Management Policies for Invasive Alien Species: Addressing the Impacts Rather than the Species

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Effective long-term management is needed to address the impacts of invasive alien species (IAS) that cannot be eradicated. We describe the fundamental characteristics of long-term management policies for IAS, diagnose a major shortcoming, and outline how to produce effective IAS management. Key international and transnational management policies conflate addressing IAS impacts with controlling IAS populations. This serious purpose–implementation gap can preclude the development of broader portfolios of interventions to tackle IAS impacts. We posit that IAS management strategies should directly address impacts via impact-based interventions, and we propose six criteria to inform the choice of these interventions. We review examples of interventions focused on tackling IAS impacts, including IAS control, which reveal the range of interventions available and their varying effectiveness in counteracting IAS impacts. As the impacts caused by IAS increase globally, stakeholders need to have access to a broader and more effective set of tools to respond.

Keywords: alien species, decision criteria, impact-based management, population control and suppression, uncertainty

Invasive alien species (IAS) are those alien species that successfully transition the three initial invasion stages (transport, introduction, and establishment) and subsequently establish multiple self-sustaining populations, composed of individuals that breed, survive, and disperse, in a landscape beyond their native range (Blackburn et al. 2011). A subset of IAS produce a range of negative environmental, social, and economic impacts at various spatial scales (Bradshaw et al. 2016, Linders et al. 2020, Pyšek et al. 2020). For clarity, we consider an impact to be any measurable change in a social, economic, or environmental feature caused by an IAS (Ricciardi et al. 2013, Jeschke et al. 2014, Cassey et al. 2018).

The eradication of IAS is the ideal outcome of interventions aimed at eliminating their environmental impacts, albeit sometimes resulting in unintended and even detrimental consequences (Jones et al. 2016, Torres et al. 2018). Unfortunately, eradication is frequently unfeasible, particularly on continental landmasses, in oceans, and when IAS have been present in the region for a long time (Bomford and O'Brien 1995, Clout and Williams 2009). When eradication of IAS is highly uncertain or unlikely, often nothing further is attempted (Mačić et al. 2018, Robertson et al. 2020). Alternately, policies and strategies are developed and implemented for the long-term management of IAS (figure 1; Bomford and O'Brien 1995, Pyšek et al. 2020, Robertson et al. 2020). These policies and strategies deal with IAS that cannot be eradicated and, therefore, need to be continually managed over medium and long-term horizons.

In the present article, we aim to understand current policies and implementation strategies for the long-term management of IAS and identify opportunities for their improvement. We do so in three steps. First, we analyze key international and transnational policies and strategies for the long-term management of IAS to understand both their fundamental objectives and the proposed interventions to address the threat of IAS. We complement this analysis with a review that reveals consequential gaps between the stated objectives of those policies and strategies and the prescribed interventions to achieve them. Second, we argue for the paramount importance of bridging these gaps through impact-based management to craft effective policies and strategies for the long-term management of IAS. We conclude by describing criteria and reviewing examples for

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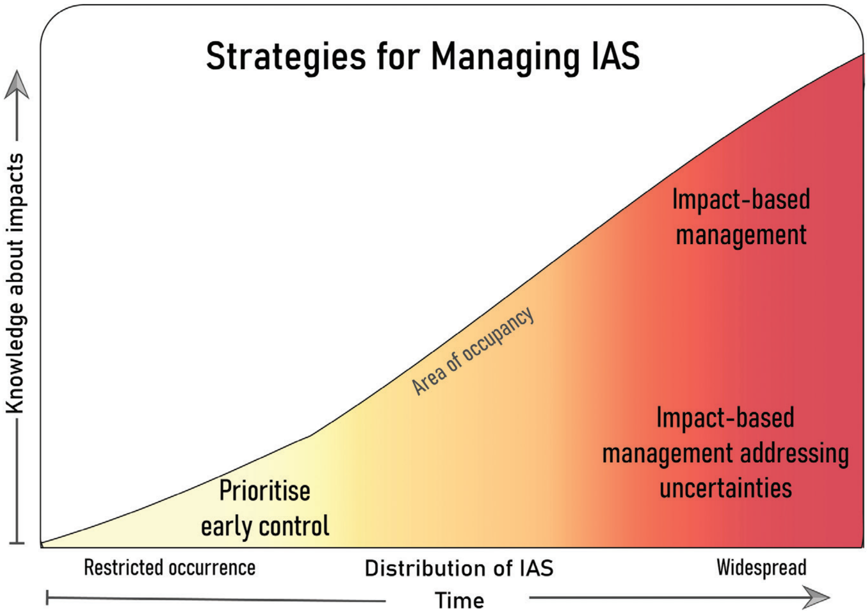

Figure 1. Defining long-term management strategies for IAS that cannot be eradicated. The ongoing long-term management of an IAS commences when the species has already spread through a portion of its suitable area of occupancy (shaded part of the curve). The proportion of the region occupied, the time since invasion (x-axis), and the knowledge about the impacts of the IAS (y-axis) help define the objectives of management strategies and guide justifiable interventions. Scant context-specific information on impacts of long-established IAS (bottom right) will require assessing the effects of such heavy uncertainty on the success of the intervention and proposing ways to contend with that lack of information. Control interventions may be part of all strategies, but their use needs to be evaluated on the basis of their capacity to address the impacts of the IAS.

aligning policy objectives and management interventions. Our ultimate goal is to showcase tools for creating long-term management policies and strategies that are fit for the task of addressing and mitigating IAS impacts.

State of the art: How are we managing IAS in the long term?

The long-term management of IAS is a loosely defined practice, and its meaning and implications can be best understood by examining the objectives and interventions proposed in policies and strategies. At the global level, the UN Sustainable Development Goal 15, concerned with life on land (Division for Sustainable Development Goals, United Nations), states its target 15.8 to "reduce the impact of invasive alien species on land and water ecosystems and control or eradicate the priority species." The indicator for the accomplishment of this target is the "proportion of countries adopting relevant national legislation and adequately resourcing the prevention or control of IAS." This means that addressing IAS impacts is the objective, but progress is tracked through species-based population control. IAS population control (hereafter, *control*) is the ongoing suppression of IAS abundance or population size (Robertson et al. 2020). This includes control to maintain current abundance levels and to reduce the current IAS abundance (Mack et al. 2000, Kopf et al. 2017, Robertson et al. 2020). The rationale for the Aichi biodiversity target 9 of the Convention on Biological Diversity is that IAS pose a threat to biodiversity and ecosystem services, and it recommends prioritizing species for control (Convention on Biological Diversity 2020a). The recently released "Zero Draft of the Post-2020 Global Biodiversity Framework" for the Convention on Biological Diversity is similarly fashioned (Convention on Biological Diversity 2020b). The 2030 action target 3 states a goal to "control invasive alien species to eliminate or reduce their impacts by 2030 in at least [50%] of priority sites." In both cases, the focus is on addressing impacts, and the prescribed intervention is again controlling the IAS populations at designated priority sites.

Transnational entities have created policies and strategies along the same lines. The European Union's regulations for dealing with IAS highlights their impacts and damage as their justification (European Union 2014). The EU regulation refers to long-term management of IAS included in its priority list that are widespread in the territory of at least one member state. Rapid interventions for more localized populations are outside the scope of long-term management under this regulation. The EU regulation recognizes the potential for increasing the resilience of the recipient environment to IAS in conjunction with control because "where appropriate, management actions shall include actions applied to the receiving ecosystem" (article 19.2). Despite this recognition, long-term management interventions other than control were found in only 3.8% of the technical notes on "measures and costs for prevention, early detection, rapid eradication, and management" (two out of 53 plant and animal technical notes reviewed by PG-D on 19 March 2020 from here: www.iucn.org/theme/species/our-work/invasive-species/eu-regulation-invasive-alien-species).

This list of policies and strategies shows that the mainstream prescription for counteracting the impacts of IAS is invariably species-based control. This implicitly assumes that IAS control is the tool of choice for managing their impacts. We contend that this represents a serious disconnect: Addressing IAS impacts is the focus and justifies these long-term management policies, but this is meant to be achieved solely by focusing on control interventions, rather than through impact mitigation interventions (table 1). Therefore, addressing IAS impacts is conflated

Table 1. Examples of strategies and interventions for managing invasive alien species (IAS) that focus on impact-based applications.

Case example	Problem statement and objectives	Approach	Outcomes	Supporting references
Working for Water program Scale: Country level	Mitigating the reduction in water availability for human use produced by invasive alien plants.	Two options considered: IAS control and construction of a new dam. IAS control was chosen as the cheapest option. Job creation through IAS control interventions prioritized.	Improved water availability, IAS cleared from large areas, and abundant jobs created. IAS control effort not sufficient to contain the spread of those IAS. IAS control efforts allocated to low priority areas.	(van Wilgen et al. 2012, Mandle et al. 2019)
IAS-free sanctuaries Scale: Landscape and patch level (islands and sanctuaries	Offsetting of IAS impacts by creating insurance populations.	Translocation of the species or asset affected to an IAS-free place to create insurance populations.	Frequent in Australia and New Zealand. It is often a last-resort option. Effective at conserving native biodiversity seriously affected by IAS. Costly, operationally challenging, and not always feasible.	(Dickman 2012, Miskelly and Powlesland 2013, Innes et al. 2019, McInturff et al. 2020, Smith et al. 2020)
Restoration Scale: Landscape and local levels	Preemption of plant IAS impacts by restoring diverse native plant communities on disturbed or degraded sites.	Active restoration or promotion of natural regeneration of native plant communities.	Increased ecosystem resilience to IAS impacts. Active restoration of plant communities potentially affected by plant IAS. Costly, likely only suitable for localized vulnerable sites.	(Bakker and Wilson 2004, Funk et al. 2008, Gaertner et al. 2012)
Genetically modified pest-resistant crops Scale: Local level (properties and plantations)	Adaption of production crops to IAS agricultural pests.	Creation and plantation of crop varieties that are resistant to agricultural pests.	Reduction in the quantities of crops lost to agricultural pests. GMO crops are a source of societal controversies. GMO plants can themselves become IAS.	(Qaim and Zilberman 2003, Buttel 2005, Gatehouse et al. 2011)
Exclusion fences Scale: Local level (properties, paddocks, and patches)	Protection of livestock, poultry, nesting grounds, and insurance populations from mammalian IAS.	Use of fences to exclude mammalian IAS.	Commonly used method. Mitigates losses to mammalian IAS. Fences may not be effective in increasing population sizes of the species affected by IAS; e.g., reptiles in Australia. Costly and unfeasible to cover large areas.	(Aviss and Roberts 1994, Moseby et al. 2009, Bode and Wintle 2010, Smith et al. 2011, 2020, Breton et al. 2014, Doherty and Ritchie 2017, McInturff et al. 2020)
Guard dogs Scale: Local level (properties and paddocks)	Protection from mammal IAS predators.	Use of dogs to protect poultry, livestock, and biodiversity from mammalian IAS predators (e.g., wild dogs and foxes)	Guard dogs have been successful in protecting livestock and biodiversity in a variety of contexts. Uptake not widespread. Not adequate for all mammalian IAS predators.	(Van Bommel and Johnson 2012, Doherty and Ritchie 2017)
Netting and fences Scale: Very local level (e.g., orchards within properties or individual trees)	Protection of food production crops from IAS agricultural bird and insect pests.	Use of nets and fences to cover and exclude IAS insects and birds from crops and fruit production trees.	Commonly used methods. Reduces losses to IAS birds and insects. Costly and time-consuming to cover large areas.	(Tracey et al. 2007, Ebbenga et al. 2019)
Nest cages Scale: Very local level (prey population and individual nests)	Protection of individual nests of birds and turtles from predation.	Deployment of individual nest cages excluding predators (including IAS)	Effective in increasing hatching success. Results can vary considerably depending on the prey species being protected, the predator being excluded, and the location. Finding the nests to protect can be costly and time consuming.	(Isaksson et al. 2007, Pauliny et al. 2008, Smith et al. 2011, Buzuleciu et al. 2015)
Behavioral change: prey avoidance Scale: Local level (predator populations)	Mitigation of the impacts of an IAS prey on a native predator.	Australian northern quolls (*Dasyurus hallucatus*) prey on toxic invasive cane toads (*Rhinella marina*). Use and delivery of toxic sausages to train quolls to avoid eating the poisonous toads.	Quolls exposed to the sausages tend to avoid preying on cane toads. Broadscale deployment can be challenging.	(Webb et al. 2015, Indigo et al. 2018)
Behavioral change: concealment and deterrence of predators Scale: Local and very local levels (prey populations and individual nest levels)	Reduction of IAS predation pressure on vulnerable native bird nests	Use of compounds to conceal or deter IAS predators (e.g., rats, *Ratus* spp., and hedgehogs, *Erinaceus europaeus*) from bird nests	Reduced nest mammalian IAS predation rates in field trials. IAS predators can get accustomed to the used compounds, leading to reduced efficacy and increased predation over time. Broadscale use would likely be costly and unfeasible.	(Baylis et al. 2012, Price and Banks 2012, Latham et al. 2019)

Note: These are sorted in decreasing order of spatial scale. We provide selected references, not a comprehensive list, to support each case.

with species-based control. Unless IAS control is explicitly linked to the management of impacts, there is a purpose–implementation gap that leads policies and strategies to mistake the ends for the means (i.e., tackling IAS populations rather than their impacts).

There are many challenges to conducting a systematic review on how the purpose–implementation gap affects the effectiveness and efficacy of IAS long-term management policies and strategies. As the policy examples above show, interventions other than IAS control are rarely considered in concert or in comparison to control. The presumption that IAS control will necessarily or invariably be effective to address impacts is not warranted (Reddiex and Forsyth 2006, Thomas and Reid 2007, Walsh et al. 2012, Byrom et al. 2016, Doherty and Ritchie 2017, Kopf et al. 2019). The outcomes (i.e., the extent to which the intervention mitigated the IAS impacts) and outputs (e.g., percentage of IAS population removed) might be monitored during IAS control interventions. Unfortunately, the outcomes of IAS control interventions are seldom monitored adequately, making independent assessments difficult (Reddiex and Forsyth 2006, Thomas and Reid 2007, Artelle et al. 2018, Rytwinski et al. 2019, Hulme 2020).

A Web of Science search for the terms *invasive species control efficacy* yielded 682 publications (García-Díaz et al. 2020). A total of 373 studies were relevant, and less than a quarter evaluated the outcomes of IAS control interventions (21.7%, 81 out of 373). Of these 373 studies, 37% included assessments of the effects of IAS control on nontarget species and other side effects. However, these are not proper evaluations of outcomes because they tested the specificity of the control methods, not their efficacy nor effectiveness in addressing IAS impacts. Similarly, a survey of 1915 IAS mammal control interventions aimed at protecting native biodiversity in Australia (1990–2003) reported that over 72% of interventions did not monitor outcomes (Reddiex and Forsyth 2006). A global survey of IAS fish removal, including control and eradication, showed that 76% of interventions (out of 158) were poorly designed and documented (Rytwinski et al. 2019). The latter did not provide information on outcomes but on the efficacy of interventions in removing IAS fish species. A meta-analysis of the efficacy of IAS plant biocontrol agents in Australia (n = 290) revealed only two related to outcomes (i.e., effects on the recipient plant communities, 0.69% of all measures reported; Thomas and Reid 2007). A global meta-analysis of the effectiveness of biological control (n = 173) reported only 11 measures of outcomes in terms of changes in IAS impacts. Of these 11 measures, 3.5% measured native plant abundance (n = 6), and 2.9% quantified native plant diversity (n = 5; Clewley et al. 2012). A further meta-analysis investigating the management of the invasive field bindweed (*Convolvulus arvensis*) showed that only 27% (n = 560) reported the short-term effects of IAS control on crop yields (Davis et al. 2018).

Despite the paucity of information, existing quantitative research paints a mixed picture of the efficacy and effectiveness of IAS control as the main tool for impact management. Even for the well-known role of invasive mammalian predators on biodiversity loss (Bellard et al. 2016, Jones et al. 2016), there are inconsistencies in the reported responses of biodiversity to IAS mammalian control. A quantitative 23-year study in Australia showed that control of invasive foxes (*Vulpes vulpes*) to conserve malleefowl (*Leipoa ocellata*) populations delivered little benefits to this threatened bird and was not cost effective (Walsh et al. 2012). A population viability analysis showed that malleefowl reintroductions would be more cost effective than fox control in slowing population declines, and a combination of both was the best intervention (Bode and Brennan 2011). In a manipulative experiment in Western Australia, native small mammals responded positively to fox and cat (*Felis catus*) control, whereas native reptiles showed no response (Risbey et al. 2000). On the other hand, a meta-analysis of 35 studies on the efficacy of invasive brushtail possum (*Trichosurus vulpeculus*) control in New Zealand showed generalized benefits to native biodiversity (Byrom et al. 2016). On the basis of 32 invasive mammal control interventions in New Zealand, another study showed no overall benefit to bird communities (Fea et al. 2020). However, a detailed examination of individual bird species revealed a wide range of responses to IAS mammal control. This included positive, negative, and no changes in bird population abundance in response to invasive mammal control (Fea et al. 2020). The situation appears similar for IAS plant control. For example, a global meta-analysis of 61 studies showed that control of IAS plants with biocontrol agents increased overall native plant diversity while making no difference to their abundance, and these effects depended on the time since the biocontrol release (Clewley et al. 2012). However, these conclusions were based on small sample sizes, using six and five measures of abundance and diversity, respectively (Clewley et al. 2012). The efficacy of IAS control in counteracting IAS impacts, therefore, is not ubiquitous and certainly scantly documented. The benefits of control are more likely to be realized when reductions in IAS abundance are well linked to impact mitigation through empirical abundance–impact relationships, so the target reduction in IAS abundance is evidence-based rather than arbitrary (Yokomizo et al. 2009, Sofaer et al. 2018).

The need for impact-based long-term management of IAS

In the present article, we argue that mitigating the negative impacts caused by IAS should be at the core of policies and interventions for the long-term management of IAS. These interventions will aim to reduce, minimize, offset, locally eliminate, protect from, and adapt to the diverse array of impacts caused by IAS (table 1). In other words, the focus should be on interventions that target impact-based management including, but far from exclusively, species-based control. Mandating and evaluating long-term IAS management policies and strategies on the basis of control interventions alone can preclude a broader integration of alternative and complementary interventions tailored to the relevant impacts and local circumstances.

Previous authors have raised the need for interventions to mitigate and adapt to IAS impacts (Mack et al. 2000, Lodge et al. 2006, Dunham et al. 2020). However, these have typically lacked detailed articulations of the practicalities and actions for integrating impact-based interventions into IAS management policies, or the interventions have been suggested as alternatives when control was impossible. We describe a more coherent approach to impact-based long-term management of IAS. First, we do not treat control and other IAS management interventions as mutually exclusive but, rather, as part of a broader array of potential interventions available. Second, we describe six explicit guideposts to design and evaluate impact-based interventions. Third, we explain how to deal with the uncertainties associated with IAS impacts and their management. Finally, we provide examples of impact-based interventions to illustrate their application and potential shortcomings (table 1).

A proper understanding of impact-based long-term management of IAS reveals another fundamental feature that deserves proper consideration. IAS belong to social–ecological systems and, by extension, are embedded within the broader society. Multiple societal values and perceptions of IAS impacts can coexist, generating tensions among stakeholders and between stakeholders and government agencies tasked with IAS management. Some of the impacts of IAS can be positive, and some IAS have both positive and negative impacts (Estévez et al. 2015). Moreover, these positive and negative impacts may occur within contrasting domains such as socioeconomic, cultural, and environmental IAS impacts. These nuances are not always well captured in species-based control and can lead to societal conflicts and controversies and, in turn, ineffective policies (Estévez et al. 2015).

Examples of IAS causing opposite impacts abound (figure 2). For instance, IAS such as the rainbow trout (*Oncorhynchus mykiss*) or the brown trout (*Salmo trutta*) are a source of recreational and economic activity where they have been deliberately introduced (angling: positive socioeconomic impact), but among other negative environmental impacts they depredate native amphibians and alter the dynamics of vulnerable freshwater ecosystems (Izaguirre et al. 2018, Bosch et al. 2019). Multiple types of pastures and crops are essential for sustaining human and domestic animal nutritional needs (positive economic and social impacts) but have local negative impacts in many of the places in which they have become IAS (Driscoll et al. 2014, Xing et al. 2020). Likewise, agroforestry and commercial plantations are a substantial source of economic activity, but at the same time, some planted tree species are a major IAS threat to native biodiversity and negatively affect other economic activities such as tourism whenever they spread outside plantations (Taylor et al. 2016, Nuñez et al. 2017, Bravo-Vargas et al. 2019). In the ranches of Tierra del Fuego, introduced beavers (*Castor canadensis*) are both a nuisance and a welcome ecosystem engineer (Ogden 2018). Beavers dislodge fence posts (negative: nuisance) and create new ponds that can be used by livestock (natural dam building; Ogden 2018).

These cases demonstrate the complexities associated with the long-term management of IAS. An appropriate strategy could attain a (imperfect) balance between both positive and negative impacts by taking an impact-based approach suited for context-specific interventions (figure 2). For example, interventions for mitigating negative impacts and fostering positive impacts could be implemented separately, either in space or in time. Likewise, control as an impact-based management intervention can maintain sustainable IAS abundances, which allow for the reaping of positive impacts, while ensuring that negative impacts are mitigated adequately. This could increase the odds of obtaining societal support for the IAS management policy and reduce the likelihood of conflicts between stakeholders (Estévez et al. 2015, Crowley et al. 2017). Alternatively, an appropriate impact-based strategy could help elucidate the magnitude of those conflicting impacts and proceed accordingly if some impacts (positive or negative) are deemed sufficiently important to outweigh any other consideration.

Impact-based IAS policies and strategies also link directly to Sustainable Development and the Sustainable Development Goals (SDGs). The livelihoods of many disadvantaged groups, such as those with limited access to resources, are likely to be most vulnerable to the impacts of IAS and IAS control (when there are positive benefits), because they have a more limited ability to mitigate and adapt to the impacts relative to other groups within society (Reynolds et al. 2020). Therefore, considering the overall impacts but also which groups are affected is important. In many regions, but especially in developing economies, significant investments are made to support economic development and the SDGs to improve the livelihoods of individuals and the disadvantaged in society (Mandle et al. 2019). Impact-based IAS policies and strategies are more likely to align with these wider economic development goals.

Traditionally, obtaining resources for biodiversity-focused projects in developing countries is challenging, and NGOs and research groups conducting these projects usually need to pursue external (international) funding. The success of these projects hinges on well-defined objectives and a demonstrable benefit to threatened species or ecosystems. In this context, IAS control in itself may not be a winning tactic for securing resources for IAS management. In contrast, impact-based policies more explicitly couple IAS management with societal and biodiversity benefits and offer a way to ensure both the delivery of desired outcomes and improve the odds of IAS management being resourced and supported (van Wilgen et al. 2012, Ministerio de Ambiente y Desarrollo Sustentable, Presidencia de la Nacion 2017, Mandle et al. 2019).

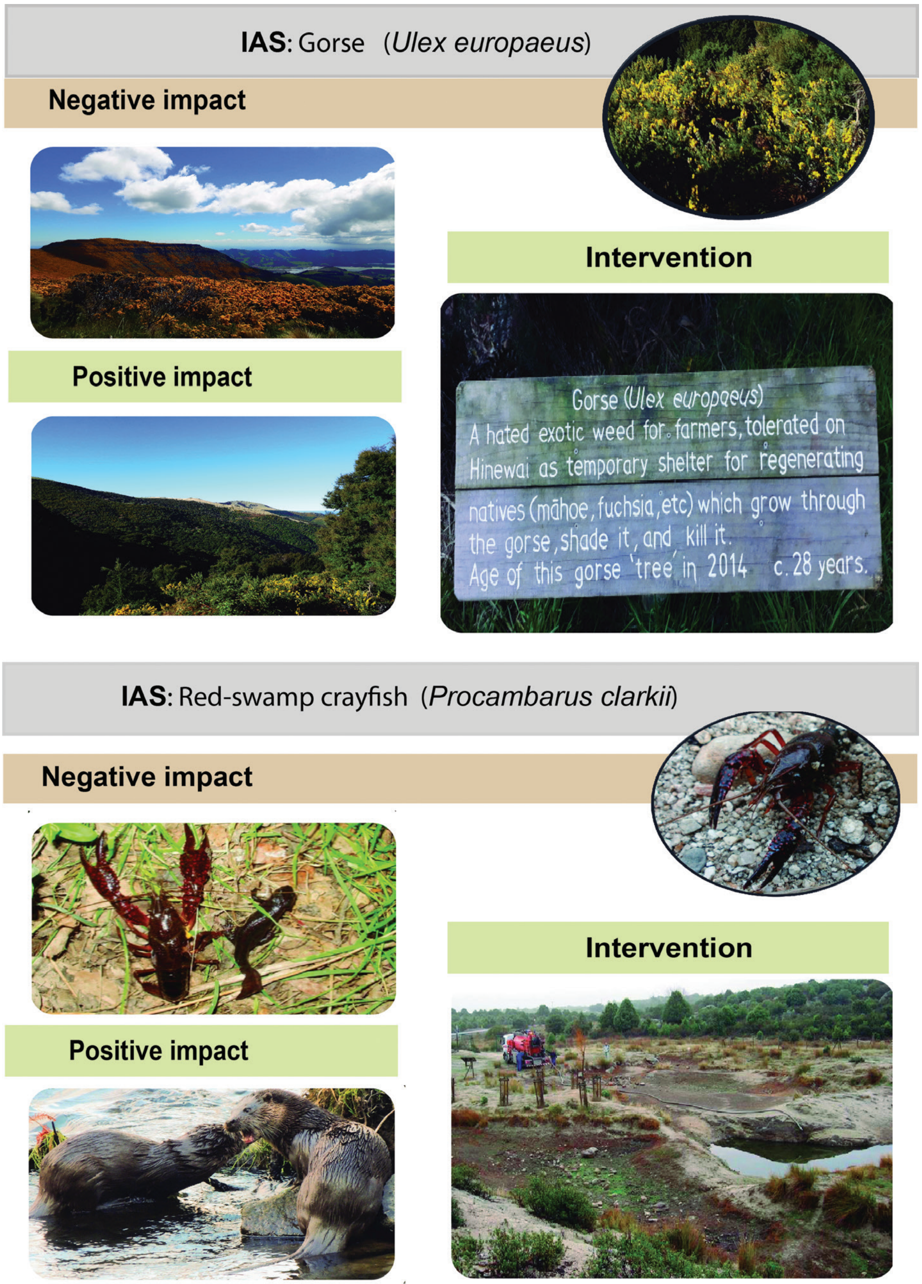

*Figure 2. The devil is in the details and prioritizing species-based control of IAS can miss those details. (a) Invasive gorse (*Ulex europaeus*) can have both positive and negative impacts. The species has invaded extensive areas in New Zealand, where it can affect native vegetation and farming practices (negative impacts panel). On the other hand, this IAS is used for promoting the restoration of native vegetation in the Hinewai Reserve (Banks Peninsula, New Zealand), as was shown by the native plants growing through the flowering gorse (panel on positive impacts) and explained in the pictured informative panel. (b) Invasive red swamp crayfish (*Procambarus clarkii*) in the Iberian Peninsula have negatively affected native amphibians such as the pictured marbled newt (*Triturus marmoratus*; illustrated in the negative impacts picture alongside an invasive crayfish). On the other hand, the abundance and widespread availability of this crayfish have helped foster the recovery of the native Eurasian otter (*Lutra lutra*; positive impact panel). To protect the local community of amphibians from invasive crayfish and invasive mosquitofish (*Gambusia holbrooki*), this pond in Madrid (Spain) was treated with the poison rotenone and drained resulting in the removal of both IAS. An intervention for protecting amphibians in a different pond only applied rotenone, removing all invasive fish and leading to an apparent release of invasive crayfish, a testimony to the importance of evaluating the potential for unintended consequences (criterion 5). Photographs: Alberto Álvarez (pond treated with rotenone and drained), Valentín Arévalo (crayfish), César Ayres (crayfish with newt) and Pablo García-Díaz (all gorse photos and the otter).*

In summary, IAS impacts require careful attention if a long-term management policy is to succeed. A main obstacle to impact-based management is that our understanding of the impacts of a target IAS will often be incomplete, which can result in some impacts being neglected when initially formulating a long-term management strategy (Dunham et al. 2020). We address these uncertainties and challenges in the next section. Notwithstanding these hurdles, the alternative of exclusively resorting to IAS control runs the risk of encountering the problems discussed above. Importantly, focusing on IAS control may result in prioritizing interventions for IAS species that have low or unmanageable impacts, at the cost of tackling IAS that are known to cause impacts that are more amenable to intervention.

Designing and planning impact-based long-term management: It's not just about control

Long-term management policies and strategies to address IAS impacts should be based on the tenets of adaptive management and policymaking cycles (Conroy and Peterson 2013, Dunn 2017). From a policy and strategy perspective, deciding on interventions for the impact-based long-term management of IAS should be guided by six criteria (see figure 1 for the interplay between the first three criteria): how widespread the IAS is; the time of residency of the IAS in the recipient region; the uncertainty about the impacts produced by the IAS; the range of interventions that are available and socially, economically, and technically feasible; the risks of potential negative and unintended consequences of the proposed interventions (Kopf et al. 2017); and the capital and recurring costs and benefits associated with the impacts and interventions. Producing generalized recommendations for the use and ranking of these criteria is purposeless because we anticipate that their application will be highly dependent on the context of the strategy. For example, there will be a limited number of possible interventions (criterion 4) available for managing a widespread IAS (criterion 1), and these interventions will likely be costly (criterion 6). Nevertheless, in this section we delve further into four critical criteria: time of residency, costs and benefits, uncertainties, and available interventions.

The time of residency is a prominent criterion for deciding on a course of action because there might be a delay between when the species becomes invasive and when it starts having noticeable impacts (Sapsford et al. 2020). It might also take time for an impact to be detected and acted on by researchers and managers (Lockwood et al. 2013), and the strength and reversibility of the impacts might change with the time of residency (Sapsford et al. 2020, Crystal-Ornelas and Lockwood 2020a).

The criterion on costs and benefits will be critical for ranking interventions and uncovers an underestimated facet of relying primarily on IAS control. Focusing exclusively on control neglects opportunity costs (Shwiff et al. 2013). These opportunity costs will be those incurred because of the foregone benefits of choosing IAS control without considering potentially better alternative or complementary interventions (Shwiff et al. 2013). Opportunity costs should be included in evaluations of the costs of potential interventions. Not considering options other than control at the outset of the strategy formulation will underestimate the costs of IAS control interventions.

The adequacy of IAS control to manage impacts needs to be evaluated against its capacity to deal with those impacts following the six criteria outlined above. In this way, a defensible case can be made to start early control interventions for recently arrived IAS with localized populations, which may not be feasible to eradicate and which may have poorly understood impacts at the location (figure 1). Notwithstanding examples outlined earlier of little or unknown effect of IAS control on impacts, there is evidence of reductions in impacts on primary production and biodiversity following control interventions (Norbury et al. 2015, Sofaer et al. 2018, Bradley et al. 2019). The precautionary principle, together with a narrow window of opportunity, supports a call for acting rapidly in these situations (Hone et al. 2015).

For widespread IAS, which have been present in an area for some time already, it is reasonable to expect greater planning of interventions, including control, to address their impacts (figure 1). The impacts of these IAS are likely to be better understood compared with recent arrivals. Understanding does not mean comprehensive information on the IAS impacts including their intensity, extent, mechanisms, and other characteristics. A suitable management strategy should have room for uncovering and tackling critical knowledge gaps, fundamental to adaptive management approaches (Conroy and Peterson 2013). We are referring to a level of knowledge that permits an appraisal of the negative and positive impacts using one of the many existing standardized impact measurement and assessment tools (Blackburn et al. 2014, Nentwig et al. 2016, Dick et al. 2017, Bacher et al. 2018, Martinez-Cillero et al. 2019). This includes poorly understood impacts that will merit further exploration and interdisciplinary research (Crowley et al. 2017, Crystal-Ornelas and Lockwood 2020b). Although our ability to forecast the likely impacts of any IAS remains limited (Hulme et al. 2013, Ricciardi et al. 2013, Cassey et al. 2018), adopting an impact-based perspective for long-term management strategies will facilitate the use of functional classifications of IAS that could be helpful in data-poor situations (Hulme et al. 2013, Milanović et al. 2020, Novoa et al. 2020). For example, existing information on the functional ecology of species that are related to the target IAS can act as a proxy for the impacts when data for the target IAS are unavailable or scant (Gallardo et al. 2016, Milanović et al. 2020, Novoa et al. 2020). Moreover, value of information analyses and social impact assessments can be used to evaluate whether there is sufficient information and social license for sound interventions to address the impacts of the target IAS (Canessa et al. 2015, Crowley et al. 2017).

Regardless of the chosen intervention, the outcomes—and not just the outputs—should be monitored for investigating the effectiveness of the intervention (Reddiex and Forsyth 2006, Thomas and Reid 2007, Walsh et al. 2012, Hulme 2020). Monitoring the outcomes will enable the evaluation of the performance of the intervention and whether the intervention has achieved the policy objectives or has led to undesirable negative and unintended consequences (Conroy and Peterson 2013, Dunn 2017, Kopf et al. 2017). As was discussed above, to ensure that impact-based IAS management strategies are linked to the wider economic development goals and the SDGs, any evaluation should consider the distributional impacts of IAS interventions (i.e., who gains and who loses, with a particular focus on groups most frequently disadvantaged; e.g., indigenous populations, landless youth, and women). Furthermore, impact-based interventions should incorporate a component that allows for the collection of new data to reduce uncertainties, especially gaps in our understanding of IAS impacts (Conroy and Peterson 2013, Dunham et al. 2020, Crystal-Ornelas and Lockwood 2020b).

What do impact-based management interventions look like? To date, alternatives to IAS control have been implemented for only a small subset of long-term management policies and strategies. We describe illustrative examples of strategies and interventions that give greater centrality to the impact-based long-term management of IAS in table 1. In addition, it is worth showcasing two generic types of interventions in more detail to exemplify the concept.

In the first case, restoration of native plant communities may be used to target IAS impacts by either reducing the likelihood of invasions in the first place or by mitigating impacts by actively promoting the recovery of native species affected by the IAS (Bakker and Wilson 2004, Funk et al. 2008, Sapsford et al. 2020, Weidlich et al. 2020). These interventions are underpinned by the observation that intact ecosystems possess greater resistance to invasions than disturbed or degraded ecosystems (Funk et al. 2008, Sapsford et al. 2020, Weidlich et al. 2020). In rare cases, IAS may be beneficial in restoring native plant species, as is exemplified by the use of gorse (*Ulex europaeus*) as a nursery species in some regions of New Zealand (figure 2). Restoration interventions should always be carefully designed and tailored to local environmental conditions as well as the traits of native species and potential IAS (Funk et al. 2008, Sapsford et al. 2020).

The establishment of IAS-free sanctuaries is an intervention sometimes used for offsetting IAS impacts on native animals (Dickman 2012, Innes et al. 2019). IAS-free sanctuaries are established at sites that are naturally free from IAS (e.g., islands) or following local eradication or control (Dickman 2012, Norbury et al. 2014, Innes et al. 2019). Vulnerable native animals are then translocated and maintained in these sites to act as insurance populations. Although in many instances this is a last resort intervention, IAS-free sanctuaries are becoming common in New Zealand and Australia for the recovery of native animals whose viability in the wild does not depend solely on creating insurance populations (Dickman 2012, Innes et al. 2019). Therefore, IAS-free sanctuaries are not just a last-resort intervention but a complementary effort for conserving vulnerable species. Recently, Christmas Island blue-tailed skinks (*Cryptoblepharus egeriae*), a species extinct in the wild because of IAS negative impacts (Smith et al. 2012), have been bred in captivity and translocated to an IAS-free island in Cocos (Keeling) to establish the first new wild population (www.abc.net.au/news/2019-09-09/near-extinct-blue-tailed-skink-recovers-on-cocos-islands/11486788). In New Zealand, both IAS-free islands and IAS-free sanctuaries exist throughout the country (Norbury et al. 2014, Innes et al. 2019). The iconic kākāpō (*Strigops habroptilus*) was saved from extinction from predation by IAS mammals by creating insurance populations on IAS-free islands (Elliott et al. 2001).

There are important lessons from these examples and those presented in table 1. First, these interventions are designed and tailored to each case and may not have broader applicability or be scalable, nor is that necessarily their goal or intention. Notably, these interventions are not mutually exclusive, and multiple interventions can be implemented sequentially or simultaneously in space and time to deal with specific circumstances. Both the restoration and IAS-free sanctuaries cases demonstrate the complementarity of control and other interventions. The Working for Water program case demonstrates how IAS control can be the most effective intervention available for dealing with IAS impacts, while also showcasing the role of evaluating alternative interventions to arrive at such a conclusion. The outcomes of all of these exemplary interventions show how, just like IAS control, their efficacy and effectiveness are also mixed. More broadly, it is clear that the long-term management of IAS is a complex, multifaceted problem and no single intervention can be expected to always be the best option. The suitability of impact-based interventions needs to be assessed against the six criteria outlined above, and the outcomes of such interventions monitored properly.

Conclusions

Relying on species-based control is not a guaranteed approach for the long-term management of IAS impacts, as many policies and strategies assume. IAS control should be seen as one of a wider range of potential interventions available for impact-based long-term management policies and strategies. We stress that IAS control remains vital, but this is not the only intervention available, nor should it be taken as a synonym for long-term management of IAS. Policy and decision-makers, managers, practitioners, and researchers need to be aware of the purpose–implementation gap that we have highlighted, and work toward dealing with it if they want to see progress toward effective long-term management policies and strategies. A better alignment between objectives and implementation, while emphasizing impacts as the raison d'être, will ensure that the long-term management policies are legitimate, transparent, and sound. In turn this is also likely to improve acceptance by the broader society and reduce, but not eliminate, conflicts and controversies. There are no easy and simple solutions to the multifaceted issue of long-term IAS management. However, having a diversified toolbox and developing impact-based policies and strategies that adapt to the local conditions and existing opportunities will be invaluable. Moreover, maintaining a focus on impacts is a straightforward way to measure and monitor progress. More generally, strategies and interventions should be underpinned by formal approaches such as adaptive management and policymaking cycles (Conroy and Peterson 2013, Dunn 2017). This will ensure that lessons are learned from the interventions that are implemented, including those carried out elsewhere, and that scientific evidence is integrated with policies and interventions where appropriate.

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