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Scientific and normative foundations for the valuation of alien species impacts: Thirteen core principles

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Abstract

Biological invasions cause many impacts that differ widely in how they are perceived. We argue that many conflicts in the valuation of impacts of alien species' impacts are attributable to differences in the framing of the issue and implicit assumptions – such conflicts are often not acknowledged. We present 13 principles that can help guide valuation and hence inform the management of alien species. Seven of these relate to the science domain, representing aspects of change caused by alien species that can be measured or otherwise assessed using scientific methods. The remaining six principles invoke values, risk perception and environmental ethics, but also cognitive and motivational decision biases. We illustrate the consequences of insufficient appreciation of these principles. Finally, we provide guidance rooted in political agreements and environmental ethics for improving the consideration of the consequences of these principles, and present appropriate tools for management decisions relating to alien species.

Key words: biological invasions, decision making, environmental ethics, perception, values

Introduction

Alien species have many impacts on the environment and socio-economy (Schlaepfer et al. 2011; Blackburn et al. 2014; Jeschke et al. 2014). The valuation of any given change attributed (directly or indirectly) to an alien species depends on a range of parameters. Key factors are the environmental and socio-economic contexts, personal value systems of the assessor, vested economic interests, risk perception, and available alternative opportunities (Maguire 2004). Different stakeholders perceive such impacts differently; this means that an invasion of an alien species can be viewed as detrimental (often hence termed "invasive" *sensu* CBD 2002), neutral, beneficial or simply irrelevant (Estévez et al. 2015).

The variation in how alien species impacts are perceived and the ensuing disagreements between stakeholders create substantial challenges when decisions must be taken by politicians and managers (Estévez et al. 2015; Redpath et al. 2015). Additionally, the criteria for making decisions about interventions to manage alien species generally differ along the different invasion stages from introduction into a region, subsequent establishment and spread (sensu Blackburn et al. 2011). Where interventions are undertaken, these often focus primarily on pre-entry precautionary measures (e.g. border control, pathway management) for alien species not yet present in the region of interest, early response measures (e.g. eradication, containment) for alien species in their incipient phase of spread, and finally long-term management for widely distributed alien species. Pest management measures (e.g. biological control, application of pesticides) tend to target only those species that are perceived to have a significant impact on agricultural production, forestry, biodiversity or human health or agroecosystems. The role of government and private citizens in alien species management also changes along the sequence of invasion stages. Government is expected to allocate resources for preventing new problems and eradicating alien species perceived to be harmful before they become permanently established. Once eradication or regional containment is no longer feasible, responsibility for management often shifts to individual landowners, local or regional governmental bodies, NGOs or interested community groups (Lovett et al. 2016).

We argue that many conflicts in the valuation of impacts of alien species are attributable to strong differences in both the framing of the issue and implicit assumptions, which are often unacknowledged or neglected (Humair et al. 2013). This lack of appreciation of normative predispositions has hindered communication among invasion biologists as well as with scholars of other disciplines, policy makers and practitioners, has hampered scientific progress, and has repeatedly caused heated discussions on how to value alien species and their impacts (Larson 2011).

We highlight the importance of recognizing such underlying core principles and distil recommendations for alien species management and policy. We agree that totally eliminating conflicting views is impossible (Gutiérrez et al. 2015). Rather, we aim to provide a framework that elucidates the causes for disagreement and conflict. Such elucidation is required to improve communication and pave the way for subsequent conflict resolution, and hence for evidence-based environmental management and decision making (Sutherland et al. 2004). Finally, we indicate how these recommendations can be applied to management and political agreements relating to alien species. We focus on how the principles are considered and weighed, and discuss some of the ensuing implications for decision making.

Core principles for valuing alien species impacts

In a world where human agency and natural systems have become increasingly interconnected, decision making in environmental policy is inherently complex (Gregory et al. 2012, Gutiérrez et al. 2015). Such complexity is especially prominent in the case of alien species management, as the evaluation of alien species impacts demands the consideration and weighing of scientific evidence and societal or individual norms (“values”). In many cases vested interests (“agendas”) and personal biases (e.g. overconfidence bias, anchoring, https://www.boundless.com/management/definition/groupthink) are inescapable mediators of decisions that affect management and policy outcomes. This frequently leads to conflicts in evaluating the risks and impacts associated with alien species (Estévez et al. 2015). In addition, seemingly simple management solutions tend to disregard the full range of ramifications they may cause. This is particularly so if impacts occur at locations far away (spatial discounting), in the far future (temporal discounting), if benefits and costs are enjoyed and incurred by different sectors of society, and if uncertainties are large (Gardiner 2011).

We have identified 13 core principles that, if addressed, will help to guide valuation and hence the management of alien species (summarized in Table 1). The first seven of these principles relate predominantly to the science domain; they represent aspects of change caused by alien species that can – at least in principle – be quantified and measured at relevant spatial and temporal scales, or otherwise be assessed or quantified using scientific methods (e.g. uncertainty, irreversibility, risks). These different aspects of change require appropriate, yet different, metrics for measurement, and such metrics are often not directly comparable, or they may interact with each other (e.g. across geographic or temporal scales) (Figure 1). Consequently, any process involving comparisons of different impact metrics (e.g. as done in calculating compound impacts of alien species; Blackburn et al. 2014; Kumschick et al. 2015) invokes normative decisions. This problem is often exacerbated by a lack of relevant data (Hulme et al. 2013), by proponents of particular views ignoring existing data (Sutherland et al. 2004), or situations where available data are equivocal or have large uncertainties which are difficult to quantify and sometimes impossible to reduce (Gregory et al. 2012) (Figure 2).

The remaining six principles (Table 1) invoke values, risk perception and environmental ethics, but also decision biases related to cognitive (e.g. anchoring) and motivational biases (e.g. overconfidence) (Hämäläinen & Alaja 2008; Montibeller & von Winterfeldt 2015). These principles relate to the decision-making process, articulating fundamental values, selecting relevant objectives and impacts, and ranking their importance during decision making. In other words, there is unavoidably a strong normative element in evaluating risks and impacts of alien species which often results in "conflicts of beliefs and values" (Redpath et al. 2015). Such differences in normative perceptions can be non-negotiable which greatly reduces the likelihood of reaching consensus (Voinov & Farley 2007; Redpath et al. 2015). For instance, the widely used concept of human relationships with nature (Kellert 1993) distinguishes eight fundamental worldviews. These include seeing nature as resource ("utilitarian"), as physical attraction ("aesthetic") or as something to be controlled ("dominionistic"). Although it is rare for one of these values to solely define the relationship of a particular person to nature, the relative importance attributed in a personal value system to these values may vary widely. However, even having a similar personal value system may lead to conflicting views when boundary conditions are set differently. A good example of the importance of such boundary conditions is the time scale that is considered when assessing impacts, in particular when short-term impacts attributable to alien species differ from those measured over longer periods (Strayer et al. 2006). Under a utilitarian view of the natural world, short-term costs associated with precautionary management (e.g. costs to agencies and commerce of implementing quarantine and phytosanitary measures) may be valued very differently than under a long-term utilitarian perspective – the latter taking into account the merits of avoiding the full range of impacts of agricultural, horticultural or forestry pests by applying such measures.

Another prominent example is the application of fixed annual discount rates which effectively down-weigh long-term impacts. This effect increases with the discount rate and the period over which it is applied. For long-term and often irreversible environmental impacts (e.g. species extinctions, changes in ecosystem properties), discounting has profound consequences. For instance, if there are immediate or near-future positive socio-economic impacts of introducing a particular species, even very large long-term negative socio-economic impacts may be discounted to very small amounts today (Gardiner 2011; Voinov & Farley 2007; Stern 2015b). To put this in context, based on high discount rates of up to 6% annually as used by the IPCC (1995) and advocated by Nordhaus (2007) for climate-change impacts, we would not spend US$2500 today to prevent a US$30 trillion loss in 400 years (Voinov & Farley 2007). This loss is approximately equivalent to the gross global product today. Environmental economists argue for variable, generally lower discount rates or for applying none at all (Stern 2015a), as pure-time discounting "involves attaching lower social values to lives which start later", and "a high rate of pure-time preference is equivalent to discrimination against future generations" (Stern 2015a, p. 3). Clearly, applying high discount rates may render any long-term impacts meaningless in relation to any short-term benefits or costs. This conclusion is particularly relevant in the context of biological invasions, as alien species management usually involves immediate costs (e.g. ballast water treatment, border inspections), whereas the benefits (e.g. foregone losses from the invasion) do not accrue until (often considerably) later. As with temporal discounting, spatial discounting may also affect the valuation of alien species impacts. For instance, impacts which occur at distant locations (e.g. other countries) may be considered less relevant (Hulme 2015). At local scales, impacts that seemingly do not directly affect the stakeholder are often down-weighed (selective attention) (Clavero 2014).

The relevance of the core principles representing values and environmental ethics for assessing alien species impacts has been inadequately acknowledged, which means that the root causes for differences in valuation of impacts of alien species have often been masked or made insufficiently transparent. We thus agree with others (e.g. Larson 2011; Sagoff 2005; Schlaepfer et al. 2011; Estévez et al. 2015) that a stronger focus and more detailed reporting on the value dimensions of alien species problems is urgently needed.

Illustrating the consequences of different norms for valuing alien species impacts

Frames are cognitive shortcuts that people use to help make sense of complex information. They help to interpret the world around us and represent that world to others (Kaufmann et al. 2003). When we label a phenomenon, we give meaning to some aspects of what is observed, while discounting other aspects because they appear less relevant or even counter-intuitive. Thus, frames provide meaning through selective simplification, by filtering people's perceptions and providing them with a field of vision for a problem. Accordingly, norms play an important role in shaping frames and for interpreting the assessment of and management decisions about environmental issues such as biological invasions. Such norms may be widely shared within a society and therefore codified (e.g. in legislation, international agreements, or implicitly as social norms), or they may differ strongly between different people within a society. While there is little disagreement in cases where environmental and socio-economic impacts of an alien species are both widely considered either negative or positive, conflicts arise where different core principles for assessing impacts are given priority by different stakeholders (Humair et al. 2013; Simberloff et al. 2013). Such differences in framing are most evident between people predominantly interested either in impacts on the environment or on socio-economy, but are, however, not restricted to such situations (cf. examples of conflicting views on alien species impacts in Appendix S1).

For instance, the American mink (*Neovison vison*) and black locust (*Robinia pseudoacacia*) are used in the fur and forestry industries, respectively, in Europe where both species have been introduced and bring substantial socio-economic benefits to people involved in these sectors. Consequently, well documented impacts on the environment are often either externalized (i.e. not considered at all) or ignored (i.e. not considered relevant). Such "selective attention" has become particularly apparent during the development of the recent European Union legislation on invasive alien species (see below). In contrast, people who base their assessments largely on the environmental changes, which are widely considered to be negative, arrive at opposing overall assessments of the existence and scale of impacts of these two species (e.g. DAISIE 2009).

However, in many cases there is no simple dichotomy between socio-economic and environmental impacts. Conflicts in the valuation of impacts also often arise when value systems lead to differences in the interpretation or consideration of core principles (Figure 3). For instance, the European plant *Echium plantagineum* causes detrimental economic impacts in Australian agriculture due to its toxicity to livestock but simultaneously provides beneficial economic impact to beekeepers because its abundant nectar is used by honeybees. This species also has contrasting environmental impacts on different taxa, as it replaces native plant species through competition but is beneficial to native pollinators early in the season (Cullen & Delfosse 1985). Thus, different constituencies view this species very differently.

Sometimes certain impacts of alien species are considered to be beneficial to the environment; these may result from a variety of mechanisms (trophic subsidy, pollination, competitive or predatory release; Rodriguez 2006). However, widespread indirect impacts extending over different levels of organization (e.g. multitrophic interactions, invasional meltdown; Pyšek et al. 2012) and often associated with time lags (Essl et al. 2015) may lead to opposing overall assessments. This becomes particularly apparent in differing valuations of the impacts of zebra mussel (*Dreissena polymorpha*) and red swamp crayfish (*Procambarus clarkii*) (Appendix S1).

Another set of conflicting views emerges when considerations beyond the realm of biological invasions are considered. A prominent example is the potential of alien species to contribute to climate-change mitigation. While for some stakeholders the use of fast-growing plant species for biofuel production to reduce greenhouse-gas emissions is of overriding importance (e.g. discussion in Tilman et al. 2009), others consider the risks of detrimental impacts by fostering invasions highly relevant (Raghu et al. 2006). As another example, the eradication plan of grey squirrels (*Sciurus carolinensis*) in Italy was opposed and ultimately halted by animal rights people (Bertolino & Genovesi 2003), on the premise that killing mammals is unethical.

Recommendations for defining norms in alien species management and policy

Providing recommendations for useful norms in considering and interpreting the 13 core principles may seem inappropriate at first, as the development of widely accepted norms usually is a long process based on a societal discourse which involves different stakeholders. In such a process, scientists play an essential, yet limited role (e.g. as information providers and advisors) (Pielke 2011). Having said this, we believe that if recommendations of scientists are clearly linked to principles of environmental policies and environmental ethics, they provide a useful foundation for further discussions (Santo et al. 2015).

We argue and recommend that environmental ethics needs *inter alia* to account comprehensively for intergenerational justice, irreversibility, and uncertainties (Table 1), and therefore should prioritize public interests over those of individuals or sectors that do not give consideration to the full range of impacts (Gardiner 2011; Stern 2015b). These aspects are becoming increasingly prominent in international political agreements (e.g. CBD 2002; FAO 2009; EU 2014; including the forthcoming global IPBES assessment on invasive alien species and their control), and the recent literature on biological invasions (e.g. Beckage et al. 2011; Blackburn et al. 2014; Hulme et al. 2015) and other global change phenomena (e.g. Stern 2015b; Gardiner 2011).

Different impacts of alien species demand different metrics; direct comparisons between different impacts are therefore problematic (Nentwig et al. 2010; Hulme et al. 2013), and usually subject to strong normative decisions (Gregory et al. 2012). Hence, calculating overall impacts for a given alien species is a complex, value-laden task (e.g. Humair et al. 2013). A possible solution – and the best approach in our opinion – is to follow the logic of “relative severity” as suggested by Blackburn et al. (2014) for environmental impacts. This concept is based on a scaling of the magnitude of different types of impacts ranging from minimal to massive, whereupon the scaling may be quantitative or qualitative. For instance, Blackburn et al. (2014) defined 13 impact mechanisms of alien species on the environment, and five semi-quantitative scenarios of different magnitudes of impacts for each, thereby accounting for uncertainty. For other types of impacts (e.g. to socio-economy, health, ecosystem services), no such framework is yet available. However, once such complementary frameworks are developed, scaling of the impact scenarios should ideally be done qualitatively in the same way for each type of impact (cf. Blackburn et al. 2014). This would facilitate the application of the principle of relative severity across different types of impact. These could then also be weighted in a decision-making process to account for specific purposes and needs, and within different contexts.

However, we note that the full potential impact of many alien species may be masked by management interventions (e.g. many agricultural plant pests that are controlled by pesticides). For instance, some risk assessment schemes for alien species include on-going management activities, which means that they better reflect current reality, but downplay the gross impacts which would occur in the absence of management. The current impact of the Colorado potato beetle (*Leptinotarsa decemlineata*) in Europe is under substantial (chemical) control. Because of this intervention, the species is not considered a high-risk alien species. The future impact of ragweed (*Ambrosia artemisiifolia*) without control in Europe would be an order of magnitude higher than current estimates (Richter et al. 2013). Particularly socio-economic impacts are often assessed in combination with existing management activities which masks the full range of impacts that would occur without management.

In principle, the concept of ecosystem services provides the means to place impacts of alien species firmly on political agendas (Pejchar & Mooney 2009; but see Silvertown 2015), and considerable research has been done to develop methods and frameworks for comparing different kinds of impacts caused by alien species. Cost-benefit analyses (e.g. Keller et al. 2007) and multi-criteria analyses (Liu et al. 2011; Monterroso et al. 2011) are examples of promising methods. Although useful, these approaches are anthropocentric and utilitarian, and explicitly ignore other values of nature (sensu Kellert 1993). Another problem is that from an economic perspective, many ecosystem services represent public goods, i.e. goods and services whose consumption is non-excludable (if they are provided to one, then they are provided to all, irrespective of who pays), and non-rival (the benefits obtained from them do not depend on the number of people who benefit). Many regulating ecosystem services that depend on biodiversity, such as water retention or carbon storage, fall in the category of services for which market prices that accurately reflect the full benefits they provide to society are difficult to compute. Provisioning ecosystem services (e.g. timber production, agricultural products) do not represent such public goods, and market prices are well-established and easy to justify. Incentives are thus skewed towards the production of market-valued goods and away from public goods, contributing to clashes in alien species valuation and management when a particular species causes negative impacts on public goods, but positive ones on market-valued goods. Non-market damages are often difficult to quantify due to the complex interactions among species in an ecosystem and the lack of information about the public's preferences across alternative ecological states. In addition, ecosystem services that are being negatively affected by alien species require the calculation of replacement costs (i.e. costs that incur by technical or restoration efforts). Monetizing such replacement costs is problematic and can lead to distorted outcomes, e.g. because some costs cannot be calculated in monetary terms, and some impacts are unrealistic to be replaced at all. As a result, only very few studies have produced estimates of non-market damages attributable to alien species. Consequently, outcomes differ widely depending on which ecosystem services are considered relevant and how they are weighed.

Alien species management and policies as a test case for applying the core principles

National laws and international legal agreements aim to promote and safeguard societal interests and thus reflect shared sets of societal values (Trouwborst 2015). Although the process of developing such agreements involves certain idiosyncratic factors (e.g. access to information, lobbying, interests of decision makers), some commonalities exist that are relevant for alien species policies.

Many of the policies addressing alien species in principle give fairly equal consideration to negative impacts on society and the environment (e.g. USDA 1999; EU 2014). In fact, alien species that harm humans, livestock and crops have been relatively well managed (Keller et al. 2015) because there is general agreement that such impacts are important and undesirable. However, it has become clear that "… all alien species that are not human, livestock, or crop diseases" have been managed much less effectively (Keller et al. 2015), because their impacts are typically distributed across society (and thereby externalized, i.e. not reflected by the polluter-pays principle) and in many cases there is disagreement on whether such impacts (and if any, then which ones) justify management intervention (and if so, to what extent). Thus, many invasive alien species policies have been biased in favour of addressing direct impacts of alien species on socio-economy and land use (e.g. phytosanitary and aquaculture regulations), while impacts on the environment with indirect consequences for society have been less considered.

The newly adopted EU-regulation "On the prevention and management of the introduction and spread of invasive alien species" (EU 2014) will become a key instrument in European alien species management, as it regulates a wide range of issues (from prevention to eradication) for 28 member states. This legal instrument requires *inter alia* risk assessments to consider "the potential benefits of uses [of alien species] and the costs of mitigation to weigh them against the adverse impact, […] to further justify action" (our underlines). This explicit requirement for weighing benefits against adverse impacts in the new EU IAS-regulation clearly calls for protocols for considering positive and negative environmental and socio-economic impacts. For instance, when alien species have socio-economic benefits to some sectors or stakeholders, understandably the framing for valuing the overall impacts of these species by people with vested interests tends to be reflected in an interpretation of the principles which conforms to their interests. Consequently, while socio-economic benefits are often accrued by a few people or economic sectors, other impacts are externalized (e.g. long-term consequences, and impacts other than those considered socio-economically positive), and damage is transferred to society, the environment, or to future generations (Gardiner 2011). In New Zealand, the Biosecurity Act (Anonymous 1993) requires a detailed assessment of the costs and benefits of proposed alien species management under different proposed control strategies, including an assurance that the net benefits of government intervention outweigh the benefits of pest control by the public (e.g. landowners). Such an approach helps ensuring that the regional government has determined the least costly way to achieve regional pest management. Cost-benefit analyses can also be important for mitigating legal challenges from landowners and other rate-payers that dispute regional government priorities.

Such a framing of alien species impacts has received prominence in the implementation of the European Union legislation on invasive alien species (EU 2014). For instance, several EU member states have linked their support of the legislation with the commitment of the European Commission that alien species which are economically important in their country will not be included in the "List of invasive alien species of Union concern", which is the central instrument of the legislation. For instance, Hungary – the country with the largest stands of black locust trees in Europe – requested that this species should not be listed, and Denmark – home to a major fur industry – did the same for the American mink (Tollington et al. 2015). More generally, stakeholders representing several sectors have articulated the view that, according to their principles of valuing alien species impacts, benefits of several species are of overriding public interest and that they should not be regulated by EU legislation. In this regard, the forestry sector was most articulate and vocal (e.g. Vor et al. 2015) and, therefore, despite the fact that 22% of all alien plant species on the list of 100 of the worst invasive alien species in Europe (DAISIE 2009) were trees, no alien tree species was suggested for inclusion in the first list for the EU regulation (EU 2015). Consequently, and despite pressure from the scientific community for a more inclusive approach (Tollington et al. 2015), the first list of 37 alien species of European Union concern is fragmentary and includes only a small number of the more than 1000 alien species in Europe that are considered to have negative impacts on biodiversity or socio-economy (Vilà et al. 2010).

Unfortunately, the establishment of the EU IAS legislation has not been accompanied by providing a European Union-wide funding scheme for implementing it (Tollington et al. 2015). Ultimately, this lack of resources deepens the gap between political will (as enshrined in the provisions of legislation) and enforcement: member states and the institutions that have to implement the EU IAS legislation carry the full financial burden, and given strained public budgets, reducing short-term institutional expenditures by cautiously implementing the legislation is consequent. Further, an integrated assessment of potential long-term consequences of inaction of IAS management is hampered by highly fragmented competences between institutions in EU member states.

Of facts and values: structured decision making for alien species management

Making decisions about complex environmental issues requires (i) the identification of the scale and boundaries of the issue and the stakeholders concerned, and (ii) a transparent unpacking of scientific evidence, values and risk perceptions. This can be best achieved in a structured decision-making and conflict-solution process (Redpath et al. 2015; Gregory et al. 2012). Several techniques have been developed and tested for solving conflicts in conservation (e.g. multi-criteria analyses, consultation and consensus processes, voting systems), each of which may be appropriate in some situations but inappropriate in others (e.g. Maguire 2004; García-Llorente et al. 2008; Monterroso et al. 2011; Gregory et al. 2012; Gutiérrez et al. 2015). In addition, risk assessments, cost-benefit analyses, multi-criteria frameworks and sensitivity analyses may support the decision-making process by providing information on risks and uncertainties associated with the outcomes of different decisions (e.g. Liu et al. 2011). However, such methods have rarely been used for making decisions about alien species management.

Decision making in alien species management often involves people from different domains (e.g. natural sciences, social sciences, policy, the general public), with differing values and objectives. In many situations, structured decision making, i.e. the collaborative and facilitated application of multiple objective decision making and group deliberation methods (Gregory et al. 2012), provide a strong tool to aid and inform decision makers in alien species management. Nevertheless, these methods have limited applicability in situations when rapid decisions are needed (e.g. some alien species incursions). In this scenario, effective risk communication from decision makers to stakeholders is critical. This structured discourse can be facilitated by advancing the scientific understanding of impacts of alien species (e.g. currency, scale, context-dependency, reversibility of risks), and by proposing, testing and applying frameworks with clearly defined criteria rooted in clearly defined norms (e.g. as codified in political agreements such as CBD 2002; EU 2014) (Table 1). Also important, however, are tools that assist individuals or groups to make informed judgements based on decision theory, but which can be adapted for practical needs and constraints facing decision makers in real-world situations. Such tools should provide guidance on the appropriate procedure for making complex choices, a definition of the scope and boundaries of the problem, an identification of alternative actions, their likely consequences and trade-offs (Table 2).

Finally, taking into account the complexity of environmental problems will not always pave the way for arriving at consensus, in particular in situations where values differ strongly, when substantial trade-offs exist among different alternatives, or when there is no impetus for seeking a consensus on behalf of at least one of the involved parties (Gregory et al. 2012). While consensus may be desirable or – in some situations – even essential, sometimes lasting disagreements may be unavoidable; these should not distract from the value of the consultation process and explicitly documenting the underlying reasons for disagreement in transparent ways.

Conclusions

Complex environmental problems such as those caused by biological invasions pose major challenges for science and society. Scientific evidence, values, beliefs, and interests all need to be given transparent consideration in assessing alien species impacts, but they are often confounded and not made explicit. Consequently, guiding alien species management and policy is subject to constraints beyond the realm of traditional science. In many situations, there may well be not one correct answer; there may be a range of solutions, each with its own set of trade-offs. For guiding decision-making processes, the use of structured decision-making approaches and other multi-criteria decision tools often have substantial advantages, but may be time consuming. Complementary approaches, such as identifying, screening and assessing risks prior to the introduction are needed to prioritize species for prevention efforts, and to allow for a quick response once a species is introduced (Leung et al. 2012).

We argue that science must play a central role in providing information and advice to policy makers firmly rooted in political agreements and environmental ethics. Scientists can act as information brokers and advisors and should aim to highlight the likely consequences of different management or policy decisions. Scientists also need to overcome several challenges to implement scientific evidence in decisions. These include: the gap between research and its practical implementation; the lack of consensus among researchers regarding management options and their effectiveness; and the need for scientists to be independent, honest brokers of information to assist in framing problems and providing the means for the evaluation of potential outcomes of different intervention options (Pielke 2011) rather than acting as advocates for any option. This ambitious expectation can only be achieved if pitfalls and biases in the valuation of alien species are made explicit and accounted for. The concept of relative severity, the precautionary approach and taking into account the 13 core principles we have proposed here seem particularly relevant to us.

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Table 1. Thirteen core principles for valuing impacts of alien species, corresponding implications for decision making in alien species management, and recommendations for alien species management and policy. The principles are grouped into two domains that relate primarily to measurement and valuation of impacts, respectively.

No	Domain	Principle	Description	Implications	Relevance	Recommendations	Key references
1	Science domain – MEASURING & DATA	Impact metric	Changes inflicted by alien species can be measured with different metrics (e.g. numbers of native species affected, amount of resources pre-empted by alien species, yield reductions etc.)	Different metrics are generally not directly comparable, making it difficult to compare changes caused by alien species, or impacts of the same species measured with different metrics	Impacts need to be measured using metrics appropriate for the purpose of the study and that are relevant to decision makers	Develop standard metrics for measuring impacts of alien species that allow comparisons of impacts caused by different mechanisms and alien species	Nentwig et al. (2010), Pyšek et al. (2012), Hulme et al. (2013), Humair et al. (2013), Blackburn et al. (2014), Jeschke et al. (2014), Kumschick et al. (2015)
2		Temporal scale	The length of the time considered	Long-term and persisting impacts become more relevant as the time period considered increases	The length of the time period considered affects the importance of long-term vs. short-term impacts in the assessment	Consider alien species impacts over long time periods to account for potential time lags and long-term impacts (>several decades)	Simberloff & Gibbons (2004), Strayer et al. (2006), Jeschke et al. (2014), Essl et al. (2015)
3		Spatial scale	Impacts may be scale-dependent (e.g. an alien species may increase species numbers in a plot, but may reduce between-plot heterogeneity and thus beta-diversity)	The spatial scale considered for analysing impacts may affect the direction and severity of changes	Impacts need to be analysed on the appropriate scale with awareness of the limitations posed by the spatial scale used	Identify the relevant spatial scale(s) for a given policy or management decision	Jeschke et al. (2014), Hulme et al. (2013, 2015)

4		Reversibility	The likelihood that impacts can be reversed (by intervention or spontaneously)	Potential for reversibility of the impacts of an alien species may widely differ, and be subject to future changes (e.g. development of new management tools)	Irreversible (or practically irreversible) impacts are widespread in biological invasions, the likelihood of irreversibility increases as alien species spread	Assess the likelihood of reversibility of changes based on known and tested management measures	Hobbs et al. (2013), Blackburn et al. (2014)
5		Uncertainty	The outcome of a process in complex systems can only insufficiently be predicted / measured (epistemic uncertainty) and communication may amplify uncertainties (linguistic uncertainty)	The existence, type and scale of impacts of an alien species are uncertain, uncertainty is higher at the onset of the invasion, uncertainties are larger for the more distant future, and language used for communicating impacts may be vague and ambiguous.	Decision making in alien species management and policy is subject to (partly irreducible) uncertainties	Be explicit about the context sensitivity of available evidences, refine the level of uncertainty, and apply sensitivity analyses, precautionary approaches, using clearly defined terms	Mastrandrea et al. (2010), Beckage et al. (2011), Liu et al. (2011), Blackburn et al. (2014)
6		Thresholds and tipping points	Small changes close to thresholds may cause large changes in a complex system	Impacts of alien species may change disproportionally close to tipping points by amplifying feedbacks (e.g. inducing regime shifts)	Predictability of alien species impacts is limited, and the impacts may be profoundly different when tipping points are crossed	Develop methods and indicators for early detection of tipping-points (e.g. critical slowing down)	Scheffer et al. (2009), Boettiger et al. (2013), Hobbs et al. (2013), Gaertner et al. (2014)
7		Indirect impacts	The existence of	Indirect impacts of alien	Direct impacts of alien	Develop criteria to identify	Lau (2012), Pyšek et al.

			relevant secondary impacts	species are widespread, uncertain, may occur with time lags, and may be more important than direct impacts	species cascade through different levels of e.g. ecological or socio-economic systems by way of indirect impacts; considering at least the most important indirect impacts is essential to capture the whole dimension of the impact of an alien species	and rank indirect impacts according to their relevance	(2012)
8	**Ethical-political domain - VALUES**	Impacts and risk perception	The relevance attributed to different impacts and risks by people may differ, and there may be systematic differences due to gender, social and cultural factors	Different values, interests and perceptions modify the valuation of impacts and risks	Different values, interests and perceptions may lead to conflicts between stakeholders and social groups that preclude agreement on how to proceed	Apply methods (e.g. structured decision making) that take into account different objectives and value systems of stakeholders and social and cultural contexts	García-Llorente et al. (2008), Liu et al. (2011), Gregory et al. (2012), Redpath et al. (2015), Estévez et al. (2015)
9		Context dependency	Impacts of the same magnitude may be valued differently depending on the environmental, spatial, temporal or societal context in which they	Impacts of alien species inside / outside the region of interest may be valued differently as well as the same impacts in different contexts (e.g. health or agricultural impacts in poor or rich	The valuation of the same impacts but which occur at distant places ("spatial discounting"), in the far future ("temporal discounting") or which affect other	Identify the context appropriate for the study	Clavero (2014), González-Moreno et al. (2014)

			occur	societies)	people may differ from those which affect someone directly		
10		Commensurability	Some values affected may be considered unique or of overriding interest (e.g. risks to human lives)	Impacts in natural ecosystems may be valued as more important than in other ecosystems; impacts on endemic species may be valued as more important than impacts on other species; impacts on human health may be valued higher than on socio-economy	Impacts on unique values may be considered genuinely different to impacts on non-unique values, and thus there may be non-commensurable trade-offs	Identify irreplaceable values (e.g. human lives or health)	Munda (2004)
11		Comparability	Different types of impacts have to be evaluated by using appropriate, yet different, metrics that are comparable	Assessment of overall impacts depends strongly on the methods used for aggregating different metrics	Only a traceable and transparent overall assessment of impact may provide the basis for agreement among (a majority of) stakeholders	Aggregation of metrics should be based on the principle of applying the logic of comparable “relative severity”	Nentwig et al. (2010), Blackburn et al. (2014), Kumschick et al. (2015)
12		Discounting	Long-term impacts may be discounted by a fixed annual rate (or not)	Impacts become less important the further in the future they are likely to manifest	Long-term and persisting impacts are (much) down-weighted by high discounting rates; relates to principles of	Apply no or moderate discounting rates (to conform to the precautionary principle)	Zavaletta (2000), Voinov & Farley (2007), Gardiner (2011)

					environmental ethics and justice		
13		Personal decision biases	Widespread personal predispositions such as cognitive (e.g. anchoring, weighing biases) and motivational biases (e.g. overconfidence) influence decision making	Widespread decision biases may increase or create conflicts in alien species valuation and management	Personal, yet usually unaccounted decision biases modify the valuation of impacts and risks of alien species	Reduce personal biases in decision-making processes (e.g. by using appropriate analytical tools such as Bayesian Belief Networks)	Hämäläinen & Alaja (2008), Gregory et al. (2012), Humair et al. (2013), Montibeller & von Winterfeldt (2015)

Table 2. Eight key issues of structured decision-making processes in alien species management and policy. Based on Maguire (2004), Gregory et al. (2012), and Redpath et al. (2015).

No	Points of consideration	Purpose and relevance
1	Clarify the context of the decision	Define the scope and bounds of the decision, including who are the relevant stakeholders, what are the time horizon and available resources for the management
2	Identify objectives, and performance measures	Define the relevant objectives and suitable performance measures (e.g. reduction in alien species populations size)
3	Identify alternatives (e.g. management options, or alternatives to the planned introduction of a species that might become alien), available means to implement them and their likely consequences	Broaden the horizon, identify and consider different options to ensure that the full range of available opportunities is being taken into account
4	Identify uncertainties and trade-offs between different alternatives	Investigate explicitly the pros and cons, trade-offs and risks associated with the different alternatives available
5	Identify the key points for implementing a decision, and ensure adaptive implementation	Identify the decisive points of implementation once a decision has been made, identify potential obstacles and how they can be overcome, and develop indicators which allow for monitoring and tuning the implementation
6	Achieving consensus: desirable, but not always imperative	Aim for consensus, but allow for disagreement. Document unresolved (minority) views and perceptions, and the reasons for disagreement
7	Avoid double counting and omissions when possible	Double counting (i.e. including the same impacts more than once under different criteria) as well as omissions (i.e. only a fraction of the relevant impacts is considered) may bias the decision process and results
8	Separate means and objectives	Clearly separate means (measures to achieve the desired outcome) and ultimate goals (objectives)

Figure legends

Figure 1. Relevance of the interaction of metrics, geographic scale and uncertainty for assessing impacts of alien species on biodiversity. This hypothetical example is informed by conflicting interpretations of study results (e.g. Thomas & Palmer 2015 and Hulme et al. 2015). The y-axis refers to measured impacts of alien species on biodiversity, whereupon different metrics (e.g. species richness, abundance) and different taxonomic groups may be used. The x-axis represents the variation in geographic scale from very small (<< m^2) to very large regions (>> km^2) on which such an analysis can be performed. We report the results of using two different, but closely related metrics (e.g. measures of alien species occurrence such as species number, cover, abundance) (black, red), their mean values at different scales (dots), their variation due to different contexts (e.g. study ecosystems, biogeographic situation such as islands vs. mainland regions) (whiskers). Some data points additionally include measures of uncertainties (e.g. due to measurement errors), which are shown with lighter-coloured whiskers, whereas others do not (as uncertainty was not considered). Different proxy metrics for impacts on biodiversity across scale may deliver different, even opposing results (a) with varying degrees of context dependency, and some metrics may have strong changes at a particular scale-dependent threshold (such as shown for the black dots in b). Note that uncertainties may become very large and skewed (particularly at large scales), e.g. when additional aspects of uncertainty such as long-term impacts are included (c). Finally, at the largest scale (i.e. the global, separated by the broken orange line) the relationships in impacts may be reversed, as global species richness declines as a consequence of species extinctions caused by alien species (d).

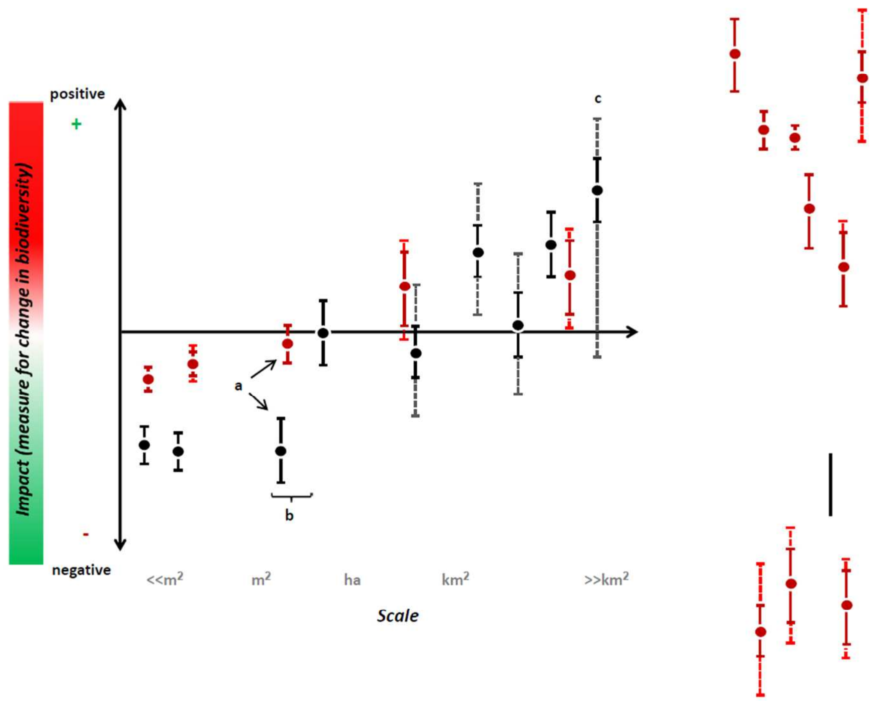
Figure 2. Examples of sources of uncertainty in alien species data sampling and model predictions. The figure shows the accumulation of established alien vascular plant species in the UK (upper black line) from 1900 until 2000 (vertical dashed line; species recorded before 1900 are included in the base number) taken from the Global Alien Species First Record Database (Seebens et al. in prep.). The cumulative development of alien species numbers was projected until 2060 assuming the same rate of introduction as the average observed during 1950-2000 (orange). To simulate various plausible storylines of future alien species accumulation (e.g. taking into account different activities which increase or decrease alien species introductions), the rate of introduction was considered to increase annually by 1% (blue) or to decline by 1% (red) and 5% (green). To analyse the effect of incomplete recording of years of first records on uncertainty, we repeated this 1000 times for random subsets of 25% and 50% of the whole data set; the mean (lower black lines) and variance (grey areas) are shown. The maximum span of projected alien species numbers at 2060 across all storylines is indicated by grey bars with the number of alien species assuming a constant introduction rate shown in orange. Uncertainty on cumulative alien species numbers at a given point in time is directly related to sampling intensity and future introduction rates, and it increases with the temporal distance to the year 2000 if historical sampling was incomplete. Most of these components of uncertainty are de facto largely irreducible.

Figure 3. Conceptual map of the core principles of two different stakeholders (red, green) for valuing a hypothetical alien species. For simplicity, we show just five (of the thirteen) core principles (numbered circles), their relevance to each stakeholder (vertical axis), and the directionality of perceived impacts (horizontal axis). The size of the circles corresponds to the weighting of core

principles in the overall decision-making process of the stakeholder. The potential for conflicts is illustrated. It increases with the differences in valuation in directionality and relevance of core principles between stakeholders. Similarly, it is larger when the magnitude of impacts is considered to be large, and when the importance attributed is high. Consequently, there is no or little conflict potential for principles 2, 3 and 4, but high conflict potential for principle 5; principle 1 falls in between these extremes: While the red and green stakeholders agree that for principle 1 the impacts are negative, this principle is considered to be highly relevant by the red stakeholder, but irrelevant by the green stakeholder.

Supporting Material

Appendix S1. Examples highlighting differences in the application or interpretation of the thirteen core principles that causes conflicts in the valuation of environmental and socio-economic impacts of alien species.


positive
+
Impact (measure for change in biodiversity)
-
negative
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b
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<<m^2
m^2
ha
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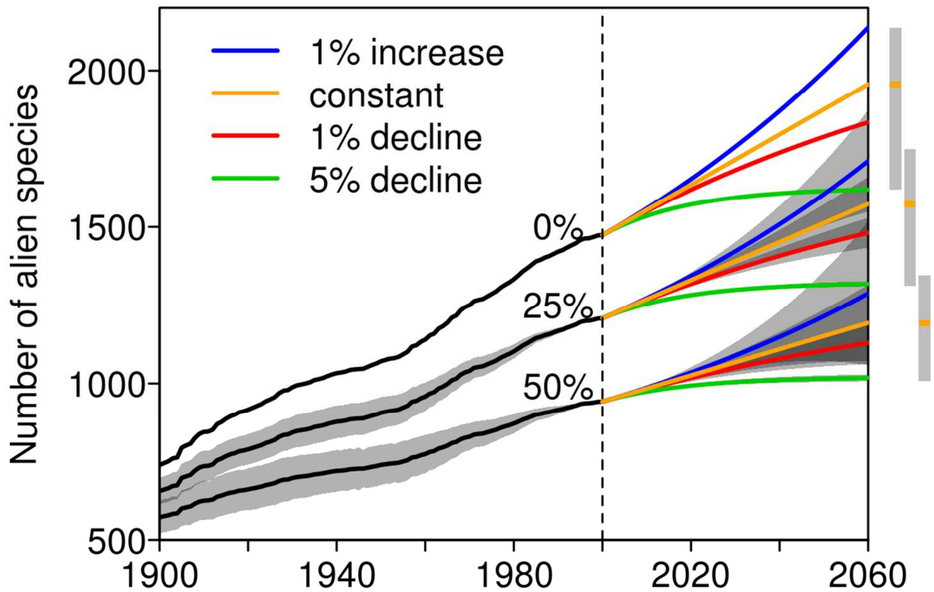
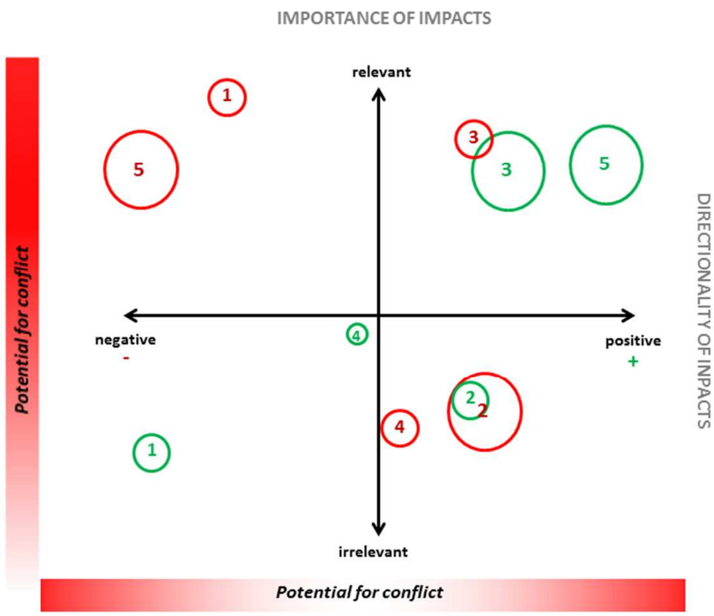
>>km^2
Scale



119x76mm (300 x 300 DPI)



254x190mm (96 x 96 DPI)

Appendix S1. Examples highlighting differences in the application or interpretation of the thirteen core principles that causes conflicts in the valuation of environmental and socio-economic impacts of alien species.

Species / location	Conflicting view A	Conflicting view B	Causes of disagreement	Relevant core principles	Reference
European rabbit (*Oryctolagus cuniculus*) / Australia	*Oryctolagus cuniculus* cause soil erosion by overgrazing and burrowing activities which impacts on native animal and plant communities	*Oryctolagus cuniculus* maintains short sward heights in heathland and grassland ecosystems which are needed by several endangered plant and animal species	Different impacts on ecosystem functioning and biodiversity conservation are considered relevant ("selective attention")	1 (impact metric), 8 (impacts and risk perception), 11 (comparability)	Lees & Bell (2008), James et al. (2011), Scalera et al. (2012)
Tree of Heaven (*Ailanthus altissima*) / Europe	Conservation scientists perceive Tree of Heaven as a harmful invader (e.g. of dry grasslands, forests) with the potential to threaten native species	People on Mediterranean islands and in urban environments appreciate its ability to grow on dry soils, to tolerate urban climates, and to provide shade	Differences in the spatial distribution of impacts which are widely considered positive or negative	3 (spatial scale), 8 (impacts and risk perception), 9 (context dependency)	Bardsley & Edwards-Jones (2007), Kowarik & Säumel (2007), Heger et al. (2013)
Asian kudzu bug (*Megacopta cribraria*) / USA	*Megacopta cribraria* is a pest of soybeans and other leguminous crops	Control of this species is opposed by environmentalists because the bug also feeds on (and effectively reduces) kudzu, an invasive weed from Asia	Differences in considering negative impacts on agriculture (yields) vs. positive impacts on conservation (biocontrol of an invasive alien plant)	8 (impacts and risk perception), (13) personal decision biases	Ruberson et al. (2013)
Buffel grass (*Cenchrus*	*Cenchrus ciliaris* is used and promoted for	*Cenchrus ciliaris* is causing significant deleterious	Biodiversity conservation vs. agricultural production	1 (impact metric), 8 (impacts and risk	Marshall et al. (2011), Driscoll et

ciliaris) / Australia	livestock pastures in Australia	environmental impacts by changing fire-regimes and outcompeting native species		perception), 11 (comparability)	al. (2014)
Grey Squirrel (*Sciurus carolinensis*) / Italy	Eradication of *Sciurus carolinensis* was proposed by environmentalists due to the threat of outcompeting native *Sciurus vulgaris*	Animal rights activists considered killing grey squirrels unethical and successfully lobbied to end the eradication efforts	Biodiversity conservation vs. animal rights (i.e. impacts of management measures)	8 (impacts and risk perception), 10 (commensurability), 11 (comparability)	Bertolino & Genovesi (2003)
Fifteen alien species / Coto Doñana (Spain)	Willingness to pay for management of alien species was lower for alien species being present in the region for a long time, for people with low incomes and if there were direct socio-economic benefits derived from the alien species	Willingness to pay for management of alien species was higher for new alien species, for people with higher incomes and if there were no direct socio-economic benefits derived from the alien species	Different perceptions about the impacts and sectoral or individual socio-economic benefits of alien species lead to different attitudes towards their introduction or management	8 (impacts and risk perception), 9 (context dependency), (13) personal decision biases	García-Llorente et al. (2008)
Zebra Mussel (*Dreissena polymorpha*) / North America	Zebra mussel causes environmental impacts by competition and feeding which are widely considered to be	*Dreissena polymorpha* is used as food resource by some fish and birds, has positive impacts on the abundance of some	Differences in which impacts on ecosystem functioning and biodiversity conservation are considered relevant	1 (impact metric), 7 (indirect impacts), 9 (context dependency)	Ricciardi et al. (1998), Ward & Ricciardi (2007), Strayer (2009), McLaughlan &

	detrimental	macroinvertebrates and may increase water quality			Aldridge (2013)
Red swamp crayfish (*Procambarus clarkii*) / Europe	Red swamp crayfish transmits the deadly agent of crayfish plague to native crayfish in Europe	Red swamp crayfish serves as food for vulnerable Eurasian bittern (*Botaurus stellaris*) in France and for several predators in Spain.	Different focus, perception and weighting of impacts on native biota	1 (impact metric), 11 (comparability)	Poulin et al. (2007), Tablado et al. (2010)
Alien plant species used for biofuel / worldwide	Introduced plants may be particularly suitable for biofuel production, and may contribute to climate change mitigation	Fast growing introduced plants pose substantial risks of becoming invasive	Climate change mitigation vs. risks of unintended negative impacts on biodiversity	5 (uncertainty), 8 (impacts and risk perception), 10 (commensurability)	Raghu et al. (2006), Schnitzler & Essl (2015)
Alien grass species (e.g. *Eragrostis lehmaniana* / Southwestern USA	*Eragrostis lehmaniana* was introduced to rehabilitate grasslands degraded by drought and overgrazing	*Eragrostis lehmaniana* out-competes native species in natural grasslands and has substantial impacts on ecosystems	Different focus, perception and weighting of impacts on native biota	8 (impacts and risk perception), (13) personal decision biases	Schussman et al. (2006)
Pasture plants / worldwide	Introduced pasture plants can help to meet the growing demands for food and fodder through sustainable intensification, and	Introduced pasture plants pose high risks of invading natural ecosystems (e.g. grasslands) with negative impacts on biodiversity, ecosystem processes (e.g.	Different focus, perception and weighting of impacts on native biota	8 (impacts and risk perception), (13) personal decision biases	Driscoll et al. (2014)

	thereby they help to spare land for biodiversity conservation	fire regime) and succession			
Spotted knapweed (*Centaurea maculosa*) / USA	Spotted knapweed is a serious concern for agriculture. The California State Department of Agriculture proposed an herbicide treatment	Local communities (Karuk Tribe) strongly opposed the use of herbicide in their ancestral territory	Different values and risk perceptions about pesticides	8 (impacts and risk perception), (10) commensurability	Norgaard (2007)

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