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Confronting the wicked problem of managing biological invasions

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Abstract

The Anthropocene Epoch is characterized by novel and increasingly complex dependencies between the environment and human civilization, with many challenges of biodiversity management emerging as wicked problems. Problems arising from the management of biological invasions can be either tame (with simple or obvious solutions) or wicked, where difficulty in appropriately defining the problem can make complete solutions impossible to find. We review four case studies that reflect the main goals in the management of biological invasions – prevention, eradication, and impact reduction – assessing the drivers and extent of wickedness in each. We find that a disconnect between the perception and reality of how wicked a problem is can profoundly influence the likelihood of successful management. For example, managing species introductions can be wicked, but shifting from species-focused to vector-focused risk management can greatly reduce the complexity, making it a tame problem. The scope and scale of the overall management goal will also dictate the wickedness of the problem and the achievability of management solutions (cf. eradication and ecosystem restoration). Finally, managing species that have both positive and negative impacts requires engagement with all stakeholders and scenario-based planning. Effective management of invasions requires either recognizing unavoidable wickedness, or circumventing it by seeking alternative management perspectives.

Keywords
Invasive species, conflict species, stakeholder engagement

Introduction

The Anthropocene Epoch represents an era of unprecedented environmental change driven by human activities, a key component of which is the widespread transportation, spread, and resulting homogenization of fauna and flora (Williams et al. 2015). In a world fundamentally altered by anthropogenic processes, problems encountered in ecosystem management, and in particular in conservation biology and resource management, are becoming increasingly complex, where problems may not have a single, technical solution (Haubold 2012). More specifically, decisions regarding conservation in the Anthropocene need to consider the social and economic context (Ban et al. 2013), including the differing values stakeholders use when assessing risk (Liu et al. 2011, Kumschick et al. 2012). Conservation goals are set more often by the social-political perspectives of different stakeholders than by the empirical evidence (Geist and Galatowitsch 1999, Sagoff 2009). The consequent multitude of conflicting perspectives, objectives, and management goals can make the problem almost impossible to characterize, let alone solve, to the satisfaction of all stakeholders.

Such problems were first recognized in the policy and planning field by Rittel and Webber (1973), who coined the term "wicked problem". They defined a wicked problem according to 10 interrelated criteria, later condensed to six criteria by Conklin (2005; see Box 1). Wicked problems can also be viewed in the context of complexity theory as management problems where the cause-and-effect relationships between components, whether they be logistical components or stakeholders involved in management, are unordered and thus have solutions that are not obvious and require collaboration among stakeholders to determine appropriate actions (Kurtz and Snowdon 2003, Van Beurden et al. 2011). Such problems are contrasted against "tame" problems where the cause-and-effect relationships between components are ordered and the solutions obvious or discernible after careful investigation (Box 1).

Problems in the management of biological invasions have previously been referred to as wicked problems. The term was used by Evans et al. (2008), citing difficulties encountered when managing aquatic pests in the Crystal River, Florida; by McNeely (2013) when describing the management of plant introductions in conservation areas; and by Seastedt (2014) when describing the socio-political and ethical issues surrounding biocontrol. The management of biological invasions is particularly susceptible to wickedness in the form of conflicting social pressures. Differing values and risks ascribed to individual taxa by affected parties can lead to social conflicts around their management (Liu et al. 2011, Estévez et al. 2015). The wickedness of a problem will vary from case to case. Not all criteria might apply, some criteria may out-weigh others in making a particular problem more or less wicked, and the wickedness of a problem can vary by region or country according to the perspectives of the different stakehold-

Box 1. Criteria for a wicked problem and glossary of related terms.

A wicked problem is defined as one with the following properties:[1]

1) **You do not understand the problem until you have developed a solution.** Different stakeholders might disagree on some or all aspects of another stakeholder's definition to the problem, if they are personally invested in pursuing a particular solution.
2) **There is no stopping rule.** Because neither the problem nor its potential solutions are definitive, there is no obvious point or stage at which problem solving activities can be curtailed.
3) **Solutions to the problem are not right or wrong.** Rather, you can have solutions that are viewed as "better" or "worse" by consensus of the stakeholders.
4) **Every solution to the problem is a 'one-shot operation'.** An enacted solution causes new aspects of the problem to emerge, which must then be dealt with in turn, using follow-up solutions.
5) **Wicked problems have no given alternative solutions.** Many potential solutions could be thought of, but only some will be appropriate to pursue, depending on the problem's individual nature and social context.
6) **Each problem is essentially unique.** The source of wickedness lies in the social complexity of the stakeholders, and this will always vary from case to case.

Glossary of related terms

Complexity: In the context of project management, complexity is the number of components required to solve a problem, and the nature of the interactions between all components[2]. In complexity theory, the gradient of increasing complexity can be divided into ordered (where interactions between components are known or knowable), and unordered (where these relationships are unknown or disputed)[3,4]. Wicked problems thus represent problems with unordered complexity.

Tame: A problem which falls within the ordered domain of complexity theory. The components to the problem may vary in number, but their interactions are known or knowable[4].

Simple: A tame problem with few components, which share known interactions[4].

Complicated: A tame problem with many components, which share known or knowable interactions[4].

[1] Conklin 2005; [2] Baccarini 1996; [3] Kurtz and Snowdon 2007; [4] Van Beurden et al. 2011

ers involved. In each of these cases, however, it is important to understand how the nature of the problem affects how it can be managed.

In this review, we assess how altering perceptions of managers and stakeholders to the nature and scope of problems presented by biological invasions can complicate or simplify the management solution. The options available to conservationists and environmental managers change with subsequent stages of invasion from initial incursion to spread to widespread establishment (Blackburn et al. 2011, McGeoch et al. 2016) and the complexity associated with solving the problem will intensify as invasions progress through these phases. We interrogate four examples of invasive species management problems across aquatic and terrestrial ecosystems, which focus on achieving prevention, eradication, or impact reduction. Our aim was to illustrate how wickedness in conservation management can arise and might be counteracted, realising that this is not always possible. We also identify situations where biological invasions can best be managed by shifting one's perspective and subsequent management approach to the problem.

Case study 1: Limiting wickedness in the prevention of invasions: managing ballast water in the Laurentian Great Lakes.

Much of the complexity in invasive species management stems from the complications of managing individual species once they have arrived in an environment. This can, however, be avoided by minimizing the chance of such species arriving in the first place. Indeed, many governments and policies worldwide (e.g. Convention on Biological Diversity) now focus on vector management, aiming to preclude non-indigenous species from being introduced (e.g. Environment Protection and Biodiversity Conservation Act 1999 (Australia); Environment Canada 2004; National Environmental Management: Biodiversity Act (South Africa) 2004; EU Regulation 1143/2014 (European Union) 2014; Genovesi et al. 2015). A substantial literature recognizes the importance and addresses the issue of vector (or pathway) prioritization (e.g. see Ruiz and Carlton 2003, Hulme 2009, Essl et al. 2015).

Ballast water and hull fouling are potent vectors responsible for transmitting alien species internationally. Both vectors represent major threats to ecosystems for two reasons: they carry from tens to hundreds of species simultaneously, and the number of individuals of each species may range from low to very high (Briski et al. 2014). The task of preventing the arrival of these species may initially appear to be a wicked problem, but can be approached as a straightforward, tame problem, provided it is addressed appropriately (Box 2).

Managers seek to reduce the risk of introducing a new species either by targeting the species itself or by focusing on pathways that allow the target species, and others, to arrive in a new environment. Species-specific risk assessment uses information on the number of individuals introduced and other demographic data. This approach may allow researchers to prioritize areas at highest risk of an invasion by a single species, although estimating the probability of successful establishment in any one ecosystem remains problematic (Herborg et al. 2007). It is, however, extremely challenging to develop single-species risk assessment models for species that use a vector capable of transporting multiple taxa. The wickedness of this problem lies in the fact that each newly introduced species will have its own propagule pressure, physiological tolerance to ambient conditions, and demographic constraints (see Seebens et al. 2013, Chan et al. 2014). This combination of factors results in tremendous variation in the probability of individual species successfully establishing in a new community and renders it virtually impossible to calculate the overall probability of a successful invasion. Drake and Lodge (2004) attempted to identify areas of greatest risk of future invasions from ballast water releases by analysing global shipping networks. Seebens et al. (2013) took a similar approach but also considered environmental matching and biogeography.

By switching the approach from species management to vector management, the risk management proposition becomes far simpler, as does the number of possible solutions (Box 2 - Figure 2). The framing of the problem around introduction events rather than focusing on species, removes nearly all wickedness from the problem according

Box 2. Ballast water management in the Laurentian Great Lakes.

Background

Water was first utilized as a form of shipping ballast in English coal vessels during the 1850s[1]. Ballast water largely supplanted soil ballast by the early twentieth century, after which invasions to the Great Lakes became increasingly dominated by this vector[2]. Following the opening in the late 1950s of the modern St. Lawrence Seaway – which provided access to all five lakes by transoceanic commercial ships – ballast water dominated all other vectors of introduction, accounting for between 55 and 70% of the 56 known aquatic invasive species that were recognized during this period[3]. Formal ballast-water regulation began in 1993 for international vessels with tanks filled with fresh water. In 2006 (Canada) and 2008 (USA), these regulations were extended to vessels with only residual water in tanks. In both cases, vessels were required to conduct open-ocean exchange or flush salt water through their tanks, respectively, to reduce invasion risk. No new ballast-mediated invasions have occurred since 2006.

Mediators of wickedness

Species-specific risk assessments consider the likelihood of a species interfacing with, and being transported by, a transport vector, survival during transit, and likelihood of introduction to and survival in a new environment. Assessing overall risk is highly problematic when discharged ballast water contains multiple species, each with a different population abundance, life history, and physiological tolerance. The alternative approach of a pathway-level assessment treats each species and every propagule as equivalent, akin to neutral theory models used to predict species replacements in natural communities[4]. Managers can then assess total propagule pressure combined across all species, as well as colonization pressure (number of species introduced), released into the new environment to determine relative invasion risks of different introduction events[5]. This approach allows a wicked problem to be analysed at the pathway level, transforming it into a resolvable or tame problem. It should be noted that, within this conceptual framework, increasing numbers of vectors can make a simple problem become complicated in terms of the number of pathways and variation in associated regulations that can be brought to bear to maintain biosecurity[6].

Figure B2-1. Ballast water being emptied into the St Lawrence River

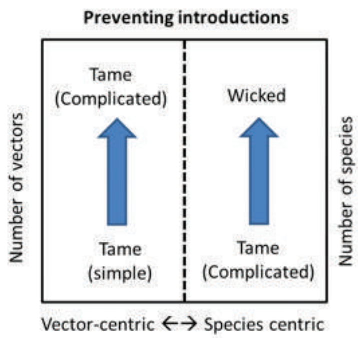

Figure B2-2. Conceptual diagram for Case 1*.

[1] Carlton 1985; [2] Mills et al. 1993; [3] see Bailey et al. 2011; [4] Hubbell 2001; [5] Drake et al. 2014; [6] e.g. Padilla and Williams 2004.

* In this conceptual diagram, the dichotomous x-axis reflects the two management approaches that can be brought to bear on biosecurity management. The left and right y-axes reflect the dominant driver of complexity for each approach, although both drivers (number of species and number of vectors) can affect overall complexity of a particular management problem whether a species-centric or vector-centric approach is taken.

to Conklin's criteria (Table 1). Ultimately, the solution to the problem of ballast-water introductions lies in the effective regulation of the use of ballast water in shipping. This has been partially achieved in the Great Lakes, as both USA and Canadian authorities enacted regulations (see Bailey et al. 2011) that have resulted in measurable declines in new introductions to the Laurentian Great Lakes (Box 2). These empirical findings are consistent with Drake and Lodge's (2004) theoretical model that predicted that reducing per-ship invasion risk would be more effective at preventing invasions than knocking out key ports in a shipping network.

Successful vector management in the case of the Great Lakes works because focusing on one stage — a choke point — in the invasion process simultaneously knocks out the vast majority (but not all; MacIsaac et al. 2015) of the possible invaders prior to introduction. Vector control may not always be as simple, however. Other trade vectors that allow hitchhiking by invasive species can be harder to treat effectively (e.g. wood dunnage in shipping), despite internationally mandated treatment standards (Haack et al. 2014). Moreover, some pathways for introduction (e.g. the aquarium pet trade) comprise multiple vectors and are largely unregulated at a global scale (Padilla and Williams 2004). In such cases, biosecurity risk management becomes far more complicated, due to the diverse number of companies and organizations involved, and the fact most of the players are not subject to a uniform set of regulations that is enforceable in practice, unlike ballast water management in North American waterways. Thus, the geo-political scope of the vectors will determine the practicality of vector management and the availability of workable solutions (Box 2). Nonetheless, we advocate that vector-centric management solutions to problems of biosecurity should be explored given their potential to reduce wickedness.

Case study 2: Ecological scope can determine wickedness: the eradication of invasive species from islands

The case of multiple vectors enabling the transport of potential invaders highlights that, while changing problem formulation can often reduce the wickedness of a problem, the scope of the problem can be a fundamental driver of complexity in the management of biological invaders. This is illustrated by our second case study, which examines the challenge of eradicating invasive species (Box 3). At a superficial level, the tamest invasive species problem is that of an invader that has established on a small island with no human habitation, high conservation value, and where the chance of reinvasion is negligible (e.g. Donlan et al. 2014). There is often, though not always, agreement among stakeholders (in this case the governmental custodians of the island) that, if budget allows, an attempt should be made to eradicate the invader. The removal of such a species, however, is implicitly an attempt to remove its impacts on the receiving environment, which adds multiple permutations to the formulation of the goal (Box 3 - Figure 2). As one increases the scope of the problem to reflect broader conservation goals, the number of potential solutions, and the number of potential

Box 3. Eradicating invasive species from islands.

Background

Here, we consider eradication to be the elimination of a species from an area to which recolonization is unlikely to occur[1]. In this sense, invasive vertebrates have been eradicated from islands a number of times as part of conservation initiatives[2]. Eradication success generally depends on the biological traits of the target species, the ecology and environment of the island (especially whether it is remote enough for recolonization to be unlikely), and socio-economic factors involved in implementing the eradication attempt. While such eradication efforts might be pro-active (e.g. to remove a new incursion), they are often in response to documented evidence of substantial undesirable impacts. The goal of eradication in this case is essentially to contribute towards island restoration.

Mediators of wickedness

The eradication of invasive mammals from islands has led to substantial conservation benefits[3], but such actions can result in unintended consequences[4]. Thankfully, past experiences have provided a framework for planning that has worked in practice[5], so while the problem might be complicated, it is still tame. However, the problem becomes more challenging if all non-native species on a given island are considered. The eradication of plants, invertebrates, and micro-organisms pose additional practical and theoretical challenges (e.g. being able to detect and treat all individuals and to understand which taxa are actually non-native). This quickly leads to a management problem that is impractical to solve under any reasonable budget. Similarly, larger islands, and those with multiple stakeholders (in particular those that are inhabited), will typically be more difficult to manage[6].

Where the problem becomes wicked (as opposed to being complicated in terms of resource allocation) is if the management goal is not eradication per se, but island restoration. Often, after an agent of perturbation (the invader) has been removed, even if there is a clear baseline to which the island should be restored, the process will need to be on-going and adaptive. Instead of following set best-practice procedures for eradicating a particular species, or proscribed good practice for eradicating multiple taxa, there will need to be an emergent practice of restoration tailored for the local conditions.

Figure B3-1. Baited rat station in Gwaii Haanas National Park Reserve, British Columbia, Canada. Photo courtesy of Laurie Wein, Parks Canada.

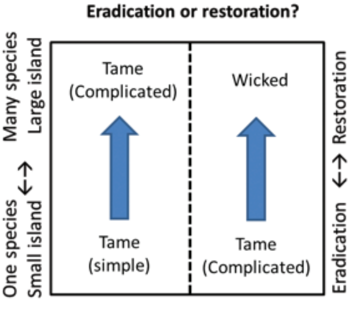

Figure B3-2. Conceptual diagram for Case 2*

[1] Myers et al. 1998; [2] DIISE 2015; [3] Jones et al. 2016; [4] Bergstrom et al. 2009; [5] Cout et al. 2009; [6] Glen et al. 2013.

* Note: In this conceptual diagram, the left-hand y-axis represents the drivers of complexity for eradication, while the right-hand y-axis represents the impact of a shift of strategy from eradication to restoration. Eradication tends to be more complicated as more species are targeted or the island is larger. But, shifting the overall goal from individual species to ecosystem processes can transform the problem from complicated to wicked. If multiple stakeholders are involved (e.g. inhabited islands), the problem can also become wicked (see case studies 3 and 4 below).

unintended consequences, increases rapidly to the point of posing a wicked problem in terms of most criteria (Table 1). The ecological context of the invasive species on the island might also add complexity to the problem that, if unaddressed, may lead to management solutions that exacerbate, rather than improve, the situation. A classic example is that of the feral cat *Felis catus* eradication on Macquarie Island. The successful eradication of cats led to an upsurge in the invasive rabbit *Oryctolagus cuniculus* population that worsened the ecological functioning and conservation status of the island (Bergstrom et al. 2009). This example clearly illustrates the implications of criteria 4-6 in Conklins' (2005) formulation (Table 1). Recognizing the interplay between different invasive and native species in the island ecosystem has prevented such unintended negative consequences on other islands (Caut et al. 2009), but avoiding such surprises requires a more comprehensive assessment of the ecosystem-level consequences of a management plan (e.g. incorporating food web and functional networks into ecological risk assessment) prior to its implementation (Zavaleta et al. 2001).

To provide a meaningful assessment of the ecological risk of a planned eradication, heuristic, qualitative modelling approaches such as community matrix loop analysis (to determine likely positive and negative trophic interactions) and fuzzy interaction webs (providing qualitative predictions of complex community responses to a particular perturbation) can broadly model the likely interactions within island food webs under different consumer control regimes (Dambacher et al. 2002, Ramsay and Veltman 2005). These approaches thus provide a tool for managers to recognize the hidden wickedness within a superficially tame problem. Through these heuristic approaches, managers can select individual management strategies (e.g. targeting high-impact predators with weak trophic links to invasive grazer species) that are less likely to result in novel and unintended consequences.

The eradication of individual species from islands is, thus, a management problem that can be worthwhile pursuing, provided that the likely implications of the chosen solution are adequately understood. In contrast, there will be invasive species which have little impact on ecological communities. In such cases, it might be a waste of limited resources to attempt eradication. A prioritization framework proposed by Kumschick et al. (2012) provides a structured procedure by which managers can focus limited budgets towards invasive species with high negative environmental impact. This framework is also applicable in the case of inhabited islands where humans are potentially impacted by the invasive species, or may object to an eradication program on ethical (in the case of animal eradications) or aesthetic (in the case of flowering plants) grounds (Estévez et al. 2015). Through such prioritization mechanisms, conservation managers can choose sufficiently tame goals that are specific, measurable, achievable, relevant, and time-bound, following the principles of management goal-setting advocated by Doran (1981).

The potential for conflict surround eradications on inhabited islands demonstrates a major diver of wickedness in invasive species management, namely the involvement of multiple stakeholders with different perspectives on the invasive species problem (Glen et al. 2013). Problems in invasive species management shift from complicated to truly wicked when one has to deal with species that can be either harmful or useful depending on the socio-economic context within which they are assessed, so that eradication is no longer a viable option. At this point, management of the species generally shifts towards minimizing the known or perceived negative impacts of the species, which allows many new opportunities for the problem to become wicked. This is especially true in cases where the species in question was deliberately introduced to provide benefits. The final two case studies of this review explore "conflict species" in terrestrial and aquatic ecosystems respectively. Both case-studies focus on taxa that proved extremely difficult to manage for contrasting reasons. In the first of these (case study 3), the problem was initially formulated without all stakeholders engaged, and so the enacted solutions were incomplete and largely ineffective.

Case study 3: Changing circumstances heighten wickedness: Controlling invasive alien pine trees in the Cape Floristic Region of South Africa

Pine trees (*Pinus* spp.) were originally planted in the Cape Floristic Region of South Africa to provide timber in a region that had few natural forests. While that benefit still applies today, they are now also seen as a threat to water resources and biodiversity (Box 4). Pines are, therefore, conflict species—they are simultaneously seen as useful (by foresters) and harmful (by conservationists). Moreover, the funding for projects aimed at reducing the extent of invasive populations is secured on the basis that these control projects can generate employment (van Wilgen et al. 1998). This has meant that the primary focus of management has shifted from utilization to control to job creation, adding to the difficulty of achieving effective control in priority areas. Instituting partial solutions over time that address the problems of some, but not all, affected stakeholders, has given rise to new problems, and this cycle has led to a situation that meets every criterion of a wicked problem (Table 1). Here, a shortage of timber was addressed by planting alien trees (ignoring conservation), which led to invasions; this was addressed by retaining commercial forestry but combining control programs with job creation. The addition of job creation to the stated goals of the management solution has led to a loss of focus on control, making control ineffective, and further fuelling on-going, intractable conflict. Thus, as the invasion spread over time, the competing interests regarding their preferred management has resulted in a clearly wicked management problem (Box 4 - Figure 2).

In theory, there is a solution to the problem of pine management that would satisfy all stakeholders. Such a solution would see populations of invasive pines in vulnerable catchment areas reduced to levels where they can be sustainably controlled at these low levels and where plantations of the same species can simultaneously be maintained for their benefits in the landscape. The very large extent of invasions and the exorbitant costs of such a solution render it practically unattainable, and all alternative partial solutions are contentious (van Wilgen and Richardson 2012). For example, it may be advantageous to focus control efforts on priority areas while abandoning others, to

Box 4. Controlling invasive alien pine trees in the Cape Floristic Region of South Africa.

Background

Pine trees (*Pinus species*) have been extensively planted in South Africa since the 1930s to provide timber[1]. Pines began spreading beyond the borders of formal plantations, where they invaded the adjacent fynbos shrubland vegetation of the Cape Floristic Region. Invasion by alien pine trees was recognized as a problem as early as the 1940s, and coordinated attempts to clear these invasions began in the 1970s. Although clearing attempts have continued at often substantial levels since then, the extent of invasions continues to grow[2]. Because pine trees are simultaneously useful and harmful, depending on the perspective adopted, the situation becomes more and more polarized, exacerbated by the fact that perspectives change over time as value systems and economic circumstances change[3].

Mediators of wickedness

The problems associated with the management of pine invasions were initially complicated, but arguably manageable. Complexity initially arose from attempts to grow a crop species that was also highly invasive. The species spread into inaccessible areas where clearing was difficult, and wildfires promoted further spread, making control difficult. However, with time and increasing geographic extent of invasions, a number of new factors were added to this complexity. Both the need to prevent biodiversity loss and to stimulate economic growth are becoming more acute, leading to polarized views regarding the advantages (timber, shade and amenity values) and disadvantages (biodiversity and water losses, and increased fire hazard) of pines. Recent analysis predicts the net value of benefits minus impacts will become negative as invasive pines spread[3], but suggestions to phase out pine based plantation forestry[1] and introduce biological control agents[4] have been met with strong opposition from stakeholders with interests in the current benefits from forestry and downstream industries. A shift in the emphasis of control projects (from the restoration of ecosystems to employment creation and poverty relief associated with managing the invasive stands) has introduced the often competing needs of meeting dual goals. To date, suitable compromises to these problems have not been found, nor do they seem possible, signalling that this issue has become wicked.

Figure B4-1. Invasive pines spreading from a plantation in the Cape Floristic Region.

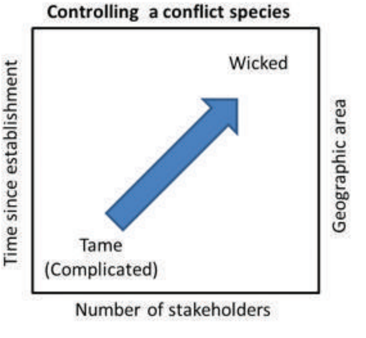

Figure B4-2. Conceptual diagram for Case 3*.

[1] van Wilgen and Richardson 2012; [2] van Wilgen et al. 2012; [3] van Wilgen and Richardson 2014; [4] Hoffmann et al. 2011.

* Note: In this conceptual diagram, the x-axis and both y-axes represent independent drivers that can impact complexity individually or in combination. Invasive pines were originally perceived by managers to be in the lower left of the concept space, though in reality the problem was more towards the upper right. Today, all three drivers continue to contribute to the wickedness of invasive pine management.

more effectively utilize scarce funds (Forsyth et al. 2012). There is, however, reluctance to phase out control projects in lower-priority areas to achieve this, because of the political implications of cutting jobs in areas where unemployment is high. Similarly, phasing out plantation forestry to reduce propagule pressure on vulnerable watersheds is an option (van Wilgen and Richardson 2012), but this proposal was met with stiff resistance from the forest industry (van Wilgen and Richardson 2014). Finally, it may be necessary to accept that the problem cannot be solved and that management may need to recognize the existence of a novel ecosystem (*sensu* Hobbs et al. 2014) in which pines constitute a permanent component.

As the pine management example demonstrates, acknowledgement of all relevant stakeholders to an invasive species management problem is a key requirement for generating sustainable solutions that can be supported by both government and civil society. Knowing all the players does not, however, mean a solution that satisfies all is easy or even possible. Our final case study deals with an invasion problem where key stakeholders hold diametrically opposed positions on the nature of the problem and its preferred solution.

Case study 4: Conflict species with polarized stakeholders maximize wickedness: Managing invasive rainbow trout around the world.

Invasive alien rainbow trout (*Oncorhynchus mykiss*) is a classic conflict species. It is both highly desirable as a resource and detrimental to the aquatic environments in which it establishes (Box 5). Where introduced, salmonids have had considerable ecological impacts on recipient ecosystems that span multiple biological domains (e.g., Dunham et al. 2004, Garcia De Leaniz et al. 2010, Ellender and Weyl 2014). They nonetheless represent significant recreational and economic value for the regions into which they were introduced, with the result that management goals can be polarized among conservationists, anglers, and fish farmers.

This has resulted in direct opposition by some stakeholders to the management goals of others. In New Zealand, proposed efforts to control invasive trout by the Department of Conservation were vociferously opposed by angling bodies, seeing the proposals as the "thin edge of the wedge" to begin removing their preferred sport fish from popular fishing waters (Chadderton 2003). In South Africa, trout are held in such esteem by some recreational anglers that they have prompted the formation of sporting associations such as the Federation of South African Flyfishers, whose mandate is to protect trout angling from the threat of conservation authorities (Ellender et al. 2014). This organized reaction to conservation authorities in government became more active in response to draft regulations in 2013 that classified trout as an alien species requiring control (Ellender et al. 2014). The result was a coordinated lobbying effort that managed to prevent the inclusion of trout on the promulgated list of regulated alien species, despite scientific evidence that demonstrated the invasiveness and impact of trout within South Africa (e.g. Ellender and Weyl 2014, Shelton et al. 2014).

Box 5. Managing invasive rainbow trout around the world.

Background

The rainbow trout (*Oncorhynchus mykiss*), included in a list of 100 of the world's worst invaders[1], has been introduced to 99 countries[2]. Like most invasive fishes, it is among a few groups of organisms that have been deliberately introduced into the environment with the express purpose of creating self-sustaining populations in the wild or to maintain wild population abundance, regardless of wild reproduction[2]. Trout introductions often achieved the desired objective of developing sport and commercial fisheries that contribute significantly to local and regional economies[3]. For example, one estimate places the economic benefit of alien sport fishes to the USA at US$69 billion annually[4]. These intentional introductions continue to occur despite changing views on the stocking of alien species due to their potential ecological impacts[5]. Negative impacts of the species include hybridization with congeneric species, parasite transfers between cultured and wild individuals, extirpations of native fishes and amphibians due to competition and predation, and cascading food web impacts at community and ecosystem levels.

Mediators of wickedness

Management of alien salmonids is complicated by differences in value systems and the risk perceptions of stakeholders and decision makers. For example, illegal introductions of invasive fishes are also a source of conservation concern and the effective long-term management of invasive fishes relies on stakeholder support[6]. This is complicated by the predominantly positive angling values associated with invasive salmonids, which are a source for conflicts when attempting to control invasions and typically resolved in favour of alien sport fisheries[6]. A major problem with managing invasive fishes is that, once established, control is extremely difficult. In many regions, implementing management interventions is also complicated by the economic contributions of angling and aquaculture to local economies[7] and by resistance by some anglers and managers, whom actively support stocking and argue in favour of considering alien salmonids part of the native biodiversity[6] and often use the term “naturalized” to distance themselves from the term “invasive”.

Figure B5-1. A rainbow trout caught and about to be released back into the Broken River, New Zealand.

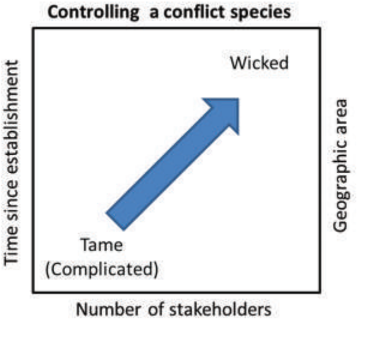

Figure B5-2. Conceptual diagram for Case 4*.

[1] www.issg.org; [2] Crawford and Muir 2007; [3] Cambray 2003; [4] Gozlan et al. 2010; [5] Helfman 2007; [6] Ellender et al. 2014; [7] Quist and Hubert 2004.

* Note: In this conceptual diagram, the x-axis and both y-axes represent independent drivers that can impact complexity individually or in combination. The problem of managing introduced trout tends to fall in the upper right of the concept space in regions where the species is established. Unlike with pines, time since establishment has not been a major driver of complexity in trout management, as the underlying problems were apparent shortly after initial establishment in most countries.

The situation is less polarized but more spatially complex in North America, where invasive rainbow trout is highly valued as a sport fish by anglers, except when it is perceived to impact other sport fishes, often congeners, of higher value. In the past, rainbow trout, brown trout (*Salmo trutta*), and brook trout (*Salvelinus fontinalis*) had been stocked over native cutthroat trout (*O. clarkii*) populations in many Rocky Mountain streams to enhance angling opportunities. This has resulted in competition from all three invasive salmonids and, more alarmingly, introgression with rainbow trout, threatening the persistence of pure strains of cutthroat trout (COSEWIC 2006). As cutthroat trout is preferred by anglers, particularly fly fishers, angling organizations like Trout Unlimited support the eradication of rainbow trout from waters where the cutthroat trout is present. This organization aims, "to conserve, protect and restore North America's coldwater fisheries and their watersheds" and to "ensure that robust populations of native and wild coldwater fish once again thrive within their North American range…" and is against stocking non-native hatchery trout on top of native wild trout populations (Trout Unlimited 2015).

As a result of the apparent conflicts between establishment and eradication, and associated economic and ecological impacts, the management of introduced salmonids provides a thoroughly wicked set of problem formulations and potential solutions, further influenced by spatial and political variation globally (Table 1). The likelihood of achieving practical solutions for managing conflict species such as pines or trout will depend on managers understanding the different players, their perspectives, and directly engaging with them to identify equitable management goals.

Conclusion: Recognizing and effectively dealing with wickedness in invasive species management

The four case studies represent the types of problems that conservation managers regularly face when managing the incursion, establishment, and impact of invasive species. A consistent theme throughout these examples is the frequent disconnect between the perception of the problem by managers and the reality they face. Indeed, the first, and possibly most important, of Conklin's criteria is that of problem formulation. In many ways, wickedness begins when the scope of the problem is misinterpreted or, worse, underestimated. This disconnect can lead to a succession of inappropriate or incomplete solutions being offered that, in the case of pines in South Africa, have historically led to ineffective management policy. Our four case studies represent a matrix of management problems in which the perception and the reality of wickedness vary (Figure 1). By recognizing when such disconnects exist, managers may be able to devise management solutions to biological invasions that are more effective, more sustainable and less prone to unexpected negative consequences, whether it be unwanted ecological interactions or push-back from negatively affected stakeholders.

In the case of ballast-water management, shifting the problem formulation from species-oriented to vector-oriented actually revealed a perceived wicked problem to be a

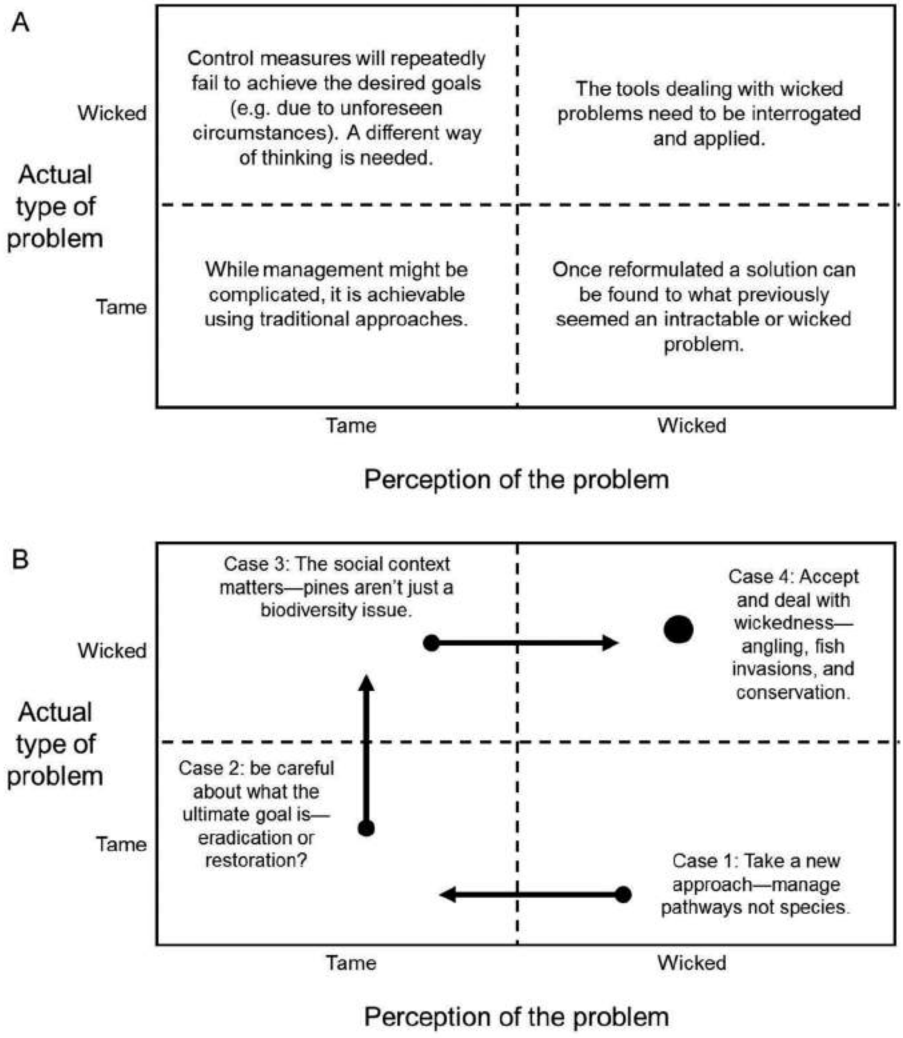

Figure 1. Conceptual diagram of perceived and real wicked problems in managing biological invasions. **Panel A** represents a matrix of how perceived and actual wickedness can influence the outcome of management; **Panel B** illustrates emergent lessons from the four case studies of invasive species management discussed here. Vectors represent shifts in problem perception and management paradigms necessary for improving the manageability of each case study.

relatively tame, if complicated and potentially expensive, problem to tackle. The key to the ultimate success of ballast-water control in the Great Lakes was to realize that the risk posed by the vector would apply to any species that used it for dispersal. Thus, a shift in perspective was the key to limiting the scope of problem formulation and its solutions.

Once an unwanted invasion has occurred, the management problem shifts from one of biosecurity to one of ecosystem management, where conservation managers seek first to eradicate, then to control the invader. In the case of mammal eradications from islands, most operations have been highly successful, with the few examples of documented negative impacts usually temporary in nature (Jones et al. 2016). However, eradication programs do need to explore the potential consequences of individual species eradications to ecosystem restoration before settling on a management direction. Our assessment of the complexities of island eradications revealed them to ultimately conform to 4 of the 6 criteria for wicked problems (Table 1), highlighting how managers will need to recognize the wickedness hidden within an apparently tame problem if they are to achieve success (Figure 1). Nonetheless, it is important for managers to recognize when limited funds mean that complete solutions, such as the removal of all invasive species from the island, are unachievable. It is in these situations that prioritization of invasive species and their likely impact is critical for pragmatic management solutions (Kumschick et al. 2012, McGeoch et al. 2016). The only criteria not met by case study 2 (Criteria 2 and 3; Table 1) are implicitly linked to variation in stakeholder perspectives, which can rapidly increase the complexity of invasive species management.

Conflict species represent the most widespread kind of wicked problem in invasive species management, because there is inherent disagreement on the formulation of the problem and its potential solutions. Invasive pines and trout do, however, differ in the divergence between the perception and reality of wickedness. In the case of the pines, it was the sequence of historical management solutions, put in place reactively as perceptions and the socio-economic context of pines changed over time, which led to a build-up of unintended consequences reflected in the present-day situation (an inherently wicked problem was, at first, incorrectly perceived as tame; Figure 1). A greater acknowledgement of contrasting stakeholder groups may have enabled a more balanced set of solutions to be implemented earlier, if the wickedness of the problem created by multiple stakeholders with divergent perspectives and priorities had been recognised from the start (Figure 1). The trout example, in contrast, represents an invasive species problem perceived as wicked from the outset of it being considered a problem at all (Figure 1). By the time conservation managers began to recognize the species' negative impacts, a strong lobby of anglers opposed proposed control in principle. Here, all the relevant stakeholders were recognized since the start of the conflict, but their opposing views on the nature of the problem have, in some cases, prevented any solutions from being developed.

An emerging field of structured stakeholder engagement, including scenario-based planning (SBP) can enable the development of solutions for wicked problems in invasive species management. The fundamental strength of SBP is that it enables stakeholders to bridge the gaps in their relative perceptions of a problem, by creating plausible future scenarios based on a limited set of proposed management actions, and then deciding which scenario is likely to have the most agreeable outcome to all parties (Peterson et al. 2003). This technique offers solutions that unify the problem

Table 1. Fitting Conklin's (2005) criteria of wickedness to four case studies of invasive species management.

Criterion	Case 1: Tame problems that may appear wicked – managing ballast water as a vector	Case 2: Problems that may be tame or wicked, depending on management goals – eradications on islands	Case 3: Wicked problems incorrectly perceived as tame become more wicked – invasive forestry species	Case 4: Disagreement over the nature of the problem ensures wickedness – invasive sport fishes
1) You don't understand the problem until you have developed a solution	**No.** Although management plans aimed at every potential invasive species are impractical, a management approach that deals with all potential invaders simultaneously (e.g. vector control) becomes simple to define.	**Yes.** Although the problem of eradicating a single species is easy to define, and has a clear solution, this would not guarantee ecosystem restoration. If the problem is more appropriately formulated as "Restore Island A to pre-invasion state" both the problems and potential solutions arguably become difficult to define *a priori*.	**Yes.** The solutions proposed to address this problem have dealt with a particular aspect of the problem (e.g. provide timber, protect water resources or biodiversity, or create employment) which has led to unsatisfactory outcomes for stakeholders who were ignored initially.	**Yes.** Many countries recognize invasive salmonids as a both problem and an asset, and hence have not developed a broadly accepted solution. In most countries, stakeholders have a diversity of views based on varying perspectives, values, politics, and financial resources. As a result, if deemed a problem, solutions may vary widely.
2) Wicked problems have no stopping rule	**No.** A comprehensive risk assessment and management plan for all species transported in ballast water is impossible, as the potential species pool is unbounded. It is however possible to successfully manage the vector itself.	**No.** The problem might be declared solved if a single species is eradicated, and new introductions can be prevented.	**Yes.** Pines can never be eradicated, so their management can never be stopped. The question becomes one of whether the invasions can be brought to a level where they can be contained sustainably. This should be possible but, despite considerable control efforts, pines continue to spread.	**Yes**. When management for any of the conflicting goals is the solution, there is never a point of ultimate success. Decision makers are often reluctant to identify a stopping rule given the diversity of stakeholder views.
3) Solutions to wicked problems are not right or wrong	**No.** One could argue that the vector-management approach to ballast water invasions is appropriate, as it nullifies other drivers of wickedness in this case.	**No.** A method that completely eradicates a single species can be called "correct", although methods used to restore ecosystems may be subjectively assessed on their overall success.	**Yes.** Pines are "conflict" species (simultaneously bringing benefits and doing harm), so it is necessary to make trade-offs, because it is both "right" to encourage benefits and "wrong" to tolerate harm.	**Yes**. Managing against the spread of invasive trout and its impacts may be viewed as "right" by conservationists but are likely to be viewed simultaneously as "wrong" by anglers who utilize the resource.

Criterion	Case 1: Tame problems that may appear wicked – managing ballast water as a vector	Case 2: Problems that may be tame or wicked, depending on management goals – eradications on islands	Case 3: Wicked problems incorrectly perceived as tame become more wicked – invasive forestry species	Case 4: Disagreement over the nature of the problem ensures wickedness – invasive sport fishes
4) Every solution to a wicked problem is a 'one-shot operation' that leads to new problems.	**No.** The management of invasion risk by controlling the vector through effective regulations means that each potential species invasion is prevented by the same, repeatable method.	**Yes.** Eradicating a species from an island will always depend on environmental context (geographic extent, logistical feasibility) for its success. Context dependency increases significantly with island size and ecosystem diversity. Removal of one species can lead to new problems.	**Yes.** Pines were introduced to provide timber, but became invasive, leading to reduced water supplies and biodiversity. The solution was to initiate control operations, but these could not be sustained. This was "solved" by combining control with poverty-relief to create employment leading to a shift in emphasis to job creation at the expense of effective control.	**Yes**. The historical, social and environmental context of each invasive trout population makes each solution have a wide range of potential unintended consequences.
5) Wicked problems have no given alternative solutions	**No.** Whether attempting to prevent a single species or all species from successfully using the ballast water pathway to enter North American waters, the treatment of ballast water is the clear solution to minimize the risk of introduction.	**Yes.** Some species can be eradicated from a defined geographic area using a small number of known methods. Ecosystem restoration has innumerable potential solutions based on the definition of restoration.	**Yes.** We seek to maintain forestry production in conjunction with control, but this appears to be unattainable, and all alternative partial solutions remain contentious.	**Yes**. There are at least three solutions – accept the invasion, eradicate, control. The latter two have many options, though many would be considered unacceptable by anglers.
6) Every wicked problem is essentially unique and novel	**No.** Ballast water as a vector has several key traits that make standardized treatment solutions viable across many different shipping routes.	**Yes.** The solution for eradicating one species on an island is likely to work on another island with the same species, but the implications of the eradication for ecosystem rehabilitation will be case-specific.	**Yes**. The problem of invasive pines in the Cape Floristic Region is embedded in a dynamic social-ecological context, where numerous factors interact, resulting in a unique situation for each stand of invasive pines.	**Yes**. Each salmonid population will have unique logistical constraints surrounding its management, as well as an associated group of stakeholders, who add individuality to the nature of the problem and its potential solutions.

formulation among stakeholders, thus, leading to negotiated solution sets that can limit wickedness. Building such scenarios can also alert managers to the potential unintended consequences of a proposed management action (Game et al. 2014). There will be cases where the perceived risk of an invasive species to different stakeholders is extremely variable, and the values attributed to impacts of a management action may fundamentally differ among them (e.g. for pine management: the risk to conservation vs. forestry revenue vs. poverty alleviation by contracting conservation work to rural communities). In such situations, a structured risk evaluation such as the Deliberative Multi-Criteria Evaluation approach (DMCE; Liu et al. 2011) could offer a potential way forward in the negotiation process. This approach compels each stakeholder to rank perceived risks of a proposed management strategy in terms of importance, thus, potentially highlighting cases where projected negative outcomes of management are likely to be less severe than initially perceived. For example, a potentially contentious action, such as controlling an economically important invasive species within a vulnerable conservation area, may be less prone to protest from stakeholders if it can be demonstrated that the management action will not pose a significant risk to their continued utilization of nearby invasive populations (Weyl et al. 2014).

To illustrate how SBP might enable solution development for trout management, we can examine a specific conflict currently underway in South Africa. Rainbow trout is fished for, and grown in a hatchery, within a sub-catchment of the Breede River system, which is also a conservation area that contains a threatened native fish species (Weyl et al. 2015). It is clear that removing the trout from some reaches also used by anglers would improve the conservation status of the native species, though local angling organizations have opposed this proposed intervention. To negotiate a solution, SBP could be used, involving conservation authorities, fish biologists with expert knowledge on the species involved, local NGOs, the angling society responsible for the trout fishery and the trout hatchery owners. Scenarios for different management options (e.g. the removal of trout from different river sections) could be proposed, mapped out and debated for their likely impacts on the various stakeholders present at the negotiating table. A key logistical consideration of these scenarios would be the construction of artificial barriers to upstream movement, to ensure reclaimed river reaches are not re-invaded (Weyl et al. 2014). In this particular example, the positions and risk-perceptions of the players involved are likely to be well enough understood that a DMCE process is unnecessary, although engaging the stakeholders in this process may nonetheless facilitate the softening of positions on trout control, thus facilitating negotiation towards and equitable solution.

In any country where invasive species have become established, there can be no hope for all-encompassing, "silver bullet" solutions to the problem. Rather, management practices should be focused on mitigating the long-term negative impacts of the species, at whatever spatial scale consensus can be reached among stakeholders on the nature of the problem, with the consensus being found through structured engagements such as SBP or DMCE. But, as the invasive pines case study shows, identifying and including all the stakeholders in the negotiation and planning will be critical to ensure that even pragmatic, partial solutions are less likely to create new problems for conservation management. Similarly, even if stakeholders can be brought to a negotiated consensus, the chosen solution set must be within the capacity of the management authority to act upon, lest budget or technical constraints render the preferred solution unachievable (as in the island eradications case study).

As the human-mediated biogeographic processes that characterize the Anthropocene continue to intensify, there is a growing recognition of wicked problems in conservation management around the world (Game et al. 2014, Seastedt 2014). As anthropogenic dispersal of organisms continues to grow and conservation budgets remain constrained in a volatile global economy, the management of invasive species will increasingly require novel approaches, including heuristic assessments of the ecological risk associated with proposed interventions, and adaptive, stakeholder-conscious management through structured engagement initiatives, to enable positive outcomes for ecosystem integrity. By correctly identifying the complexity of interactions between these species, their environment, and the people that benefit or suffer from their presence, managers may better frame their response to the threat of new invasions and, thus, produce more pragmatic and effective solutions.

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