Journal of Environmental Management 402 (2026) 128931

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Review

# Parallel concepts and future opportunities across the biological control and invasion sciences

Ross N. Cuthbert[a,b,2,*], Nompumelelo Baso[b,2], Tressia Chikodza[c], Candice Coombes[c], Jane Doherty[c], Michael Githae[c], Tamzin C. Griffith[c], Marco R. Hernandez[d], Karla M. Jaschke[c], Michael D. Jukes[c,e], David Kinsler[c], Hugh J. MacIsaac[d,f], Hlumelo T. Mantshi[c], Pippa Muskett[c], Reyard Mutamiswa[c,g], Anthony Ricciardi[h,i], Guy F. Sutton[c], Deric V. Tanka[c], Jaqui van Dyk[b,c], Clarke van Steenderen[c], Jaimie T.A. Dick[a,1], Julie Coetzee[b,c,1]

[a] *Institute for Global Food Security, School of Biological Sciences, Queen's University Belfast, United Kingdom*
[b] *South African Institute for Aquatic Biodiversity, Johannesburg, South Africa*
[c] *Centre for Biological Control, Department of Zoology and Entomology, Rhodes University, South Africa*
[d] *Great Lakes Institute for Environmental Research, University of Windsor, Windsor, Ontario, Canada*
[e] *Department of Biochemistry, Microbiology, and Bioinformatics, Rhodes University, South Africa*
[f] *School of Ecology and Environmental Science, Yunnan University, Kunming, China*
[g] *Tugwi Mukosi Multidisciplinary Research Institute, Midlands State University, Gweru, Zimbabwe*
[h] *Department of Biology, McGill University, Montreal, Canada*
[i] *Bieler School of Environment, McGill University, Montreal, Canada*

ARTICLE INFO

*Keywords:*
Biological control
Biological invasions
Pest species
Plant pathogens
Research prioritization
Social science
Weeds

ABSTRACT

The biological control and invasion sciences are long-standing research fields that have accrued enormous fundamental and applied interest. However, their theoretical and practical integration remains in its infancy. Utilizing an expert elicitation process with participants spanning these sciences, we identify conceptual parallels and future opportunities to strengthen links and address future challenges in both fields. We found that the biological control and invasion sciences face pervasive context-dependencies that must be understood to improve outcome predictions, including climatic changes, spatiotemporal scales, and 'ecological surprises'. Both sciences would further benefit from terminological streamlining to improve communication, sharing of emerging technologies, and mitigation of the taxonomic decline. The two fields are strongly affected by social perceptions and awareness by decision makers, requiring more effective engagement and translation efforts. Our exercise promotes cross-cutting interdisciplinary advances to improve understanding of fundamental ecological and evolutionary processes, socio-ecological challenges, and management efficacy across the biological control and invasion sciences.

## 1. Background

Biological control and biological invasions are large research fields with fundamental and applied components spanning natural and social sciences (Heimpel and Mills, 2017; Musseau et al., 2024). Biological control is largely an applied science that concerns the use of living organisms to suppress populations of weeds, animal pests, or plant pathogens through classical, augmentative, or conservation means (van Driesche and Bellows, 2014). Invasion science is centred on the fundamental process of biological invasion, whereby non-native organisms are introduced outside of their natural ranges by human activities, with a focus on drivers, impacts, and management (Lockwood et al., 2013).

Both biological control and invasion sciences are thriving, with rapidly growing numbers of publications and a diversity of methods

---

* Corresponding author. Institute for Global Food Security, School of Biological Sciences, Queen's University Belfast, United Kingdom.
*E-mail address:* r.cuthbert@qub.ac.uk (R.N. Cuthbert).

[1] Joint last author.

[2] Joint first author.

https://doi.org/10.1016/j.jenvman.2026.128931
Received 20 August 2025; Received in revised form 26 January 2026; Accepted 5 February 2026

employed across world regions and habitat types (Faria et al., 2023; Galli et al., 2024). Moreover, both fields have transdisciplinary dimensions that are affected by myriad natural and social factors while affecting multisectoral stakeholders. These factors mediate the success of species and populations in novel and changing environments, and in turn inform practical management strategies and government policy. However, despite sharing many similar conceptual foundations and fundamental processes (Heimpel and Mills, 2017), and some authors integrating concepts and methods between the disciplines (e.g., Dick et al., 2014; Cuthbert et al., 2018), the fields have surprisingly thus far remained disjointed and lack full integration. Harmonising these sciences and identifying their parallels could better equip researchers and practitioners to achieve conservation targets, reduce redundancy in theory and practice, and more efficiently address global sustainability challenges through both sciences.

Biological control has a longstanding history spanning centuries and employs three main intervention forms (Huffaker and Messenger, 2012). First, classical biological control comprises the introduction of a non-native natural enemy to achieve long-term suppression of a target organism; second, augmentative biological control aims to increase the numbers of natural enemies in the environment, typically requiring repeated inundative or inoculative release events; and third, conservation biological control uses habitat manipulation techniques to enhance the impact of native enemies that are already present in an environment. Integrated biological control has also been proposed as a means to synergise approaches by simultaneously improving the habitat for agents that have been released through classical or augmentative means (Gurr and Wratten, 1991). One of the first classical applications was in 1865, when the cochineal insect *Dactylopius ceylonicus* was introduced from southern India into Ceylon for prickly pear cactus control. As a result of its early applications, biological control research paved the way for the development of fundamental theory underpinning consumer-resource interactions and ecological stability (Murdoch and Briggs, 1996), by providing model trophic systems with strong management relevance. In some world regions, an increased emphasis on biological control has emerged in recent decades by a greater awareness of the non-target harm and evolved resistance associated with unsustainable chemical control measures, contributing to alternative 'nature-based' approaches within the 'OneHealth' framework (Schaffner et al., 2024).

Paradigms of positive and negative implications of biological control have shifted over time, with negative consequences having been seldom considered in early applications (i.e., the so-called 'benefits era' between 1888 and 1990). In the 1990s, papers accrued highlighting the severity of non-target impacts that can occur following classical biological control applications with insufficient prior planning (Howarth, 1991; Simberloff, 1992). Since the 1990s (i.e., the 'risk era'), there has been a shift towards precaution around biological control in several parts of the world, especially concerning classical approaches in the European Union (Heimpel and Cock, 2018). These risk-averse perceptions of classical biological control have promulgated as a result of a few disastrous releases of generalist agents, notably the cane toad, mosquitofish, and indian mongoose — releases that resulted from insufficient historical risk assessment protocols (Heimpel and Cock, 2018). Most recently, a new paradigm that considers both risks and benefits concurrently has been proposed, with the view to minimise risks while maximising benefits (Heimpel and Cock, 2018), which must nevertheless be sensitive to differential value judgements among stakeholders (Simberloff, 2012). Inclusive policy redesign would be required in several regions to overcome regulatory and perceptual deadlocks around biological control applications (Abram and Moffat, 2018).

Although biological invasions have also been occurring for centuries, invasion science is a relatively young field, with research into the phenomenon accelerating decades after Elton's (1958) classic book, initiated by the seminal work by the SCOPE programme during the 1980s (Richardson and Pyšek, 2008). The rapid growth in invasion science research has provided further opportunities to test and apply broader ecological theories relating to eco-evolutionary dynamics, biogeography, and anthropogenic disturbance, among others, while also culminating in a plethora of terminology, metrics, and hypotheses (Enders et al., 2018; Soto et al., 2024). Like biological control, both costs and benefits of biological invasions have been considered, but evidence strongly suggests pervasive negative impacts that outweigh benefits (Carneiro et al., 2024) — although negative and positive effects can be incurred by different actors, even through the same invasion events (Kourantidou et al., 2022). Invasion science has sometimes been slow to integrate classical ecological theory and well-known biological control methodologies (Dick et al., 2014). Fundamental ecological and evolutionary mechanisms underpinning the success and impacts of biological control agents and biological invasions are exemplified in Boxes 1 and 2.

Alongside this theoretical basis, from a management standpoint, biological control and biological invasions are closely aligned and interlinked. Biological control agents are often introduced classically as part of (integrated) efforts towards invasion management, but have occasionally become invasive in their own right, especially in early release programmes almost a century ago that lacked rigorous pretesting to ensure agent host specificity (e.g., Shine et al., 2020). Under current best practice, the chances of non-native agents that are released through classical biological control becoming invasive is low (Heimpel and Cock, 2018) — but caution should still be exercised, as impacts can be disproportionately high from even a relatively small number of releases that lack sufficient planning, and many impacts may be subtle, delayed, or unreported (Simberloff, 2012). Both fields are further underpinned by socio-economic context of the recipient human community. For example, biological invasions and their impacts can strongly resemble patterns in globalized trade and transport (Seebens et al., 2017; Hudgins et al., 2023; Fenn-Moltu et al., 2024). Public perceptions, alongside breadth of awareness through value chains (e.g., agricultural sectors), further influence the success of management strategies, monitoring, and decision making in both areas, with citizen science providing a useful avenue to augment management applications (Weaver et al., 2021). Furthermore, each field is set to benefit from the development of new technologies designed to predict population success and future trajectories, using resources such as machine learning, remote sensing, and environmental DNA (Fricke and Olden, 2023). Because both biological control and invasion science face similar future challenges and opportunities across natural and social dimensions, including context dependencies linked to climate change, eco-evolutionary context, and socio-cultural values, these sciences could bidirectionally benefit from cross-cutting and transdisciplinary perspectives, but these possibilities remain largely as yet underexplored.

We thus discuss a series of areas to better integrate biological control and invasion sciences, stemming from a workshop that elicited perceptions from both fields. The workshop was held in August 2024 at the South African Institute for Aquatic Biodiversity (SAIAB) that included scientists and practitioners working in biological control and invasion sciences (Fig. 1). Although we aimed to have representation from both fields, attendees were primarily ecologists, with the majority constituting researchers and practitioners at the Centre for Biological Control (Rhodes University, South Africa), alongside invited experts in invasion biology from the United Kingdom and Canada (i.e., reflected in the authorship of the present paper). The majority of attendees (approximately two thirds) were early career researchers, defined as being up to postdoctoral level. The suggestions from the present study should thus be viewed with respect to these disciplinary, geographical, and career stage biases.

An elicitation process during the workshop aimed to thematically identify (*i*) current parallel concepts and (*ii*) future opportunities, from the participants' perspectives. This exercise followed three steps. Firstly, the participants were requested to individually submit a list of three current parallels and three future opportunities one month in advance of the workshop, each with a brief explanation to provide rationale for

**Box 1**

Impact prediction approaches between biological control and invasion sciences.

Impact prediction (positive and negative) of introduced organisms is an essential component in both biological control and invasion sciences — often called “agents” and “invaders”, respectively. Functional responses classically quantify feeding rates of consumers in relation to the availability of resources in their environment (Holling, 1959). This provides a foundation to characterize how consumers, such as predators and parasitoids, interact with and impact upon their resources, such as prey or hosts (Hassell, 1978). The form of functional response has implications for consumer-resource interactions; Type II interactions are deemed destabilizing towards e.g., prey populations owing to the absence of low-density refuge effects; whereas Type III functional responses may be more stabilizing (Dick et al., 2014). The magnitude of the functional response and its parameters (e.g., maximum feeding rate) can be further harnessed quantitatively to compare species, populations, or individuals in both sciences.

Because of use in characterizing trophic interactions, for decades, functional responses have been pivotal in predicting the efficacy of biological control agents (Van Driesche and Bellows, 2012). The use of functional responses in invasion science is much more recent (Dick et al., 2014; Faria et al., 2023). In the last decade, invasion scientists have rapidly adopted functional response metrics to predict the impacts of existing and emerging invaders (Cuthbert et al., 2019) — a ‘win’ for both sciences and an indication there might be other latent parallels and opportunities. While the approach transcends both fields, recent syntheses have nevertheless highlighted a discordance between biological control and invasion in their assessment of functional responses across contexts, with a strong bias towards aquatic predators in invasion applications (Faria et al., 2023). Moreover, critics of the approach suggest that trophic impacts are more dependent on factors such as conversion efficiency and background mortality, alongside broader trophic network complexities, which comparative functional responses often do not consider when focused on pairwise interactions (Vonesh et al., 2017; Landi et al., 2022).

One limitation of comparative functional response studies is that they are inherently constrained to the *per capita* level. Fusing both the functional response and numerical response into a cohesive metric (i.e., the classic ‘total response’; Holling, 1959) has improved predictions for both fields (Carrillo and Pena, 2012; Dick et al., 2017; Cuthbert et al., 2018). Population-level data, such as consumer field abundance, total biomass, percentage cover, and other proxies, have recently been integrated with functional responses to form new metrics, namely the Relative Control Potential (RCP) and Relative Impact Potential (RIP) (Dick et al., 2017; Cuthbert et al., 2018; Dickey et al., 2020) (Figure A). These two metrics are based on almost identical frameworks, which permit the comparison of different agents, non-native species, and environmental conditions by fusing their functional response parameters (e.g., maximum feeding rate) and numerical response proxies (e.g., consumer field abundance). Furthermore, RCP and RIP allow for the incorporation of abiotic factors such as temperature changes, nutrient availability, habitat complexity, as well as biotic interactions including competition, commensalism, and resource reproduction (Cuthbert et al., 2019; South et al., 2022; but see Landi et al., 2022). However, challenges still remain with regards to the scalability and context-dependence of applications, given that both individual and population-level variables can differ greatly within and among populations, and with a current predominance of laboratory-based studies limiting mechanistic interpretability, comparability, and empirical applications.

One practical consideration to further bridge this gap is for better integration and availability of interaction strength and life history trait data. The FoRAGE database, which collates functional response data across a wide range of species and ecological conditions, exemplifies efforts to facilitate this integration (Uiterwaal et al., 2022). Furthermore, while functional responses are a classic tool to quantify interaction strengths, modern assessments of biological control agent and invasive species impacts employ a blend of *in vivo*, *in silico*, and in-field approaches to more comprehensively characterize food web and community-level effects. These more advanced approaches can allow for a better understanding, including through tools such as life table analysis coupled with distribution modelling (Zhu et al., 2021; Chi et al., 2023), thereby unveiling factors that mediate the success and impacts of biological control agents and invasive species.

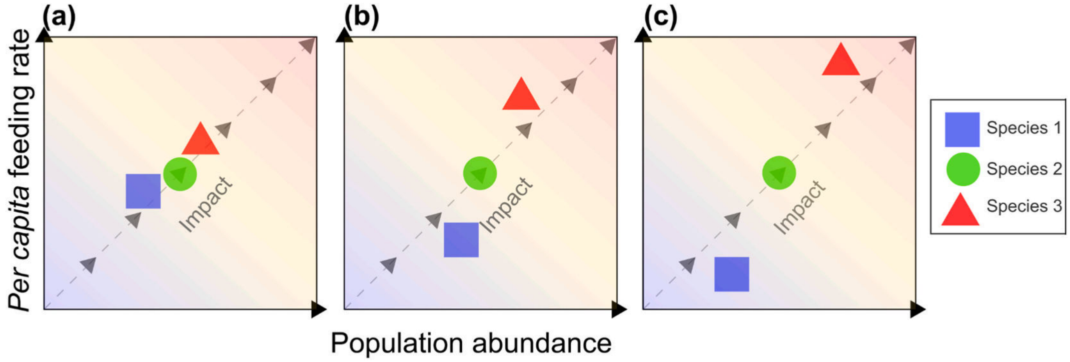

**Figure A.** Conceptual biplot showing variables underpinning the Relative Control Potential (RCP; biological control) and Relative Impact Potential (RIP; invasion science) metrics used to compare biological control agent efficacies and invasive species impacts, respectively. Consumer *per capita* effects (e.g., maximum feeding rates from functional response experiments) are scaled on the y-axis and population size of the consumer (e.g., field abundance, fecundity) on the x-axis. Impact increases diagonally by fusing these individual- and population-level metrics. Three scenarios are presented (panels a-c), with the three species compared therein having increasing impact dissimilarity from left to right. We note that the scenarios presented in the figure are hypothetical and thus not empirically based.

their suggestion. This allowed for each participant to make structured suggestions for balanced consideration *a priori* before the workshop, without influence from other participants. A collated list was then shared with all participants (i.e., the authors of the present study) and amalgamated into preliminary themes that encompassed all individual suggestions. Second, during the 2-day in-person workshop, participant suggestions were summarized and thematically presented as talks, with participants then split into four small working groups including representatives from both fields and balance with regards to disciplinary seniority. Each group was tasked with refining the top parallels and

**Box 2**

Understanding and predicting success of biological control agents and biological invasions.

Both fields have multiple commonalities with regards to the success of organisms in new environments. Population dynamics are very similar at the initial stages of both processes. Indeed, some forms of biological control can be viewed as a 'planned invasion', surpassing the critical transport and introduction stages and moving straight into establishment and spread (Abram and Moffat, 2018). This is parallel to the concept of 'hard' and 'soft' releases in invasion science, where establishment success is increased by releasing high quality individuals into suitable habitats (e.g., deer and bird releases). This field also side-steps the 'time-spent hypothesis', whereby plants with a longer residence time naturally accrue a greater diversity of natural enemies (Strong Jr, 1974). Therefore, there are valuable lessons to be learned from the well-described contexts which mediate the success of biological control agents, such as propagule pressure (i.e., introduction effort) and genetic diversity, which also contribute to the success of biological invasions, including the size and timing of those that are released through augmentative efforts.

One of the key factors influencing the success of both biological control and biological invasions is propagule pressure, which is the number of individuals, frequency of introduction events, and viability of individuals introduced into a new environment. Similarities in biological control and invasion can be drawn because a sufficient number of biological control agent individuals must be released to establish a self-sustaining population and effectively suppress the target organism, while a high propagule pressure in terms of introduction events can increase the likelihood of establishment and subsequent spread of an introduced species (Shea and Possingham, 2000). High propagule pressure helps species to overcome demographic and environmental stochasticity (Grevstad, 1999; Memmott et al., 2005). A key difference between biological control and biological invasion processes is that propagule pressure is typically known and controllable in the former, and often unknown and uncontrollable in the latter. Further, whilst biological control emphasizes agency viability (e.g., health, parasitism, fecundity), this is less frequently measured in invasion science; progress here is thus required, such as in the assessment of fitness of recently introduced individuals. Furthermore, genetic diversity can underpin population success and impact (Cuthbert et al., 2025), which heavily depends on pre-introduction selective processes in both fields (including mass rearing conditions in biological control), as well as the composition of source population individuals. The movement ecology and spread rates of introduced biota can further influence population success by mediating genetic bottlenecks (Heimpel and Asplen, 2011; Phillips, 2025). Another parallel that has received little direct narrative is that biological control success can require initial trialing of many different agent species, while colonization pressure, a term favored by invasion science, follows the same mechanism, whereby the number of potential invader taxa can be correlated with eventual invasion success by one or a subset of them (MacIsaac and Johansson, 2017).

Enemy release is another shared concept that is responsible for both biological control and invasion success, based on the premise of non-native species escaping their natural enemies (e.g., predators, parasites, diseases) in their new range. In classical biological control, this principle is harnessed to the advantage of biological control agents. By introducing host-specific natural enemies from the target organism's native range, it is possible to leverage their ability to suppress the target species without harm to non-target species. The populations of these host-specific agents naturally decline once the target population has been suppressed. In contrast, when non-native species are introduced into a new environment, they may escape their natural enemies, such as predators, parasites, and pathogens that usually regulate them in the native range (Keane and Crawley, 2002). This can lead to rapid population growth and ecological impacts from biological invasions (Baso et al., 2024).

Among these three processes, propagule pressure is accepted in both fields, and is easier to study in an experimental setting. However, other aspects are difficult to isolate from confounding factors (e.g., biotic interactions, environmental variability, temporal changes). Today, there exist more rigorous protocols for the release of biological control agents as well as the promotion of endemic control agents, including microorganisms released as biopesticides (Nouri-Aiin and Görres, 2021), recognizing possible harm associated with unanticipated ecological effects (Abram and Moffat, 2018). By carefully considering factors such as propagule pressure, colonization pressure, enemy release, and biotic resistance, it may be possible to mitigate risks associated with these practices while promoting the conservation of biodiversity.

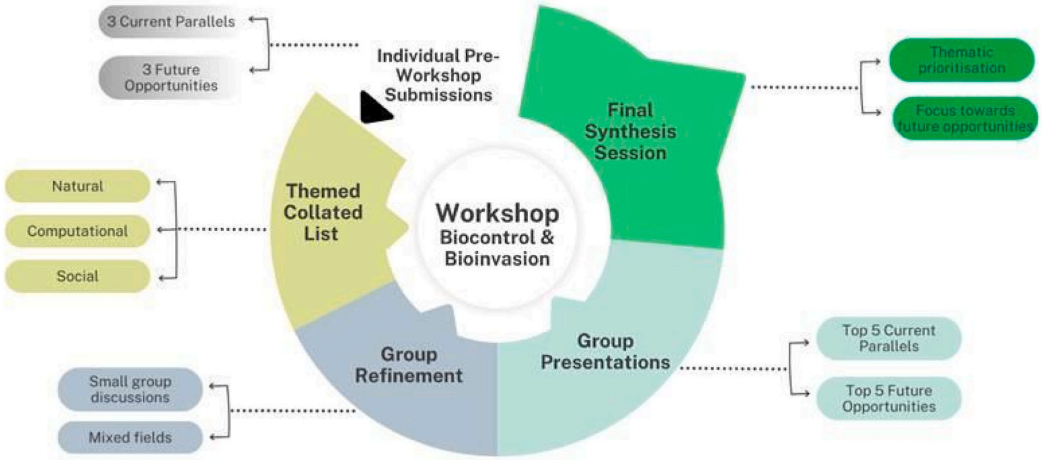

**Fig. 1.** Flowchart showing summary of workshop expert elicitation process. Before the workshop, participants were requested to submit independent lists of three current parallels and opportunities with a brief justification for each. These lists were collated, synthesised thematically, and presented back to all participants at the start of a two-day in-person workshop. During the workshop, individual groups with representatives from biological control (biocontrol) and invasion (bioinvasion) sciences further prioritized their top five current parallels and future opportunities, before feeding back to the whole group. A final synthesis session across participants produced a targeted list of themes elucidated in the present paper, where future opportunities were prioritized.

opportunities proposed, to produce a top five of each to feed back to all groups in plenary. Third, a final synthesis session across all participants identified overlaps and amalgamated the topics presented by the groups into the three themes (natural, computational, and social) discussed in the present paper. This synthesis session was chaired to ensure that each group had equal opportunity to present their suggestions, which were subsequently grouped into topical themes in a non-ranked manner, thereby ensuring that there was broad agreement across participants and enabling inclusiveness with regards to suggestions. During this final session, it was ultimately agreed that there was a stronger weighting towards future opportunities over current parallels, with our focus therefore placed on the former. We thus present these opportunities across natural, computational, and social axes, with the aim to foster improved discussion, collaboration, and knowledge exchange between these research areas. The highlighted areas from our elicitation exercise should not be interpreted as an exhaustive list, but rather as a series of pertinent parallels from our perspective.

## 2. Natural dimensions

### *2.1. Climate change*

Global climate is rapidly shifting, with increasing temperatures, precipitation intensity, sea levels, and severity of extreme weather events, such as heat waves, cold snaps, and flooding (Sun et al., 2020). These changes are likely to directly mediate success and impacts of introduced populations (both positive and negative), with effects from individual to ecosystem levels. The geographical range limit of biological control agents and invaders is dependent on their physiological tolerance to shifting environmental conditions, underpinning the need to incorporate thermal responses in biogeography. These climatic changes can also affect phenology between biological control agents and their targets, for example, with herbivore phenology progressing faster than that of plants owing to their higher thermal sensitivity (Korner and Basler, 2010). As a result, climate matching assessments are now an integral component of pre-release evaluations for biological control agents, or are used in post-release evaluations to understand establishment failures. At the same time, thermally-driven biological invasions are projected to increase, presenting possible increasing risks to ecosystem services, socio-economies, and biodiversity, while biological control agent efficacy may also be affected. Moreover, disruptions to trophic dynamics as a result of introduced organisms can compromise ecosystem services provided by native natural enemies, such as through pronounced intraguild predation, selective feeding, or competition (Carneiro et al., 2025), thus affecting biotic resistance.

Species distribution models (SDMs) are valuable tools for understanding the current and future potential distribution of both biological control agents and invasive species. These models help to allocate and optimize tools and resources in border surveillance by understanding which geographic areas are most climatically suitable for a given species, determining future spread potential, and identifying suitable climate niches where taxa have a higher likelihood of establishment (Lantschner et al., 2019). However, evidence from biological invasions shows how niche shifts can compromise the transferability of these models (Liu et al., 2022). While niche shifts have been viewed as being unlikely under current best practice for biological control applications that use highly specialist agents (Heimpel and Cock, 2018), they should not be discounted in biological control applications. This is particularly pertinent concerning target biota such as insects, where host specificity testing is more challenging, as well as under climate change conditions that can reshape species distributions and ecological interactions (Simberloff, 2012). Indeed, climate change and associated environmental alterations pose a particular challenge to predicting biological control and invasion outcomes and constitutes a major growth area in both fields, as range shifts of various biota can obfuscate predictions based on assumed stable climatic niches. Phenological, interaction strength, and life history trait changes — alongside undesirable spread to unintended regions by biological control agents — can also result from climatic alterations and drastically affect ecological predictions and thus practical outcomes (Simberloff, 2012).

Species distribution models such as MaxEnt (Phillips et al., 2006) have nevertheless been routinely used to analyse climatic suitability of classical biological control agents. For example, they have been applied considering three parasitoids, *Megarhyssa nortoni*, *Ibalia leucospoides*, and *Rhyssa persuasoria*, that were introduced in the Southern Hemisphere for biological control of pine pest, *Sirex noctilio*. These models successfully predicted the establishment of *I. leucospoides* and *M. nortoni* in their current regions, demonstrating the importance of climatic factors in the success of biological control programmes (Mukherjee et al., 2021). Biological control agents with a strong climatic match between native and release locations establish more readily and become more effective than those with a weaker match (Sun et al., 2017). For example, Minghetti et al. (2020) used environmental niche models to identify areas within the introduced range of the shrub, *Solanum mauritianum* that are suitable for its biological control agent, *Gargaphia decoris*. Analyses demonstrated that the entire introduced range of *S. mauritianum* was suitable for *G. decoris* under current and future climatic scenarios, indicating a potential for successful control. Thus, climate matching proves valuable in identifying suitable regions for biological control agent release, and explains failures in establishment, informing both biological control and invasion science (Sun et al., 2017; Harms et al., 2021). Joint species distribution models have recently emerged as a novel analytical framework that can integrate species interactions into metacommunity and macroecology, providing a more realistic forecast of establishment likelihood (Pichler and Hartig, 2021).

Climate change can reshape invasion pathways by altering ecosystem abiotic conditions and biotic relationships. For example, melting sea ice opens new shipping routes, creating additional pathways for invasion, while warmer temperatures can facilitate warm-adapted invaders to further expand their distributions (Nong et al., 2019). The isotherm tracking hypothesis suggests that 'neo-native' species will also 'naturally' shift their ranges in response to changing temperature gradients. These shifts include movement to higher latitudes for terrestrial organisms, upslope movement for terrestrial and freshwater species, and deeper habitat ranges for aquatic organisms (Rubenstein et al., 2023). Such changes are expected to influence trophic interactions and ecosystem structures in terrestrial and aquatic biomes, with wide-reaching implications for ecosystem resilience and function (Sun et al., 2020). Moreover, they can interact with other environmental changes within a multiple stressor framework, further complicating ecological outcomes. Lastly, climatic changes could also drive movements of natural enemies into invaded areas, thereby changing ecological outcomes.

### *2.2. Research scales*

The scale at which ecological studies are conducted significantly influences the outcomes and applicability of findings (Tscharntke et al., 2007). Research conducted across different organizational, trophic, spatial, temporal, and geographical scales can yield varying results, impacting the interpretation of ecological interactions, species responses, and management strategies (Fortin et al., 2005; Tscharntke et al., 2007).

Biological control and biological invasion are intrinsically linked by scale, but also differ in important ways. Biological control efforts often start small by design (e.g., host-specificity trials in greenhouses or quarantine labs) but can scale dramatically when successful. Notably, the use of *Cactoblastis cactorum* against prickly pear (*Opuntia stricta*) in Australia is an example of biological control operating at an enormous scale, covering millions of hectares (Zimmermann et al., 2004). This means that biological control can be both hyper-local and broadly dispersed. Initial releases often occur at landscape or sub-landscape scales, followed by evaluation of agent establishment and spread (which can include undesirable locations for classical applications). Success hinges on both spatial match with the target population and the broader landscape context, including climatic suitability. Similarly, invasion events often begin at small unnoticed scales (i.e., 'sleeper populations'), arising from a single introduction, but can rapidly expand to continental or even global levels through natural dispersal, trait changes, and anthropogenic movements (Spear et al., 2021). In invasion science, research often focuses on broader global, national, or regional levels, while management solutions, including biological control options, are often implemented at a landscape level, resulting in discrepancies between theory and application (Esler et al., 2010). Like invasions, which may require multiple introductions from distinct populations to succeed, biological control often requires concerted effort over multiple releases to achieve establishment (Abram and Moffat, 2018); indeed, repeated release efforts underpin augmentative biological control efforts.

Both biological control and invasion science research is disproportionately concentrated in developed countries, leaving Africa, parts of Asia, Central and South America, and many island nations underrepresented (Bellard and Jeschke, 2016; Pyšek et al., 2008). Biological control programmes are often best funded and implemented in countries with existing regulatory and quarantine infrastructure, yet, many of the biodiversity hotspots most affected by invasive species remain underrepresented. This geographical bias stems from limited funding and, in some cases, underdeveloped academic and research systems (Pyšek et al., 2008). This leads to an imbalanced understanding of mechanisms and a lack of knowledge regarding regionally-specific biological control options and invasion dynamics (Pyšek et al., 2008). Since invasions do not adhere to political boundaries, this disparity can delay invader detection and management in vulnerable areas, potentially worsening invasion impacts (Bellard and Jeschke, 2016). Addressing this requires increased research funding in developing countries, promoting international collaboration, and strengthening of academic infrastructure (Measey et al., 2019). Despite this, some of the most successful biological control applications have occurred in Africa and the Asia-Pacific (Mason, 2021). Moreover, many regions (e.g., the European Union) have adopted precautionary principles with regards to classical biological control, resulting in risk-averse attitudes that have stalled releases in the last three decades and potentially yielded opportunity costs.

Temporally, biological control programmes often operate on extended timescales, spanning decades from discovery, testing, and release to population-level impact (van Lenteren, 2012). Some agents exhibit time lags before desired impacts are observable, leading to perceptions of inefficacy unless long-term monitoring is in place. However, when successful, biological control can provide enduring suppression and dynamic equilibrium, as seen with *C. cactorum* in Australia or *Uroplata girardi* against *Lantana camara* in South Africa (Zachariades et al., 2017). These long-term outcomes can contrast with invasion events, which often involve sudden and acute shifts. Nevertheless, biological invasions can also be associated with substantive time lags to proliferation and impact, with multi-decadal sigmoid population and impact dynamics identified across taxa (Soto et al., 2023). Environmental changes or arrival of new genetic material have been identified as catalysts for rapid surges in invasive populations and their potential impacts (Spear et al., 2021). While these processes likely also alter biological control agent efficacy, it is possible that population dynamics of biological control agents follow a shorter trajectory (i.e., reduced time lags) due to the intensity of pre-introduction trait selections that could prime performance immediately after introduction.

Invasion science relies heavily on stage-based frameworks to understand the process of biological invasion, with the current framework consolidated into four steps: transport, introduction, establishment, and spread (Blackburn et al., 2011). This framework further informs on the management required to address biological invasions at different stages, as well as the primary reasons for their failure. While biological control often circumvents initial invasion stages through intentional release or promotion, there are opportunities to draw from these stages, and particularly the reasons for invasion failure, to mechanistically understand the challenges that biological control agents face when introduced and the potential barriers to their success (Zenni and Nuñez, 2013). This opportunity is also reciprocal, as invasion scientists can draw from the reasons for success or failure that are often well-documented in biological control programmes.

The spatio-temporal scale of biological control and invasion science research is often limited (Becker et al., 2019; Gonzalez et al., 2020). Spatially, biodiversity processes can differ between local and regional scales, as species interaction networks tend to be locally nested but regionally modular, reflecting distinct ecological and evolutionary dynamics (Delmas et al., 2019; Gonzalez et al., 2020). Temporally, long-term data are crucial for detecting patterns and mechanisms behind large-scale biodiversity changes, such as the global insect decline (Wagner et al., 2021; Zhou et al., 2023). However, limited funding, logistics, and deadlines often restrict the scope of research (Reynolds-Hogland and Mitchell, 2007). Consistent funding, stakeholder engagement, and collaborative efforts, such as combining datasets across studies, can help to overcome these constraints and expand the spatiotemporal scale of research (Heffernan et al., 2014). To fully understand invasion dynamics, research must consider these cross-scale interactions.

Biological invasions can impact biodiversity across various organizational scales, altering genetic, phylogenetic, taxonomic, and functional diversity. At the ecosystem level, they disrupt trophic networks that form the functional basis of ecological interactions. Invasions can permanently change trophic interaction strengths, modify connections, or cause species loss (Wainright et al., 2021). The efficacy of biological control releases and effects of invasion events are thus inherently multi-scaled, complex, and diverse considering both direct and indirect effects. Both biological control and invasion science require research-scaling that aligns with the complex nature of ecological processes. Mismatches between study scale and management needs, as well as between management actions and ecosystem responses, along with geographical research biases, limit effective interventions. Addressing these mismatches requires embracing cross-scale thinking, such as integrating short-term trials with long-term monitoring, or local release data with regional invasion models. This requires uninterrupted budgets, as well as expanding research efforts across spatial, temporal, and organizational levels, particularly in underrepresented regions, to enhance our ability to predict, mitigate, and manage the impact of introduction events.

### 2.3. Ecological surprises

There is a rich potential for the development of theory that explains unexpected indirect impacts ('ecological surprises') of biological control agents, and particularly those stemming from early releases that lacked the rigorous pre-release testing of modern times, such as the cane toad and mosquitofish (Heimpel and Cock, 2018). One important finding from invasion science is the immense potential scope of indirect effects of introduced species (e.g., Traveset and Richardson, 2006; Koel et al., 2019), which suggests that non-target effects of introduced biological control agents could be far more diverse and frequent than is currently documented (Simberloff, 2012). A common conception is that non-target effects are almost always caused by generalist species with broad host repertoires, but some case studies challenge this view (Pearson and Callaway, 2003). A classic example of cascading non-target impacts is the unauthorized introduction of *Myxoma* virus to the UK to control rabbits. Rabbit grazing creates patches of short grass, which favors ants that have a mutualistic relationship with caterpillars of a rare butterfly in the UK. The decline of the rabbit population thus ultimately contributed to the butterfly's local extirpation, which has, however, since recovered following reintroduction (Elmes and Thomas, 1992). Similarly, gall flies released to the southwestern U.S. to control an invasive spotted knapweed (*Centaurea maculosa*) became abundant on the plants and thus provided a novel food source for deer mice (*Peromyscus maniculatus*) — a non-target species — which are the primary reservoir for hantavirus in the region (Pearson and Callaway, 2003). Infected deer mice became more abundant in the presence of gall flies, thereby increasing human disease risk.

The likelihood of cascading impacts could depend on the interaction strength between the agent and both target and non-target species (Pearson and Callaway, 2003). Interaction strength is context-dependent, subject to the influence of local environmental variables. A predictive understanding of context dependencies, and hence some of the factors and mechanisms contributing to unexpected impacts, could be enhanced through consideration of the Environmental Matching Hypothesis — a conceptual framework for experimental design and predictions (Ricciardi et al., 2013). The hypothesis is based on the premise that although myriad environmental variables can influence the performance of an introduced species, often only one or a few of them explain most variation in performance across space and time. This highlights the potential for an introduced biological control agent to have substantively different effects across a physically heterogeneous ecosystem or multiple ecosystems; for example, the same introduced species can be a superior intraguild predator at one site and an inferior predator in another site, along a physicochemical gradient (e.g., Kestrup and Ricciardi, 2009). A related concept is the 'sleeper cell' phenomenon, in which introduced species that are apparently innocuous for long periods of time are triggered to become invasive and damaging, owing to an environmental change (Spear et al., 2021).

It has been hypothesized that the risk of non-target impacts is higher in natural ecosystems versus human-disturbed ones because natural ecosystems can include species-rich communities with a higher diversity of non-target species and indirect interactions (Heimpel and Mills, 2017). One could expand this hypothesis to also consider the possibility of interactions with external stressors that could synergistically amplify the influence of the biological control agent. Conversely, invasion theory suggests that diverse systems might also have higher biotic resistance to the biological control agent (especially if introduced classically) and could plausibly dampen its effects through antagonistic interactions (Ricciardi et al., 2013). Contrariwise, species-rich ecosystems and diverse landscapes can also inherently increase habitat availability and resilience for various agents, particularly when viewing conservation biological control through an ecosystem services lens. In that case, the fortified biotic resistance conferred through integrated biological control in biodiverse systems could dampen risks from non-target ecological impacts, and help to ensure community stability and various forms of population suppression over the longer term. Indeed, more recent paradigms in biological control seek to explicitly consider risks and benefits concurrently, such that decisions can actively minimise the former and maximise the latter (Heimpel and Cock, 2018; but see Simberloff, 2012 concerning challenges in monetisation of ecological effects). While species-rich systems might in some cases offer greater opportunities for a generalist agent to expand its host repertoire, anthropogenically disturbed systems could impose selective pressures to increase the environmental tolerance of the agent such that it can increase its habitat range; the rationale for this outcome stems from the Anthropogenically Induced Adaptation to Invade (AIAI) hypothesis and the concept of the bridgehead effect — in which an introduced population undergoes evolution that increases its colonization potential and thus becomes the source of future invasions elsewhere (Hufbauer et al., 2012).

To improve risk assessment, both biological control and invasion sciences must address context dependence of indirect effects. Such context-dependence can drastically change the sign and strength of ecological effects (Ricciardi et al., 2021). Through invasion science, biological control science is offered insight into potential indirect impacts, as well as underexploited hypotheses and concepts (e.g., AIAI; Environmental Matching). Conversely, biological control science offers cases in which time-since-introduction, origin, genetics, propagule pressure, and colonization pressure of the introduced organism(s) are known and can be used in meta-analytical tests of hypotheses. Biological control also offers post-release evaluations; however, an important consideration is the timing of these evaluations. Delayed indirect effects, such as post-establishment evolution, invasion meltdowns, or environmental triggers that cause biological control agents to become invasive, may take years or decades to emerge (Spear et al., 2021). Therefore, risk assessments should incorporate long-term post-release evaluations to identify any delayed indirect impacts of biological control agents (Barratt et al., 2018; Carson et al., 2008). While evidence suggests that instances of unintended negative consequences reported from biological control agents have declined since the 1960s from both direct and indirect mechanisms (Neuenschwander, 2001; Heimpel and Cock, 2018), given the breadth and complexity of ecological interactions in natural systems, an increased understanding of the context-dependence of indirect effects could help to reduce future risks and make improved predictions across both fields (Simberloff, 2012).

## 3. Computational dimensions

### 3.1. Developing technologies

A crucial yet ever-changing aspect of biological control and invasion science is the development of technologies used to capture and measure raw data, monitor sites, process data, model results, and make useable predictions for future applications. Several key parallel developing technologies between the disciplines of biological control and invasion science include the application of high-throughput genetic sequencing, advanced remote sensing, machine learning, and improvements in data accessibility.

The application of molecular biology techniques, in particular genetic sequencing technologies, are commonplace in many biological fields, including biological control and biological invasion. Various genetic markers are routinely used to study population genetics, each of which offer differing degrees of variability and precision by targeting specific regions of DNA by PCR (i.e., mtDNA or cpDNA) or analyzing genomic characteristics using specific techniques, such as restriction fragment length polymorphism analysis, amplified fragment length polymorphism analysis, or microsatellites (Le Roux and Wieczorek, 2009).

Fitzpatrick et al. (2012) highlighted the fact that in biological invasions (and similarly in the introduction of biological control agents), when considering the historical timescale of an invasion, the rate of mutation and genetic drift for most organisms may be insufficient. As such, this lack of required genetic resolution may leave many questions unresolved (Cuthbert et al., 2025). However, significant advances have been achieved in recent years in high-throughput genetic sequencing (Hu et al., 2021, Santam et al., 2023). This explosion in sequence data may enable the identification of novel methods for evaluating population genetics in the fields of biological control and biological invasion, providing the necessary resolution. Coupling these advancements to the array of novel applications these technologies bring, including but not limited to transcriptomics, epigenetics, and metagenomics (Santam et al., 2023), researchers may further identify novel research methods and approaches. It is important that the impact of high-throughput sequencing not be overestimated, but large data-driven science may provide valuable insight in future years when coupled with other developing technologies.

As with genetic information, collecting spatial data on biological invasions is important both for understanding occurrence and spread, as well as for guiding management interventions such as early detection and control. Lessons could also be learned and tools applied between fields concerning the evolution of traits with the spatial diffusion of populations from introduction points (Phillips, 2025), with intermediate (compared to fast or slow) spread rates posited to maximise biological control agent establishment and spread probabilities by mitigating Allee effects and genetic bottlenecks (Heimpel and Asplen, 2011). Moreover, these relationships could inform risk of spread to new unintended areas in biological control releases, through a combination of natural dispersal and human movements (Simberloff, 2012). Despite long-standing challenges in remote sensing, such as limited image resolutions, continued improvements in sensor technology, increased data availability, and cloud-based computing platforms have increased the utility of remote sensing by providing synoptic, repeatable, and cost-effective monitoring solutions, including assessments of spread rates (Woodcock et al., 2020).

While utilized by both fields, remote sensing plays a more prominent role in invasion science, where it is used to map species distributions, monitor spread dynamics, and model habitat suitability (Vaz et al., 2019). In contrast, biological control research primarily relies on localized assessments of agent establishment and impact, with remote sensing playing a more indirect role, such as evaluating target species recovery post-agent release (Coetzee et al., 2022). Biological control stands to benefit from utilizing remote sensing in post-release monitoring by providing long-term, landscape-scale assessments of impact and control. For example, satellite-based remote sensing was used to monitor the extent and health of water hyacinth in Hartbeespoort Dam, South Africa, to evaluate the effectiveness of its biological control programme (Coetzee et al., 2022). By integrating satellite-derived cover estimates with monthly field surveys, the study demonstrated how remote sensing information can provide historical and near-real-time insights into invasion dynamics while complementing field data collection, thereby enhancing assessments of biological control efficacy. Similarly, Herbert et al. (2024) highlighted the importance of early intervention and continuous remote sensing monitoring of the biological control programme against *Salvinia molesta* using the biological control agent, *Cyrtobagous salviniae*, in Lake Ossa, Cameroon, where local livelihoods were threatened by the mats of weed covering the water surface, and where the endangered African manatee disappeared as a result of the invasion. They proposed that the integration of biological control and remote sensing technology is becoming more accessible and can be automated, and should therefore become a replicable model for future invasive weed programmes around the world. Future research can thus prioritize the integration of remotely sensed data with *in situ* monitoring to improve validation of control outcomes and inform adaptive management strategies.

Beyond remote sensing, 'sentinel' systems could be developed to monitor populations of biological control agents following their release or promotion in the environment. For example, sentinel plants that are highly susceptible to the biota that biological control targets could be established, with recruitment rates of agents and their efficacy subsequently monitored as a novel indicator of biological control success (Lovell-Read et al., 2023). In turn, these sentinel systems could provide an opportunity to test hypotheses around the context-dependence of biological control efficacy, through placing standardised sentinels in different environmental conditions (e.g., relative to agent release locations or human disturbance gradients). They thus serve as a novel metric for evaluating biological control success, moving beyond traditional measures like population suppression or agent establishment.

More broadly, the application of data science and machine learning techniques in invasion science and biological control has shown promising results, albeit these have yet to be fully demonstrated (Xiao et al., 2018; Segoli et al., 2023; Sittaro et al., 2023; Shen et al., 2024; Rojas-Sandoval et al., 2025). This is partially due to the need for more descriptive and detailed trait data for success and impact prediction in both fields (Segoli et al., 2023; Cuthbert et al., 2025) - such large scale data advances will elevate the relative importance of field-based biological observations. For example, machine learning models and big data analytics can enhance biological control outcomes by identifying optimal release strategies and trait profiles, thereby improving resource allocation and implementation efficiency (White et al., 2022). Moreover, emerging opportunities around automatic monitoring and detection are harnessing deep-learning (informed by e.g., acoustics, radar, eDNA, and image recognition) for improved population tracking, as well as behavioural monitoring, species interaction network analyses, species identification and discovery, and citizen science initiatives (van Klink et al., 2022; Fricke and Olden, 2023). Similarly, genetic data-driven approaches can enhance our understanding of invasion pathways and improve predictions (Brazier et al., 2022). These developing technologies, as in molecular biology and remote sensing, will facilitate better real-time monitoring, adaptive management, and improved ecological modelling across both disciplines.

### 3.2. *Taxonomic imperative*

Taxonomy is one of the oldest disciplines in science, and aims to describe and classify organisms into discrete categories (Britz et al., 2020). Historically, this was achieved primarily through the use of morphological characteristics to discern between evolutionary groups, while modern taxonomy tends towards an integrative approach that incorporates genetic, ecological, behavioral, and other informative data as additional independent lines of evidence (Karbstein et al., 2024). The importance of taxonomy cannot be overstated, considering that some biodiversity estimates have suggested that less than 20% of the extant species on Earth have been formally described (referred to as the "taxonomic impediment") (Costello et al., 2013; Liu et al., 2022). Taxonomic expertise is particularly relevant in the applied fields of conservation and biological control and invasion science, where the correct identification of target taxonomic groups lays the fundamental groundwork in research programmes and management plans (Shimbori et al., 2023; Marvaldi, 2024).

The success of a biological control programme relies on the correct matching of target organisms to their natural enemies, ensuring that the most damaging and host-specific control agent is selected (e.g., Barratt et al., 2018), and that post-release evaluations are accurate. Similarly, and often overlapping with biological control research, invasion science relies on accurate taxonomic identifications to assess factors such as the impacts of invasions on ecosystems, predictions of invasive potential, and the compilation of risk assessments and prioritization lists. Both disciplines face the difficulties associated with the practical applications of taxonomic classification methods, particularly with regards to the determination of inter-and intraspecific taxonomic boundaries and the choice of meaningful and consistent terminology to refer to distinct taxa at differential stages of evolutionary divergence (e.g., the use of terms such as populations, lineages, biotypes, species, and evolutionary units; see Downie, 2010). Additionally, the hybridization of invaders with native species, and between different biological control agent populations (or closely-related species), poses further challenges to identification and the unpredictable impacts on ecosystem dynamics, such as competition and feeding behavior. These impacts can significantly affect the performance of biological control agents, as well the direct and indirect effects of invaders in novel environments.

The rapid growth of genetic technologies such as next-generation sequencing (NGS) platforms, and the overall shift towards genome-wide applications rather than conventional single-gene analyses (e.g., COI barcoding) is already changing the nature of research outputs in the domains of both biological control and invasion science (Leung et al., 2020). The recent uptake in RADseq methods exemplifies this (Li et al., 2024; McGaughran et al., 2024; van Steenderen et al., 2025), with a focus on much larger datasets for detecting population-level differences. Other applications include genome assembly (Huang et al., 2024; Wang et al., 2024), gene mapping to identify genomic regions associated with specific phenotypic traits (i.e., quantitative trait loci) (Whitney et al., 2015; Prapas et al., 2022), gene expression (e.g., transcriptomics and proteomics) (Benoist et al., 2017; Marin et al., 2020; Vaughan and Dhami, 2025), and gene editing (Harvey-Samuel et al., 2017; Leung et al., 2020; McGaughran et al., 2024). This, in addition to the exponential advancements in artificial intelligence (AI) (e.g., image recognition tools and genome assembly methods), will continue to offer new opportunities and insights into taxonomic knowledge gaps (Karbstein et al., 2024). These technological advancements also offer greater opportunity for interdisciplinary collaboration between biological control practitioners, invasion scientists, taxonomists, programmers, modelers, and molecular biologists, to ensure that these advancements attain the full scope of their potential. The advancements of NGS and AI tools have, however, also contributed towards a growing shortage of well-trained taxonomists (Engel et al., 2021), with a relatively lower value placed on traditional taxonomic work (Agnarsson and Kuntner, 2007). Both biological disciplines should take notice of this emerging trend and emphasise the incorporation of integrative taxonomic approaches going forward. This presents a further opportunity for biological control and invasion science to promote and secure funding for traditional taxonomic work.

As we look further into the future, advanced genetic technologies such as CRISPR and gene drives may dramatically alter the landscape of biological control (El-Awaad and Merzendorfer, 2025; Faber et al., 2025). CRISPR technology has already been applied to pest species (e.g., *Anopheles gambiae*), and could be similarly used to modify natural enemies, enhancing their effectiveness or ensuring that they exclusively target invaders without impacting non-target species. Gene drives, which propagate specific genes through populations, may offer a way to control or even eradicate invasions by altering their reproduction or survival traits (Ricciardi et al., 2017). However, the use of gene drives will require careful taxonomic consideration to ensure that gene-altered organisms do not negatively affect non-target species or ecosystems. The ethical and ecological implications of releasing genetically modified organisms into the wild highlight the continued importance of taxonomy in predicting and managing the potential risks associated with these new technologies. Taxonomy may be considered the foundation on which informed decisions by biological control practitioners and invasion scientists can be made, with many shared challenges and opportunities for their resolution that will result in enhancing the effectiveness of biological control, as well as early detection and rapid response programmes.

## 4. Social dimensions

### 4.1. Public awareness and collaboration

Public awareness and robust collaboration form a focal point between biological control and invasion science, necessary for both scientific fields to progress and to manage populations efficiently. Public engagement is essential to both disciplines to improve understanding, gather data, and generate support and potential funding for management strategies. The increasing awareness of the importance of reaching diverse audiences, including non-scientists, policymakers, and local communities, is a key parallel between the two fields (Jubase et al., 2021; Weaver et al., 2021). Both fields have to justify interventions, explain ecological risks and benefits, and gain public support for management actions. Conveying the importance of control efforts is necessary for achieving conservation goals (Pocock et al., 2024) and securing funding and access for research and application.

Both disciplines grapple with communication hurdles. Explaining the nuances of ecological interactions, potential non-target effects (in biological control), or the long-term negative or positive impacts of invasions can be challenging — particularly in the context of multiple stakeholders that can experience positive and negative effects from the same invasion, causing conflicts, engagement challenges, and potential management oppositions (Kourantidou et al., 2022). The overwhelming majority of contemporary science outreach is based on communication models that have been shown to be ineffective and can undermine public trust (Varner, 2014). Each field runs the risk of working in an 'ivory tower', losing touch with the public values and concerns, and ultimately limiting acceptance or engagement (Varner, 2014). Avoiding technical jargon and sharing findings in accessible formats are common imperatives.

Citizen science is an example tool that bridges both fields and can be effective for invasive species surveillance, management, and research, while providing large datasets (Pocock et al., 2024; Gervazoni et al., 2023). Platforms like iNaturalist are increasingly used in invasion science to monitor species distributions and report new incursions, although user behavior and potential data biases require consideration (Pocock et al., 2024; Di Cecco et al., 2021). These tools offer open-source data valuable for tracking species distribution, monitoring control agent establishment, and identifying new invasions (August et al., 2020; Cock et al., 2025; Di Cecco et al., 2021). The first study of its kind in Argentina used citizen science to improve the known and potential distribution of *Iris pseudacorus* (a flowering plant), which is a significant wetland invader (Gervazoni et al., 2023). SDMs using different datasets, including GBIF data, citizen science data, as well as survey data, showed that the citizen science-tailored approach provided more data over a wider geographical extent compared to other data sources. In combination with survey data, these records were used to highlight the extent and potential further invasion by this highly invasive plant species. A further example is the use of participatory field campaigns with the general public to better understand the distribution, abundance, and habitat preference of invaders, as well as to implement novel integrated biological control tools that include fungal biopesticides (Ziter et al., 2021; Nouri-Aiin and Görres, 2021; Pandit et al., 2022). In these cases, citizen science is particularly important to challenge perceptions for 'socially cryptic' taxa, which are broadly seen as functionally important. This includes invasive earthworms that can be beneficial for agriculture and indicate soil health, but can also be highly ecologically damaging in invaded soils (Frelich et al., 2019). A similar point holds for charismatic taxa that could be perceived positively by the public despite their environmental harm. Indeed, species characteristics can contribute to acceptability of management among the general public and the level of opposition received (Jarić et al., 2020).

A compelling example of successful community engagement, specifically within biological control, is the management of water hyacinth (*Pontederia crassipes*) at Hartbeespoort Dam, South Africa. Faced with overwhelming infestations, a community-driven initiative, supported by researchers, established satellite rearing stations for the biological control agent *Megamelus scutellaris* (Moffat et al., 2024). The continual and inundative releases of high numbers of agents, facilitated by mass-rearing efforts (Hill et al., 2021) that included community rearing stations, contributed significantly to the success in controlling water hyacinth at the Dam (Coetzee et al., 2022; Moffat et al., 2024). This collaboration demonstrably reduced water hyacinth cover, showcasing how public investment and agency can directly contribute to successful biological control outcomes (Moffat et al., 2024; Coetzee et al., 2022).

While successful engagement initiatives demonstrate what is possible under favourable conditions, social responses to biological control and invasion management are also frequently characterized by resistance, mistrust, and conflict. This is especially true when ecological objectives intersect with economic, cultural, or aesthetic values (Kourantidou et al., 2022). In such cases, even well-designed management programmes may stall or fail due to lack of social licence rather than technical feasibility. Furthermore, experiences from both fields show that awareness-raising campaigns do not necessarily translate into behavioural change, and in some instances have reinforced distrust when communities feel excluded from decision-making processes (Varner, 2014). So, while citizen science constitutes one effective route to improving public awareness, more wide-reaching approaches such as information campaigns and education are also invaluable, provided that they are implemented alongside initiatives that bring together multi-stakeholder groups to identify information gaps, co-design interventions, and resolve conflicting perspectives. Furthermore, science communication articles should also be aware of the terminology used, and avoid overly emotive language in order to manage expectations and reduce conflict.

Significant opportunities exist for biological control and invasion science to collaborate more closely on public awareness and engagement strategies. Developing joint communication strategies could be highly effective. The fields can present a stronger, more consistent message by speaking with a more unified voice about the issue of invasions and the benefits and potential costs of biological control. This includes collaborative efforts targeting schools, utilizing social media effectively, and working with traditional media to counter misinformation and denialism using shared, accessible language (Weaver et al., 2021).

Future citizen science initiatives could be designed to serve both fields explicitly. Programmes could train volunteers to monitor not only the presence and impact of invasive species but also the establishment and effectiveness of introduced biological control agents, as demonstrated by tracking agents using citizen science images and DNA barcodes (Cock et al., 2025; Pocock et al., 2024). This integrated approach would provide richer datasets for adaptive management and streamline public participation efforts.

Both fields recognize the imperative to work more closely with other disciplines, particularly the social sciences, communication experts, and economists, to better understand the socio-economic drivers and consequences of invasions and control actions, and to design more effective engagement approaches (Weaver et al., 2021). This point could extend to value chains that can contribute to biological invasions (e.g., agriculture), thereby helping to target management efforts along the riskiest parts of the introduction pathway. Recent efforts through the 'InvaCost' project that harnessed natural and social sciences globally have bolstered public and decision maker awareness by placing a monetary value on the economic costs of biological invasions, thereby making these effects more tangible (Diagne et al., 2021), while also considering the concurrence of beneficial effects between sectors (Carneiro et al., 2024). Using monetary costs and cost-benefit analyses considering interventions could similarly be a useful means to improve support for biological control initiatives, given the predominantly negative consequences of invasions (Carneiro et al., 2024) and potential low cost of long-term biological control. In particular, models have been developed to quantify the 'cost of inaction' of management actions towards biological invasions as well as forecast their damages, which can motivate timely interventions in both fields through quantification of beneficial cost savings (Ahmed et al., 2022). This is especially relevant for taxa that can cause substantive impacts through cascading mechanisms across biotic and abiotic system components (Frelich et al., 2019), as well as in cases where costs for novel product development (e.g., biopesticides) seem prohibitively high relative to current damages. In biological control, assessments of benefits are currently inconsistently included in pre-release risk assessments, with longer-term assessments hampered by short-term funding cycles that preclude comprehensive evaluations of ecological and socio-economic returns. Therefore, a multidisciplinary awareness of costs and benefits can help to improve management strategies (Abram and Moffat, 2018). Furthermore, strengthening international collaboration, particularly between the Global North and South, is crucial. Joint efforts can help address the uneven distribution of research capacity and funding (Weaver et al., 2021), fill knowledge gaps in under-researched regions, facilitate access and benefit-sharing agreements, and leverage large databases of mutual relevance, potentially through greater co-development with public stakeholders globally (Pocock et al., 2024).

Moving beyond raising awareness, future efforts should focus on fostering public agency and co-designing solutions. The Hartbeespoort Dam example illustrates the power of community involvement in implementation of control methods through establishing a 'community of practice' (Moffat et al., 2024). Local stakeholders gain empowerment through collaborative projects, which enable them to actively monitor and make management decisions and evaluate different approaches, while building shared responsibility and stewardship. The collaboration involves joint work on tool development and application through transdisciplinary methods, which results in user-friendly tools that fulfill community requirements. Particular care is, however, needed when engaging with multiple stakeholders that may simultaneously incur benefits and costs from management initiatives.

### 4.2. *Unifying terminology and coordinating policy*

Despite the overlap in their goals, biological control and invasion sciences have developed distinct terminologies, often leading to redundancy and confusion. Unifying terminology between these fields is essential to enhance communication and improve the effectiveness of research, policy and management strategies. However, doing so would require the breaking down of institutional, regulatory, and cultural barriers that sustain divergent vocabularies. The disjointed nature between the fields of biological control and invasion science is evident in the terminology used to describe similar concepts. For example, the hypothesis of how native species influence the establishment of non-native species is commonly termed 'biotic interference' in biological control studies (Goeden and Louda, 1976) and 'biotic resistance' in invasion literature (Levine et al., 2004). Other examples include 'inundative release' vs 'propagule pressure', 'multiple agents' vs 'colonization pressure', 'host specific' vs 'monophagous', and 'broad host range' vs 'polyphagous', respectively, between biological control and invasion sciences. Discrepancies such as these complicate reviews and meta-analyses, as researchers must navigate and reconcile differing terms to synthesize findings effectively (Herrando-Pérez et al., 2014). Moreover, the lack of standardized terminology can lead to misunderstandings and misinterpretations of research outcomes, and potential misrepresentations in public science communication (Janovsky and Larson, 2019).

Creating a unified terminology for biological control and invasion offers several advantages. First, it reduces redundancy, ensuring that similar concepts are described consistently across studies. This improves the clarity and precision of scientific communication, facilitating more effective collaboration and knowledge sharing. Secondly, standardizing terms enhances the interpretability of statistical models and their coefficients, allowing for more accurate comparisons and integrations of research findings across the two fields (Soto et al., 2024). Despite the clear benefits, unifying terminology presents several challenges. One major obstacle is the inconsistent enforcement of top-down term changes by journals. For example, some journals have moved away from using the term 'alien' to describe non-native species, while others continue to use it (Occhipinti-Ambrogi and Galil, 2004; Robinson et al., 2016). This inconsistency is also common among regional policy nomenclature, further creating confusion and hampering efforts to standardize terminology and implement management (Soto et al., 2024; Ahmed et al., 2025). Another challenge is the need to include non-English terms in the unified glossary, ensuring that research from non-English-speaking regions is accurately represented and integrated. Moreover, changing deeply entrenched terminology would be challenged by a variety of existing cultural, institutional, and political barriers, thus requiring long-term planning. This is because regulatory agencies often operate under legal definitions that are slow to change; journals and professional societies reinforce disciplinary norms through editorial conventions; and practitioners are trained with field-specific jargon that shape how problems are framed and solutions evaluated. These realities mean that our call for unifying terminology is unlikely to occur through top-down standardization alone, but must be supported by practical, co-ordinated, and incremental mechanisms that work within existing systems.

This can be achieved through collaborative efforts among researchers, journals, and institutions, including the development of transdisciplinary working groups to consider how terminology is applied between fields. More specifically, we propose: (1) the establishment of transdisciplinary terminology panels within existing professional societies (e.g., IUCN and IOBC); (2) journal-level policies that encourage cross-referencing of equivalent concepts, promoting gradual convergence; and (3) funder-led incentives that promote shared language in interdisciplinary projects, thus providing tangible incentives for researchers to adopt shared language. Complementing these structural approaches, targeted training, and professional development can normalize bilingualism between fields, allowing researchers and practitioners to navigate divergent vocabularies without erasing disciplinary identities. Downstream, this could lead to policy documents that cross-reference common terminologies, and therefore reduce regulatory fragmentation over time. Successful examples of unified terminology in other scientific fields can serve as valuable case studies. For example, the standardization of terminologies in medical research has significantly improved the clarity and efficiency of scientific communication (Bodenreider, 2004). Similar strategies can be adopted in ecological research, with the potential to enhance the coherence and impact of studies on biological control and invasion. Researchers can also draw on examples from conservation biology, where consistent terminology has facilitated more effective policy-making and management practices (Salafsky et al., 2024). Applications in species delimitation exercises, and taxonomic classification more generally, provide further examples of the importance of the adoption of consistent terminology in the naming of taxa at varying levels of evolutionary distance (Downie, 2010).

Harmonization of terminology and actions could further allow for more cohesive policies to address biological invasions and promote effective biological control (e.g., within a ‘OneHealth’ framework; Schaffner et al., 2024). Government departments around the world are often separately assigned to biological invasions (e.g., conservation management for biodiversity and ecosystems) and biological control (e.g., integrated pest management for agriculture) issues, resulting in regulatory frameworks that are misaligned between the fields and potentially inefficient. Improved integration of policy towards management of invasions while considering biological control through natural enemies as a tool could thus reduce redundancy and improve efficiency in ecological management interventions. Although legislation on the prevention and management of biological invasions does exist, often the lack of financial and human resources to implement them on the ground makes it challenging to enforce regulations. Furthermore, it is important to coordinate the enforcement of actions against invasions in neighboring countries, as a species that is being controlled or eradicated in one country might simply reinvade from an invaded neighboring country. An excellent example of regional legislative collaboration is the European and Mediterranean Plant Protection Organisation (EPPO), responsible for European cooperation in plant health. Its objectives are “to protect plants, to develop international strategies against the introduction and spread of dangerous organisms and to promote safe and effective control methods”. The EPPO, which was founded in 1951 by 15 member states, has grown to today's 51 member countries, including nearly every country in the European and Mediterranean region.

Lessons could also be learned from biological control practitioners concerning regulated biosafety protocols that must be adhered to when rearing agents, which could in turn inform biosecurity practices to contain non-native species, prevent spread, and improve proactivity. For both fields, it is also important that well-intentioned policy frameworks do not overburden researchers and practitioners to the extent that they stifle rapid management actions, such as early detection and rapid response protocols for invasions that could include biological control interventions. Moreover, precautionary principles could thwart attempts to employ classical biological controls, even where non-target risk is very low (Heimpel and Cock, 2018). It is thus imperative to design sensible policies that ensure rigorous testing and holistic cost-benefit analyses before management actions are implemented, such that social and natural interests are best served.

## 5. Synthesis

Our perspective gives a structured overview of the current parallels and opportunities linking biological control and invasion sciences obtained through expert elicitation (Fig. 2). Core areas of overlap span ecological mechanisms (e.g., propagule pressure, colonization pressure, functional responses and enemy release), ecological consequences (such as indirect effects and unexpected trophic cascades), anthropogenic disturbances and environmental drivers (such as climate change and biotic resistance), computational advances (including remote sensing and machine learning), research dimensions, such as taxonomic precision and scale mismatches, as well as societal engagement. These domains intersect through shared theoretical frameworks and practical challenges, revealing strong parallels in success metrics, impact pathways, and risks. Furthermore, these parallels suggest that more bidirectional engagement between fields is not only possible, but also necessary to resolve discrepancies and make progress. Mechanisms to foster this are exemplified by the co-development of functional response metrics (e.g., RCP and RIP; Dick et al., 2017; Cuthbert et al., 2018; Box 1), with a particular future need to unify terminology, harmonize risk assessment protocols, and invest in interoperable data platforms and collaborative research agendas.

Integration of both research areas is particularly lacking within the socio-political dimension, neglecting key components such as the policy integration necessary for translating ecological findings into actionable frameworks across jurisdictions. Discussions on parallels on the socio-economic front, such as funding models, community livelihoods, and cost-benefit trade-offs, also require urgent development. Likewise, public awareness and collaboration, especially through citizen science and inclusive communication, are underrepresented, yet hold potential to bridge knowledge gaps and foster trust. Finally, broader anthropogenic disturbances beyond climate and habitat, such as urbanization, pollution, globalization, and infrastructure expansion, also require more explicit integration into future discussions, given their accelerating influence on species movement and ecosystem vulnerability.

Addressing these bidirectional areas is not just a matter of completeness, but of equity and sustainability. Research biases, whether geographic, taxonomic, or institutional, limit our collective capacity to respond to biodiversity challenges globally. Thus, tackling these biases by amplifying marginalized perspectives, investing in the Global South, and embracing diverse knowledge systems is crucial. By doing so, and by fostering a more integrated, inclusive, and responsive scientific dialogue, the biological control and invasion communities can meaningfully advance the sustainability agenda, ensuring environmental management strategies that are robust, just, and future-ready.

## CRediT authorship contribution statement

**Ross N. Cuthbert:** Writing – original draft, Visualization, Project administration, Investigation, Conceptualization. **Nompumelelo Baso:** Writing – original draft, Visualization. **Tressia Chikodza:** Writing – original draft. **Candice Coombes:** Writing – original draft. **Jane Doherty:** Writing – original draft. **Michael Githae:** Writing – original draft. **Tamzin C. Griffith:** Writing – original draft. **Marco R. Hernandez:** Writing – original draft. **Karla M. Jaschke:** Writing – original draft. **Michael D. Jukes:** Writing – original draft. **David Kinsler:** Writing – original draft. **Hugh J. MacIsaac:** Writing – original draft. **Hlumelo T. Mantshi:** Writing – original draft. **Pippa Muskett:** Writing – original draft. **Reyard Mutamiswa:** Writing – original draft. **Anthony Ricciardi:** Writing – original draft. **Guy F. Sutton:** Writing – original draft. **Deric V. Tanka:** Writing – original draft. **Jaqui van Dyk:** Writing – original draft. **Clarke van Steenderen:** Writing – original draft. **Jaimie T.A. Dick:** Writing – original draft, Conceptualization. **Julie Coetzee:** Writing – original draft, Conceptualization.

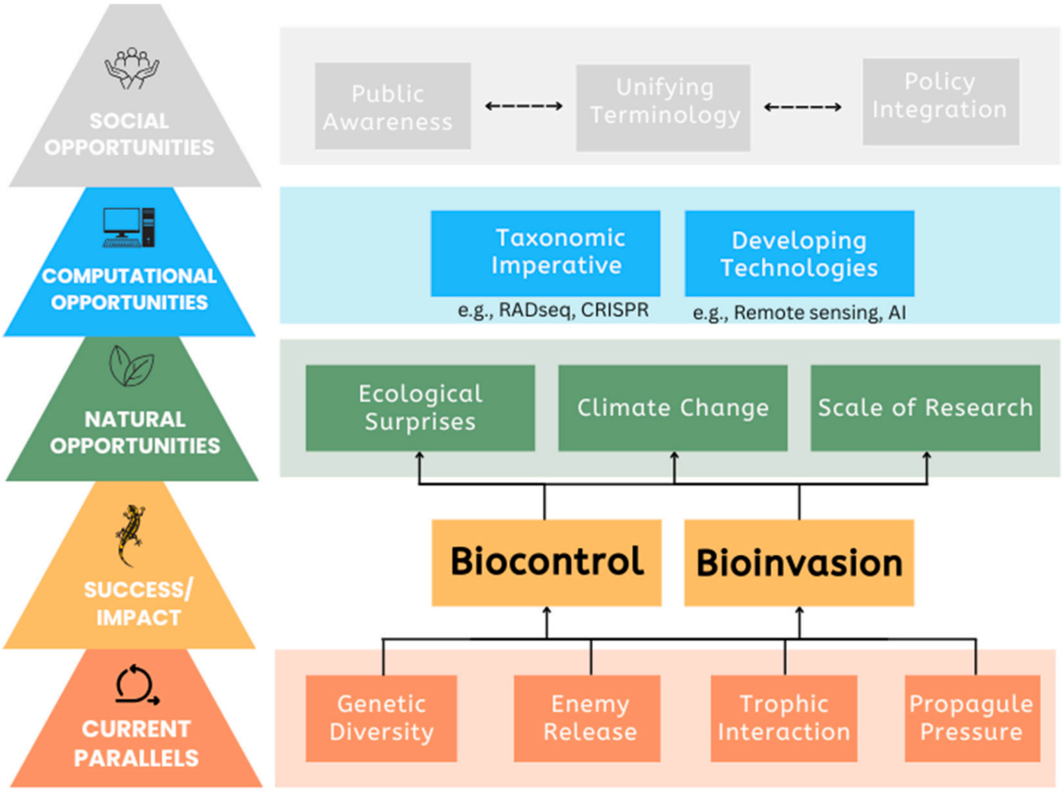

**Fig. 2.** Graphic summary of parallel concepts and future opportunities of biological control (biocontrol) and biological invasion (bioinvasion) sciences discussed in this perspective.

## 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.

## Acknowledgements

We acknowledge involvement of all participants at the workshop “Biological Control and Invasion Science: Parallel Concepts and Future Opportunities”, which was held at the South African Institute for Aquatic Biodiversity over 7–8th August 2024. RNC acknowledges funding by the Leverhulme Trust (ECF-2021-001). AR and HJM were supported by NSERC Discovery grants.

## Data availability

No data was used for the research described in the article.

## References

Abram, P.K., Moffat, C.E., 2018. Rethinking biological control programs as planned invasions. Curr. Opin. Insect Sci. 27, 9–15.

Agnarsson, I., Kuntner, M., 2007. Taxonomy in a changing world: seeking solutions for a science in crisis. Syst. Biol. 56, 531–539.

Ahmed, D.A., Hudgins, E.J., Cuthbert, R.N., Kourantidou, M., Diagne, C., Haubrock, P.J., Leung, B., et al., 2022. Managing biological invasions: the cost of inaction. Biol. Invasions 24, 1927–1946.

Ahmed, D.A., Sousa, R., Bortolus, A., Aldemir, C., Angeli, N.F., Błońska, D., Briski, E., et al., 2025. Parallels and discrepancies between non-native species introductions and human migration. Biol. Rev. 100, 1365–1395.

August, T.A., Pescott, O.L., Joly, A., Bonnet, P., 2020. AI naturalists might hold the key to unlocking biodiversity data in social media imagery. Patterns 1, 100116.

Barratt, B.I.P., Cock, M.J.W., Oberprieler, R.G., 2018. Weevils as targets for biological control, and the importance of taxonomy and phylogeny for efficacy and biosafety. Diversity 10, 73.

Baso, N.C., Bownes, A., Paynter, Q., Cartier, A., Hill, M.P., Coetzee, J.A., 2024. Biogeographical comparison of *Lagarosiphon major* between native South Africa and invaded New Zealand: a natural enemy release case study? Biol. Control 196, 105584.

Becker, D.J., Crowley, D.E., Washburne, A.D., Plowright, R.K., 2019. Temporal and spatial limitations in global surveillance for bat filoviruses and henipaviruses. Biol. Lett. 15, 20190423.

Bellard, C., Jeschke, J.M., 2016. A spatial mismatch between invader impacts and research publications. Conserv. Biol. 30, 230–232.

Benoist, R., Chantre, C., Capdevielle-Dulac, C., Bodet, M., Mougel, F., Calatayud, P.A., Dupas, S., Huguet, E., Jeannette, R., Obonyo, J., Odorico, C., 2017. Relationship between oviposition, virulence gene expression and parasitism success in *Cotesia typhae* Nov. sp. parasitoid strains. Genetica 145, 469–479.

Blackburn, T.M., Pyšek, P., Bacher, S., Carlton, J.T., Duncan, R.P., Jarošík, V., Wilson, J. R., et al., 2011. A proposed unified framework for biological invasions. Trends Ecol. Evol. 26, 333–339.

Bodenreider, O., 2004. The unified medical language system (UMLS): integrating biomedical terminology. Nucleic Acids Res. 32, D267–D270.

Brazier, T., Cherif, E., Martin, J.F., Gilles, A., Blanchet, S., Zhao, Y., Combe, M., et al., 2022. The influence of native populations' genetic history on the reconstruction of invasion routes: the case of a highly invasive aquatic species. Biol. Invasions 24, 2399–2420.

Britz, R., Hundsdorfer, A., Fritz, U., 2020. Funding, training, permits—the three big challenges of taxonomy. Megataxa 1, 49–52.

Carneiro, L., Hulme, P.E., Cuthbert, R.N., Kourantidou, M., Bang, A., Haubrock, P.J., Bradshaw, C.J., et al., 2024. Benefits do not balance costs of biological invasions. Bioscience 74, 340–344.

Carneiro, L., Leroy, B., Capinha, C., Bradshaw, C.J., Bertolino, S., Catford, J.A., Camacho-Cervantes, M., et al., 2025. Typology of the ecological impacts of biological invasions. Trends Ecol. Evol. 40, 563–574.

Carrillo, D., Pena, J.E., 2012. Prey-stage preferences and functional and numerical responses of *Amblyseius largoensis* (Acari: Phytoseiidae) to *Raoiella indica* (Acari: Tenuipalpidae). Exp. Appl. Acarol. 57, 361–372.

Chi, H., Kavousi, A., Gharekhani, G., Atlihan, R., Salih Özgökçe, M., Güncan, A., Gökçe, A., et al., 2023. Advances in theory, data analysis, and application of the age-stage, two-sex life table for demographic research, biological control, and pest management. Entomol. Gen. 43, 705–732.

Cock, M.J.W., Day, M.D., Solis, M.A., Winston, R.L., 2025. Publicly shared DNA barcodes and citizen science images provide new evidence on the establishment and spread of a lantana biological control agent, *Orphanostigma haemorrhoidalis* (Lepidoptera, Crambidae). CABI Agric. Biosci. 6, 10.

Coetzee, J.A., Miller, B.E., Kinsler, D., Sebola, K., Hill, M.P., 2022. It's a numbers game: inundative biological control of water hyacinth (*Pontederia crassipes*), using

*Megamelus scutellaris* (Hemiptera: Delphacidae) yields success at a high elevation, hypertrophic reservoir in South Africa, 32, 1302–1311.

Costello, M.J., May, R.M., Stork, N.E., 2013. Can we name Earth's species before they go extinct? Science 339, 413–416.

Cuthbert, R.N., Bodey, T.W., Briski, E., Capellini, I., Dick, J.T.A., Kourantidou, M., Ricciardi, A., Pincheira-Donoso, D., 2025. Harnessing traits to predict economic impacts from biological invasions. Trends Ecol. Evol. 40, 639–650.

Cuthbert, R.N., Dick, J.T.A., Callaghan, A., Dickey, J.W., 2018. Biological control agent selection under environmental change using functional responses, abundances and fecundities; the Relative Control Potential (RCP) metric. Biol. Control 121, 50–57.

Cuthbert, R.N., Dickey, J.W.E., Coughlan, N.E., Joyce, P.W., Dick, J.T.A., 2019. The Functional Response Ratio (FRR): advancing comparative metrics for predicting the ecological impacts of invasive alien species. Biol. Invasions 21, 2543–2547.

Delmas, E., Besson, M., Brice, M., Burkle, L.A., Dalla Riva, G.V., Fortin, M., Gravel, D., et al., 2019. Analysing ecological networks of species interactions. Biol. Rev. 94, 16–36.

Diagne, C., Leroy, B., Vaissière, A.C., Gozlan, R.E., Roiz, D., Jarić, I., Salles, J.M., et al., 2021. High and rising economic costs of biological invasions worldwide. F Nature 592, 571–576.

Di Cecco, G.J., Barve, V., Belitz, M.W., Stucky, B.J., Guralnick, R.P., Hurlbert, A.H., 2021. Observing the observers: how participants contribute data to iNaturalist and implications for biodiversity science. Bioscience 71, 1179–1186.

Dick, J.T.A., Alexander, M.E., Jeschke, J.M., Ricciardi, A., MacIsaac, H.J., Robinson, T.B., Kumschick, S., et al., 2014. Advancing impact prediction and hypothesis testing in invasion ecology using a comparative functional response approach. Biol. Invasions 16, 735–753.

Dick, J.T.A., Laverty, C., Lennon, J.J., Barrios-O'Neill, D., Mensink, P.J., Robert Britton, J., Médoc, V., et al., 2017. Invader relative impact potential: a new metric to understand and predict the ecological impacts of existing, emerging and future invasive alien species. J. Appl. Ecol. 54, 1259–1267.

Dickey, J.W.E., Cuthbert, R.N., South, J., Britton, J.R., Caffrey, J., Chang, X., Crane, K., et al., 2020. On the RIP: using relative impact potential to assess the ecological impacts of invasive alien species. NeoBiota 55, 27–60.

Downie, D.A., 2010. Baubles, bangles, and biotypes: a critical review of the use and abuse of the biotype concept. J. Insect Sci. 10, 176.

El-Awaad, E., Merzendorfer, H., 2025. CRISPR/Cas: an emerging molecular technology for biological control of fall armyworm. New Plant Protect. 2, e26.

Elmes, G.W., Thomas, J.A., 1992. Complexity of species conservation in managed habitats—interaction between *Maculinea* butterflies and their ant hosts. Biodivers. Conserv. 1, 155–169.

Enders, M., Hütt, M.T., Jeschke, J.M., 2018. Drawing a map of invasion biology based on a network of hypotheses. Ecosphere 9, e02146.

Engel, M.S., Ceríaco, L.M., Daniel, G.M., Dellapé, P.M., Löbl, I., Marinov, M., Reis, R.E., et al., 2021. The taxonomic impediment: a shortage of taxonomists, not the lack of technical approaches. Zool. J. Linn. Soc. 193, 381–387.

Esler, K.J., Prozesky, H., Sharma, G.P., McGeoch, M., 2010. How wide is the "knowing-doing" gap in invasion biology? Biol. Invasions 12, 4065–4075.

Faber, N.R., Ashok, K., Venkatesan, T., Wertheim, B., Bulgarella, M., 2025. Leveraging advances in RNAi and CRISPR for improved biological pest control. Curr. Opin. Insect Sci. 73, 101453.

Faria, L., Cuthbert, R.N., Dickey, J.W.E., Jeschke, J.M., Ricciardi, A., Dick, J.T.A., Vitule, J.R., 2023. The rise of the functional response in invasion science: a systematic review. NeoBiota 85, 43–79.

Fenn-Moltu, G., Liebhold, A.M., Weber, D.C., Bertelsmeier, C., 2024. Pathways for accidental biocontrol: the human-mediated dispersal of insect predators and parasitoids. Ecol. Appl. 34, e3047.

Fitzpatrick, B.M., Fordyce, J.A., Niemiller, M.L., Reynolds, R.G., 2012. What can DNA tell us about biological invasions? Biol. Invasions 14, 245–253.

Fortin, D., Beyer, H.L., Boyce, M.S., Smith, D.W., Duchesne, T., Mao, J.S., 2005. Wolves influence elk movements: behavior shapes a trophic cascade in yellowstone national park. Ecology 86, 132–1330.

Frelich, L.E., Blossey, B., Cameron, E.K., Dávalos, A., Eisenhauer, N., Fahey, T., Ferlian, O., et al., 2019. Side-swiped: ecological cascades emanating from earthworm invasions. Front. Ecol. Environ. 17, 502–510.

Fricke, R.M., Olden, J.D., 2023. Technological innovations enhance invasive species management in the Anthropocene. Bioscience 73, 261–279.

Galli, M., Feldmann, F., Vogler, U.K., Kogel, K.H., 2024. Can biocontrol be the game-changer in integrated pest management? A review of definitions, methods and strategies. J. Plant Dis. Prot. 131, 265–291.

Gervazoni, P., Minuti, G., Fuentes-Rodriguez, D., Coetzee, J., Sosa, A., Sabater, L., Franceschini, C., 2023. Citizen science improves the known and potential distribution of a strong wetland invader: implications for niche modeling and invasion management. Environ. Manag. 71, 1176–1187.

Goeden, R.D., Louda, S.M., 1976. Biotic interference with insects imported for weed control. Annu. Rev. Entomol. 21, 325–342.

Gonzalez, A., Germain, R.M., Srivastava, D.S., Filotas, E., Dee, L.E., Gravel, D., Thompson, P.L., et al., 2020. Scaling-up biodiversity-ecosystem functioning research. Ecol. Lett. 23, 757–776.

Grevstad, F.S., 1999. Experimental invasions using biological control introductions: the influence of release size on the chance of population establishment. Biol. Invasions 1, 313–323.

Gurr, G.M., Wratten, S.D., 1991. 'Integrated biological control': a proposal for enhancing success in biological control. Int. J. Pest Manag. 45, 81–84.

Harms, N.E., Knight, I.A., Pratt, P.D., Reddy, A.M., Mukherjee, A., Gong, P., Coetzee, J., et al., 2021. Climate mismatch between introduced biological control agents and their invasive host plants: improving biological control of tropical weeds in temperate regions. Insects 12, 549.

Harvey-Samuel, T., Ant, T., Alphey, L., 2017. Towards the genetic control of invasive species. Biol. Invasions 19, 1683–1703.

Hassell, M.P., 1978. The Dynamics of Arthropod predator-prey Systems. Princeton University Press.

Heffernan, J.B., Soranno, P.A., Angilletta, M.J., Buckley, L.B., Gruner, D.S., Keitt, T.H., Kellner, J.R., et al., 2014. Macrosystems ecology: understanding ecological patterns and processes at continental scales. Front. Ecol. Environ. 12, 5–14.

Heimpel, G.E., Asplen, M.K., 2011. A 'Goldilocks' hypothesis for dispersal of biological control agents. BioControl 56, 441–450.

Heimpel, G.E., Mills, N.J., 2017. Biological Control: Ecology and Applications. Cambridge University Press.

Heimpel, G.E., Cock, M.J., 2018. Shifting paradigms in the history of classical biological control. BioControl 63, 27–37.

Herbert, L., Zanga, A., Kinsler, D., Ayala, V., Kamla, A.T., Diaz, R., 2024. Optimizing aquatic weed management in Lake Ossa, Cameroon: harnessing the power of biological control and real-time satellite monitoring. Biol. Control 199, 105650.

Herrando-Pérez, S., Brook, B.W., Bradshaw, C.J., 2014. Ecology needs a convention of nomenclature. Bioscience 64, 311–321.

Hill, M.P., Conlong, D., Zachariades, C., Coetzee, J.A., Paterson, I.D., Miller, B.E., Foxcroft, L., Van Der Westhuizen, L., 2021. The role of mass-rearing in weed biological control projects in South Africa. Afr. Entomol. 29, 1030–1044.

Holling, C.S., 1959. Some characteristics of simple types of predation and parasitism. Can. Entomol. 91, 385–398.

Howarth, F.G., 1991. Environmental impacts of classical biological control. Annu. Rev. Entomol. 36, 485–509.

Hu, T., Chitnis, N., Monos, D., Dinh, A., 2021. Next-generation sequencing technologies: an overview. Hum. Immunol. 82, 801–811.

Huang, L., Wang, L., Sun, H.Q., Huai, W.X., Lin, R.Z., Wei, S.J., Yao, Y.X., 2024. The chromosome-level genome assembly and annotation of an invasive forest pest *Obolodiplosis robiniae*. Sci. Data 11, 1227.

Hudgins, E.J., Cuthbert, R.N., Haubrock, P.J., Taylor, N.G., Kourantidou, M., Nguyen, D., Bang, A., et al., 2023. Unevenly distributed biological invasion costs among origin and recipient regions. Nat. Sustain. 6, 1113–1124.

Hufbauer, R.A., Facon, B., Ravigne, V., Turgeon, J., Foucaud, J., Lee, C.E., Rey, O., Estoup, A., 2012. Anthropogenically induced adaptation to invade (AIAI): contemporary adaptation to human-altered habitats within the native range can promote invasions. Evol. Appl. 5, 89–101.

Huffaker, C.B., Messenger, P.S., 2012. Theory and Practice of Biological Control. Elsevier.

Janovsky, R.M., Larson, E.R., 2019. Does invasive species research use more militaristic language than other ecology and conservation biology literature? NeoBiota 44, 27–38.

Jarić, I., Courchamp, F., Correia, R.A., Crowley, S.L., Essl, F., Fischer, A., González-Moreno, P., et al., 2020. The role of species charisma in biological invasions. Front. Ecol. Environ. 18, 345–353.

Jubase, N., Shackleton, R.T., Measey, J., 2021. Public awareness and perceptions of invasive alien species in small towns. Biology 10, 1322.

Karbstein, K., Kösters, L., Hodač, L., Hofmann, M., Hörandl, E., Tomasello, S., Wagner, N. D., 2024. Species delimitation 4.0: integrative taxonomy meets artificial intelligence. Trends Ecol. Evol. 39, 771–784.

Keane, R.M., Crawley, M.J., 2002. Exotic plant invasions and the enemy release hypothesis. Trends Ecol. Evol. 17, 164–170.

Kestrup, Å.M., Ricciardi, A., 2009. Environmental heterogeneity limits the local dominance of an invasive freshwater crustacean. Biol. Invasions 11, 2095–2105.

Koel, T.M., Tronstad, L.M., Arnold, J.L., Gunther, K.A., Smith, D.W., Syslo, J.M., White, P.J., 2019. Predatory fish invasion induces within and across ecosystem effects in Yellowstone National Park. Sci. Adv. 5 eaav1139.

Korner, C., Basler, D., 2010. Phenology under global warming. Science 327, 1461–1462.

Kourantidou, M., Haubrock, P.J., Cuthbert, R.N., Bodey, T.W., Lenzner, B., Gozlan, R.E., Nuñez, M.A., et al., 2022. Invasive alien species as simultaneous benefits and burdens: trends, stakeholder perceptions and management. Biol. Invasions 24, 1905–1926.

Landi, P., McCoy, M.W., Vonesh, J.R., 2022. Predicting invasive consumer impact via the comparative functional response approach: linking application to ecological theory. Biol. Invasions 24, 3565–3579.

Lantschner, M.V., de la Vega, G., Corley, J.C., 2019. Predicting the distribution of harmful species and their natural enemies in agricultural, livestock and forestry systems: an overview. Int. J. Pest Manag. 65, 190–206.

Le Roux, J., Wieczorek, A.M., 2009. Molecular systematics and population genetics of biological invasions: towards a better understanding of invasive species management. Ann. Appl. Biol. 154, 1–17.

Leung, K., Ras, E., Ferguson, K.B., Ariëns, S., Babendreier, D., Bijma, P., Bourtzis, K., et al., 2020. Next-generation biological control: the need for integrating genetics and genomics. Biol. Rev. 95, 1838–1854.

Levine, J.M., Adler, P.B., Yelenik, S.G., 2004. A meta-analysis of biotic resistance to exotic plant invasions. Ecol. Lett. 7, 975–989.

Li, F., Gao, K., Oduor, A.M., Zhu, J., Liu, X., Li, J., Zhao, C., 2024. High-throughput DNA sequencing identifies population genetic structure and signatures of local adaptation in invasive populations of *Spartina alterniflora* in China. Biol. Invasions 26, 1535–1559.

Liu, C., Wolter, C., Courchamp, F., Roura-Pascual, N., Jeschke, J.M., 2022. Biological invasions reveal how niche change affects the transferability of species distribution models. Ecology 103, e3719.

Liu, J., Slik, F., Zheng, S., Lindenmayer, D.B., 2022. Undescribed species have higher extinction risk than known species. Conserv. Lett. 15, e12876.

Lockwood, J.L., Hoopes, M.F., Marchetti, M.P., 2013. Invasion Ecology. John Wiley and Sons.

Lovell-Read, F.A., Parnell, S., Cunniffe, N.J., Thompson, R.N., 2023. Using 'sentinel' plants to improve early detection of invasive plant pathogens. PLoS Comput. Biol. 19, e1010884.

Marvaldi, A.E., 2024. Phylogenetic systematics and integrative taxonomy contribute to weed biological control. Biol. Control 197, 105599.

MacIsaac, H.J., Johansson, M.L., 2017. Higher colonization pressure increases the risk of sustaining invasion by invasive non-indigenous species. Aquatic *Ecosystem Health and Management*, 20, 378–383.

Marin, P., Genitoni, J., Barloy, D., Maury, S., Gibert, P., Ghalambor, C.K., Vieira, C., 2020. Biological invasion: the influence of the hidden side of the (epi) genome. Funct. Ecol. 34, 385–400.

Mason, P.G., 2021. Biological Control: Global Impacts, Challenges and Future Directions of Pest Management. CSIRO Publishing.

McGaughran, A., Dhami, M.K., Parvizi, E., Vaughan, A.L., Gleeson, D.M., Hodgins, K.A., Rollins, L.A., et al., 2024. Genomic tools in biological invasions: current state and future frontiers. Genome Biol. Evol. 16, evad230.

Measey, J., Visser, V., Dgebuadze, Y., Inderjit, Li, B., Dechoum, M., Ziller, S.R., Richardson, D.M., 2019. The world needs BRICS countries to build capacity in invasion science. PLoS Biol. 17, e3000404.

Memmott, J., Craze, P.G., Harman, H.M., Syrett, P., Fowler, S.V., 2005. The effect of propagule size on the invasion of an alien insect. J. Anim. Ecol. 74, 50–62.

Minghetti, E., Olivera, L., Montemayor, S.I., 2020. Ecological niche modelling of *Gargaphia decoris* (Heteroptera), a biological control agent of the invasive tree *Solanum mauritianum* (Solanales: Solanaceae). Pest Manag. Sci. 76, 1273–1281.

Moffat, R., Weaver, K., Ngxande-Koza, S., Sebola, K., English, K., Kinsler, D., Coetzee, J., 2024. Bridging boundaries: six years of community engagement with biological control implementation and monitoring of water hyacinth on Hartbeespoort Dam, South Africa. Biol. Control 194, 105544.

Mukherjee, A., Banerjee, A.K., Raghu, S., 2021. Biological control of Parkinsonia aculeata: using species distribution models to refine agent surveys and releases. Biol. Control 159, 104630.

Murdoch, W.W., Briggs, C.J., 1996. Theory for biological control: recent developments. Ecology 77, 2001–2013.

Musseau, C.L., Bernard-Verdier, M., Heger, T., Skopeteas, L.H., Strasiewsky, D., Mietchen, D., Jeschke, J.M., 2024. A conceptual classification scheme of invasion science. Bioscience 74, 840–850.

Neuenschwander, P., 2001. Biological control of the cassava mealybug in Africa: a review. Biol. Control 21, 214–229.

Nong, D., Warziniack, T., Countryman, A.M., Grey, E.K., 2019. Melting Arctic sea ice: implications for nonindigenous species (NIS) spread in the United States. Environ. Sci. Pol. 91, 81–91.

Nouri-Aiin, M., Görres, J.H., 2021. Biocontrol of invasive pheretimoid earthworms using *Beauveria bassiana*. PeerJ 9, e11101.

Occhipinti-Ambrogi, A., Galil, B.S., 2004. A uniform terminology on bioinvasions: a chimera or an operative tool? Mar. Pollut. Bull. 49, 688–694.

Pandit, M.A., Kumar, J., Gulati, S., Bhandari, N., Mehta, P., Katyal, R., Rawat, C.D., et al., 2022. Major biological control strategies for plant pathogens. Pathogens 11, 273.

Pearson, D.E., Callaway, R.M., 2003. Indirect effects of host-specific biological control agents. Trends Ecol. Evol. 18, 456–461.

Phillips, B., 2025. The Ecology and Evolution of Invasive Populations. Oxford University Press.

Phillips, S.J., Anderson, R.P., Schapire, R.E., 2006. Maximum entropy modeling of species geographic distributions. Ecol. Model. 190, 231–259.

Pichler, M., Hartig, F., 2021. A new joint species distribution model for faster and more accurate inference of species associations from big community data. Methods Ecol. Evol. 12, 2159–2173.

Pocock, M.J., Adriaens, T., Bertolino, S., Eschen, R., Essl, F., Hulme, P.E., Jeschke, J.M., et al., 2024. Citizen science is a vital partnership for invasive alien species management and research. iScience 27, 108623.

Prapas, D., Scalone, R., Lee, J., Nurkowski, K.A., Bou-assi, S., Rieseberg, L., Battlay, P., et al., 2022. Quantitative trait loci mapping reveals an oligogenic architecture of a rapidly adapting trait during the European invasion of common ragweed. Evol. Appl. 15, 1249–1263.

Pyšek, P., Richardson, D.M., Pergl, J., Jarošík, V., Sixtová, Z., Weber, E., 2008. Geographical and taxonomic biases in invasion ecology. Trends Ecol. Evol. 23, 237–244.

Reynolds-Hogland, M.J., Mitchell, M.S., 2007. Three axes of ecological studies: matching process and time in landscape ecology. In: Bissonette, J.A., Storch, I. (Eds.), Temporal Dimensions of Landscape Ecology. Springer, pp. 174–194.

Ricciardi, A., Blackburn, T.M., Carlton, J.T., Dick, J.T.A., Hulme, P.E., Iacarella, J.C., Jeschke, J.M., et al., 2017. Invasion science: a horizon scan of emerging challenges and opportunities. Trends Ecol. Evol. 32, 464–474.

Ricciardi, A., Hoopes, M.F., Marchetti, M.P., Lockwood, J.L., 2013. Progress toward understanding the ecological impacts of non-native species. Ecol. Monogr. 83, 263–282.

Ricciardi, A., Iacarella, J.C., Aldridge, D.C., Blackburn, T.M., Carlton, J.T., Catford, J.A., Dick, J.T.A., et al., 2021. Four priority areas to advance invasion science in the face of rapid environmental change. Environ. Rev. 29, 119–141.

Richardson, D.M., Pyšek, P., 2008. Fifty years of invasion ecology–the legacy of Charles Elton. Divers. Distrib. 14, 161–168.

Robinson, T.B., Alexander, M.E., Simon, C.A., Griffiths, C.L., Peters, K., Sibanda, S., Miza, S., et al., 2016. Lost in translation? Standardising the terminology used in marine invasion biology and updating South African alien species lists. Afr. J. Mar. Sci. 38, 129–140.

Rojas-Sandoval, J., Anglés-Alcázar, D., Willig, M.R., 2025. Machine learning for biosecurity: a probabilistic framework for invasive species management. J. Appl. Ecol. (in press).

Rubenstein, M.A., Weiskopf, S.R., Bertrand, R., Carter, S.L., Comte, L., Eaton, M.J., Johnson, C.G., et al., 2023. Climate change and the global redistribution of biodiversity: substantial variation in empirical support for expected range shifts. Environ. Evid. 12, 7.

Salafsky, N., Mejía Cortez, P., de Meyer, K., Dudley, N., Klimmek, H., Lewis, A., MacRae, D., et al., 2024. A standard lexicon of terms for area-based conservation version 1.0. Conserv. Biol. 38, e14269.

Schaffner, U., Heimpel, G.E., Mills, N.J., Muriithi, B.W., Thomas, M.B., Wyckhuys, K.A., 2024. Biological control for one health. Sci. Total Environ. 951, 175800.

Seebens, H., Blackburn, T.M., Dyer, E.E., Genovesi, P., Hulme, P.E., Jeschke, J.M., Pagad, S., et al., 2017. No saturation in the accumulation of alien species worldwide. Nat. Commun. 8, 14435.

Segoli, M., Abram, P.K., Ellers, J., Greenbaum, G., Hardy, I.C., Heimpel, G.E., Keasar, T., et al., 2023. Trait-based approaches to predicting biological control success: challenges and prospects. Trends Ecol. Evol. 38, 802–811.

Shea, K., Possingham, H.P., 2000. Optimal release strategies for biological control agents: an application of stochastic dynamic programming to population management. J. Appl. Ecol. 37, 77–86.

Shen, L., LaRue, E., Fei, S., Zhang, H., 2024. Spatial prediction of plant invasion using a hybrid of machine learning and geostatistical method. Ecol. Evol. 14, e11605.

Shimbori, E.M., Querino, R.B., Costa, V.A., Zucchi, R.A., 2023. Taxonomy and biological control: new challenges in an old relationship. Neotrop. Entomol. 52, 351–372.

Shine, R., Ward-Fear, G., Brown, G.P., 2020. A famous failure: why were cane toads an ineffective biocontrol in Australia? Conserv. Sci. Pract. 2, e296.

Simberloff, D., 1992. Conservation of pristine habitats and unintended effects of biological control. In: Kauffman, W.C., Nechols, J.R. (Eds.), Selection Criteria and Ecological Consequences of Importing Natural Enemies. Entomological Society of America, pp. 103–117.

Simberloff, D., 2012. Risks of biological control for conservation purposes. BioControl 57, 263–276.

Sittaro, F., Hutengs, C., Vohland, M., 2023. Which factors determine the invasion of plant species? Machine learning based habitat modelling integrating environmental factors and climate scenarios. Int. J. Appl. Earth Obs. Geoinf. 116, 103158.

Soto, I., Ahmed, D.A., Balzani, P., Cuthbert, R.N., Haubrock, P.J., 2023. Sigmoidal curves reflect impacts and dynamics of aquatic invasive species. Sci. Total Environ. 872, 161818.

Soto, I., Balzani, P., Carneiro, L., Cuthbert, R.N., Macêdo, R., Serhan Tarkan, A., Ahmed, D.A., et al., 2024. Taming the terminological tempest in invasion science. Biol. Rev. 99, 1357–1390.

South, J., Dickey, J.W.E., Cuthbert, R.N., Dick, J.T.A., 2022. Combining resource population dynamics into impact assessments of native and invasive species under abiotic change. Ecol. Indic. 142, 109260.

Spear, M.J., Walsh, J.R., Ricciardi, A., Vander Zanden, M.J., 2021. The invasion ecology of sleeper populations: prevalence, persistence, and abrupt shifts. Bioscience 71, 357–369.

Strong, Jr D.R., 1974. The insects of British trees: community equilibration in ecological time. Ann. Mo. Bot. Gard. 61, 692–701.

Sun, Y., Brönnimann, O., Roderick, G.K., Poltavsky, A., Lommen, S.T., Müller-Schärer, H., 2017. Climatic suitability ranking of biological control candidates: a biogeographic approach for ragweed management in Europe. Ecosphere 8, e01731.

Sun, Y., Ding, J., Siemann, E., Keller, S.R., 2020. Biocontrol of invasive weeds under climate change: progress, challenges and management implications. Curr. Opin. Insect Sci. 38, 72–78.

Traveset, A., Richardson, D.M., 2006. Biological invasions as disruptors of plant reproductive mutualisms. Trends Ecol. Evol. 21, 208–216.

Tscharntke, T., Bommarco, R., Clough, Y., Crist, T.O., Kleijn, D., Rand, T.A., Tylianakis, J.M., et al., 2007. Conservation biological control and enemy diversity on a landscape scale. Biol. Control 43, 294–309.

Uiterwaal, S.F., Lagerstrom, I.T., Lyon, S.R., DeLong, J.P., 2022. FoRAGE database: a compilation of functional responses for consumers and parasitoids. Ecology 103, e3706.

Van Driesche, R., Bellows Jr, T.S., 2012. Biological Control. Springer Science and Business Media.

Van Klink, R., August, T., Bas, Y., Bodesheim, P., Bonn, A., Fossøy, F., Høye, T.T., et al., 2022. Emerging technologies revolutionise insect ecology and monitoring. Trends Ecol. Evol. 37, 872–885.

van Lenteren, J.C., 2012. The state of biological control. In: Biological Control: a Global Perspective. CABI, pp. 3–22.

van Steenderen, C.J.M., Sandenbergh, E., Brookes, D., Moran, P., Paterson, I.D., 2025. Population genetics reveals the invasion pathways of *Mesembryanthemum nodiflorum* in North America. Ecology and Evolution (in press).

Varner, J., 2014. Scientific outreach: toward effective public engagement with biological science. Bioscience 64, 333–340.

Vaughan, A.L., Dhami, M.K., 2025. Can transcriptomics elucidate the role of regulation in invasion success? Mol. Ecol. 34, e17583.

Vaz, A.S., Alcaraz-Segura, D., Vicente, J.R., Honrado, J.P., 2019. The many roles of remote sensing in invasion science. Front. Ecol. Evol. 7, 370.

Vonesh, J., McCoy, M., Altwegg, R., Landi, P., Measey, J., 2017. Functional responses can't unify invasion ecology. Biol. Invasions 19, 1673–1676.

Wagner, D.L., Grames, E.M., Forister, M.L., Berenbaum, M.R., Stopak, D., 2021. Insect Decline in the Anthropocene: Death by a Thousand Cuts, 118. Proceedings of the National Academy of Sciences, e2023989118.

Wainright, C.A., Muhlfeld, C.C., Elser, J.J., Bourret, S.L., Devlin, S.P., 2021. Species Invasion Progressively Disrupts the Trophic Structure of Native Food Webs, 118. Proceedings of the National Academy of Sciences, e2102179118.

Wang, C., Liu, L., Yin, M., Liu, B., Wu, Y., Eller, F., Gao, Y., et al., 2024. Chromosome-level genome assemblies reveal genome evolution of an invasive plant *Phragmites australis*. Commun. Biol. 7, 1007.

Weaver, K.N., Hill, M.P., Byrne, M.J., Ivey, P., 2021. Efforts towards engaging communities to promote the benefits of biological control research and implementation in South Africa. Afr. Entomol. 29, 1045–1059.

White, D.T., Antoniou, T.M., Martin, J.M., Kmetz, W., Twiss, M.R., 2022. A machine-learning approach to predict success of a biocontrol for invasive Eurasian watermilfoil reduction. Ecol. Appl. 32, e2625.

Whitney, K.D., Broman, K.W., Kane, N.C., Hovick, S.M., Randell, R.A., Rieseberg, L.H., 2015. Quantitative trait locus mapping identifies candidate alleles involved in adaptive introgression and range expansion in a wild sunflower. Mol. Ecol. 24, 2194–2211.

Woodcock, C.E., Loveland, T.R., Herold, M., Bauer, M.E., 2020. Transitioning from change detection to monitoring with remote sensing: a paradigm shift. Rem. Sens. Environ. 238, 111558.

Xiao, Y., Greiner, R., Lewis, M.A., 2018. Evaluation of machine learning methods for predicting eradication of aquatic invasive species. Biol. Invasions 20, 2485–2503.

Zachariades, C., Strathie, L.W., Kluge, R.L., Hill, M.P., 2017. The biological control of weeds in South Africa. Afr. Entomol. 25, 177–191.

Zenni, R.D., Nuñez, M.A., 2013. The elephant in the room: the role of failed invasions in understanding invasion biology. Oikos 122, 801–815.

Zimmermann, H.G., Moran, V.C., Hoffmann, J.H., 2004. Biological control of cactus weeds of the genus *Opuntia* in South Africa. Afr. Entomol. 12, 1–13.

Ziter, C.D., Herrick, B.M., Johnston, M.R., Turner, M.G., 2021. Ready, set, go: community science field campaign reveals habitat preferences of nonnative Asian earthworms in an urban landscape. Bioscience 71, 280–291.

Zhou, Y., Zhang, H., Liu, D., Khashaveh, A., Li, Q., Wyckhuys, K.A.G., Wu, K., 2023. Long-term insect censuses capture progressive loss of ecosystem functioning in East Asia. Sci. Adv. 9, eade9341.

Zhu, G., Gutierrez Illan, J., Crowder, D.W., 2021. The use of insect life tables in optimizing invasive pest distributional models. Ecography 44, 1501–1510.