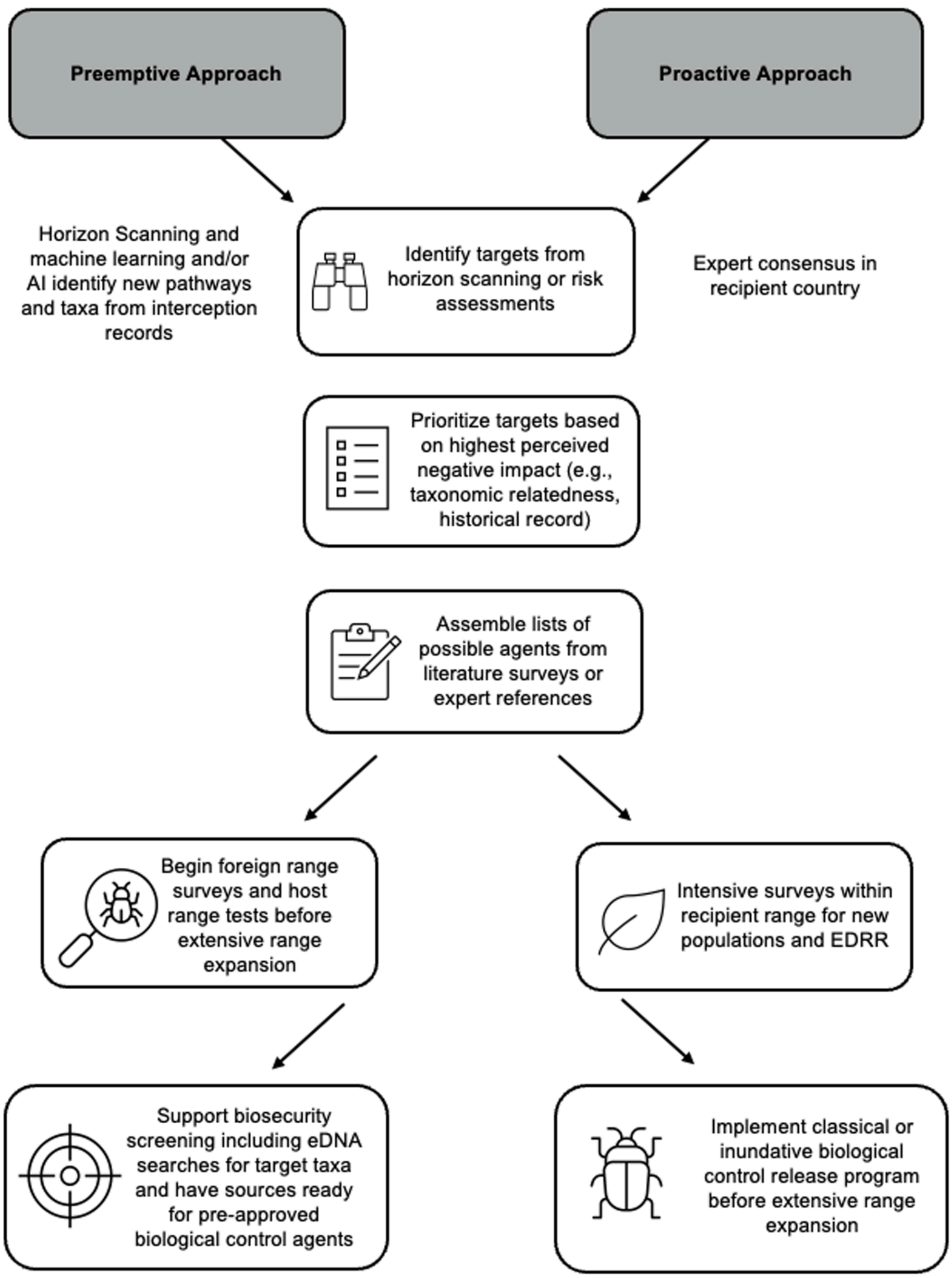

Fig. 1. Flowcharts for preemptive and proactive biological control of invasion plants. Both rely on identifying targets through horizon scanning, risk assessments, and expert impressions. Proactive biological control takes place before invasion has reached its highest impact, whereas preemptive biological control builds structure to pursue biological control before a taxon arrives. In addition to the early phases, both approaches reply on multidisciplinary methods through multinational agreements and increase the possibilities for cooperation and investments into training and conservation.

chemical control methods (e.g., the re-examination of chemistries developed and approved for use before the passage of the U.S. Endangered Species Act of 1970), puts increasing reliance on more environmentally sustainable control methods such as those that integrate classical, inundative, or augmentative biological control (Lake and Minteer, 2018; US EPA, 2023).

In a review by Hinz et al. (2019), the authors succinctly point out that the modern safety record for biological control is well proven, suggesting that testing methods for direct impacts effectively predict a biological control agent's ecological host range. Historically, efficacy has varied with approximately 30 % of established agents exhibiting only slight impact on their target, and 7 % of agents failing to make any meaningful impact (Schwarzländer et al., 2018). But recent introductions and screenings have taken impact and multispecies interactions into account to mitigate the failure rate (e.g., impacts of biotic resistance) (Paynter et al., 2018; Schwarzländer et al., 2018). Additionally, despite a well-documented safety record for biological control of weeds, the regulatory agencies remain risk averse, often demanding unrealistic no-choice outcomes (Paynter et al., 2018). Due to these roadblocks, developing and releasing new agents for biological control can often exceed a decade, highlighting the advantage in terms of time and potential impact of programs that begin early (DiTomaso et al., 2017).

Herein, we make a case for implementing and investigating biological control of Invasive Alien Plants (IAPs) before invasion/entry or earlier in the invasion 'curve' (The State of Victoria, 2010). By conducting several elements of these investigations earlier in the decision tree related to identifying and prioritizing IAPs, time and effort can be utilized more efficiently and shared amongst impacted entities.

2. Preemptive and proactive biological control – Defining terms

Preemptive and proactive development of biological control for invasive plants encompass many of the same elements as traditional biological control of weeds, but differ in time, opportunity and approach (Fig. 1). Day and Callander (2024) outline this well when discussing potential applications and real examples of preemptive biological control of weeds in Australia. We utilize their definitions of preemptive and proactive biological control to shape our arguments. Preemptive biological control scenarios include circumstances where the target weed is not yet invasive inside of a country or region, but represents a tangible, yet unrealized risk (Day and Callander, 2024, cases 2–4). Proactive biological control scenarios, in comparison, include situations in which the invasive species is already present in the range of concern but is not yet impactful, but biological control may be beneficial to mitigate damage (Day and Callander, 2024, cases 5,6).

3. Costs and benefits of preemptive and proactive intervention

Targeting IAPs in their early stages of invasion will likely enhance the prospects for success (Olckers, 2004). Yet preemptive and proactive biological control of IAPs has not yet been incorporated into research organizations as common practice due to costly investments in terms of both time and money, though this is hopefully shifting (Avila et al., 2023; Day and Callander, 2024).

Once a species arrives (or in reality, arrives several times), establishes and naturalizes, populations increase towards some heretofore unrealized population asymptote over a generally unpredictable amount of time (i.e., k or carrying capacity) (Sakai et al., 2001; Sherpa and Després, 2021). This asymptote, however, may be an arbitrary designation of impact if the impact to abundance relationship of the species is particularly high (Bradley et al., 2019). Bradley et al. (2019) found that as populations of invasive species grew in the log phases of an invasion, native populations declined most rapidly (as compared to invasive and native populations interacting at steady states). This finding reinforces the ecological importance of earlier management and intervention for species invasions to mitigate the possible detrimental impacts to native populations.

Global costs for plant invasions reach well into the hundreds of billions of US dollars spent in both controlling the plants and in indirect and direct impacts from the invasions (IPBES, 2019; Novoa et al., 2021). For example, ragweed *Ambrosia artemesiifolia* L. Asteraceae, incurs billions of euros in healthcare costs in Europe treating people for allergies associated with ragweed pollen (Schaffner et al., 2020). Throughout the tropics and subtropics, water hyacinth, *Pontederia crassipes* Mart. (Pontederiaceae and formerly *Eichhornia*), incurs millions in costs from both management and health effects due to stagnant water (Villamagna and Murphy, 2010). Costs associated with these, and other invasions are unlikely to decrease and will likely become more difficult to manage as regulations surrounding the use of synthetic herbicides increase due to mounting cases to reduce their use (e.g., legacy effects, herbicide resistance, toxicology concerns) (Bueno de Mesquita et al., 2023; Ofosu et al., 2023; Phan et al., 2023).

The costs associated with preemptive and proactive biological control fall primarily into research and enforcement (Day and Callander, 2024). Research and development (i.e., R&D) costs are often incurred and performed by only a handful of countries (e.g., USA, South Africa, Australia, New Zealand) and one intergovernmental not-for-profit organization (CABI) (Schwarzländer et al., 2018; Sheppard et al., 2003). These nations also, not coincidentally, invest the most in pre-screening biosecurity measures (i.e., enforcement) (Lieurance et al., 2023).

Many researchers and nations have long recognized that investments into prevention of invasions is often where they may expect the greatest return on investments (ROI) (Ahmed et al., 2022; Cuthbert et al., 2022; Leung et al., 2002). Many nations have made extensive investments into biosecurity screenings and quarantines to attempt to intercept invaders as they enter borders (Lieurance et al., 2023; Singh et al., 2015). In addition to screening utilizing human and canine inspectors, many nations now use passive screening including eDNA to determine the arrival of novel taxa, among other new technological developments (Harrison et al., 2019). Despite the clear payoff and potential for high impact by investments into early prevention, potential for failure often stymies research and development at early stages of invasions (Diagne et al., 2021). Haden Chomphosy et al. (2023) provide compelling evidence that increased R & D on the front end of the invasion curve (i.e., preemptive and proactive measures) drastically improves outcomes for control including lessened negative impact. Impact though is difficult to estimate when negative impacts from the IAPs are never realized – damage from a diverted ecological disaster is difficult to quantify. The costs of inaction though, can be quantified through post-hoc analyses based on previous cases (Ahmed et al., 2022).

In a recent exercise, Cuthbert et al. (2022) utilized InvaCost, a public database of the economic costs of biological invasions worldwide, to estimate costs of several management strategies including inaction. Their cost estimates for negative damage due to invasive species fall in line with other estimates (e.g., Diagne et al., 2021; Pimentel et al., 2005), but they calculated the average management delay for species causing negative harm is 11 years, and estimated the cost of that delay to be approximately $1.2 trillion USD globally. Coincidentally, the management costs for invasions during the pre-invasion stage were a small fraction of the costs – 25 times lower – compared to reactive, post-invasion management. Timely interventions are rare though the financial and ecological benefits arguably outweigh the costs (Cuthbert et al., 2022).

4. Preemptive biological control examples

As Avila et al. (2023) point out in their argument for preemptive biological control of arthropod pests, prevention and anticipation of future risks considerably reduces the potential impact of invasive species in both natural and agro-ecosystems. Most of the examples for preemptive control come from measures to reduce the risk from invasive arthropod pests. For example, in Australia – a strong practitioner of preventive biosecurity policies – they are actively pursuing surveys for natural enemies of Brown Marmorated Stink Bug (*Halymorpha halys* Stål [Hemiptera: Pentatomidae]) hereafter BMSB (Caron et al., 2021; Nelson et al., 2014). BMSB has a broad host range encompassing upwards of 300 known species including important agricultural crops (Kriticos et al., 2017). Its invasion into Europe and North America is relatively recent, but its damages are already in the tens of millions of US dollars in North America, primarily due to crop losses (Leskey and Nielsen, 2018). Kriticos et al. (2017) and others have modeled their expansion into Australia and New Zealand. In Australia, inspections at ports of import have resulted in several interceptions, leading regulators to presume that either *H. halys* has already entered unnoticed or will at some point soon. Two biological control agents are currently in use elsewhere to manage *H. halys:* the egg parasitoids *Trissolcus japonicus* (Ashmead) and *Trissolcus mitsukurii* (Ashmead) (Hymenoptera: Scelionidae) (Sabbatini-Peverieri et al., 2020). *Trissolcus mitsukurii* was reported in Australia in 1916 and was further introduced as a biological control agent to control the green vegetable bug (*Nezara viridula*) L. (Hemiptera: Pentatomidae) in the 1960′s (Caron et al., 2021). *Trissolcus mitsukurii* was detected in collections as recent as 2016, but has not been found in current surveys (Caron et al., 2021). Although little is known about its biology, *T. mitsukurii,* like *T. japonicus*, shows a broad host range within the Pentatomidae. Due to this, the latter will not be pursued for biological control, but a full assessment of *T. mitsukurii* is currently underway for use as a potential biological control agent in Australia and New Zealand (Caron et al., 2021).

A few examples of preemptive biological control for weeds have recently been published and highlighted from Australia and South Africa (Chikowore et al., 2023; Coetzee et al., 2021; Day and Callander, 2024). Currently, the Centre for Biological Control in South Africa have established a preemptive biological control program on Amazon frogbit, *Hydrocharis laevigata* (Humb. & Bonpl. ex Willd.) Byng & Christenh. (Chikowore et al., 2023; Coetzee et al., 2021; Howard et al., 2016). Though the plant has not yet been reported in South Africa, it has recently been discovered to have established in neighboring countries, Zambia and Zimbabwe, and is considered likely to arrive in the near future (Howard et al., 2016). In response to this threat, a biological control program was started to survey for potential agents in the native range (Chikowore et al., 2023). An agent has been identified *Listronotus cinnamomeus* (Hustache) and is currently undergoing host specificity testing (Cordo and DeLoach, 1982) (M. Hill, *personal communication*).

5. Proactive biological control examples

An example of proactive biological control comes from Florida, USA where biological control was started just as the plant was breaking through the “lag phase” of the invasion curve (Antunes and Schamp, 2017). During the late 2000 s, land managers and biologists identified *Acacia auriculiformis* A. Cunn. ex Benth as a possible high-impact invasive tree (Minteer et al., 2020). They did so based on the invasion history of other Australian *Acacia* species, such as those in South Africa, and the invasion history of co-occuring Australian species such as *Melaleuca quinquenervia* (Cav.) S. T. Blake (Mytraceae) in Florida (Minteer et al., 2020). Once biological control practitioners recognized the potential for this species to spread and cause widespread damage, a biological control feasibility study was conducted and determined that biological control for *A. auriculiformis* had substantial probability for success (Minteer et al., 2020). Foreign range surveys began in 2015 and produced several viable options for biological control, from which two species have been prioritized for testing (Minteer et al., 2020; Sanderson et al., 2023). While these investigations have benefited from two laboratory locations simultaneously tackling an extensive host plant test list, the earliest an agent will be released after undergoing the regulatory processes in the USA is 2026 − a full decade from when the project began and 20 years after initial concerns. During those decades, *A. auriculiformis* has intensified in density and expanded its range northward and further inland in Florida, highlighting the importance of developing control strategies for these species during the “lag” phase of an invasion (Antunes and Schamp, 2017; University of Georgia, 2017). These biological control agent releases would still likely begin before *A. auriculiformis* would reach its full distribution potential within the USA and could potentially keep *A. auriculiformis* from spreading into all areas that are climatically suitable for its invasion (Salgado et al., *in review*).

The previous example advocates for an earlier application of the well-established process for developing biological control agents. In contrast, or even in conjunction, a preemptive approach wherein lists of potential agents for potential targets could also be developed. For example, Florida could use the successes derived from biological control of Acacias in South Africa as a starting point for surveys and testing (e.g., *Trichilogaster* spp., *Uromycladium* spp.) (Impson et al., 2023). South Africa has a long history with the introduction of *Acacia* spp. for timber/tannin production, dune stabilization, soil remediation, and ornamental use, with the first introductions of these Australian acacias starting in the mid-1800 s (Richardson et al., 2015). Magona et al. (2018) found that 141 *Acacia* species have been introduced into South Africa, 15 of which are considered invasive as of the early 1990 s. Observed management and damage costs of *Acacia* species in South Africa (reported from 1995 to 2015) exceeded $13 M USD as of 2017 (standardized from original currency/year to 2017 US dollars) (Diagne et al., 2020, InvaCost database). Earlier intervention could have greatly decreased the economic and environmental impact of these invasive trees. However, early biological control efforts were complicated due to the need to preserve some of the useful timber contributions of *Acacia* species for the acacia timber industry (Dennill and Donnelly, 1991; Impson et al., 2004). Biological control for invasive Australian *Acacia* species was started in South Africa in the early 1970 s, with first releases beginning in 1982. Several of these releases have been successful at controlling flowering and seed production, and spread and vigor of *Acacia* species (Impson et al., 2023).

6. Pairing risk analyses, horizon scanning to prioritize targets

One of the major hinderances of early intervention for invasive species management is identifying which species are likely to cross the threshold from nuisance and naturalized to damaging beyond hope of containment (Ahmed et al., 2022). The Early Detection and Rapid Response (EDRR) designation is theoretically meant to establish risk of invasion and send out a rapid response to mitigate and neutralize the threat of that species proliferating (National Invasive Species Council, 2016). In the US, the National Invasive Species Council outlines in its 2016–2018 Action Plan that watchlists are comprised of species that may or may not be present in an area, but have been determined, through some heretofore unmentioned risk assessment or screening, to merit detection and surveillance (Reaser et al., 2020). Adjacent regions and countries may share species watchlists because they share other ecological or physiognomic similarities and therefore risk from invasion. Countries may even share national level data or severity of impacts for specific taxa (e.g., the now defunct Global Register of Introduced and Invasive Species or GRIIN) (Reaser et al., 2020). These though, all hinge on the variable and inexact science of risk assessment whose best examples are largely unimproved upon three decades later (Pheloung et al., 1999; Lieurance & Culley, 2024; Reichard and Hamilton, 1997; Roy et al., 2014). In an effort to improve the speed and consensus for species posing the most risk, horizon scanning has been developed (Lieurance et al., 2023; Roy et al., 2014). This method combines rapid risk assessment incorporating data-driven conclusions with consensus among experts with extensive knowledge of the systems to maximize the efficiency of the decision-making process (Mulema et al., 2022; Roy et al., 2014; Verbrugge et al., 2019).

The product of horizon scans and similar exercises is the systematic prioritization of species for targeted control. Such an approach has been taken in South Africa and the western USA with the development and adaptation of the Biological Control Target Selection (BCTS) system that prioritizes species based on scoring of attributes related to the importance and impact of the weed, the likelihood of biological control success, and potential costs, although it may have limited application currently to species that are in low density or not yet present (Paterson et al., 2021; Winston et al., 2024). The BCTS system could be adapted after horizon scanning to assess species that present the highest potential risk of invasion to a region and determine which ones are likely to be the best targets for biological control. Scoring involves compilation of relevant information such as knowledge of natural enemies and biological control precedence (Canavan et al., 2021). This would allow for any known natural enemies that have promise as biological control agents to be identified prior to the initiation of a program. Horizon scans and the scoring process used for prioritization could be employed as a starting point to identify which plants present the highest risk of invasion and in turn what options may be available for biological control.

7. Risk sharing and cost sharing

The investment into developing biological control, though, is not trivial either in time or financial resources. Although ROI can reach into the thousands in some cases, building a case for early investment in R & D of control methods for taxa that have not yet reached landscape level impacts is hard in any circumstance, and particularly in one with steadily dwindling investments in biological control. Cross-border initiatives for invasive species management are rare in most regions (Cuthbert et al., 2022). However, recent regulations and mandates in some areas have pushed to improve this, for example the European Union requires collective prevention, control and eradication of certain invasive alien species (Branquart et al., 2016). Regional scale management improves efficiency and expenditure and lessens negative impact (Faulkner et al., 2020).

In the examples laid out by Day and Callander (2024), Australia invested in the development of biological agents for *Chromolaena odorata* for use in neighboring countries. They did this due to the anticipated, and later realized, risk of introduction into northern Queensland. By investing into a shared risk, Australia was able to respond relatively quickly to the establishment of *C. odorata* once eradication efforts failed. This shared-effort scenario makes the most sense for countries that share borders and eco-regions but could also be applied for regions with high rates of trade coupled with physiognomic similarities. For example, Ding et al. (2006) lay out a compelling argument (e.g., shared resources, goals, and training opportunities for students and scholars) for the expansion of collaborative biological control research on 14 shared invasive taxa between China and the USA. Sheppard et al. (2006) also point out that IAPs often impact agriculture and the environment, where multiple stakeholders and nations have a vested interest in funding development and fostering cooperation for control measures, including biological control.

8. Prioritize research and resources

The scarcity of preemptive and proactive biological control may reflect the funding systems in place. Biological control is government funded or co-funded in almost all research institutes and selection of targets is therefore generally driven by risk-averse government stakeholders and land managers (Canavan et al., 2021; Palmer and Miller, 1996). Preemptive and proactive biological control programs will also be time-dependent so that agents are released before the plants become major environmental or economic problems. Yet government procurement is often a lengthy process. Within the confines of these bureaucratic structures, it will be challenging to apply for funding on plants that have not yet born out their economic or environmental impacts. Bioeconomic risk models have found that far less is invested into biosecurity actions than is needed (Leung et al., 2002). Management of invasive plants at the early stages is generally driven by evidence of impacts elsewhere in contrast to late-invasion stage management that is often implemented due to realized impacts *in situ* (Simberloff et al., 2013). Convincing the public and their government representatives of the need for preemptive biological control will rely on outlining this approach as a way in which to keep these impacts elsewhere and “not in their backyard”. This final point though is quite well described in the data both in terms of positive environmental and economic impacts from increased population control (e.g., Barratt et al., 2018) and lack of negative impacts from intervention through biological control (e.g., Pearson et al., 2021). To this latter point, several recent *meta*-analyses and comprehensive post-hoc analyses provide support that modern testing procedures adequately gauge risk from biological control of weeds using arthropods or pathogens (Hinz et al., 2019; Pearson et al., 2021).

9. Realized and collateral benefits

The cost of inaction against damaging IAPs dwarfs the cost of prevention and early intervention (Cuthbert et al., 2022; Diagne et al., 2021; Novoa et al., 2021). Beyond these direct costs though, lie potential collateral benefits for donor and recipient nations in terms of cataloguing and understanding the natural resources and ecology of natural systems. Much of global biodiversity is imperiled due to habitat loss, exploitation, biological invasions, and global climate change among others (Bellard et al., 2022). While not isolated to preemptive or proactive biological control, the need for expanded biological control could provide incentive for large-scale surveys for plants, herbivores, pathogens, taxonomic and natural history studies, and species and habitat conservation (Silvestri and Mason, 2023). In both the preemptive approach and the proactive approach, a reliable source population of potential agents is needed. This sets up a scenario wherein all potentially impacted nations and regions could collectively invest in the conservation and management of areas expected to be sources of these agents.

10. Recommendations and conclusions

We lay out two possible decision and action flowcharts (Fig. 1). Both approaches rely on international cooperation and networks of observers and collaborators to share possible early detections, pathways for potential entry, and notification of potential risk. They also both rely on consensus among subject experts and policy makers to identify, assemble, and prioritize lists of potential target species and identify funding pathways to mount large scale surveys in the native and potential (or actual) recipient ranges. After this, the approaches diverge: the preemptive approach puts more resources towards identifying potential candidates for biological control agents and bolstering biosecurity measures. The proactive approach relies on EDRR in the affected range and rapid decision making to address potential “outbreaks” of suspected invaders. Ideally, this would be happening concurrently with development of biological control where feasible, though could also potentially utilize inundative or conservation biological control with native herbivores (Eilenberg et al., 2001). In addition to collaboration, both sides of the framework rely on the expertise of observers to identify weed risks and specialized herbivores and pathogens on targeted and prioritized plant species. This emphasizes the importance of investment not only in conservation as mentioned previously, but on training ecologists, entomologists, botanists, and taxonomists on field-based observational techniques and methods and modern tools such as reference scanning using machine learning or artificial intelligence (AI). Although future costs for controlling plant invasions are unlikely to decrease, we can mitigate their impact by pursuing management strategies including biological control at earlier phases or even before their arrival.

Author Contributions.

All authors assisted with conceptualization and framework. MC Smith and CR Minteer drafted the first manuscript, to which D Lieurance and K Canavan contributed significantly. All authors reviewed and edited the manuscript. MC Smith conceptualized the initial figure to which all other authors contributed.

CRediT authorship contribution statement

Melissa C. Smith: Writing – review & editing, Writing – original draft, Visualization, Project administration, Conceptualization. **Kim Canavan:** Writing – review & editing, Writing – original draft, Conceptualization. **Carey R. Minteer:** Writing – review & editing, Writing – original draft, Conceptualization. **Deah Lieurance:** Writing – review & editing, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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