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Opinion

Invasion Biology: Specific Problems and Possible Solutions

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Biological invasions have been unambiguously shown to be one of the major global causes of biodiversity loss. Despite the magnitude of this threat and recent scientific advances, this field remains a regular target of criticism – from outright deniers of the threat to scientists questioning the utility of the discipline. This unique situation, combining internal strife and an unaware society, greatly hinders the progress of invasion biology. It is crucial to identify the specificities of this discipline that lead to such difficulties. We outline here 24 specificities and problems of this discipline and categorize them into four groups: understanding, alerting, supporting, and implementing the issues associated with invasive alien species, and we offer solutions to tackle these problems and push the field forward.

Invasion Biology in Turmoil

Despite some recent strife [1], invasion biology is generally regarded as an important and useful scientific endeavor at the crossroads of ecology and conservation biology [2]. It has a strong management component because it is – just like conservation biology – both a field of research and a field of action. Support from society is therefore essential for this discipline – from the policy makers that decide the focus of research programs to the citizens that can help to implement management actions. However, there is a marked tendency to negate the benefits and even the necessity of invasion biology, with increasingly frequent articles in newspapers and popular science books, as well as scientific opinion articles [3].

More generally, it appears that, other than a few countries such as New Zealand and Australia, citizens and organizations of the world very seldom feel concerned with – or are even simply aware of – the impacts caused by invasive alien species (e.g., [4,5]). This is especially true for the ecological impacts of biological invasions, which generally go disregarded by most. The sympathetic respondents are generally few, and can sometimes be overcome by an active, hostile minority who may weaken or even jeopardize the efforts of both scientists and managers. Understanding this lack of support is therefore crucial given that other major causes of biodiversity loss such as habitat loss, overexploitation, or pollution do not suffer from the same societal resistance. It is only once we have made explicit which difficulties are faced by invasion biology that we can propose adequate solutions (Figure 1).

Specific Difficulties Related to Invasion Biology

We identify here 24 specific difficulties and problems of invasion biology that we, as scientists, need to act upon. We classify these problems into four distinct types of difficulties: understanding, alerting, supporting, and implementing issues stemming from invasion biology.

Trends

Global analyses and recent syntheses confirm what the scientific community has claimed for decades: biological invasions cause major impacts and are a major cause of biodiversity loss worldwide.

Despite increasing evidence, the importance of biological invasions is not generally acknowledged by the public, is not fully accepted by decision makers, and has even recently been increasingly disputed by some scientists.

The mismatch between the urgency to deal with a major environmental issue and the little concern it receives from several key components of society needs to be recognized and the underlying reasons identified and addressed.

Many reasons for this mismatch are not shared with other global change aspects and are specific to invasion biology; in particular, these include difficulties in raising awareness and understanding as well as in obtaining support for the implementation of conservation programs.

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Understanding

The concept of invasive alien species (IAS) is generally poorly understood by society. First and foremost, this is because invasion biology resides in ecology, a science with complexity as its essence [6]. Understanding the concept of IAS and the problems generated in invaded ecosystems requires a general understanding of ecology and evolution, and in particular of interspecific relationships, population dynamics, co-evolutionary processes, and so forth. Those without an ecological background often hold the candid view that species can simply be added into ecosystems without consequences. Conversely, the harms related to removing species, such as cutting large areas of forest or destroying fish stocks, are more straightforward to understand.

Another difficulty is that the outlines of the key notions of biological invasions are ambiguously delineated [6]. For example, some authors wish to include native species into the concept of invasion (e.g., [7,8], but see also [9,10]). The concept of an invasive species is also shifting because of climate change: species naturally colonizing new adjacent areas because of the geographic expansion of their suitable climatic niche are considered invasive by some, but not by others [11]. The necessity to invoke a human cause in the process of invasion is also a point of discussion [12]. The understanding of biological invasions by the general public would benefit from greater rigor and consistency within the scientific community [13,14].

Although some definitions (e.g., [15]) and unified frameworks [16,17] have been proposed, terminology issues persist. The terms alien, allochthonous, domesticated, exotic, foreign, introduced, invasive, naturalized, non-indigenous, non-native, or pest can all be found in the literature, sometimes used interchangeably but also sometimes with different meanings. Definitions vary according to the scientific field concerned – ecology, economics, philosophy, law, ethics, sociology, management, etc. – and the actors and objectives targeted [18] (Figure 2). In addition, the status of 'invasive' is dynamic in space and time (Box 1). For all the aforementioned reasons, the scientific messages themselves may be multiple, even contradictory, and therefore unclear. Thus, standard and clear definitions would make understanding on invasive species more efficient.

Moreover, the complexity of the processes in action in biological invasions often prevents specialists from issuing scenarios with simple, quantitative alternatives and uncertainty measures [6]. Because invasions depend on the combination of dynamic interspecific relationships, abiotic effects, and anthropogenic influences, it is extremely complicated to obtain reliable predictions of spread and impacts. Contrary to the effects of other global threats on biodiversity, such as climate change (e.g., [19]), global scenarios for biological invasions are seldom proposed by experts because of the aforementioned complexities of the systems. This lack of scenarios hinders political credibility and public acceptance, and maintains the lack of a sound basis for decision makers to work from.

Because of a lack of consensus within the scientific community and the inherent complexity of biological invasions, the public is much less aware of this global threat than of most other drivers of biodiversity loss. However, increasing understanding about IAS alone is not sufficient. The public also needs to be alerted and convinced (not necessarily by scientists) that IAS need close attention.

Alerting

The main difficulty in alerting the public to the need to pay closer attention to IAS lies in the ongoing challenge to demonstrate the impact of IAS. Although some scientists would prefer impacts not to be part of the definition of IAS [20], the ecological and socioeconomic damage these species cause is often the ultimate reason for studying and counteracting them [17].

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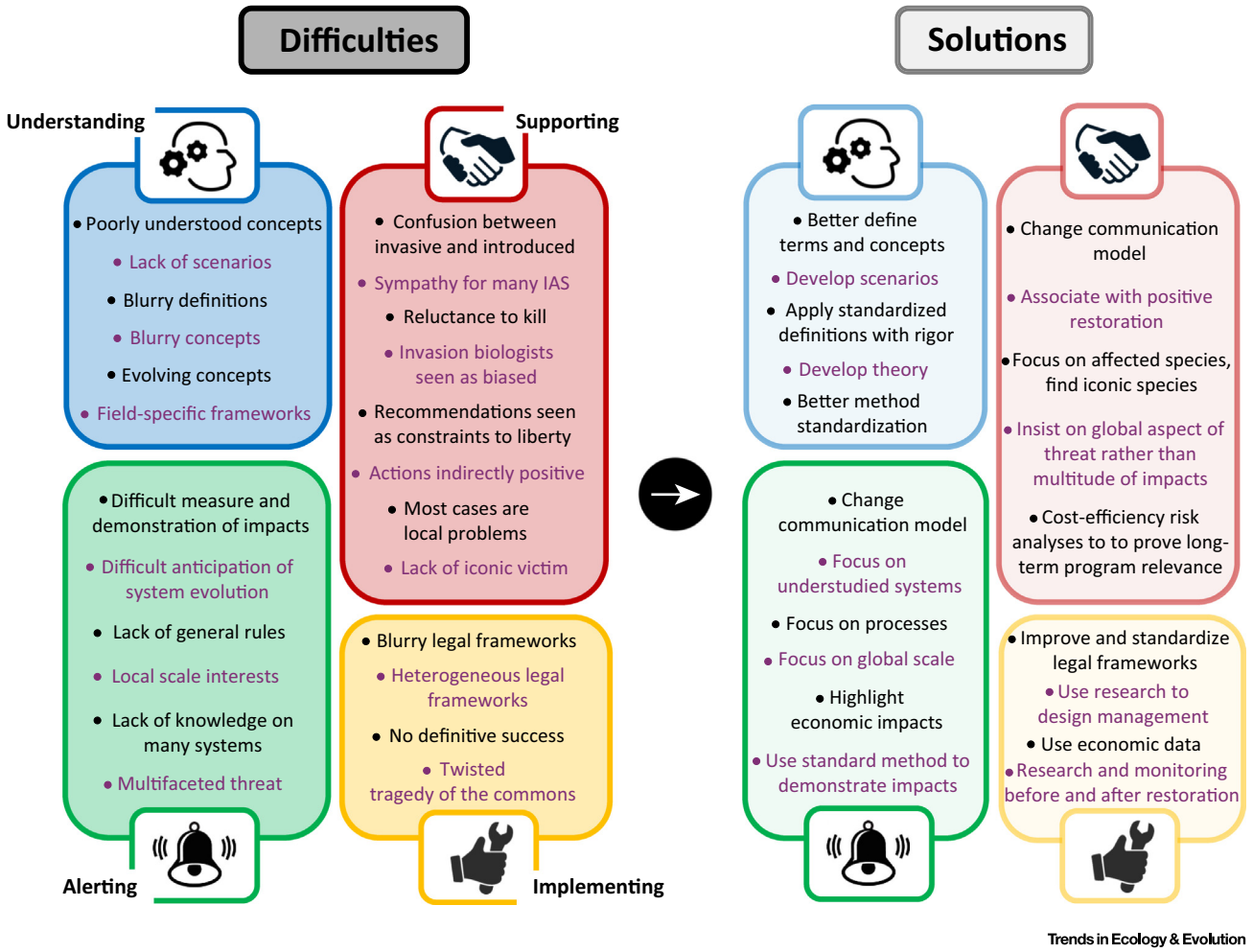

Figure 1. Difficulties and Proposed Solutions for Advancing Invasion Biology, According to the Four Categories of Issues Identified. The alternation of text colors in the boxes is purely for ease of reading.

Economic impacts can be relatively straightforward to estimate but, even so, recent studies show how little is known about the economic impacts of even the most damaging IAS [21]. Defining an ecological impact is different and even more complex [17,22,23]. The metric of the impact, the threshold above which a process is considered problematic, the amplitude and duration of such effects, and the markers of consequences all need to be defined, measured, and distinguished from the background noise of normal ecological variation. A recent study showed that environmental impacts were demonstrated for only 30% of alien bird species, while data are lacking for the remaining species [24].

Two dimensions make it difficult to demonstrate the significant impact of IAS: time and spatial scales [25]. Several decades generally separate introduction from invasion [26,27], the changes are usually gradual, tending to pass unnoticed, and the impacts are context-, region-, and species-dependent. Second, showing that the observed changes are a consequence of the invasion generally requires complex experimental approaches. This represents a heavy burden of proof for the invasion biologist, especially for taxonomic groups that are less well studied, known, or appealing to the public (Box 2).

Box 1. What Time-Frames and Impact Thresholds Define an IAS?

There is no commonly agreed time-frame or scale of impact after introduction that define a species as invasive. Each species has its own specific timespan before it comes into stasis with the local ecosystem, and even that is also species- and context-specific. For example, the European honey bee *Apis mellifera*, introduced worldwide as a pollinator centuries ago, is now rarely presented as invasive, its negative impact on local pollinators being generally overlooked. By contrast, the Asian *Megachile sculpturalis*, recently detected in Europe, is suspected to be invasive, based on a single record of nest eviction of a native pollinator in the USA, and its potential for pollination has been ignored. To objectively prioritize for management, it is necessary to consider both the ecological and economic impacts, as well as the time since introduction, of the species in question. Furthermore, impacts of invasive species can take decades to occur, a scale at which awareness of change is harder. Even if impacts are not detected since introduction, potential synergies with climate change could generate novel impacts that did not occur before, challenging further the concept of invasive species (see main text). This further illustrates the lack of any rigorous time-frame characterization of the key definitions. This overall paucity of clear delineation of the concepts adds further confusion to the general lack of understanding of invasion sciences among citizens.

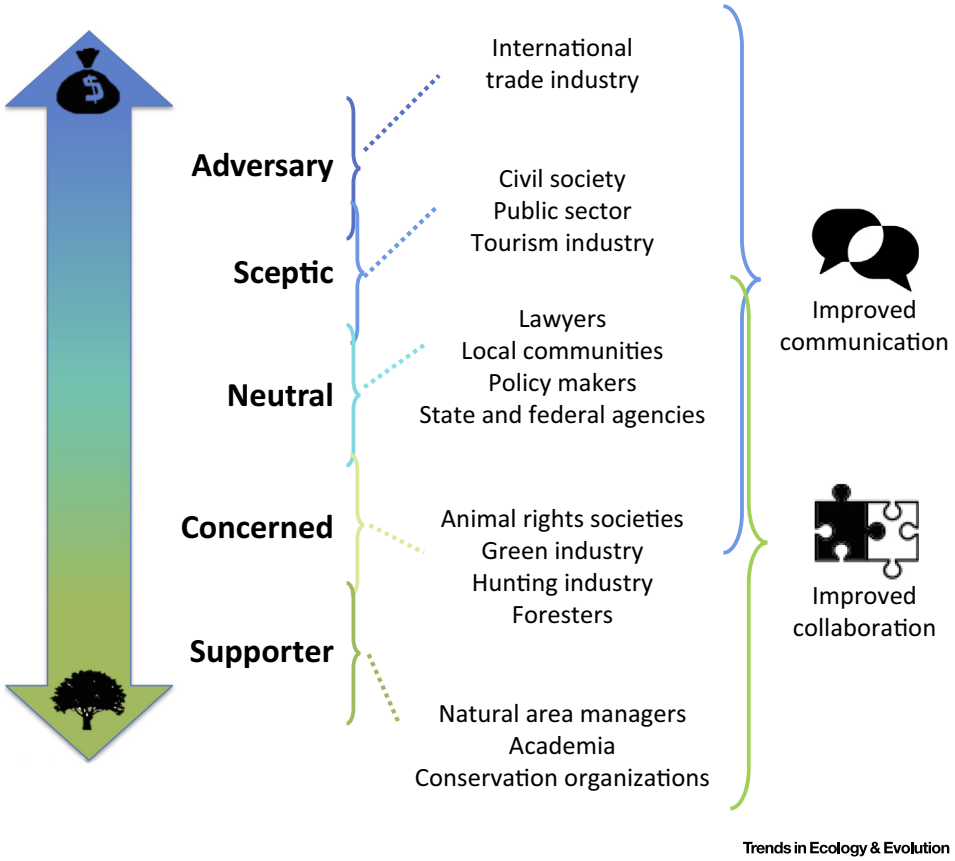

Figure 2. Different Types of Stakeholders with which Invasion Biologists Interact. Their position regarding biological invasions is not always in consensus and can be context-specific.

The history of invasion biology has shown that the generally poor understanding of the intricacies of invaded trophic webs, communities, and ecological networks has regularly made it impossible to accurately predict the outcome of invasions, or the outcome of the removal of invaders. Unexpected indirect effects, also called surprise effects, have generated undesired outcomes [28–30]. Such mishaps are damaging the credibility of invasion biologists and the messages they attempt to deliver.

The lack of a universal theoretical context and general rules is a further impediment to raising awareness on the magnitude of this threat. Even the ecological traits that characterize IAS

Box 2. Complexities in Demonstrating the Impact of IAS

Proving and measuring the impact of IAS on invaded ecosystems is extremely difficult. A typical example is the introduction of rats on islands [59]. Rats have been unambiguously observed to prey upon eggs, chicks, and adult birds. Even so, these repeated observations are insufficient to prove that they have an impact at the population level and endanger entire bird populations. Although well documented and recognized by the scientific community, demonstrating and quantifying to what extent they affect local communities requires population dynamics studies, which are intensive. This is one example of an IAS that is undoubtedly known to have a consistent impact on the invaded ecosystems, but scientists must still collect evidence to support their warnings and management recommendations.

An additional difficulty in alerting the public about the threat that IAS represent arises from the fact that a majority of IAS are unknown or unfamiliar to most people. For example, many invasive invertebrates and microorganisms can have dramatic impacts. Not only are these taxa less studied by researchers but also, if impacts are ultimately proven, the results are deemed harder to communicate to the public as compared to research on charismatic mammals, birds, and plants. For some invasions, such as earthworms in deglaciated parts of North America where the impacts on soil communities are wide-ranging both in scale and in type, there is very little public awareness, and therefore interest is not stimulated. These examples illustrate two types of obstacle that make it complicated to voice concerns about the threat that IAS represent.

(or communities sensitive to invasion) are generally lacking [31–33], although there are exceptions [34]. Historically, conservation biologists have dealt with key new invasions on a case-by-case basis, without theoretical methodologies or conceptual frameworks. No general rules for prevention and response actions are highlighted, which further weakens the perception that IAS are a crucial threat.

An additional issue that makes alerting difficult is that invasive species are a multi-faceted threat. Owing to the tremendously high number of IAS and species that may potentially become invasive, it is challenging to 'put a face' on the problem of biological invasions, which is not the case with deforestation, pollution, climate change, or overexploitation. It is also arduous to view a species as problematic when the species is damaging in one place, but not so (or even sometimes endangered) in its native habitat. In that case, one must grasp that it is not the (many) species that are a potential problem, but the species–environment interaction. The myriad of studies on IAS generally focus on one or a few species, diluting the recognition of each. As a result, communication on IAS is often local, and related to specific cases, either of which misses most of the global audience, or addresses them with foreign issues generally irrelevant to the global audience. It presents invasions as a gathering of multiple cases varying in time and space rather than as a general issue, with a global cause, upon which we can act.

Supporting

One major impediment to the support of studies and actions in biological invasions is the huge sympathy capital for many IAS. Some have been introduced because they are beautiful (e.g., ornamental flowers, aquarium fish, exotic pets), cute and/or domestic (e.g., cats, grey squirrels), or useful (e.g., game, fur mammals). Strong conflicts of interest may also arise that prevent support for IAS removal [35]. In addition, even when people recognize the need for invasive species management, they may not support early eradications or preventive measures when threats are less apparent [36]. A related argument is that, because invasive species have been introduced by humans, it is neither fair nor ethical to kill them, suggesting that their eradication may be considered akin to a punishment following a fault that was not their own. Cats are a strong illustration of this sympathy capital: eradicating invasive cats can be difficult, and often inefficient actions such as live trapping, transporting, sheltering, and neutering are regulated [37]. The case of the grey squirrel in Italy is also a good illustration of the difficulties invasion biologists can encounter because of the public empathy for IAS [38,39].

Similarly, there are strong ethical implications of basing conservation programs on killing, even if it is to protect other species. There is a general reluctance to support conservation programs

that are only indirectly positive, but remain directly negative for life in the short term. This leads to a lack of support from animal rights proponents. It remains arduous to justify killing some individuals, even if it is for the benefits of entire populations or species [40], because animal ethics does not put species conservation above individual suffering. Although lethal removal can sometimes be the only sustainable solution [41], this is not readily accepted by many. For all other drivers of biodiversity loss, the actions are directly positive: for example, planting trees, refraining from buying wildlife products, or cleaning up polluted beaches. Killing species to protect the environment can be seen as too indirectly positive, at best.

Of course, actions to mitigate biological invasions are not limited to eradicating or controlling IAS, and the general public can be advised to act appropriately, or more often, to refrain from particular activities. Asking them not to release plants or animals in locations outside their native range, for instance, can be viewed as a constraint to their liberty and is therefore not implemented willingly, even if the underlying rationale is understood. Recommendations are also often counterintuitive; for example, people can consider releasing animals into wild habitats as a righteous action.

Another source of the lack of support comes from the confusion between naturalized alien species of economic value (e.g., cultivated plants) and harmful invasive species. The messages that invasion biologists strive to put forward is that management actions are limited to species that have important negative impacts on ecosystems or socioeconomies, and are not directed at species that have no or positive impacts [2].

Likewise, the recurrent reproaches that invasion biologists are xenophobic because their models of study are alien species are as unfounded as they are unreasonable. Refraining from using war-like vocabulary is one step towards this. It is noteworthy that no one seems shocked that conservationists 'fight' against deforestation or poaching, but 'fighting' against invasive species has negative connotations because it is directed against other living organisms.

While the species responsible for invasions are too numerous to assign a clear face to the problem, invasion biologists also lack iconic victims that need to be saved. Climate change is personified by the polar bear, poaching shows rhinos and elephants, deforestation is illustrated, for example, by orang-utans, overexploitation campaigns show whales, and marine pollution is associated with seabirds trapped in oil spills and sea turtles tangled in plastic. By contrast, invasion biology has no global face to focus salvation efforts on.

Implementing

When implementing actions against biological invasions, the first challenge is that their success is never definitive: years of management can be negated by a single biosecurity breach. Conservation programs face the challenge to predict IAS distributions, prevent introductions, intercept and monitor IAS, and, where possible, perform eradication measures; all these steps are extremely challenging, especially in the final phases when the remaining individuals are at low density and eradication seems complete. Because the success of management actions cannot be guaranteed, most funders and decision makers are hesitant to support invasion biology programs.

More than in many other struggles for biodiversity, there are legal difficulties associated with IAS. First, where does the burden of responsibility lie: when an alien species is released into the wild, is it the responsibility of the trader (e.g., pet store), of the user (e.g., pet owners), or of the releaser (often unknown)? Most countries such as in Europe still use black lists (species proved to be invasive are intercepted; this approach is also used by the new EU regulation on IAS [42]) to regulate the entry of alien species, while from an ecological perspective it would be advisable to

use white lists (only species known to have a very low invasion potential are to be allowed in). Moreover, species are considered to be non-native only if they come from distinct political borders, not geographical ones. This is obviously problematic in the case of overseas territories: in France, any invasive species can legally be imported from French Guyana or New Caledonia, even when they cause important damage there. Although increasing numbers of countries have adopted legislation to address the issues of IAS [43,44], very few are adequate, even fewer are satisfyingly implemented, and none are enforced across geopolitical frontiers. For instance, it is only illegal to farm invasive American mink in some European countries; other European countries continue to breed them, and the fur industry constitutes an important and continuous source of invasive American mink in Europe [45]. Moreover, legislation for and the implementation of conservation programs across geopolitical frontiers are complicated because restrictions on goods flow and quarantine measures tend to clash with the economic goals of global free trade. A review on social conflicts in invasive species management found that they arose based largely on differences in value systems and on risk perceptions of stakeholders and decision makers [46], something that now needs to be taken into account in management strategies.

Finally, the 'tragedy of the commons' [47] applies maliciously to biological invasions because short-term individual or economic interests may be greater than the common good; but, unlike climate change for example, the loss is rarely shared by all. Some can benefit from actions that will lead to biological invasions, while not directly suffering from the resulting damage (losses to biodiversity are often economic externalities and damage can be localized). Typical examples are the substantial economic costs caused by invasive insects transported accidentally by international trade. These introductions could be avoided, but only at a high cost for the importers, who have no economic incentive to do so. Many other types of examples exist, from the human cost of herbicide use to remove alien plants to interests from different stakeholders in horticulture, forestry, or sport-fishing industries [48–51].

As illustrated here, invasion biology is characterized by a wicked combination of multiple difficulties, many of which are idiosyncratic to this discipline. Consequently, we need to clearly delineate them and find specific solutions to address them (Figure 1).

Towards Possible Solutions

Scientific Progress

Although invasion biology has grown enormously in the past decades, a new level must now be reached to face the current challenges of this field both from within and outside. As suggested above, improving the theoretical corpus and developing new predictive tools, both at the level of ecosystem trajectories and at larger scales (scenarios for global invasions in the coming decades), would benefit the discipline not only regarding the issue of understanding but also well beyond, into alerting and supporting. Qualitative progress in deciphering the processes of invasions, the traits leading to invasiveness or invasibility, and the dynamics of introduced species can now benefit from the latest quantitative developments of modern data science and advanced statistics. Better incorporation of economics and social sciences into ecological studies, especially regarding impacts, is also now crucial. Lastly, in parallel to better defining and quantifying ecological impacts, scientists should focus on further advancing solution-based approaches that also imply a more integrated collaboration with political and social scientists.

Standardization

Another important category of solutions common to many of the specific difficulties mentioned above will come from standardization efforts. Consensual definitions have recently been proposed [15,16]. Although it is unrealistic to propose that everyone uses exactly the same set of definitions, we recommend that people are explicit and clear about the definitions they use. For instance, one should be clear whether the term IAS is only used to refer to species that cause

Box 3. Shifting Our Science Communication Paradigm

Part of the lack of broader support from society is because some of the main principles of invasion biology diverge from personal interests, and even sometimes with the core values of individuals. Invasion biology is indeed a clear example where scientific understanding can conflict with central beliefs of members of the public, creating a tension between scientists and society. In such cases, scientists, who frequently attribute public disagreement to ignorance or misunderstanding, must realize that more genuine interactions between experts and citizens depend upon a shift of science communication and upon recognition of different values and motivations. We now need to shift from the one-way model based on the belief that more knowledge is needed to convince the public, to a new communication paradigm that accepts that public resistance may not be due to lack of information alone.

This shift should help to alleviate the effects of the recent multiplication of both the transmitters and the receivers of the scientific message [57]. On the one hand, science communicators are no longer limited to a small group of prestigious experts; the already complex scientific message broadens, multiplies, and sometimes becomes contradictory, thus losing focus and impact. In parallel, the citizen sphere receiving this information is divided into many interest groups, including specialists, hobbyists, lobbyists, funding institutions, policy makers, and politicians, all having different dialogues on the issues.

The 'deficit model' of science communication (Figure I) stipulates that an increase in the transfer of information from experts to the public will convince the latter about the accuracy and reliability of the discipline [56]. In this model it is assumed that knowledge is the only factor guiding how individuals reach judgments, even though social identity, ideology, and trust often have stronger impacts [55]. It is purely one-way communication: experts decide and determine the best strategy to adopt, and then communicate their solutions to policy makers. This model is now considered to be inefficient and outdated.

By contrast, the 'dialogue model' or 'public engagement model' (Figure I) is based on a genuine interchange with the public that recognizes and incorporates differences in knowledge, values, perspectives, and interests. It is a two- or multi-way discussion with public stakeholders on benefits, drawbacks, and costs, based on deliberative public engagement techniques. Invasion biologists must be trained in these techniques to become better able to engage with the public.

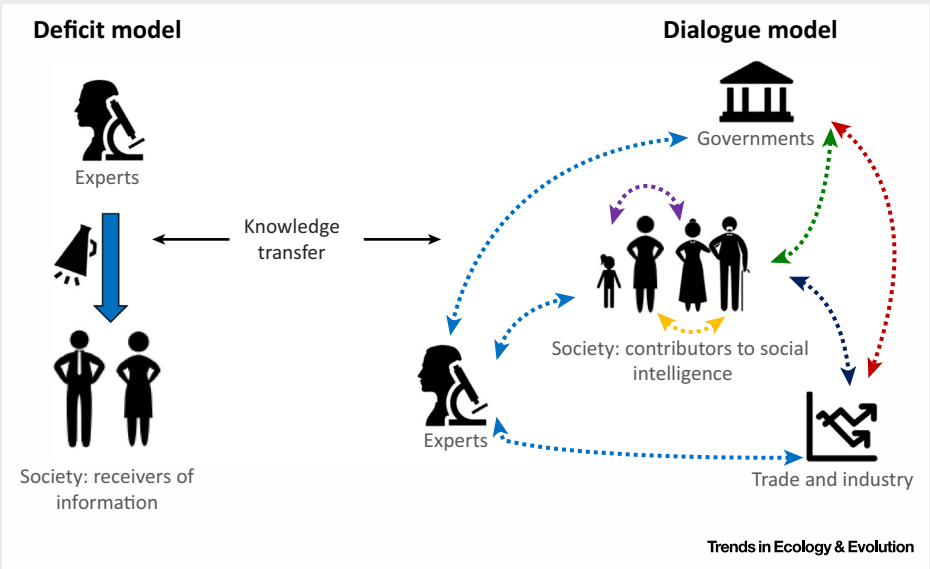

Figure I. Deficit and Dialogue Models of Science Communication.

negative impacts. Efforts should be made to improve general conceptual frameworks and tools to characterize and measure the progress and impacts of IAS [17]. These must then be adopted by the scientific community [6] to better understand, measure, and predict the outcomes of invasions, to be more persuasive, and to obtain more solid support. The management of IAS, including the different levels of involvement of various stakeholders, also needs to benefit from more standardized processes so as to optimize outcomes [50]. Standardization should also be aimed at legislation [52]. Although some progress has been achieved [42], inadequacies or lack of enforcement have been reported for many legislative frameworks (e.g., [52–54]). Across

borders, laws and economic incentives to compel importers to prevent the flow of species may help to resist the 'tragedy of the commons' scenario.

Communication

Many issues related to the acceptance and support of invasion biology by society arise from inappropriate communication, possibly because scientists rely on an out-dated model. Scientific communication must be transformed in its form and content. First, by taking full advantage of modern tools of communication [55] and citizen science. Second, by adapting our messages and our communication model [56,57] to our various audiences [55], including stakeholders with various perceptions [36] or opposing interests [49,50,58]. It is time to move from a one-way, top-down model where science aims to deliver knowledge and truth, to an authentic dialogue with the public, permitting mutual understanding and resolution for both parties (Box 3). Third, scientific concepts related to biological invasions need to be translated into simple and intelligible messages for the general public. It is urgent to clarify the ecological notions necessary to understand why IAS are a threat to biodiversity, and perhaps to focus on fewer threatened iconic species rather than on multiple IAS. This way, biological invasions might be identified as a global threat and general phenomenon against which action can be taken, rather than a patchwork of locally specific and distinct issues that are impossible to rally support against. Scientific findings and existing global scenarios should be converted into explicit and useful guidelines for decision makers and managers, and disseminated more widely. Our communication strategy must recognize and incorporate differences in knowledge, values, perspectives, and motivations [56]. Both the process of biological invasions and the identity of invasive species should be made clearer to the public, as should be the species potentially affected by them (e.g., find an 'iconic victim'). The vocabulary employed should neither be war-like nor centered on killing, nor be authoritarian, if we aim to obtain support from society for developing research, legislation, management, and prevention programs. Finally, increased awareness of IAS impacts may come through highlighting the economic costs of IAS. This will attract the attention of people other than scientists, who may then become more receptive to the growing ecological problems and perhaps shift the stance and the relationships of some stakeholders with our discipline (Figure 2).

To close, there is an imperative need and considerable potential to advance invasion biology, standardize its methods, and improve its communication strategy. We believe that it is only by acknowledging the idiosyncrasies of our scientific field, and by adapting our actions and messages to these peculiarities, compared to other drivers of biodiversity loss, that we will acquire the necessary support to advance this discipline.

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Supplemental Information

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References

1. Richardson, D.M. and Ricciardi, A. (2013) Misleading criticisms of invasion science: a field guide. *Divers. Distrib.* 19, 1461–1467
2. Simberloff, D. *et al.* (2013) Impacts of biological invasions: what's what and the way forward. *Trends Ecol. Evol.* 28, 58–66
3. Russell, J.C. and Blackburn, T.C. (2017) The rise of invasive species denialism. *Trends Ecol. Evol.* 32, http://dx.doi.org/10.1016/j.tree.2016.10.012
4. TNS Political and Social Network (2013) *Flash Eurobarometer 379: Attitudes Towards Biodiversity,* European Commission
5. Andreu, J. *et al.* (2009) An assessment of stakeholder perceptions and management of noxious alien plants in Spain. *Environ. Manage.* 43, 1244–1255
6. Heger, T. *et al.* (2013) Conceptual frameworks and methods for advancing invasion ecology. *Ambio* 42, 527–540
7. Valéry, L. *et al.* (2013) Another call for the end of invasion biology. *Oikos* 122, 1143–1146
8. Valéry, L. *et al.* (2009) Invasive species can also be native. *Trends Ecol. Evol.* 24, 585

9. Wilson, J.R.U. *et al.* (2009) Biogeographic concepts define invasion biology. *Trends Ecol. Evol.* 24, 586-586
10. Blondel, J. *et al.* (2013) The end of invasion biology: intellectual debate does not equate to nonsensical science. *Biol. Invasions* 16, 977–979
11. Webber, B.L. and Scott, J.K. (2012) Rapid global change: implications for defining natives and aliens. *Glob. Ecol. Biogeogr.* 21, 305–311
12. Hoffmann, B.D. and Courchamp, F. (2016) Biological invasions and natural colonisations: are they that different? *NeoBiota* 29, 1–14
13. Occhipinti-Ambrogi, A. and Galil, B.S. (2004) A uniform terminology on bioinvasions: a chimera or an operative tool? *Mar. Pollut. Bull.* 49, 688–694
14. Colautti, R.I. and Richardson, D.M. (2008) Subjectivity and flexibility in invasion terminology: Too much of a good thing? *Biol. Invasions* 11, 1225–1229
15. Richardson, D.M.D. *et al.* (2011) A compendium of essential concepts and terminology in invasion ecology. In *Fifty Years of Invasion Ecology: The Legacy of Charles Elton Blackwell* (Richardson, D.M., ed.), pp. 409–420, Blackwell
16. Blackburn, T.M. *et al.* (2011) A proposed unified framework for biological invasions. *Trends Ecol. Evol.* 26, 333–339
17. Blackburn, T.M. *et al.* (2014) A unified classification of alien species based on the magnitude of their environmental impacts. *PLoS Biol.* 12, e1001850
18. Humair, F. *et al.* (2014) Understanding misunderstandings in invasion science: why experts don't agree on common concepts and risk assessments. *NeoBiota* 20, 1–30
19. Pereira, H.M. *et al.* (2010) Scenarios for global biodiversity in the 21st century. *Science* 330, 1496–1501
20. Rejmánek, M. *et al.* (2002) Biological invasions: politics and the discontinuity of ecological terminology. *Bull. Ecol. Soc. Am.* 83, 131–133
21. Bradshaw, C.J.A. *et al.* (2016) Massive yet grossly underestimated global costs of invasive insects. *Nat. Commun.* 7, 12986
22. Jeschke, J.M. *et al.* (2014) Defining the impact of non-native species. *Conserv. Biol.* 28, 1188–1194
23. Parker, I.M. *et al.* (1999) Impact: toward a framework for understanding the ecological effects of invaders. *Biol. Invasions* 1, 3–19
24. Evans, T. *et al.* (2016) Application of the environmental impact classification for alien taxa (EICAT) to a global assessment of alien bird impacts. *Divers. Distrib.* 22, 919–931
25. Thomaz, S.M. *et al.* (2012) Using space-for-time substitution and time sequence approaches in invasion ecology. *Freshw. Biol.* 57, 2401–2410
26. Kowarik, I. (1995) Time lags in biological invasions with regard to the success and failure of alien species. In *Plant Invasions: General Aspects and Special Problems* (Pyšek, P. *et al.*, eds), pp. 15–38, SPB Academic
27. Essl, F. *et al.* (2011) Socioeconomic legacy yields an invasion debt. *Proc. Natl. Acad. Sci. U.S.A.* 108, 203–207
28. Caut, S. *et al.* (2009) Avoiding surprise effects on Surprise Island: alien species control in a multitrophic level perspective. *Biol. Invasions* 11, 1689–1703
29. Roemer, G.W. *et al.* (2002) Golden eagles, feral pigs, and insular carnivores: how exotic species turn native predators into prey. *Proc. Natl. Acad. Sci. U.S.A.* 99, 791–796
30. Zavaleta, E.S. *et al.* (2001) Viewing invasive species removal in a whole-ecosystem context. *Trends Ecol. Evol.* 16, 454–459
31. Hayes, K.R. and Barry, S.C. (2008) Are there any consistent predictors of invasion success? *Biol. Invasions* 10, 483–506
32. Kolar, C.S. and Lodge, D.M. (2001) Progress in invasion biology: predicting invaders. *Trends Ecol. Evol.* 16, 199–204
33. van Kleunen, M. *et al.* (2010) Are invaders different?. A conceptual framework of comparative approaches for assessing determinants of invasiveness. *Ecol. Lett.* 13, 947–958
34. Hamilton, M.A. *et al.* (2005) Life-history correlates of plant invasiveness at regional and continental scales. *Ecol. Lett.* 8, 1066–1074
35. Dickie, I.A. *et al.* (2014) Conflicting values: ecosystem services and invasive tree management. *Biol. Invasions* 16, 705–719
36. Verbrugge, L.N.H. *et al.* (2013) Exploring public perception of non-native species from a visions of nature perspective. *Environ. Manage.* 52, 1562–1573
37. Nogales, M. *et al.* (2013) Feral cats and biodiversity conservation. *Bioscience* 63, 804–810
38. Bertolino, S. and Genovesi, P. (2003) Spread and attempted eradication of the grey squirrel (*Sciurus carolinensis*) in Italy, and consequences for the red squirrel (*Sciurus vulgaris*) in Eurasia. *Biol. Conserv.* 109, 351–358
39. Bertolino, S. *et al.* (2013) A grey future for Europe: *Sciurus carolinensis* is replacing native red squirrels in Italy. *Biol. Invasions* 16, 53–62
40. Jones, H.P. *et al.* (2016) Invasive mammal eradication on islands results in substantial conservation gains. *Proc. Natl. Acad. Sci.* 113, 4033–4038
41. Russell, J.C. *et al.* (2016) Importance of lethal control of invasive predators for island conservation. *Conserv. Biol.* 30, 670–672
42. Genovesi, P. *et al.* (2015) EU adopts innovative legislation on invasive species: a step towards a global response to biological invasions? *Biol. Invasions* 17, 1307–1311
43. Leadley, P.W. *et al.* (2013) *Progress Towards the Aichi Biodiversity Targets: An Assessment of Biodiversity Trends, Policy Scenarios and Key Actions,* Global Biodiversity Outlook 4 (GBO-4) Technical Report, Secretariat of the Convention on Biological Diversity
44. McGeoch, M.A. *et al.* (2012) Uncertainty in invasive alien species listing. *Ecol. Appl.* 22, 959–971
45. Zalewski, A. *et al.* (2010) Multiple introductions determine the genetic structure of an invasive species population: American mink *Neovison vison* in Poland. *Biol. Conserv.* 143, 1355–1363
46. Estévez, R.A. *et al.* (2015) Clarifying values, risk perceptions, and attitudes to resolve or avoid social conflicts in invasive species management. *Conserv. Biol.* 29, 19–30
47. Hardin, G. (1968) The tragedy of the commons. *Science* 162, 1243–1248
48. Van Wilgen, B.W. and Richardson, D.M. (2012) Three centuries of managing introduced conifers in South Africa: Benefits, impacts, changing perceptions and conflict resolution. *J. Environ. Manage.* 106, 56–68
49. Ellender, B.R. *et al.* (2014) Managing conflicts arising from fisheries enhancements based on non-native fishes in southern Africa. *J. Fish Biol.* 85, 1890–1906
50. Novoa, A. *et al.* (2016) Resolving a prickly situation: involving stakeholders in invasive cactus management in South Africa. *Environ. Manage.* 57, 1–11
51. Norgaard, K.M. (2007) The politics of invasive weed management: gender, race, and risk perception in rural California. *Rural Sociol.* 72, 450–477
52. García-de-Lomas, J. and Vilà, M. (2015) Lists of harmful alien organisms: are the national regulations adapted to the global world? *Biol. Invasions* 17, 3081–3091
53. Morgan, E.H. and Richardson, C.A. (2012) Capricious bioinvasions versus uncoordinated management strategies: how the most unlikely invaders can prosper under the current UK legislation framework. *Aquat. Conserv. Mar. Freshw. Ecosyst.* 22, 87–103
54. Smith, A.L. *et al.* (2014) Are legislative frameworks in Canada and Ontario up to the task of addressing invasive alien species? *Biol. Invasions* 16, 1325–1344
55. Groffman, P.M. *et al.* (2010) Restarting the conversation: challenges at the interface between ecology and society. *Front. Ecol. Environ.* 8, 284–291
56. Nisbet, M.C. and Scheufele, D.A. (2009) What's next for science communication? Promising directions and lingering distractions. *Am. J. Bot.* 96, 1767–1778
57. Classen, M. (2005) *Communicating European Research,* Springer
58. Liu, S. *et al.* (2011) Incorporating uncertainty and social values in managing invasive alien species: a deliberative multi-criteria evaluation approach. *Biol. Invasions* 13, 2323–2337
59. Towns, D.R. *et al.* (2006) Have the harmful effects of introduced rats on islands been exaggerated? *Biol. Invasions* 8, 863–891