



# Do globally increasing invasion rates threaten ecosystem sustainability?

Anthony Ricciardi 

Received: 31 July 2025 / Accepted: 9 December 2025  
© The Author(s), under exclusive licence to Springer Nature Switzerland AG 2025

**Abstract** Rates of biological invasion are rarely described as a sustainability issue, yet multiple lines of evidence suggest that burgeoning invasion rates cause ecosystems to be less sustainable over time. Field data reveal that as the number of established non-native species (‘invaders’) in an ecosystem increases so does the likelihood that at least one of them will cause, directly or indirectly, an ecological disruption—i.e., a substantial alteration or interruption in ecosystem function. Furthermore, a change in environmental conditions can trigger an initially innocuous invader to become disruptive long after its establishment; invasions can thus have deferred impacts whose nature and timing are unpredictable. Finally, case studies show that invaders can interact with each other and with co-occurring stressors to produce synergistic impacts, although it is not clear how frequent such understudied interactions are in comparison with additive and antagonistic effects across ecosystems. If additive or synergistic impacts

are more frequent than antagonistic effects, then increasing colonization pressure (the number of species introduced) can cause ecosystems to become more easily disrupted and difficult to manage over time. Assuming that each new invader, on average, increases the risk of disruption to an ecosystem, then even a small reduction in the invasion rate can benefit ecosystem sustainability. These considerations justify efforts to reduce invasion rates globally, as directed by the Kunming-Montreal Global Biodiversity Framework.

**Keywords** Colonization pressure · Ecosystem stability · Ecosystem management · Invasional meltdown · Invasive species

## Introduction

Ecological sustainability is “the maintenance or restoration of the composition, structure, and processes of ecosystems including the diversity of plant and animal communities and the productive capacity of ecological systems” (Potter and Ford 2004). A sustainable ecosystem can be defined as one that maintains stability—i.e., it is resistant or resilient to changes in its biodiversity and ecological functions, including ecosystem services provided to future generations (cf. Chapin et al. 1996). Fundamental to the sustainability of ecosystems is a resiliency to episodic disturbances, both natural and anthropogenic, such as disease

---

A. Ricciardi (✉)  
Department of Biology, McGill University, 1205 Docteur  
Penfield Avenue, Montreal, QC H3A 1B1, Canada  
e-mail: tony.ricciardi@mcgill.ca

A. Ricciardi  
Bieler School of Environment, McGill University,  
Montreal, QC, Canada

A. Ricciardi  
Centre for Invasion Biology, University of Stellenbosch,  
Stellenbosch, South Africa

outbreaks, wildfires, and biological invasion—the spread of plants, animals, and microbes into regions beyond their native range. Although biological invasion is a natural process that has occurred throughout the history of life, under human influence species are moving faster, farther, and in greater numbers than ever before, such that modern rates of invasion are orders of magnitude higher than before global human expansion (Ricciardi 2007). Driven largely by socioeconomic forces (e.g., Sardain and Leung 2019), invasion rates have accelerated over the past century and show no sign of saturation (Mormul et al. 2022; Seebens et al. 2021, 2017).

The ecological and socioeconomic impacts of invasions are diverse, potentially enormous, and globally pervasive (IPBES 2023). The introduction of a novel organism can reshape entire ecosystems (Koel et al. 2019; Doody et al. 2017; Tobin 2015; Spencer et al. 1991; Zaret and Paine 1973). Invasions have altered biological communities, nutrient cycling, primary production, and natural disturbance regimes (IPBES 2023; O’Bryan et al. 2022; Fusco et al. 2019; Simberloff et al. 2013), and they are among the leading drivers of species extinction (Bellard et al. 2016; Doherty et al. 2016; Clavero et al. 2009; Clavero and García-Berthou 2005). Invasions can also disrupt key ecological interactions, including plant-animal mutualisms that are essential for pollination and seed dispersal (Traveset and Richardson 2006), and they can produce cascading effects that transform food webs and ecosystem functions (Koel et al. 2019; Fusco et al. 2019; Doody et al. 2017; Spencer et al. 1991; Zaret and Paine 1973). Their impacts on ecosystem services are similarly extensive (Gallardo et al. 2024; Castro-Díez et al. 2019; Sandman et al. 2018; Vilà and Hulme 2017; Walsh et al. 2016) and can have repercussions for human and animal health (Burkett-Cadena et al. 2021; Mazza et al. 2014). Finally, they carry enormous and rising economic costs associated with damages to goods, services, infrastructure, and production (Diagne et al. 2021). Collectively, invasions are as financially costly as natural disasters (Turbelin et al. 2023).

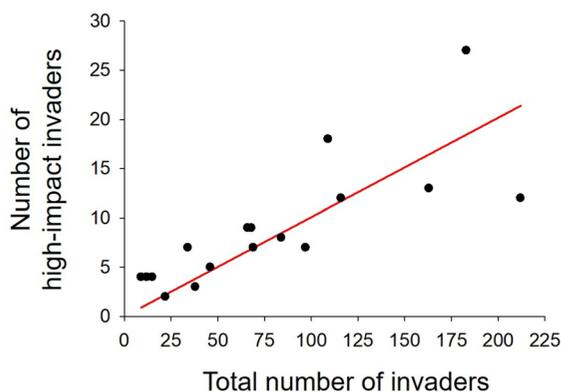
Even though non-native species are now widely recognized as a major threat to biodiversity and ecosystem services (IPBES 2023), uncontrolled rates of invasion have rarely been framed as a sustainability issue. I conducted a Clarivate Web of Science search on 18 June 2025 using the following search string:

*sustainability* AND (*non-native* OR *nonindigenous* OR *alien* OR *invasive*) AND *species*. It yielded 1544 articles, of which the first 200 most relevant articles were assessed. While some articles referred to invasive species’ impacts on economic sustainability (e.g., food security; Bebbler et al. 2014) or on the sustainable exploitation of particular native or non-native species (Pušić et al. 2024; Paul and Karr 2016), only 11 of 200 (5.5%) explicitly identified invasions as a threat to sustainable ecosystems, and none of these articles elaborated on how sustainability is affected by invasion rates or *colonization pressure*—the number of species introduced to an area. The paucity of scientific and media attention to the risks to ecosystem sustainability posed by burgeoning numbers of invasions could contribute to lower advocacy by environmental groups, which perhaps do not view invasion rates with the same concern they hold for rates of carbon emissions, as the consequences of the latter are better known and reported by climate scientists and the media widely.

Here, using theory and empirical evidence, I argue that uncontrolled invasion rates threaten ecosystem sustainability through increasingly frequent, diverse, and unpredictable impacts. This argument is based on four propositions: (1) greater colonization pressure yields a higher risk of ecological disruption by, *inter alia*, breaking or reforming links in food webs, causing rapid native species declines, promoting regime shifts, and degrading ecosystem services; (2) initially benign invaders could become disruptive later as environmental conditions change; (3) invaders can interact with each other and with external stressors synergistically—that is, their combined impact can be greater than the sum of their respective independent impacts; and (4) even a rising accumulation of invaders that have predominantly ‘positive’ impacts on one or more resident native species can result in unpredictable shifts in community structure and abundances that destabilize recipient ecological communities and challenge adaptive management. Collectively, these propositions imply that each new invasion, on average, adds to the overall risk of ecosystem disruption and thus reduces sustainability.

### Colonization pressure and risk of disruption: multiple scenarios

Some studies suggest that greater numbers of non-native species established within an ecosystem or region increase the likelihood that some of them will become highly invasive or disruptive (Ricciardi and MacIsaac 2011; Blackburn et al. 2005; Rejmánek and Randall 2004). In one scenario, the number of non-native species that becomes disruptive is a relatively small, fixed proportion—representing a sampling effect in which the risk of disruption increases linearly with each new invader (the *ecological roulette model*). For example, an analysis of 17 large freshwater and marine ecosystems (Fig. 1) indicated that as more species invade, there is a greater the likelihood that at least one of them will severely damage or extirpate a native population (Ricciardi and MacIsaac 2011). Similar linear relationships have been shown for high-impact fish invaders in 149 regions worldwide (Ricciardi and Kipp 2008) and for non-native pest plants across the United States (Rejmánek and Randall 2004). Following the same principle, plant species listed as among the 100 worst invaders in Europe are more common in areas with higher non-native species richness (Chytrý et al. 2012). Other studies have found positive relationships between the number of non-native species established on an



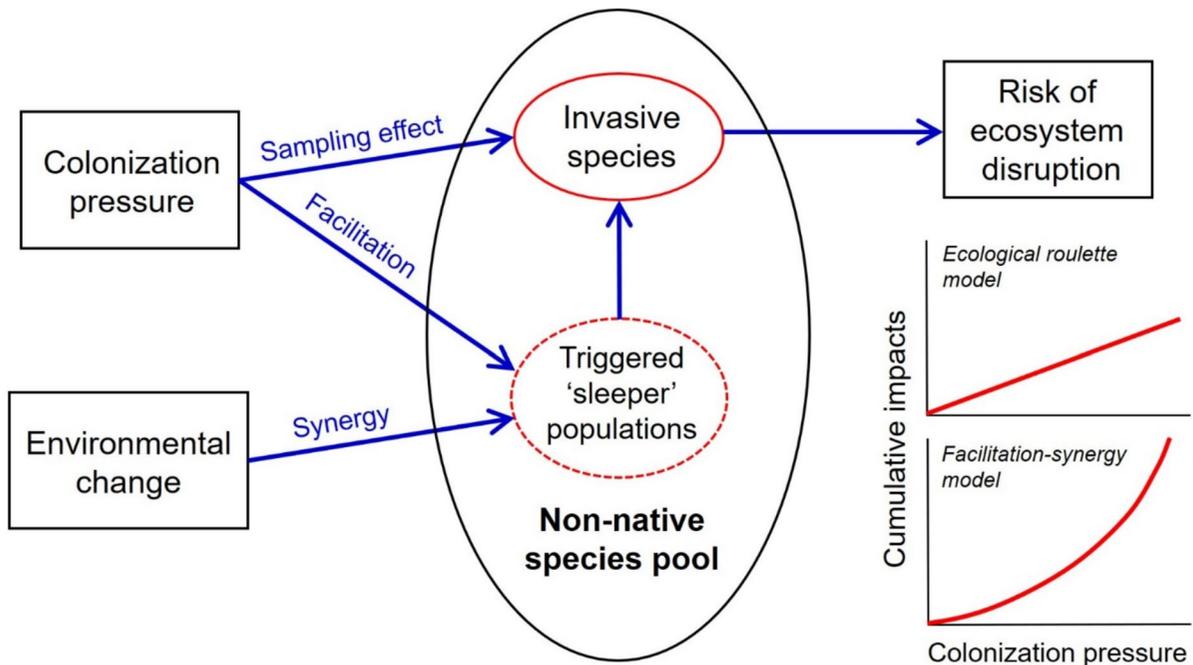
**Fig. 1** Empirical support for the ecological roulette model. Number of high-impact invaders (defined as those causing severe reductions or extirpations of one or more native populations) as a function of the total number of established non-native species in an ecosystem: slope =  $0.10 \pm 0.02$  (95% confidence limits),  $R^2 = 0.85$ ,  $p < 0.0001$ . Data are from 17 freshwater and marine systems. Redrawn from Ricciardi and MacIsaac (2011)

island and the severity of their collective impact on the island's native biodiversity (Walsh et al. 2012; Blackburn et al. 2005). Thus, multiple lines of empirical evidence indicate a direct relationship between colonization pressure and impact, suggesting that if colonization pressure remains continuous then impacts will accumulate over time (ecological roulette model; Fig. 2).

This risk can be compounded by at least three phenomena. One is the increasing accessibility to source species pools in native ranges worldwide—a consequence of expanding transportation networks and environmental change, which has resulted in continuously emerging invaders with no prior history anywhere as a non-native species (Seebens et al. 2018). The emergence of these new non-native species from previously disconnected regions challenges ecological forecasting, which often relies on documented invasion histories to predict the identities and impacts of future invaders (Kumschick et al. 2015). Furthermore, expanding source pools increase the risk of introductions of species whose traits are novel to the recipient community; such species are more likely to generate strong ecological impacts (Ricciardi et al. 2013).

Risk of ecological disruption is also compounded by the 'sleeping population' phenomenon, in which invaders that are apparently innocuous can be triggered by an environmental change to become disruptive after many years or even centuries following establishment (Spear et al. 2021; Crooks 2005). In other words, their impacts are deferred to some unpredictable future moment, in contrast with the oft-reported pattern in which a non-native population that is initially invasive ultimately declines in abundance or impact (Strayer et al. 2006). Cascading effects of triggered species can cause habitat degradation (Rohwer et al. 2024) and a substantial loss of ecosystem services (Walsh et al. 2016). The trigger is often an external stressor such as climate change (Witte et al. 2010; Scheibling and Gagnon 2006) or the arrival of another invader (Zanger and Berenbaum 2005; Stout et al. 2002; Richardson et al. 2000).

The third phenomenon that compounds the risk of disruption is that invaders can interact in commensalistic, exploitative, or mutualistic ways in which one species enhances the other's abundance and impact (Ricciardi and Simberloff 2025). It has been hypothesized that facilitation can produce a



**Fig. 2** Hypothesized mechanistic links between colonization pressure and risk of ecosystem disruption. As colonization pressure increases, disruptions by invaders are predicted to become more frequent. This can occur through a direct sampling effect—where some fixed proportion of introduced species becomes disruptive (the *ecological roulette model*)—or through facilitation, where some introduced species will aug-

ment the abundance and impacts of previously established invaders. Synergy with co-occurring environmental changes can also trigger formerly innocuous species to become disruptive. A predominance of facilitative or synergistic effects is predicted to cause a superlinear increase in accumulation of disruptive impacts (the *facilitation-synergy model*)

positive feedback in which invasions beget more invasions, leading to an increasing rate of accumulation of invaders and their impacts ('invasional meltdown' sensu Simberloff and Von Holle 1999). An example from cultivated systems in several countries is the exacerbation of Asiatic citrus canker disease by herbivory from an invasive insect, the Asian citrus leaf miner *Phyllocnistis citrella* (Hall et al. 2010). Various mechanisms can plausibly result in invasional meltdown, but cases of whole-ecosystem transformations have been rarely documented (Ricciardi and Simberloff 2025). In addition to facilitation among themselves, an accumulation of invaders can increase the risk of synergistic interactions with climate change and other co-occurring external stressors (Rodrigues et al. 2024; Warren et al. 2023; Ravi et al. 2022; Geraldi et al. 2020; Straub et al. 2019; Sainz et al. 2013). These interactive effects are predicted by the *facilitation-synergy model*

(Fig. 2). Both the facilitation-synergy and ecological roulette models are alternatives to the classical model of *biotic resistance*—which predicts that successive invasions cause a community to accumulate stronger competitors, more efficient predators, and well-defended prey, such that the number of new invaders and their impacts become increasingly limited over time (Case 1990, 1991).

The biotic resistance model has dominated ecological thinking for decades, but it is contradicted by accelerating accumulations of non-native species observed in large ecosystems (e.g., Jackson and Grey 2013; Ricciardi 2006, 2007; Gaston et al. 2003; Cohen and Carlton 1998). These patterns are consistent with invasional meltdown, but they alone do not offer support for the facilitation-synergy model in the absence of increasing trends in impact magnitude and/or frequency. Temporal data for ecological disruptions within ecosystems are scarce—which might

simply reflect the fact that the impacts of most invasions are unknown, even for relatively well studied systems. Some empirical support for the facilitation-synergy model comes from a study finding that the proportion of recently extinct birds on oceanic islands increases superlinearly with the number of introduced predatory mammals (Blackburn et al. 2005). In an apparent contradiction to the model, Jackson (2015) found an overall predominance of antagonistic (offsetting) interactions between invaders across studies for ecosystems in general; yet in at least some invaded systems, observed positive interactions are as frequent as purely negative ones (Ricciardi 2001) and synergies have been documented (Lone et al. 2024; Yu et al. 2023; Vujanović et al. 2022; Zenni et al. 2020; Ricciardi 2005). While it is logical to assume that an increase in colonization pressure also yields more opportunities for the introduction of coevolved enemies that could constrain the spread, population growth, and impact of a resident invader, in some contexts these presumed enemies can have facilitative effects on their natural hosts by disproportionately suppressing native competitors in the invaded range (the ‘Enemy-of-my-Enemy-is-my-Friend’ hypothesis; Colautti et al. 2004), or they may trigger rapid adaptive responses in their hosts that have collateral damage to other resident species. An example of the latter is rapidly evolved increased toxicity in the European plant wild parsnip *Pastinaca sativa* in response to the introduction of one of its coevolved herbivores (Zangerl and Berenbaum 2005). Finally, even where the classical biotic resistance assembly model and its asymptotic species accumulation curve might apply, invaders would continue to accumulate (albeit slowly) under sustained colonization pressure, with each one being a potential disruption. Even in that scenario, some synergistic effects are likely inevitable.

Although meta-analyses suggest that antagonisms generally dominate stressor interactions (Ahmad et al. 2025; Lopez et al. 2022; Jackson et al. 2016), synergies appear to be at least as frequent as antagonisms in some ecosystems (Smith et al. 2019). Moreover, interactions involving non-native species and other stressors can have complex ecosystem-level consequences that do not easily fit within the category of synergy or antagonism, but nonetheless can be multifaceted and disruptive (see Rodrigues et al. 2024). For example, recurring mass mortalities of tens of thousands of waterfowl in various areas of the lower

Great Lakes have been caused by toxic anaerobic bacteria whose proliferation is attributed to the interactions of multiple invasive species (Essian et al. 2016; Chun et al. 2013). Filtration by dense populations of dreissenid (zebra and quagga) mussels enhances water clarity—which, when combined with warming water temperatures, stimulates the luxuriant growth of benthic macroalgae such as *Cladophora* (Princé et al. 2018; Higgins and Vander Zanden 2010). Decomposition of a massive biomass of algae in late summer increases biological oxygen demand, generating anoxic conditions that trigger the germination of *Clostridium botulinum* bacteria (Chun et al. 2013). The bacteria are ingested by mussels (Perez-Fuentetaja et al. 2006) and passed on to an invasive molluscivorous fish, the round goby (*Neogobius melanostomus*)—a highly abundant natural predator of dreissenid mussels. Fish-eating waterfowl, particularly loons (*Gavia immer*), acquire the botulinum neurotoxin by consuming contaminated gobies (Essian et al. 2016). Without the antagonistic (exploitative) interaction of the round goby and dreissenid mussels in this system, the mass mortality event would not have been as severe or might not have occurred at all. Despite the presence of this same group of invasive species in European waterbodies for several decades, no such impact had been previously documented; so it could not have been predicted for the Great Lakes. Such ecological surprises are a logical consequence of increasing numbers of invasions and other overlapping environmental stressors (Filbee-Dexter et al. 2017).

### How do positive impacts of invaders affect ecosystem sustainability?

Logically, the number of non-native species that have predominantly positive effects on members of the invaded community or ecosystem services will also increase with increasing invasion rates. It has been asserted by various critics of invasion ecology (e.g. Pearce 2015; Sagoff 2005) that since invaders typically increase *local* species richness (Sax and Gaines 2003), and higher species richness contributes to community stability (Loreau et al. 2021; McCann 2000), it follows that invaded ecosystems should become more resistant to disturbances including further invasion. Indeed, some established non-native

species can augment the abundances of resident native species and provide resistance against certain invaders (e.g., Carlin et al. 2024). Non-native species can also replace, inhibit, or interfere with each other, resulting in an attenuation of some of their respective impacts (Liu et al. 2018; Russell et al. 2014; Griffen et al. 2008). However, there is no evidence that positive effects from some invaders on resident species generally dampen the colonization success of other non-native species; otherwise, many ecosystems would be showing signs of increased biotic resistance to invasion over time (Levine and D'Antonio 1999). Instead, invasion rates are increasing in large ecosystems globally—particularly for islands and lakes—with no sign of saturation (e.g., Pfadenhauer and Bradley 2024; Jackson and Grey 2013; Ricciardi 2001; Cohen and Carlton 1998).

In various systems, facilitations appear to be at least as common as antagonistic interactions among invaders (Gallardo and Aldridge 2015; Ricciardi 2001; Simberloff and Von Holle 1999) and, in some cases, have led to increased rates of invasion and magnification of impacts (Ricciardi and Simberloff 2025). When antagonistic interactions lead to the replacement of one invader by another, the shift in dominance could produce ecosystem changes or disruptions (e.g., David et al. 2015). Relatively few studies have investigated the cumulative impacts of multiple invaders, particularly the situations in which their impacts become additive, antagonistic, or synergistic (Kuebbing et al. 2013); all three outcomes can occur for a suite of co-invaders in the same ecosystem, across various ecosystem properties (Lone et al. 2024). Even fewer studies have directly measured how invasions affect community stability. Evidence from modern time series data for rivers around the world indicate that non-native species destabilize native fish communities by increasing their temporal variability (Czeglédi et al. 2025; Erős et al. 2020). Similarly, evidence from plant communities suggests that invasions have complex but strong negative effects on community stability (Frost et al. 2024; Valone and Balaban-Feld 2018).

Various studies suggest that the negative impacts of invasion on native biodiversity exceed positive impacts (Bescond-Michel et al. 2025; IPBES 2023; Paolucci et al. 2013; Salo et al. 2007)—as might be expected when considering the potential evolutionary mismatches between invasive and native species

(Ricciardi et al. 2013); though some authors have alleged, without evidence, a bias toward reporting negative impacts. For non-native species that are known to have positive impacts on certain native species within the community or on ecosystem services of importance to certain stakeholders, their effects can be compromised by other invaders, whose occurrence becomes more probable as invasion rates increase. One example is the frequent mass die-offs of introduced European honeybees *Apis mellifera* by viral disease transfer from invasive varroa mites (Traynor et al. 2020), a global pest that has developed resistance to multiple acaricides (Lester 2023). Another case is the chinook salmon (*Oncorhynchus tshawytscha*), a commercially valuable Pacific species introduced to the Great Lakes, where it is a major component of a multi-billion-dollar fishery. The principle threat to the chinook salmon population is the invasive quagga mussel (*Dreissena rostriformis bugensis*), whose consumption of phytoplankton has diverted nutrients from the pelagic food web, thereby effectively starving the salmon population (Kao et al. 2018).

Invaders can produce ecosystem services and disservices simultaneously (e.g., Milanović et al. 2020; Limburg et al. 2010). For example, invasive dreissenid (zebra and quagga) mussels are recognized for have greatly improved water clarity in invaded lakes (Higgins and Vander Zanden 2010), but they also reduce dissolved oxygen (Canale and Chapra 2002; Caraco et al. 2000) and promote toxic algal blooms (Steffen et al. 2014; Bierman et al. 2005; Vanderploeg et al. 2001). Moreover, non-native species impacts can change over time such that some that are initially positive can become detrimental later (e.g., Soto et al. 2024; Spear et al. 2021) and perhaps vice versa. Even where some invasions cause positive impacts on certain native species (i.e., increases in the abundance of one or more native populations), one can imagine the difficulty in developing sustainable management plans for an ecosystem in which the population abundances of various components of the community change substantially, precipitously, and unpredictably.

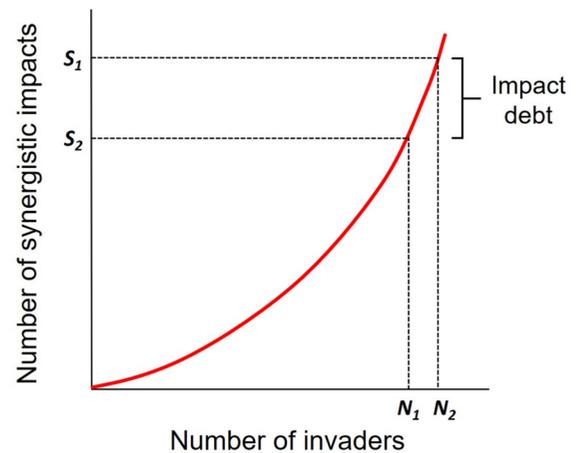
### Challenges for ecosystem management

The *ecological roulette* and the *facilitation-synergy* models (Fig. 2) need to be further explored to

understand the situations in which they apply. They have at least three significant implications for our ability to manage ecosystems. First, we would expect that as the number of invaders in a system rises so will the number of potential synergies between invaders and other anthropogenic disturbances. There now exist many documented cases of invaders facilitating each other's invasion success and magnifying their respective impacts through a variety of mechanisms (Ricciardi and Simberloff 2025). Any additional invader could plausibly contribute to an increase in potential synergistic impacts involving complex combinations of direct and indirect interactions with native species and other invaders already established (e.g., Zenni et al. 2020; Kuebbing et al. 2016; Ricciardi 2005).

Second, predictive power will be reduced for highly invaded or multiply stressed ecosystems, where synergies and other ecological surprises can compromise risk assessment, confound adaptive management, and challenge conservation efforts (Smith et al 2019; Filbee-Dexter et al. 2017; Côté et al. 2016). Post-hoc explanation, let alone prediction, is rendered increasingly difficult by overlapping stressors. In marine coastal ecosystems, for example, the number of known pairwise interactions between stressors can exceed 100, requiring an immense number of experimental treatments to quantify (Côté et al. 2016). Moreover, some extremely consequential ecosystem-level impacts of invaders are not easily detected, further defying risk assessment (Simberloff et al. 2013).

Third, if predictions of the facilitation-synergy model are accurate and increasing numbers of invaders enhance the probability of synergistic impacts (because of a superlinear increase in potential direct and indirect interactions among invaders or between invaders and other stressors), then it follows that even a small reduction in the invasion rate will yield disproportionate benefits to management (Fig. 3). With every invasion that is prevented, we circumvent not only its potential impacts but also an unknown number of disruptive synergies with previously established invaders or co-occurring stressors. It is understood that the risk of disruption is not evenly spread across invasions; however, regardless of which of the two aforementioned models is more accurate, disruptions should increase with colonization pressure



**Fig. 3** Hypothesized relationship of the number of synergistic impacts to the number of invaders in an ecosystem, as predicted by the facilitation-synergy model. Here, synergistic impacts increase superlinearly with each additional invasion, owing to expanding opportunities for interactions with invaders and other co-occurring stressors. An incremental reduction in the number of invasions ( $N_2 - N_1$ ) due to prevention or eradication is expected to yield a disproportionate benefit ( $S_1 - S_2$ ) in avoided ‘impact debt’—the impact expected to accrue from an interval increase in invasions

(MacIsaac and Johansson 2017; Ricciardi and Kipp 2008; Rejmanek and Randall 2004).

As more scientific attention is given to understanding how ecosystems respond to the rate (rather than simply the magnitude) of disturbance (Abbott et al. 2024), I anticipate that the concept of *invasion rate thresholds* will become more prevalent in sustainability management. It is conceivable that ecosystems were more likely to accommodate (absorb with minimal consequence) introduced species under prehistoric rates of invasion (Vermeij 2005), when native communities had sufficient time to adapt, than under modern rates of invasion—which are orders of magnitude higher (Ricciardi 2007). Along with colonization pressure, rapid climate warming could render ecosystems more susceptible to invasion (Salis et al. 2023; Huang et al. 2011). Furthermore, as ecosystems are increasingly invaded, native populations can become more temporally variable and thus more vulnerable to stochastic environmental stressors, threatening their long-term survival (Czeglédi et al. 2025).

Rather than focusing on preventing the establishment of particular invasive species with known impacts, management should aim to reduce invasion

rates by controlling vectors that generate the most colonization pressure (MacIsaac and Johansson 2017). Indeed, one of the principal targets of the Kunming-Montreal Global Biodiversity Framework is to reduce invasion rates globally by at least 50% by 2030 (CBD 2022). While this target is undoubtedly ambitious, an encouraging example is the regulation enacted by Canada in 2006 and harmonized by the USA in 2008 to control ballast water carried by trans-oceanic ships into the St Lawrence Seaway; by reducing the amount of viable organisms released through ballast water discharge, this regulation led to an unprecedented 85% reduction in the invasion rate for the Great Lakes basin, one of the world's most highly invaded ecosystems (Ricciardi and MacIsaac 2022). Given the arguments presented above, progress toward the Kunming-Montreal target is crucial for slowing biodiversity loss and maintaining sustainable ecosystems globally.

**Acknowledgements** This paper was presented as a keynote talk at the NEOBIOTA International Conference on Biological Invasions held in Lisbon, September 2024. I thank Dan Simberloff for comments on an early draft of the paper and two anonymous reviewers for providing constructive feedback.

**Funding** Funding was provided by the Natural Sciences and Engineering Research Council of Canada (2022-03235) and through the Bieler Chair in St Lawrence River Ecology (McGill University).

#### Declarations

**Conflict of interest** The author has no conflict of interest to disclose.

#### References

- Abbott KC, Heggerud CM, Lai Y-C, Morozov A, Petrovskii S, Cuddington K, Hastings A (2024) When and why ecological systems respond to the rate rather than the magnitude of environmental changes. *Biol Conserv* 292:110494
- Ahmad R, Lone SA, Rashid I, Khuroo AA (2025) A global synthesis of the ecological effects of co-invasions. *J Ecol* 113:570–581
- Bebber DP, Holmes T, Gurr SJ (2014) The global spread of crop pests and pathogens. *Glob Ecol Biogeogr* 23:1398–1407
- Bellard C, Cassey P, Blackburn TM (2016) Alien species as a driver of recent extinctions. *Biol Lett* 12(2):20150623
- Bescond-Michel Z, Bacher S, Vimercati G (2025) Harms of introduced large herbivores outweigh their benefits, while both are greater on islands and for higher trophic levels. *Nat Commun* 16:8260
- Bierman VJ Jr, Kaur J, DePinto JV, Feist TJ, Dilks DW (2005) Modeling the role of zebra mussels in the proliferation of blue-green algae in Saginaw Bay, Lake Huron. *J Great Lakes Res* 31:32–55
- Blackburn TM, Petchey OL, Cassey P, Gaston KJ (2005) Functional diversity of mammalian predators and extinction in island birds. *Ecology* 86:2916–2923
- Burkett-Cadena ND, Blosser EM, Loggins AA, Valente MC, Long MT, Campbell LP, Reeves LE, Bargielowski I, McCleery RA (2021) Invasive Burmese pythons alter host use and virus infection in the vector of a zoonotic virus. *Commun Biol* 4(1):804
- Canale RP, Chapra SC (2002) Modeling zebra mussel impacts on water quality of Seneca River, New York. *J Environ Eng* 128:1158–1168
- Caraco NF, Cole JJ, Findlay SEG, Fischer DT, Lampman GG, Pace ML, Strayer DL (2000) Dissolved oxygen declines in the Hudson River associated with the invasion of the zebra mussel (*Dreissena polymorpha*). *Environ Sci Technol* 34:1204–1210
- Carlin TF, Paul TS, Dudenhoeffer JH, Rolando C, Novoselov M, Vorster RS, Springford CR, Scott MB (2024) The enemy of my enemy... Exotic mammals present biotic resistance against invasive alien conifers. *Biol Invasions* 26:2647–2662
- Case TJ (1990) Invasion resistance arises in strongly interacting species-rich model competition communities. *Proc Natl Acad Sci USA* 87:9610–9614
- Case TJ (1991) Invasion resistance, species build-up and community collapse in metapopulation models with interspecies competition. *Biol J Linn Soc* 42:239–266
- Castro-Díez P, Vaz AS, Silva JS, van Loo M, Alonso A, Aponte C, Bayóon A, Bellingham PJ, Chiuffo MC, DiManno N, Julian K, Kandert S, La Porta N, Marchante H, Maule HG, Mayfield MM, Metcalfe D, Monteverdi MC, Núñez MA, Godoy O (2019) Global effects of non-native tree species on multiple ecosystem services. *Biol Rev* 94:1477–1501
- CBD (Convention on Biological Diversity) (2022) Kunming–Montreal global biodiversity framework. CBD/COP/DEC/15/4. Secretariat of the Convention on Biological Diversity, Montréal, Canada
- Chapin FS, Torn MS, Tateno M (1996) Principles of ecosystem sustainability. *Am Nat* 148:1016–1037
- Chun CL, Ochsner U, Byappanahalli MN, Whitman RL, Tepp WH, Lin GY, Johnson EA, Peller J, Sadowsky MJ (2013) Association of toxin-producing *Clostridium botulinum* with the macroalga *Cladophora* in the Great Lakes. *Environ Sci Technol* 47:2587–2594
- Chytrý M, Wild J, Pyšek P, Jarošík V, Dendoncker N, Reginster I, Pino J, Maskell LC, Vilà M, Pergl J, Kühn I, Spangenberg JH, Settele J (2012) Projecting trends in plant invasions in Europe under different scenarios of future land-use change. *Glob Ecol Biogeogr* 21:75–87
- Clavero M, García-Berthou E (2005) Invasive species are a leading cause of animal extinctions. *Trends Ecol Evol* 20:110

- Clavero M, Brotons L, Pons P, Sol D (2009) Prominent role of invasive species in avian biodiversity loss. *Biol Conserv* 142:2043–2049
- Cohen AN, Carlton JT (1998) Accelerating invasion rate in a highly invaded estuary. *Science* 279:555–558
- Colautti RI, Ricciardi A, Grigorovich IA, MacIsaac HJ (2004) Is invasion success explained by the enemy release hypothesis? *Ecol Lett* 7:721–733
- Côté IM, Darling ES, Brown CJ (2016) Interactions among ecosystem stressors and their importance in conservation. *Proc R Soc Lond B Biol Sci* 283:20152592
- Crooks JA (2005) Lag times and exotic species: the ecology and management of biological invasions in slow-motion. *Ecoscience* 12:316–329
- Czeglédi I, Takács P, Feng K, Erős T (2025) Non-native species affect the long-term dynamics of native stream fish assemblages. *Oikos* 2025:e11222
- David AS, Zarnetske PL, Hacker SD, Ruggiero P, Biel RG, Seabloom EW (2015) Invasive congeners differ in successional impacts across space and time. *PLoS ONE*. <https://doi.org/10.1371/journal.pone.0117283>
- Diagne C, Leroy B, Vaissière AC, Gozlan RE, Roiz DA, Jarić I, Salles JM, Bradshaw CJA, Courchamp F (2021) High and rising economic costs of biological invasions worldwide. *Nature* 592:571–576
- Doherty TS, Glen AS, Nimmo DG, Ritchie EG, Dickman CR (2016) Invasive predators and global biodiversity loss. *Proc Natl Acad Sci U S A* 113:11261–11265
- Doody JS, Rhind D, Green B, Castellano C, McHenry C, Clulow S (2017) Chronic effects of an invasive species on an animal community. *Ecology* 98:2093–2101
- Erős T, Comte L, Filipe AF, Ruhi A, Tedesco PA, Brose U, Fortin M-J, Giam X, Irving K, Jacquet C, Larsen S, Sharma S, Olden JD (2020) Effects of nonnative species on the stability of riverine fish communities. *Ecography* 43:1156–1166
- Essian DA, Chipault JG, Lafrancois BM, Leonard JBK (2016) Gut content analysis of Lake Michigan waterbirds in years with avian botulism type E mortality, 2010–2012. *J Great Lakes Res* 42:1118–1128
- Filbee-Dexter K, Pittman J, Haig HA, Alexander SM, Symons CC, Burke MJ (2017) Ecological surprise: concept, synthesis, and social dimensions. *Ecosphere* 8:e02005
- Frost MDT, Porensky LM, Reinhart KO, Koerner SE (2024) Invasive annual grasses destabilize plant communities in a northern mixed-grass prairie. *Ecosphere* 15:e70036
- Fusco EJ, Finn JT, Balch JK, Nagy RC, Bradley BA (2019) Invasive grasses increase fire occurrence and frequency across U.S. ecoregions. *Proc Natl Acad Sci U S A* 116:23594–23599
- Gallardo B, Aldridge DC (2015) Is Great Britain heading for a Ponto-Caspian invasional meltdown? *J Appl Ecol* 52:41–49
- Gallardo B, Bacher S, Barbosa AM, Gallien L, Gonzalez-Moreno P, Martinez-Bolea V, Sorte C, Vimercati G, Vila M (2024) Risks posed by invasive species to the provision of ecosystem services in Europe. *Nat Commun* 15:2631
- Gaston KJ, Jones AG, Hänel C, Chown SL (2003) Rates of species introduction to a remote oceanic island. *Proc R Soc Lond B Biol Sci* 270:1091–1098
- Geraldi NR, Anton A, Santana-Garçon J, Bennett S, Marbà N, Lovelock CE, Apostolaki ET, Cebrian J, Krause-Jensen D, Martinetto P, Pandolfi JM, Duarte CM (2020) Ecological effects of non-native species in marine ecosystems relate to co-occurring anthropogenic pressures. *Glob Change Biol* 26:1248–1258
- Griffen BD, Black T, Buck JC (2008) Inhibition between invasives: a newly introduced predator moderates the impacts of a previously established invasive predator. *J Anim Ecol* 77:32–40
- Hall DG, Gottwald TR, Bock CH (2010) Exacerbation of citrus canker by citrus leaf miner *Phyllocnistis citrella* in Florida. *Fla Entomol* 93:558–566
- Higgins SN, Vander Zanden MJ (2010) What a difference a species makes: a meta-analysis of dreissenid mussel impacts on freshwater ecosystems. *Ecol Monogr* 80:179–196
- Huang DC, Haack RA, Zhang RZ (2011) Does global warming increase establishment rates of invasive alien species? A centennial time series analysis. *PLoS ONE* 6:e24733
- IPBES (2023) The thematic assessment report on invasive alien species and their control. Intergovernmental Science Policy Platform on Biodiversity and Ecosystem Services. In: Roy HE, Pauchard A, Stoett P, Renard Truong T (eds), IPBES Secretariat, Bonn, Germany
- Jackson MC (2015) Interactions among multiple invasive animals. *Ecology* 96:2035–2041
- Jackson MC, Grey J (2013) Accelerating rates of freshwater invasions in the catchment of the River Thames. *Biol Invasions* 15:945–951
- Jackson MC, Loewen CJG, Vinebrooke RD, Chimimba CT (2016) Net effects of multiple stressors in freshwater ecosystems: a meta-analysis. *Glob Change Biol* 22:180–189
- Kao YC, Rogers MW, Bunnell DB (2018) Evaluating stocking efficacy in an ecosystem undergoing oligotrophication. *Ecosystems* 21:600–618
- Koel TM, Tronstad LM, Arnold JL, Gunther KA, Smith DW, Syslo JM, White PJ (2019) Predatory fish invasion induces within and across ecosystem effects in Yellowstone National Park. *Sci Adv* 5:eaav1139
- Kuebbing S, Nuñez MA, Simberloff D (2013) Current mismatch between ecological research and conservation efforts: the need to study co-occurring invasive plant species. *Biol Conserv* 160:121–129
- Kuebbing SE, Patterson CM, Classen AT, Simberloff D (2016) Co-occurring nonnative woody shrubs have additive and non-additive soil legacies. *Ecol Appl* 26:1896–1906
- Kumschick S, Gaertner M, Vilà M, Essl F, Jeschke JM, Pyšek P, Bacher S, Blackburn TM, Dick JTA, Evans T, Hulme PE, Kühn I, Mrugała A, Pergl J, Rabitsch W, Ricciardi A, Richardson DM, Sendek A, Winter M (2015) Ecological impacts of alien species: quantification, scope, caveats and recommendations. *Bioscience* 65:55–63
- Lester PJ (2023) Integrated resistance management for acaricide use on *Varroa destructor*. *Frontiers in Bee Science* 1:1297326

- Levine JM, D'Antonio CM (1999) Elton revisited: a review of evidence linking diversity and invasibility. *Oikos* 87:15–26
- Limburg K, Luzadis V, Ramsey MM, Schulz K, Mayer C (2010) The good, the bad, and the algae: perceiving ecosystem services and disservices generated by zebra and quagga mussels. *J Great Lakes Res* 36:86–92
- Liu X, Wang S, Ke Z, Cheng C, Wang Y, Zhang F, Xu F, Li X, Gao X, Jin C, Zhu W, Yan S, Li Y (2018) More invaders do not result in heavier impacts: the effects of non-native bullfrogs on native anurans are mitigated by high densities of non-native crayfish. *J Anim Ecol* 87:850–862
- Lone SA, Ahmed R, Rasray BA, Rashid I, Nuñez MA, Khuroo AA (2024) Disentangling the impacts of plant co-invasions: additive, antagonistic and synergistic. *Biol Invasions* 26:3795–3809
- Lopez BE, Allen JM, Dukes JS, Lenoir J, Vilà M, Blumenthal DM, Beaury EM, Fusco EJ, Laginhas BB, Morelli TL, O'Neill MW, Sorte CJB, Maceda-Veiga A, Whitlock R, Bradley BA (2022) Global environmental changes more frequently offset than intensify detrimental effects of biological invasions. *Proc Natl Acad Sci USA* 119:e2117389119
- Loreau M, Barbier M, Filotas E, Gravel D, Isbell F, Miller SJ, Montoya JM, Wang S, Aussenac R, Germain R, Thompson PL, Gonzalez A, Dee LE (2021) Biodiversity as insurance: from concept to measurement and application. *Biol Rev* 96(5):2333–2354
- MacIsaac HJ, Johansson ML (2017) Higher colonization pressure increases the risk of sustaining invasion by invasive non-indigenous species. *Aquat Ecosyst Health Manag* 20:378–383
- Mazza G, Tricarico E, Genovesi P, Gherardi F (2014) Biological invaders are threats to human health: an overview. *Ethol Ecol Evol* 26:112–129
- McCann K (2000) The diversity–stability debate. *Nature* 405:228–233
- Milanović M, Knapp S, Pyšek P, Kühn I (2020) Linking traits of invasive plants with ecosystem services and disservices. *Ecosystem Serv* 42:101072
- Mormul RP, Vieira DS, Bailli D, Fidanza K, Silva VFB, da Graça WJ, Pontara V, Thomaz MSM, Mendes RS (2022) Invasive alien species records are exponentially rising across the Earth. *Biol Invasions* 24:3249–3261
- O'Bryan CJ, Patton NR, Hone J, Lewis JS, Berdejo-Espinola V, Risch DR, Holden MH, McDonald-Madden E (2022) Unrecognized threat to global soil carbon by a widespread invasive species. *Glob Change Biol* 28:877–882
- Paolucci EM, MacIsaac HJ, Ricciardi A (2013) Origin matters: alien consumers inflict greater damage on prey populations than do native consumers. *Divers Distrib* 19:988–995
- Paul P, Kar TK (2016) Impacts of invasive species on the sustainable use of native exploited species. *Ecol Modell* 340:106–115
- Pearce F (2015) *The new wild*. Beacon Press, Boston
- Perez-Fuentetaja A, Clapsadl MD, Einhouse D, Bowser PR, Getchell RG, Lee WT (2006) Influence of limnological conditions on *Clostridium botulinum* type E presence in eastern Lake Erie sediments (Great Lakes, USA). *Hydrobiologia* 563:189–200
- Pfadenhauer WG, Bradley BA (2024) Quantifying vulnerability to plant invasion across global ecosystems. *Ecol Appl* 34:e3031
- Potter DU, Ford PL (2004) Grassland sustainability. In: Finch DM (ed) *Assessment of grassland ecosystem conditions in the Southwestern United States*, Vol 1. Gen. Tech. Rep. RMRS-GTR-135-vol. 1. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. pp 130–141
- Princé K, Chipault JG, White CL, Zuckerberg B (2018) Environmental conditions synchronize waterbird mortality events in the Great Lakes. *J Appl Ecol* 55:1327–1338
- Pušić M, Ljubojević M, Prvulović D, Kolarov R, Tomić M, Simikić M, Vejnović S, Narandžić T (2024) Bioenergy and biopesticides production in Serbia—could invasive alien species contribute to sustainability? *Processes* 12:art. 407
- Ravi S, Law DJ, Caplan JS, Barron-Gafford GA, Dontsova KM, Espeleta JF, Villegas JC, Okin GS, Breshears DD, Huxman TE (2022) Biological invasions and climate change amplify each other's effects on dryland degradation. *Glob Change Biol* 28:285–295
- Rejmanek M, Randall JM (2004) The total number of naturalized species can be a reliable predictor of the total number of alien pest species. *Divers Distrib* 10:367–369
- Ricciardi A (2001) Facilitative interactions among aquatic invaders: is an 'invasional meltdown' occurring in the Great Lakes? *Can J Fish Aquat Sci* 58:2513–2525
- Ricciardi A (2005) Facilitation and synergistic interactions among introduced aquatic species. In: Mooney HA, Mack RN, McNeely J, Neville LE, Schei PJ, Waage JK (eds) *Invasive alien species: a new synthesis*. Island Press, Washington, DC, pp 162–178
- Ricciardi A (2006) Patterns of invasion of the Laurentian Great Lakes in relation to changes in vector activity. *Divers Distrib* 12:425–433
- Ricciardi A (2007) Are modern biological invasions an unprecedented form of global change? *Conserv Biol* 21:329–336
- Ricciardi A, Kipp R (2008) Predicting the number of ecologically harmful exotic species in an aquatic system. *Divers Distrib* 14:374–380
- Ricciardi A, MacIsaac HJ (2011) Impacts of biological invasions on freshwater ecosystems. In: Richardson DM (ed) *Fifty years of invasion ecology: the legacy of Charles Elton*. Wiley-Blackwell, New Jersey, pp 211–224
- Ricciardi A, MacIsaac HJ (2022) Vector control reduces the rate of species invasion in the world's largest freshwater ecosystem. *Conserv Lett* 15:e12866
- Ricciardi A, Simberloff D (2025) Revisiting invasional meltdown: mechanisms and consequences of positive non-native species interactions. *Biol Invasions* 27:183
- Ricciardi A, Hoopes MF, Marchetti MP, Lockwood JL (2013) Progress toward understanding the ecological impacts of nonnative species. *Ecol Monogr* 83:263–282
- Richardson DM, Allsopp N, D'Antonio CM, Milton SJ, Rejmanek M (2000) Plant invasions: the role of mutualism. *Biol Rev* 75:65–93

- Rodrigues T, Kratina P, Setubal RB, Ferro JLS, Abe DH, Costa LO, Nova CC, Farjalla VF, Pires APF (2024) Interaction between climate change scenarios and biological invasion reveals complex cascading effects in freshwater ecosystems. *Glob Change Biol* 30:e17540
- Rohwer RR, Ladwig R, Hanson PC, Walsh JR, Vander Zanden MJ, Dugan HA (2024) Increased anoxia following species invasion of a eutrophic lake. *Limnol Oceanogr Lett* 9:3–42
- Russell JC, Sataruddin NS, Heard AD (2014) Over-invasion by functionally equivalent invasive species. *Ecology* 95:2268–2276
- Saenz D, Fucik EM, Kwiatkowski MA (2013) Synergistic effects of the invasive Chinese tallow (*Triadica sebifera*) and climate change on aquatic amphibian survival. *Ecol Evol* 3:4828–4840
- Sagoff M (2005) Do non-native species threaten the natural environment? *J Agric Environ Ethics* 18:215–236
- Salis RK, Brennan GL, Hansson LA (2023) Successful invasion to freshwater systems double with climate warming. *Limnol Oceanogr* 68:953–962
- Salo P, Korpimäki E, Banks PB, Nordstrom M, Dickman CR (2007) Alien predators are more dangerous than native predators to prey populations. *Proc Royal Soc B Biol Sci* 274:1237–1243
- Sandman AN, Näslund J, Gren IM, Norling K (2018) Effects of an invasive polychaete on benthic phosphorus cycling at sea basin scale: an ecosystem disservice. *Ambio* 47(8):884–892
- Sardain A, Sardain E, Leung B (2019) Global forecasts of shipping traffic and biological invasions to 2050. *Nat Sustain* 2:274–282
- Sax DF, Gaines SD (2003) Species diversity: from global decreases to local increases. *Trends Ecol Evol* 18:561–566
- Scheibling RE, Gagnon P (2006) Competitive interactions between the invasive green alga *Codium fragile* ssp. *tomentosoides* and native canopy-forming seaweeds in Nova Scotia (Canada). *Mar Ecol Prog Ser* 325:1–14
- Seebens H, Blackburn TM, Dyer EE, Genovesi P, Hulme PE, Jeschke JM, Pagad S, Pyšek P, Winter M, Arianoutsou M, Bacher S, Blasius B, Brundu G, Capinha C, Celesti-Grapow L, Dawson W, Dullinger S, Fuentes N, Jäger H, Kartesz J, Kenis M, Kreft H, Kühn I, Lenzner B, Liebhold A, Mosena A, Moser D, Nishino M, Pearman D, Pergl J, Rabitsch W, Rojas-Sandoval J, Roques A, Rorke S, Rossinelli S, Roy HE, Scalera R, Schindler S, Štajerová K, Tokarska-Guzik B, van Kleunen M, Walker K, Weigelt P, Yamanaka T, Essl F (2017) No saturation in the accumulation of alien species worldwide. *Nat Commun* 8:14435
- Seebens H, Blackburn TM, Dyer EE, Genovesi P, Hulme PE, Jeschke JM, Pagad S, Pyšek P, van Kleunen M, Winter M, Ansong M, Arianoutsou M, Bacher S, Blasius B, Brouckhoff EG, Brundu G, Capinha C, Causton CE, Celesti-Grapow L, Dawson W, Dullinger S, Economou EP, Fuentes N, Guénard B, Jäger H, Kartesz J, Kenis M, Kühn I, Lenzner B, Liebhold AM, Mosena A, Moser D, Nentwig W, Nishino M, Pearman D, Pergl J, Rabitsch W, Rojas-Sandoval J, Roques A, Rorke S, Rossinelli S, Roy HE, Scalera R, Schindler S, Štajerová K, Tokarska-Guzik B, Walker K, Ward DF, Yamanaka T, Essl F (2018) Global rise in emerging alien species results from increased accessibility of new source pools. *Proc Natl Acad Sci U S A* 115:E2264–E2273
- Seebens H, Bacher S, Blackburn TM, Capinha C, Dawson W, Dullinger S, Genovesi P, Hulme PE, van Kleunen M, Kühn I, Jeschke JM, Lenzner B, Liebhold AM, Pattison Z, Pergl J, Pyšek P, Winter M, Essl F (2021) Projecting the continental accumulation of alien species through to 2050. *Glob Change Biol* 27:970–982
- Simberloff D, Von Holle B (1999) Positive interactions of non-indigenous species: invasional meltdown? *Biol Invasions* 1:21–32
- Simberloff D, Martin JL, Genovesi P, Maris V, Wardle DA, Aronson J, Courchamp F, Galil B, Garcia-Berthou E, Pascal M, Pyšek P, Sousa R, Tabacchi E, Vilà M (2013) Impacts of biological invasions: what's what and the way forward. *Trends Ecol Evol* 28:58–66
- Smith SDP, Bunnell DB, Burton GA Jr., Ciborowski JJH, Davidson AD, Dickinson CE, Eaton LA, Esselman PC, Evans MA, Kashian DR, Manning NF, McIntyre PB, Nalepa TF, Perez-Fuentetaja A, Steinman AD, Uzarski DG, Allan JD (2019) Evidence for interactions among environmental stressors in the Laurentian Great Lakes. *Ecol Indic* 101:203–211
- Soto I, Macêdo RL, Carneiro L, Briski E, Kouba A, Cuthbert RN, Haubrock PJ (2024) Divergent temporal responses of native macroinvertebrate communities to biological invasions. *Glob Change Biol* 30:e17521
- Spear MJ, Walsh JR, Ricciardi A, Vander Zanden MJ (2021) The invasion ecology of sleeper populations: prevalence, persistence, and abrupt shifts. *Bioscience* 71:357–369
- Spencer CN, McClelland BR, Stanford JA (1991) Shrimp stocking, salmon collapse, and eagle displacement. *BioScience* 41:14–21
- Steffen MM, Belisle BS, Watson SB, Boyer GL, Wilhelm SW (2014) Status, causes and controls of cyanobacterial blooms in Lake Erie. *J Great Lakes Res* 40:215–225
- Stout JC, Kells AR, Goulson D (2002) Pollination of the invasive exotic shrub *Lupinus arboreus* (Fabaceae) by introduced bees in Tasmania. *Biol Conserv* 106:425–434
- Straub L, Williams GR, Vidondo B, Khongphinitbunjong K, Retschnig G, Schneeberger A, Chantawannakul P, Diemann V, Neumann P (2019) Neonicotinoids and ectoparasitic mites synergistically impact honeybees. *Sci Rep* 9(1):8159
- Strayer DL, Eviner VT, Jeschke JM, Pace ML (2006) Understanding the long-term effects of species invasions. *Trends Ecol Evol* 21:645–651
- Tobin PC (2015) Ecological consequences of pathogen and insect invasions. *Curr Forestry Rep* 1:25–32
- Traveset A, Richardson DM (2006) Biological invasions as disruptors of plant reproductive mutualisms. *Trends Ecol Evol* 21:208–216
- Traynor KS, Mondet F, de Miranda JR, Techer M, Kowallik V, Oddie MAY, Chantawannakul P, McAfee A (2020) *Varroa destructor*: a complex parasite, crippling honey bees worldwide. *Trends Parasitol* 36:592–606

- Turbelin AJ, Cuthbert RN, Essl F, Haubrock PJ, Ricciardi A, Courchamp F (2023) Biological invasions are as costly as natural hazards. *Perspect Ecol Conserv* 21:143–150
- Valone TJ, Balaban-Feld J (2018) Impact of exotic invasion on the temporal stability of natural annual plant communities. *Oikos* 127:56–62
- Vanderploeg HA, Liebig JR, Carmichael WW, Agy MA, Johengen TH, Fahnenstiel GL, Nalepa TF (2001) Zebra mussel (*Dreissena polymorpha*) selective filtration promoted toxic *Microcystis* blooms in Saginaw Bay (Lake Huron) and Lake Erie. *Can J Fish Aquat Sci* 58:1208–1221
- Vermeij GJ (2005) Invasion as expectation. In: Sax DF, Stachowicz JJ, Gaines SD (eds) *Species invasions: insights into ecology, evolution, and biogeography*. Sinauer Associates, Sunderland, Massachusetts, pp 315–339
- Vilà M, Hulme PE (2017) *Impact of biological invasions on ecosystem services*. Springer, Gewerbestrasse, Switzerland
- Vujanović D, Losapio G, Milić S, Milić D (2022) The impact of multiple species invasion on soil and plant communities increases with invasive species co-occurrence. *Front Plant Sci* 13:875824
- Walsh JC, Venter O, Watson JEM, Fuller RA, Blackburn TM, Possingham HP (2012) Exotic species richness and native species endemism increase the impact of exotic species on islands. *Glob Ecol Biogeogr* 21:841–850
- Walsh JR, Carpenter SR, Vander Zanden MJ (2016) Invasive species triggers a massive loss of ecosystem services through a trophic cascade. *Proc Natl Acad Sci U S A* 113:4081–4085
- Warren RJ, Frankson PT, Mohan JE (2023) Global change drivers synergize with the negative impacts of non-native invasive ants on native seed-dispersing ants. *Biol Invasions* 25:773–786
- Witte S, Buschbaum C, van Beusekom JE, Reise K (2010) Does climatic warming explain why an introduced barnacle finally takes over after a lag of more than 50 years? *Biol Invasions* 12:3579–3589
- Yu Y, Xu Z, Zhong S, Cheng H, Guo E, Wang C (2023) The co-invasion of the three Asteraceae invasive plants can synergistically increase soil phenol oxidase activity. *Biol Bull* 50:467–473
- Zangerl AR, Berenbaum MR (2005) Increase in toxicity of an invasive weed after reassociation with its coevolved herbivore. *Proc Natl Acad Sci USA* 102:15529–15532
- Zaret T, Paine RT (1973) Species introduction in a tropical lake. *Science* 182:449–455
- Zenni RD, da Cunha WL, Musso C, de Souza JV, Nardoto GB, Miranda HS (2020) Synergistic impacts of co-occurring invasive grasses cause persistent effects in the soil-plant system after selective removal. *Funct Ecol* 34:1102–1112

**Publisher's Note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.