Should Biological Invasions Be Managed as Natural Disasters?

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Biological invasions and natural disasters are similar phenomena: Their causes are well understood, but their occurrences are generally unpredictable and uncontrollable. Both invasions and natural disasters can generate enormous environmental damage, and the frequency of damaging events is inversely proportional to their magnitude. Many nations invest in personnel training, disaster preparedness, and emergency response plans for extreme natural hazards (e.g., earthquakes), despite the rarity of such events. Similar precautions for invasive species (apart from infectious diseases) are not comprehensively applied by any nation, even though the impacts of invasions are less predictable and often irrevocable. Furthermore, the annual combined economic cost of invasions worldwide exceeds that of natural disasters. Preventative management of invasions—like that of natural disasters—requires international coordination of early-warning systems, immediate access to critical information, specialized training of personnel, and rapid-response strategies.

Keywords: biosecurity, disaster management, invasive species, risk reduction, rapid response

Should biological invasions—the establishment and spread of organisms beyond their native ranges—be managed as natural disasters? A natural disaster is defined as a rapid and damaging socioeconomic impact caused by the natural environment (Alexander 1993) that arises when a hazard, concentrated in space and time, threatens a society "with major unwanted consequences as a result of [failed] precautions which had hitherto been accepted as adequate" (Turner 1976). These definitions are typically used to describe a physical event, such as an earthquake, tsunami, or a flood; more rarely, they are used to describe biological events, including insect infestations or disease epidemics. Despite their diversity, natural disasters share common characteristics. Their causes and consequences are generally well understood but difficult to predict, and their occurrence is almost impossible to control (Alexander 1993, Geller et al. 1997). Furthermore, many natural and technology-caused disasters (e.g., wildfires, avalanches, nuclear meltdowns) are self-replicating, and their incidence and impacts typically involve chain reactions and nonlinear phenomena such as tipping points, cascades, and synergies (Perrow 1984, Sornette 2002). This tendency was dramatically demonstrated by the collapse of levees and subsequent catastrophic flooding in the United States caused by Hurricane Katrina in 2005. The risks of disasters, natural or otherwise, have increased in diversity and complexity as a result of technological growth (Perrow 1984, Alexander 1993). As such, disaster management must deal with high uncertainty in its attempts to reduce the vulnerability of ecosystems and regions.

Here, we propose that biological invasions are fundamentally analogous to natural disasters and therefore require similar management strategies and commitments that, to our knowledge, are not currently in place in any nation. Some invasions (e.g., disease epidemics) have been treated as disasters, but not consistently so. We argue that the safety codes and standards, emergency preparedness, and rapid-response measures that are routinely applied to reduce the risk of natural disasters should also be applied to biological invasions.

Ecological and socioeconomic impacts of invasions

Like natural disasters (Alexander 1993), species invasions are becoming more frequent worldwide. Human activities—particularly international trade—have transported innumerable species of invertebrates, vertebrates, plants, bacteria, and fungi through air, land, and ship traffic to virtually every region of the planet. Some of these biological invaders have profoundly changed the normal functioning of ecosystems by altering biological communities, physical habitats, nutrient cycling, primary production, or natural disturbance regimes (Mack et al. 2000). Invasions can disrupt key ecological interactions, such as those driving the flow of energy through food webs (Spencer et al. 1991) or the plant-animal mutualisms that are crucial for pollination and seed dispersal (Traveset and Richardson 2006). Invasive species are also a major cause of the declines and extinctions of native species (Clavero and García-Berthou 2005). A dramatic example of the effects of invasions occurred in Lake Victoria, where the intentional introduction of the Nile

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perch *Lates niloticus* contributed to the disappearance of nearly 200 endemic fish species—the largest vertebrate mass extinction in modern times (Witte et al. 1992).

Animal (including human) health is threatened by the spread of pathogenic organisms and vectors of disease (e.g., mosquitoes; Lounibos 2002). No natural disaster in human history has caused as many deaths as the epidemics produced by introduced pathogens such as influenza, smallpox, cholera, and measles. Apart from disease outbreaks, biological invasions do not threaten human survival, but their socioeconomic impacts are nonetheless substantial for both developed and developing nations. Invasions can disrupt or degrade essential ecosystem services, such as water quality and agricultural yield (Pejchar and Mooney 2009). The conservation of water resources in African countries is threatened by introduced plants (Le Maitre et al. 2000). The introduction of a predatory invertebrate (*Mnemiopsis leidyi*) through the release of ballast water in the Black Sea in the 1980s caused the collapse of an international commercial fishery there (Knowler 2005). In several countries across the world, nonnative species comprise more than 40% of all harmful weeds, 30% of arthropod pests, and 70% of plant pathogens (Pimentel et al. 2001). Such pests cause the loss of nearly two-fifths of the United States' total crop production each year (Pimentel et al. 2001).

Unlike natural disasters, it is not widely appreciated among the public that invasions may carry profound economic costs. The 2001 outbreak of foot-and-mouth disease in the United Kingdom incurred at least $16 billion in damages (Perrings et al. 2009). A single invasive insect, the emerald ash borer beetle, is projected to cost the United States $10 billion during the next decade (Kovacs et al. 2010). Pimentel and colleagues (2001) estimated the combined annual cost of biological invasions in six nations to be $314 billion. Assuming similar costs worldwide, the global damage inflicted by invasions amounts to $1.4 trillion per year, which constitutes 5% of the global economy (Pimentel et al. 2001) and is nearly an order of magnitude higher than the annual global cost of natural disasters ($190 billion in 2008; Rodriguez et al. 2009).

How invasions are comparable to natural disasters

Below we outline common traits of species invasions and natural disasters.

Invasions are extremely difficult to control. There are several factors that hinder the control of invasions at large spatial scales. The probability that an introduced species will establish (i.e., form a sustainable reproducing population) increases with opportunity and the supply of propagules—individuals or life stages (e.g., adults, juveniles, eggs, cysts) (Lockwood et al. 2005). Propagules are often too dispersed to be detected early enough to prevent establishment, especially with an invasive species that is already spreading within a large region. Such is the case for the Eurasian spiny waterflea *Bythotrephes longimanus*, which has invaded more than 100 lakes in North America during the past three decades and can drastically alter their planktonic food webs (Yan et al. 2002). The waterflea's intercontinental spread has been facilitated by the movement of ballast water in ships; its regional spread is facilitated by human recreational activities that are currently impossible to control (e.g., bait-bucket dumping, or the movement of fishing and boating equipment; Weisz and Yan 2010). Like many small invertebrates, *Bythotrephes* is difficult to detect at low densities; in Harp Lake (Ontario, Canada), it was first detected at a density of 1 per cubic meter, which represented a lakewide population of 9 million individuals. Given that only a few of its propagules may be sufficient to start a population (Drake et al. 2006), this species is often discovered long after it has become established in an area.

Propagule introduction is driven almost entirely by human activities that are poorly regulated; thus, invasions, like many natural disasters, are characterized by weakest-link dynamics (Perrings et al. 2002). Spread and damage through human-dominated landscapes are exacerbated by the connectedness of ecological and social systems (e.g., transportation)—a feature that causes invasions to be generally inevitable and sometimes impossible to control after they begin.

Invasions are difficult to predict. The causes and many consequences of invasions are generally well enough understood to be explained through post hoc analysis (figure 1). However, their occurrence and impacts are very difficult to predict as a result of (a) the complexity of recipient ecosystems (Williamson 1999), (b) the strong influence of local and initial conditions on establishment (Lockwood et al. 2005, Drake et al. 2006) and on the nature and magnitude of their impact (Ricciardi 2003), (c) the predominance of indirect effects, and (d) potential synergistic interactions with local environmental variables and other stressors (Mack et al. 2000). Owing to the highly contingent nature of invasions, it has been suggested that they are as unpredictable as earthquakes (Williamson 1999). This may be true for the onset of an invasion, which is highly stochastic, but not necessarily for its impacts, which are more deterministic; certainly, some types of impacts can be predicted (Ricciardi 2003). Furthermore, although the precise timing of an invasion is impossible to forecast, the relative risk of invasion for various species can be estimated and prioritized from data on environmental conditions and changes in vector activity (Reichard and Hamilton 1997, Ricciardi and Rasmussen 1998).

The dynamics of invasion occurrence and impact resemble those of other catastrophes. As with other natural hazards, most introduced species appear to have only minor effects, whereas some can have catastrophic consequences in terms of ecological or technological disruptions, lost resources, and socioeconomic hardship. For example, native population extinctions attributable to invasions are rare but of great concern to ecologists. In terms of their magnitude and frequency, invasion-mediated extinctions exhibit a negative power-law distribution like that found for natural disasters (figure 2). The exponent of the relationship (–0.97) is

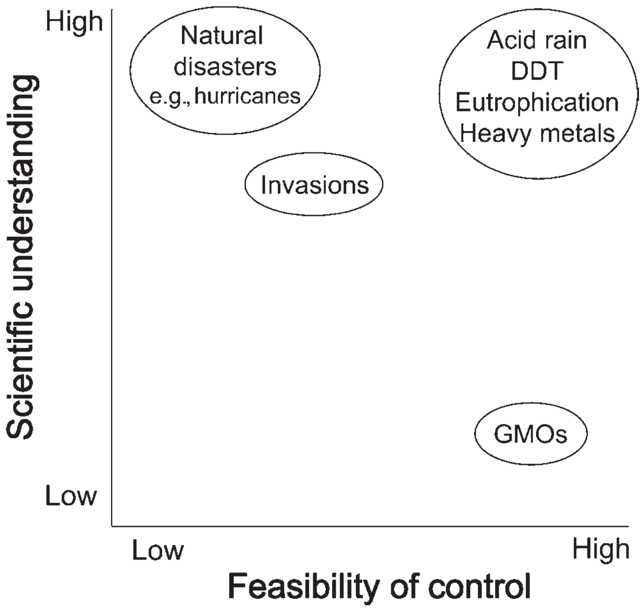

Figure 1. Environmental stressors in a current management context (axes adapted from Peterson et al. 2003). Stressors vary with respect to the degree to which they are understood and controlled. As a result of a strong societal commitment to address them, several stressors (e.g., acid rain, DDT [dichlorodiphenyltrichloroethane], eutrophication, heavy metals) have migrated to a position where they can now be well controlled. The effects of genetically modified organisms (GMOs), for example, are poorly understood but potentially controllable through enforceable legislation. Other stressors, such as natural disasters and invasions, generally defy control.

strikingly similar to that of many natural disaster phenomena (e.g., the rupture area of earthquakes), which tend to have negative power law exponents near unity (Turcotte and Malamud 2004). Although figure 2 considers an ecological impact, we would expect to see the same type of relationship for economic impacts, as well.

Invasions also resemble catastrophic accidents in high-tech industries (e.g., nuclear power, petrochemical, aerospace), in that (a) they are generally inevitable, (b) they are subject to hidden interactions, and (c) their timing and magnitude are largely unpredictable because of the tight coupling of anthropogenic and ecological systems (Perrow 1984, Sornette 2002). An alarming example of this coupling involves Eurasian freshwater mussels (zebra and quagga mussels, *Dreissena* spp.), whose filtration activities in Lake Ontario have stimulated excessive growth of filamentous benthic algae (Auer et al. 2010). Massive floating mats of detached algae can clog the water cooling systems of power plants and in fact forced an emergency shutdown of New York State's James A. Fitzpatrick nuclear reactor on three occasions in the autumn of 2007. These low-probability and often unimagined events challenge a society's ability to react adequately to control potential damage; they also underscore the need to have rapid-response measures in place to prevent the establishment of damaging invaders, or to eradicate them where possible.

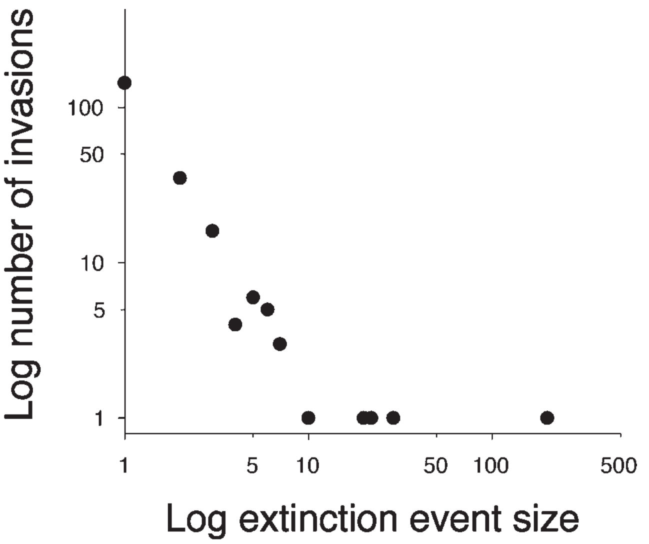

Figure 2. The frequency (log number) of invasions causing impacts (log number of local extinctions of native species) of varying size. The untransformed relationship between invasion-mediated extinctions and invasions is determined from least-squares linear regression to be $y = 33.6x^{-0.97}$*, which is strikingly similar to the magnitude-frequency relationship for many natural disasters. A total of 219 invasion events and 643 extinction events are indicated (raw data and references are available from AR).*

Comparative rankings of disasters

Sapir and Lechat (1986) considered a series of characteristics that distinguish natural disasters on relative scales: their predictability of occurrence, lethality to humans, scope of damage, onset time, and long-term impact. Although these vary over time and space, a general rank order is discernable (table 1). Overall, invasions have more persistent impacts and a greater scope of ecological and economic damage than do natural disasters. Natural disasters may have a warning phase (Sapir and Lechat 1986) signaling their impending occurrence; for some events, the warning may be quite substantial (e.g., hurricanes), or it may be nonexistent (e.g., earthquakes). Invasions tend to occupy the higher end of this scale, generally providing a lengthier warning phase, although the onset delay may be quite short for microbes and some insects. The arrival of certain invaders is predictable to some degree (given sufficient knowledge of dominant vectors and pathways; Ricciardi and Rasmussen 1998), but the timing of an invasion is almost impossible to forecast with accuracy, and in this way, invasions resemble earthquakes. However, although invasions can occur suddenly and without warning, there may be a substantial delay (years or even decades) before the onset of measurable ecological or economic damage, in contrast with most other disasters.

Table 1. Comparative ranking of large-scale disasters in terms of characteristics relevant to their management.

Characteristic	Ranking (in descending order of magnitude)
Predictability	Drought > floods > hurricanes > invasions > earthquakes
Human lethality	Invasions (introduced pathogens only) > earthquakes > hurricanes > drought > floods
Scope and area affected (extent of impact and its geographic area)	Invasions > drought > hurricanes > floods > earthquakes
Onset delay (length of time before the disaster becomes an acute emergency or reaches a significant impact; a high onset delay provides earlier warning of an impending disaster)	Drought > invasions > floods > hurricanes > earthquakes
Persistence of impact (length of time before impacts are reduced to insignificant levels; depends on the capacity for mitigation—some impacts are felt for years, and others [e.g., extinctions] may be permanent)	Invasions > drought > floods > earthquakes > hurricanes

Source: Sapir and Lechat 1986, modified by the addition of invasions.

Management implications

Of course, not all introduced species are undesirable. Invasions can have positive as well as negative effects on recipient communities, and in some cases they may perform useful ecosystem services. Similarly, many natural hazards perform natural service functions over long time scales; for example, floods can deliver fertile sediments to enhance the productivity of floodplains, and wildfires can rejuvenate forests. Historically, invasions often add to the biodiversity of a region, but modern, human-driven invasions have reduced native species richness in certain areas, sometimes catastrophically (Witte et al. 1992, Fritts and Rodda 1998), and the functions of desirable introduced species can be disrupted—often unexpectedly—by other invaders (Schäfer et al. 2010).

For both invasions and natural disasters, it is the unpredictability and uncontrollability of damaging events that demand planning for the worst. Although these events cannot be precisely forecast, hazard-reduction plans can still be implemented. The potential consequences of natural disasters are well recognized by the public and therefore there is a strong social commitment to preparedness for rare extreme events, which allows for substantial investment in risk reduction (e.g., building codes ensure structural protection against earthquakes, and reforestation of riparian zones reduces the risk of landslides and floods), rapid-response strategies, and recovery plans. It is well understood that the socioeconomic impacts of natural disasters vary greatly depending on the preparedness of the affected region (Sapir and Lechat 1986), as demonstrated by the contrasting effects of earthquakes in Haiti and Chile in 2010.

However, most governments do not currently employ such strategies to address biological invasions (apart from infectious diseases such as avian influenza), although there is a growing awareness in some countries of the need to develop emergency protocols. There currently exists no federal legal capacity for rapid-response management of aquatic invasions in either the United States or Canada (Thomas et al. 2009), but the International Joint Commission that oversees transboundary water issues between the two countries has recently proposed a policy framework in which the response to new aquatic invasions will be "handled in the same manner as other national emergencies such as disease outbreaks and natural disasters that call for a unified multi-agency command structure" (Thompson et al. 2009). Scientists and policymakers have also recommended that the management of biological invasions be integrated within existing or emerging national security frameworks because of the threat that invasive species pose to essential ecosystem services, socioeconomic systems, and even human health (Meyerson and Reaser 2002), as well as their potential deployment as a terrorist weapon (Pratt 2004). Following this approach, New Zealand has adopted legislation that addresses harmful threats to its biodiversity and various natural-resource sectors by coordinating all management and legislation under a central authority (see Meyerson and Reaser 2002). Similarly, Australia has adopted an all-hazards emergency response system to deal with disasters ranging from wildfires and disease epidemics to terrorist attacks (*www.ema.gov.au*), but invasive species other than human pathogens are handled by separate agencies (e.g., the Australian Quarantine and Inspection Service, Plant Health Australia).

The major principles of disaster preparedness also apply to invasion preparedness (box 1). Clearly, the benefits of prevention far exceed the potential economic and ecological costs of an invasion (Leung et al. 2002). Prevention and rapid response require more effective methods of early detection. As for certain natural disasters, such as earthquakes, detection is constrained by, among other things, the insidious and rapid onset of invasions. To address these problems, we must identify and focus on key pathways and on the behavior of individual people; the latter is not currently feasible, but harm can be mitigated with education, effective legislation, and policy enforcement. Unfortunately, each of these approaches appears to be inadequate even in highly developed nations. In Canada, for example, we were able to find no university or college degree programs, and very few interdisciplinary courses, devoted to biological invasions. The absence of such training has a negative impact on our capacity to assess and respond to invasion-mediated

Box 1. Essential components of invasion preparedness.

Essential elements of disaster preparedness (Alexander 1993) that should be applied to biosecurity issues such as invasions (Meyerson and Reiser 2002) include the following:

Vulnerability reduction. Preparedness against invasions involves measures that (a) prevent establishment and (b) strengthen the landscape in places predicted to be vulnerable. Prevention is the most cost-effective form of management (Leung et al. 2002), and involves vector control (e.g., ballast water management, quarantines, legislation limiting trade of live organisms) and reducing the invasibility of recipient ecosystems (e.g., agricultural practices that reduce pest outbreaks). Because invasions are governed by weakest-link dynamics, managers must focus control on key pathways and on human behavior. Recognizing that invasion pathways between source and destination points vary in strength, the control of key hubs is a more efficient use of resources than treating all potential sources equally (Muirhead and MacIsaac 2005). Above all, public education is essential to minimizing harmful behavior and garnering strong community support for management decisions. To this end, invasion biology must be communicated to the public in an accessible way, with emphasis on its applied value to public security (Meyerson and Reiser 2002).

Rapid response and assessment. Rapid response involves assessing the risk of an invasion threat and implementing a plan to address it. This approach is dependent on monitoring and early detection of incoming organisms, which requires expertise to recognize threats. A standard system of triage is needed to immediately distinguish potentially disastrous species; for example, pathogens are prioritized on the basis of their potential lethality and rate of spread. Other organisms may be prioritized, in part, on the basis of their previous impact history (Ricciardi 2003). However, monitoring systems and training in taxonomic and diagnostic tools are apparently inadequate in many countries.

Rapid response can lead to successful eradication of an introduced population, provided that resources are sufficient to complete the project and the managing agency has the authority and public support to take all necessary steps (Myers et al. 2000). An example of a success story is the discovery (through routine monitoring) and subsequent rapid eradication of an invasive mussel (*Mytilopsis sallei*) that infested three marinas in a bay in northern Australia in 1999 (Myers et al. 2000). Where prevention and eradication have failed, mitigation and recovery plans are necessary; such plans involve limiting the damage and restrengthening the landscape against further disruption.

Access to reliable information. Early detection and management decisions are facilitated by rapid access to information on the spread, impact, and control of invasive species. Ideally, this information should be provided through a global database that is updated regularly and reviewed by experts (Ricciardi et al. 2000).

Coordination among authorities. Large-scale management programs often cross multiple private and public jurisdictions. Coordination among authorities (e.g., between government agencies or between nations) is critical for a rapid and efficient management response. Where shared international boundaries are involved, complementary responses must be coordinated through treaties (e.g., Thomas et al. 2009).

disasters. Furthermore, there is obviously greater public awareness and risk perception of the effects of natural disasters than the effects of biological invasions. Consequently, policymakers tend to view invasions with less concern than they do natural disasters, whose effects are more conspicuous, more notorious, and sometimes more devastating, but whose environmental damage may not be as extensive or persistent. Given that the onset of maximum damage may be much slower for invasions than for most other natural disasters, there is a greater capacity to develop early-detection methods that can limit the impacts of the worst invasions.

Although the extent of any disaster depends on the vulnerability of the affected human population, invasions appear to involve a more complex consideration of the control of individual and societal behaviors at multiple scales. This poses another management challenge, illustrated by the example of the outbreak of foot-and-mouth disease in the United Kingdom, a disaster that resulted from a combination of (a) increasingly deregulated trade in livestock; (b) insufficient preventative measures, including vaccination, because of harmonized European common market policies; (c) inadequate inspection at borders; and (d) rapid and frequent transport of livestock throughout the region (Perrings et al. 2002). Perrings and colleagues (2002) pointed out that foot-and-mouth disease cannot be modeled as “a traditional epidemiological problem involving only the pathogen and its hosts” while ignoring the multiple human behaviors and weakest-link dynamics that led to the introduction, establishment, and spread of the disease. Effective control of invasions will require the incorporation of human behavior into disaster management schemes.

Conclusions

Just as building codes are designed to protect people and structures from earthquakes, even in low-risk areas, we argue that a precautionary system should be in place to manage vectors and pathways to safeguard against all potentially disastrous invasive species. In many nations, governments have invested in infrastructure, training, and emergency response plans against rare natural disaster events. The same consideration should be given to all rare invasion events that can potentially inflict enormous socioeconomic costs. So far, such attention has been applied only to pathogens that pose a direct threat to human health. Given their persistence and potentially irrevocable damage, biological “spills” should be treated with more caution and urgency than a chemical spill. They require national and international commitment to prevention, preparedness, and vulnerability reduction. This commitment includes the development of infrastructure to allow rapid access to critical information that can facilitate appropriate management decisions; the need for such infrastructure was identified over a decade ago (Ricciardi et al. 2000).

A blueprint for disaster risk reduction at local, national, and international scales is provided by the Hyogo Framework (*www.unisdr.org/eng/hfa/hfa.htm*), developed at the World

Conference on Disaster Reduction in Kobe, Hyogo, Japan, in 2005. It identifies priorities that are clearly applicable to invasions, including the need to improve risk information and early-warning systems, to strengthen preparedness of response, and—in particular—to build a culture of safety and resilience. We recommend that biological invasions be explicitly considered within this framework.

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