Ambio
https://doi.org/10.1007/s13280-022-01707-1

REVIEW

Misleading estimates of economic impacts of biological invasions: Including the costs but not the benefits

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Received: 8 December 2021 / Revised: 12 January 2022 / Accepted: 17 January 2022

Abstract The economic costs of non-indigenous species (NIS) are a key factor for the allocation of efforts and resources to eradicate or control baneful invasions. Their assessments are challenging, but most suffer from major flaws. Among the most important are the following: (1) the inclusion of actual damage costs together with various ancillary expenditures which may or may not be indicative of the real economic damage due to NIS; (2) the inclusion of the costs of unnecessary or counterproductive control initiatives; (3) the inclusion of controversial NIS-related costs whose economic impacts are questionable; (4) the assessment of the negative impacts only, ignoring the positive ones that most NIS have on the economy, either directly or through their ecosystem services. Such estimates necessarily arrive at negative and often highly inflated values, do not reflect the net damage and economic losses due to NIS, and can significantly misguide management and resource allocation decisions. We recommend an approach based on holistic costs and benefits that are assessed using likely scenarios and their counter-factual.

Keywords Alien species · Economic benefits · Economic costs · Ecosystem services and disservices · Introduced species · Invasive species

INTRODUCTION

Non-indigenous species (NIS hereafter; in this article the term is used without regard to the type and magnitude of their effects on the resident biota, although it largely centers on invasive NIS, which become widespread, locally dominant, and can have strong effects on the communities invaded) can represent a major problem for the conservation of native (NAT) biodiversity and ecosystem services, as well as for productive activities and human wellbeing in general, yet efforts at quantifying the damage involved in economic terms are few. To a large extent, this scarcity is due to the fact that data are sparse, and assessments of the economic impacts are complex and often very imprecise (Hui and Richardson 2017; Hanley and Roberts 2019). However, many of those attempted suffer from several flaws, and some of the most ambitious exercises in this area (Perrings et al. 2001; Pimentel et al. 2005; Pimentel 2011) have been heavily criticized for their inconsistencies, misapplication of economic methods, poorly substantiated figures, and unfounded assumptions and extrapolations (Reaser et al. 2003; Connelly et al. 2007; Davis 2009; Thompson 2014; Guiaşu 2016; Jernelöv 2017). Further, some of the highest figures are explained to a large extent by the inclusion of human diseases, in particular influenza (Thompson 2014; Guiaşu 2016). The spread of the viruses responsible for influenza date back at least 500 years (Morens et al. 2010), and probably > 2500 years (Potter 2001). Human influenza viruses underwent frequent mutations and reassortments through time and geography (Webster et al. 1992), which likely qualifies many of them as naturalized, or (some types and subtypes, strains, or genetic lineages) even native, rather than NIS.

Aside from the above, there are several other problems that make these estimates questionable. Here, we point out some of the most common and egregious flaws, with the aim of improving the quality and pertinence of future economic estimates. Because of the inherently complex issues involved, these problems may partly overlap, but for the sake of clarity they can be identified as detailed below.

Published online: 21 February 2022

ACTUAL COSTS AND INDIRECT "COSTS"

This problem stems from combining the economic losses produced by detrimental NIS and the costs of their management, together with those associated with various ancillary activities which are more loosely related with the costs of the NIS in question (e.g., research, administration, detection, surveillance, monitoring, education, communication and information, risk assessment, etc.) (Diagne et al. 2020b). These "indirect" or "mixed costs" can represent 80–90% of the totals (Xu et al. 2006; Diagne et al. 2021). For example, such "costs" may include grants for research on NIS, regardless of the outcome of such investigations. Thus, research grants are tallied as costs even if the results conclude that the species surveyed is harmless or beneficial (Katsanevakis et al. 2014; Reise et al., 2017), making their inclusion in the costs of baneful NIS speculative, at the very least.

THE "COSTS" OF UNNECESSARY, FAILED AND COUNTERPRODUCTIVE ERADICATION AND CONTROL PROGRAMS

NIS-related "costs" can include (or consist entirely of) the costs of attempting to control innocuous species, like the purple loosestrife (*Lythrum salicaria)* (Guiaşu 2016), or even NIS with some clear positive contributions (Hershner and Havens 2008; Sogge et al. 2008; Stromberg et al. 2009), "plus the costs of clearing up the mess left by such attempts, even if there's little evidence of any original harm" (Thompson 2014). These "costs" are the unforeseen consequences of the management of NIS, usually derived from poorly understood facilitation–competition relationships. Management initiatives involving costly programs can result in failures (Palmas et al. 2020), or even unexpected and unwanted outcomes whereby eradication of the target NIS ends up endangering native species and communities (Bergstrom et al. 2009; Courchamp et al. 2011; Vince 2011; Bonanno 2016; Kopf et al. 2017; Lurgi et al. 2018; Ward et al. 2019; Ortega et al. 2021; Travers et al. 2021). They can also facilitate a different invader, sometimes as damaging as—or even worse—than the one targeted. The latter situation is exemplified by the growth of mice populations in Australia when rabbit numbers were successfully reduced (Jernelöv 2017), rabbits on Macquarie Island when feral cats were extirpated (Bergstrom et al. 2009), and many analogous cases (Kopf et al. 2017; Zavaleta et al. 2001).

Although NIS effectively are at the root in both situations, there is a subtle line separating the costs of NIS sensu stricto, from those due to our lack of understanding of their impacts and the economic consequences of this ignorance.

SELECTION OF THE SOURCES OF INFORMATION

Potential biases may stem not only from tallying the costs only (which is embedded in this approach), but also from selectively choosing the sources of information and including questionable and controversial NIS-related "costs".

For example, Africanized honey bees (*Apis mellifera scutellata*) have been widely publicized as a major disaster for the honey industry in the Americas. According to the Global Invasive Species Database, their "Uses" are restricted to the fact that "Some farmers believe… they provide superior pollination to *A. mellifera*", and that "African bees deter African elephants from damaging vegetation and trees near where hives are located", with negative impacts being numerous and very significant (aggressiveness, higher labor costs, lower tolerance to winter temperatures, frequent nest abandonment, lower investment of energy into the storing of honey, outcompetition of- and less effective pollination than the European bee and native pollinators, etc.)[1]. In the USA, until 2020 the economic impacts of Africanized honey bees have been estimated at 5.7 thousand million US$ (Cuthbert et al. 2021). However, the drivers of declines (and fluctuations in general) in honey production in the USA are multiple, including diseases and parasites (both introduced and cosmopolitan), pesticides, low genetic variability, decreasing availability of adequate bee pasture, weather and climate effects, and changes in international trade trends and honey prices, among others, but "there is no evidence that Africanized honey bees have directly caused honey bee declines since their introduction into the United States in 1990" (vanEngelsdorp and Meixner 2010), and "no reason to believe that Africanized Honey Bee has significantly affected the production of honey in the United States or changed the investment behavior of beekeepers" (Livanis and Moss 2010). Further, in Mexico, Central and South America the faster colony buildup of Africanized honey bees, their higher resistance to pathogens and to dry climates, higher pollination abilities, higher honey and propolis production, and lower honey thievery (by humans, due to their more aggressive behavior) have been crucial for the survival of the honey industry (Maggi et al. 2016; Guzman-Novoa et al. 2020). Thus, one of the putatively most costly species analyzed by Cuthbert et al. (2021) may, in fact, be based on a series of equivocal (or at least challenged) assumptions.

[1] (http://www.iucngisd.org/gisd/species.php?sc=325; accessed 19 September 2021)

THE CHALLENGES OF ATTRIBUTING THE CAUSALITY OF COSTS TO NIS

One of the long-standing challenges in assessing the impacts and the costs of NIS has been to tease apart correlation from causation (Gurevitch and Padilla 2004; Sagoff 2005). Economic evaluations that do not take the time to separate cases where a NIS is the "driver" of impacts, as opposed to a simple "passenger" that tracks other human-induced changes (which are the ones actually responsible for the negative effects observed), risk over-estimating the true costs of such species (Essl et al. 2019).

A vivid example is the loss of biodiversity as an ecosystem service with potentially negative economic consequences (Bullock et al. 2008; Hanley and Perrings 2019). While invasive species have repeatedly been suggested to be a major driver of global biodiversity decreases (Bellard et al. 2016), the assumption that NIS are responsible for this trend has often been contested (Gurevitch and Padilla 2004; Gallardo et al. 2016). Wilcove et al. (1998) suggested that nearly 50% of all federally listed endangered species in the USA are threatened by invasive alien species. However, a more recent evaluation of the 1363 species protected under the United States Endangered Species Act concluded that only 6.2% were found to have scientific data supporting the assumption that they are effectively threatened by NIS (Dueñas et al. 2018; see also Chew 2015).

Management costs ascribed to NIS are often aimed at both introduced and native pests, which inflates expenditures when they are assumed to be aimed at culling NIS only. For example, glyphosate-based herbicides are by far the most intensively used for weed control worldwide, especially in agriculture (Wagner et al. 2017), where they eliminate both alien and native plants that compete with the crop species (Sesin et al. 2021). In drinking water treatment and power plants chlorine is used both as a disinfectant and to control biofouling, such as invasive mussels, even in the absence of the NIS (Connelly et al. 2007).

The involvement of NIS in some human diseases, which make up a major fraction of the purported costs of NIS and are ascribed to iconic invaders, such as the ship rat (*Rattus rattus*), have been questioned recently. Dean et al. (2018) suggested that the European bubonic plagues of the 14-19th centuries were chiefly due to human-to-human transmission by cosmopolitan ectoparasites, rather than to rats.

THE ASSESSMENT OF NEGATIVE IMPACTS ONLY

This flaw is probably the most significant: the evaluation of the costs (i.e., negative economic impacts) only (Xu et al. 2006; Nghiem et al. 2013; Diagne et al. 2020a; Bang et al. 2021; Haubrock et al. 2021) (see vol. 67 of NeoBiota, 2021), without taking the benefits into account (Schlaepfer et al. 2011; Thompson 2014; Guiaşu 2016; Jernelöv 2017). A major problem with such estimates is the fact that the overwhelming majority of NIS have wide-ranging effects which are harmful for some members of the community invaded and/or human interests, but beneficial to others.

Baneful, context-dependent, and beneficial introduced species: Harm and benefit are tightly intertwined

A major flaw is tallying the costs only of NIS whose effects are mixed (Rodriguez 2006; Pejchar and Mooney 2009; Shackleton et al. 2014; Thompson 2014; Pienkowski et al. 2015; David et al. 2017; Jernelöv 2017; Ramus et al. 2017; Martinez-Cillero et al. 2019; Correa et al. 2021; Granse et al. 2021; Muñoz et al. 2021; Starešinič et al. 2021). Because NIS comprise an enormous variety of organisms which usually become tightly intertwined with local species, it is inevitable that they will have different effects on different organisms, processes, and stakeholders (Ewel et al. 1999; Dickie et al. 2014; Buchholz and Kowarik 2019; Hanley and Roberts 2019; Shackleton et al. 2019b; Gbèdomon et al. 2020; Schlaepfer et al. 2020).

In Europe, China, Japan and the Americas, biofouling of canals, pipes, sieves and other industrial components by the invasive mussels *Limnoperna fortunei* and *Dreissena* spp. is a major nuisance for water-transfer installations and industrial and power plants, involving major costs in their cleaning and maintenance (Mackie and Claudi 2010; Boltovskoy et al. 2015). On the other hand, these invasive bivalves significantly clarify the water of lentic waterbodies, which can mitigate phytoplankton blooms, including toxic Cyanobacteria (albeit also enhance them under certain circumstances: Cataldo et al. 2012), thus precluding fish and waterfowl mortality, lessening the costs of water potabilization, and enhancing recreational activities (Ram and Palazzolo 2008; Dionisio Pires et al. 2010; Wang et al. 2021). Water clarification has also a major impact on the market value neighboring real estate. Walsh et al. (2016) estimated that the decrease in the clarity of Lake Mendota (USA) due to the invasive zooplanktivorous spiny water flea—*Bythotrephes longimanus*, which decimated algae-grazing zooplankton, produced an overall loss in neighboring properties of US$ 140 million (incidentally, Reed-Andersen et al. (2000), predicted an increase in the water clarity of this lake should dreissenids invade it, which they effectively did around 2015; Hayranto (2018)). However, using the same methods and assumptions for lakes Michigan, Huron, and Erie (USA-Canada), where water clarity increased significantly due to the filtration by invasive mussels, the increase in neighboring property value yields around 14 000 million US$ (L. Burlakova, unpublished).

The colonization of many North American lakes by the zebra (*Dreissena polymorpha*) and quagga mussels (*Dreissena rostriformis bugensis*) has been reported to drastically reduce the concentrations of P in the water (Rudstam and Gandino 2020), thus making costly programs aimed at reducing external P inputs unnecessary and helping restore the lakes to pre-existing oligotrophic conditions (Li et al. 2021). While generally positive, these changes are not free from a downside in terms of ecosystem services. For example, when lakes shift from a turbid to a clear water state the efflux of CO_2 can increase significantly (Jeppesen et al. 2015).

Invasive mussels can represent a trophic subsidy for many waterfowl, crayfishes and fishes (Guiaşu 2016). In South America, *L. fortunei* and other NIS are consumed by over 50 fish species (Cataldo 2015; Paolucci and Thuesen 2015), often accounting for large proportions of their diets (González-Bergonzoni et al. 2020), and improved food quality (Hernando et al. 2021; Melo de Rosa et al. 2021). In the northern hemisphere, several native fishes consume *Dreissena* spp. (Molloy et al. 1997; Fera et al. 2017; Culver et al. 2019; Verstijnen et al. 2019), although variable and negative effects of *Dreissena* spp. on fishes have also been noticed (Strayer et al. 2004; Smircich et al. 2017).

Trophic subsidies can also occur through a different invader. The round goby (*Neogobius melanostomus*) is an active consumer of *Dreissena* spp. (Karatayev et al. 2020), and the goby is consumed by valuable native fishes (Burkett and Jude 2015; Verstijnen et al. 2019). The abundance of North American lake sturgeon (*Acipenser fulvescens*) declined range-wide over the past century, resulting in its designation as a species of conservation concern in many USA states and Canadian provinces (Peterson et al. 2007). In the lower Niagara River, which hosts one of the few remnant lake sturgeon populations in New York State, two NIS dominate the diet of the lake sturgeon—the round goby and the amphipod *Echinogammarus ischnus*, which are responsible for the sturgeon's recovery (Bruestle et al. 2018).

Further, *L. fortunei* and *Dreissena* spp. usually enhance the biomass of other benthic invertebrates, (Karatayev et al. 2015; Sylvester and Sardiña 2015; Duchini et al. 2018; Shcherbina and Bezmaternykh 2019), thus increasing the trophic offer for fishes and mitigating the predatory pressure on native invertebrate communities.

Such impacts are ignored as economically positive ecosystem services when only costs are considered. These ecosystem services, which include nutrient recycling and storage, structural habitat, substrate and food web modification, water purification, etc., are acknowledged when provided by native (unionid) bivalves (Vaughn and Hoellein 2018), but neglected when provided by NIS when only their costs are evaluated. The zebra and quagga mussels are much more efficient than native unionids in all these functions (Karatayev et al. 2002; Li et al. 2021), but in the "costs only" approach they get no credit for these benefits.

Invasive invertebrates can also help restore lost value due to previous invasions. A vivid example is the dramatic fall of the Black Sea fisheries, estimated at US$ 250 million (Travis 1993) to US$ 1000 million per year (Caddy 1992), largely due to the invasive North Atlantic ctenophore *Mnemiopsis leydyi*, and its subsequent recovery due to a second invasive ctenophore, *Beroe ovata*, which feeds on *M. leydyi* (Kideys 2002).

These contrasting effects are extensive to most NIS, including many of those whose economic impacts are routinely used as textbook examples. Cats (*Felis catus*), including their feral populations, are considered to be among the most noxious invasive vertebrates worldwide, having caused the decline or extirpation of many native organisms, especially birds (Pimentel 2011; Doherty et al. 2016; Cuthbert et al. 2021; Diagne et al. 2021). However, cats also prey on rodents, including the very baneful black and brown rats (*Rattus* spp.) and mice (*Mus* spp.) (Doherty et al. 2015; Ozella et al. 2016), also invasive in most of the world, which cause extensive damage to the economy and are vectors of several diseases (Pimentel et al. 2005; Ward et al. 2019). They also prey on invasive pest birds, like house sparrows (*Passer domesticus*), European starlings (*Sturnus vulgaris*), and pigeons (*Columba livia*), among others (Loss et al. 2013; Pitt et al. 2018) (Fig. 1). Thus, "some birds feature as a cost when killed by cats but also as a cost when they stay alive" (Pearce 2015). Further, although the costs of invasive pest birds are chiefly based on their impacts on crops, and they have likely displaced native birds with similar feeding habits, the issue whether such replacements have actually increased the economic damage involved is not addressed.

In Australia, predation by feral introduced cats (and foxes, *Vulpes vulpes*) has contributed to the mitigation of the economic and environmental damages produced by the invasive European rabbit (*Oryctolagus cuniculus*) (Doherty et al. 2015), especially before other biological control methods were introduced (see below). Moreover, although small when compared with their costs, Australian rabbits historically have also had economic benefits: in 1944, 104 million rabbit skins/carcasses were exported from Australia, and during the last 15 years commercial rabbit farming has become a fast-growing small-scale agro-enterprise (Jernelöv 2017).

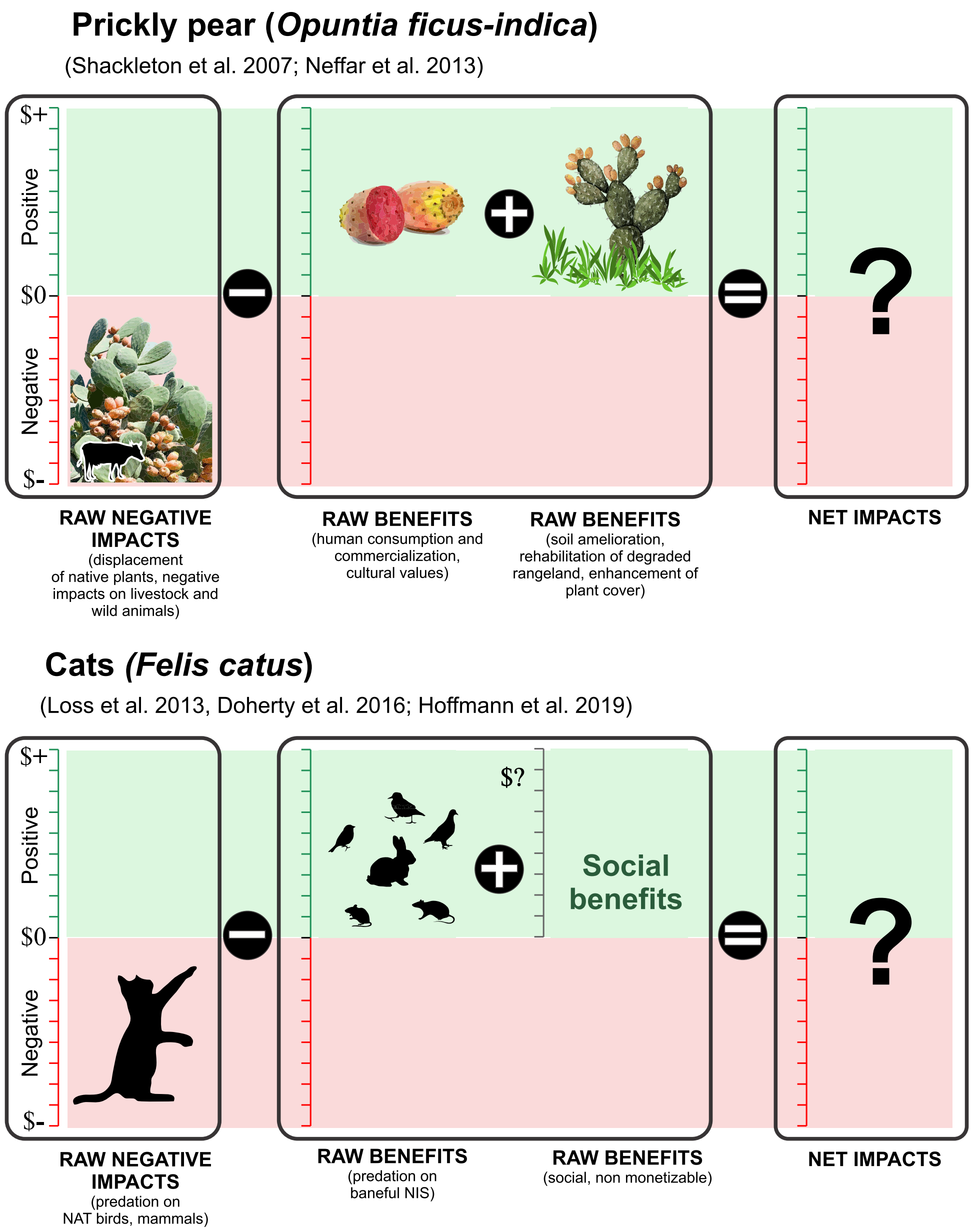

Fig. 1 Conceptual diagram of the raw (negative and positive) and net economic costs of invasive species. “Social benefits” include a wide range of values for human welfare (companionship, emotional support, sense of purpose, psychological health, etc.) whose impacts are very complex for monetizing (Hoffmann et al. 2019). NAT: native species; NIS: non-indigenous species

The water hyacinth, *Eichhornia crassipes*, native to South America and currently present in more than 50 countries on five continents, is considered as one of the worst invasives worldwide. It blocks waterways, affecting boat traffic, swimming and fishing. It prevents sunlight and oxygen from reaching the water column and submerged plants, which may reduce biological diversity, enhance water loss through evapotranspiration and promote the breeding of flies and mosquitoes, impact farmland irrigation, water transportation, and human health. Millions of US$ are spent on programs to control its growth worldwide. However, several uses of *E. crassipes* have been proposed (and some implemented) in efforts to obtain economic benefits from its control, such as substrate for hydroponic agriculture, phytoremediation, the production of composts, farm animal fodder, hydrogen, biogas, various valuable chemicals, enzymes, biopolymers, bioethanol, briquettes, etc. (Martin 2014; Su et al. 2018; Ilo et al. 2020).

In their overview of 59 meta-analyses (based on 2799 surveys) of the impacts of introduced (mostly invasive) species on resident communities and environmental variables, Boltovskoy et al. (2021) concluded that 35% of the investigations found chiefly negative impacts, but the remaining 65% showed that impacts are non-significant or context dependent, with both positive and negative outcomes for the natives. A thorough review of 107 European marine NIS concluded that 67 species have both deleterious and beneficial economic and/or ecosystem-service impacts (Katsanevakis et al. 2014). Many of these effects of NIS are difficult to monetize, yet the fact that they often are positive for native species, many of which are economically or socially valuable, or NIS themselves become a novel exploitable resource, makes them an important aspect of the positive economic impacts of NIS.

Shackleton et al. (2019b) reviewed 51 studies encompassing the impacts of 66 NIS on local livelihoods and human wellbeing worldwide. Around 50% of these species were found to have both substantial positive and negative impacts, 37% produced mainly costs, but 16% produced mainly benefits, including opportunities to earn a cash income, provision of fuelwood, fodder, timber, food products, soil improvement, shade, as well as cultural services such as recreation and spiritual values.

Impacts and time since invasion

Long-term studies based on a wide range of invasive organisms show that invader densities can change significantly at different time scales (Strayer et al. 2020), and especially with time after introduction (Strayer et al. 2017; Mehler et al. 2020), sometimes involving total population collapses (Aagaard and Lockwood 2016). Obviously, their impacts on native organisms change accordingly (Pace et al. 2010). In the context of the present article, this temporal variability is of mayor importance because the magnitude, and even the sign, of the overall impact can vary substantially depending on the time frame used (Strayer and Malcom 2007; Burlakova et al. 2014; Karatayev et al. 2018).

Provision of novel ecosystem services and resources

NIS increasingly provide novel resources (habitat, food) that are used by native organisms (Rodriguez 2006; Sogge et al. 2008; Packer et al. 2016; Johnstone et al. 2017; MacClagan et al. 2018; Valentine et al. 2020). Many NIS furnish new or replace ecological functions and ecosystem services originally provided by native species in areas where the latter have been extirpated or reduced significantly (Schlaepfer et al. 2011; Vince 2011; Pattermore and Wilcove 2012; Lagrue et al. 2014; Bonanno 2016; Ramus et al. 2017; Vizentin-Bugoni et al. 2019; Lundgren et al. 2020; Wallach et al., 2020; Zwerschke et al. 2020), or agricultural land degraded by long-term exploitation (Tassin et al. 2012).

Biological control introductions

A particularly striking omission of the positive effects of alien species are the thousands of organisms (especially viruses, bacteria, fungi, nematodes, mites, parasitoid and predatory insects) imported for biocontrol purposes (Messing and Wright 2006; Simberloff 2020), many of which proved very effective in controlling and even eradicating noxious native and invasive plants and animals, with high benefit to cost ratios and generally low impacts on non-target species (Myers and Cory 2017; Wan et al. 2017).

In Australia, the impacts of the invasive European rabbit were neutralized by the introduction of the Myxoma virus (1950), and the Rabbit Calicivirus (1995) (Robley et al. 2004; Jernelöv 2017; CSIRO - Commonwealth Scientific and Industrial Research Organisation 2021). Yet, while the high cost of wild rabbits to the economy of Australia is routinely used as a textbook example of the threats of NIS, the positive effects of their introduced pathogens, i.e., the avoided costs of damages from rabbits were control not to be implemented (Hanley and Roberts 2019) and, consequently, the benefits involved, are seldom included in the balance. Although the introduction of non-indigenous species for controlling harmful NIS can also be considered as an economic burden akin to other control measures, those that cull native pests (Wingfield et al. 2008; Kenis et al. 2017) cannot.

Implications of the "costs only" rationale

Recently, a large number of preprints and publications based on the InvaCost database (Diagne et al. 2020b) has appeared (21 of them in the 2021 special issue of NeoBiota, vol. 67, entitled "The economic costs of biological invasions around the world"), concluding that between 1970 and 2017 the worldwide costs of biological invasions have been at least US$ 1.288 $\times$ 10^{12} (2017 US$) (Diagne et al. 2021). However, reporting the negative effects only is one side of the coin, which conveys a lopsided view of the problem and a biased perception of the impacts of NIS. While important for an overall assessment of this phenomenon, they fail to objectively evaluate its real magnitude in economic terms, and therefore to provide useful guidelines for decision-making purposes. In most publications on the economic effects of NIS (including those based on the InvaCost database) this other side of the coin is either mentioned briefly, in passing, or ignored altogether. However, economically positive impacts have been estimated for a large number of NIS, in particular cultivated plants and livestock, yielding figures which largely exceed the costs brought about by damaging NIS. For example, in the USA, introduced crops and farm animals provide > 98% of the country´s food system at a value of around US$ 800 thousand million per year (Pimentel et al. 2005); in the same survey the damage caused by NIS was estimated to be ~ 7 times lower (US$ 120 thousand million per year). In New Zealand, one of the most invaded countries in the World (Turbelin et al. 2017; Mooney and Hobbs 2000), 95% of export earnings are derived from alien species (Ewel et al. 1999).

Worldwide, the common carp (*Cyprinus carpio*) and *Tilapia* spp. were reported to have had a cost of ca. 237 million US$ since 1960 (Haubrock et al. 2022), but in 2019 alone > 340 000 tons of carps (four species) and *Tilapia* were produced by aquaculture by a single country where they are both NIS (Brazil; Valenti et al. 2021), which roughly equals around 1000 million US$ at current market prices[2] (FAO 2021). These numbers pale when compared with China, the first producer of freshwater cultivated fish (> 50% of the world total, as compared with < 1% for Brazil), where up to ~ 90% of the species used in aquaculture (depending on the region) are introduced (Gu et al. 2022).

Interestingly, even for the domesticated species whose positive economic impacts throughout the world are immense, the economic gains have had their downsides. Aside from the ecosystemic pay-offs involved in terms of habitat modifications, many have undergone feralization processes producing populations that thrive either in the wild (e.g., cats, dogs, pigs, goats, cattle, etc.), or even among the domesticated cultivars (e.g., rice), where they can cause substantial economic damage (Gering et al. 2019; Scossa and Fernie 2021).

Although the examples above are based on introduced crop plants and domesticated animals, most of which require human assistance for their permanence, and are therefore often considered separately from introduced species that thrive in the wild, there also are numerous cases of deliberate introductions of organisms released in natural habitats with mixed economic and ecological impacts (Ewel et al. 1999). Many have caused much more harm than benefit (e.g., several birds, mammals, etc.), but a large number proved to also have important economic and/or ecosystem-service benefits. For example, salmonids are among the most widely introduced fishes around the world, which are both cultivated and thrive in the wild, where they can be a threat to native fishes (Korsu et al. 2010), but also coexist with them harmlessly (Juncos et al. 2015), as well as provide very important economic (Vigliano and Alonso 2007; Davis 2009; Gozlan 2017) and ecosystem-service (Muñoz et al. 2021) assets. Several mammals, such as the boar (*Sus scrofa*), red deer (*Cervus elaphus*), European hare (*Lepus europaeus*), and many others have also been introduced worldwide and thrive in the wild throughout their introduced ranges (Long 2003) where they have negative economic impacts (often on other introduced species, such as crop plants and farm animals), but also sizable benefits, in particular from tourism and sports and commercial hunting (Davis 2009; Gürtler et al. 2017).

The harmonious coexistence of NIS with native species may also involve mutual benefits, as described for the North Sea invasion of *Mytilus edulis* (mussels) beds by the Pacific oyster *Magallana* (=*Crassostrea*) *gigas* (Reise et al. 2017).

Assessing the negative effects only is akin to calculating the costs of running a factory by adding up the expenditures involved but ignoring the benefits earned from selling the products manufactured. This peculiar interpretation is at odds with the common sense practice of putting together the credit and debit sides of a balance sheet to arrive at a net cost (Thompson 2014). Or, as pointed out by (Simberloff 2002) on the evaluations of NIS-control actions based on the successful outcomes only (Perrings et al. 2001), "this approach is analogous to assessing the likely winnings from lotteries by looking only at winning tickets". Under this rationale, most introduced cultivated plants and livestock, whose raising (labor, fuel, fertilizers, pesticides, etc.) involves major investments, would also yield losses only. In fact, if one were to apply the same approach to calculating the costs of native species, the figures would certainly be staggering, and several-fold higher than those for the NIS. The assessment of NIS costs-benefits based on the "costs only" rationale is as one-sided as deriving their overall economic impacts from their benefits only.

Interestingly, even when the effects of NIS are found to be positive for the natives, authors often warn that such ameliorations might backfire by facilitating new introductions (Zhang et al. 2019). The assumption most often seems to be that non-native species will cause mainly or entirely negative impacts overall, at some point, even if these impacts cannot be proven or even detected, and the focus in invasion biology generally is on trying to confirm that assumption, while ignoring or minimizing discussions and analysis of positive contributions of species perceived as non-native (Brown and Sax 2004; Guiaşu 2016; Guiaşu and Tindale 2018; Boltovskoy et al. 2021).

Further, estimates very rarely contrast the economic costs involved in control or eradication programs with those incurred in if the programs were not undertaken. The underlying justification, i.e., that such costs would not have been borne unless they are covered by perceived values, is most probably accurate in several specific cases, such as

[2] (https://www.selinawamucii.com/insights/prices/united-states-of-america/carp-fish/; accessed 28 November 2021)

the control of fouling mussels in industrial and power plants, but very likely much looser and imprecise when system-wide NIS-culling initiatives are concerned. In the latter, the basic requirement of comparing ex ante with ex-post assessments is very often not met (Born et al. 2005; Marbuah et al. 2014).

CONCLUDING REMARKS

Focusing on the negative economic impacts of NIS only and presenting these results as if they were a valid indicator of their overall impacts undermines the scientific rigor and usefulness of invasion biology as a discipline. The circumstance that the negative effects of many NIS on the economy are greater than the positive ones does not warrant ignoring the latter, especially considering that such information can eventually be used for allocating resources which are subtracted from other societal needs. Such assessments are likely to engender two types of responses. Most scholars aligned with the notion that introduced species that are harmful will enthusiastically repeat these figures with no further scrutiny, whereas those that adhere to a more nuanced position are likely to dismiss them altogether. None of these outcomes is correct or desirable.

Partly because damage, and especially high damage estimates, attract much more attention than benefits (Jernelöv 2017; Guerin et al. 2018), few studies attempted to assess the economic benefits of NIS (McLaughlan and Aldridge 2013; Pienkowski et al. 2015; Hoffmann et al. 2019; Shackleton et al. 2019b; Vimercati et al. 2020; Wang et al. 2021). Although the positive potential or realized contributions of NIS, as well as calls for a more objective and sentient outlook are numerous (Shackleton et al. 2007; Davis 2009; Pejchar and Mooney 2009; Stromberg et al. 2009; Kull et al. 2011; Schlaepfer et al. 2011; Vince 2011; Turnhout et al. 2013; Pienkowski et al. 2015; Tassin and Kull 2015; van der Wal et al. 2015; Bonanno 2016; Guiaşu 2016; Gozlan 2017; Schlaepfer 2018; Wallach et al. 2018; Martinez-Cillero et al. 2019; Shackleton et al. 2019a; Cassini 2020; Gbèdomon et al. 2020; Lundgren et al. 2020; Albertson et al. 2021; Granse et al. 2021; Melo de Rosa et al. 2021; Muñoz et al. 2021; Ortega et al. 2021), the dominant trend still is to lump all NIS impacts on the negative side of the ledger.

Although economic impacts are clearly often very large, a more encompassing outlook is needed in order to gauge them objectively. Such approaches should go beyond the rather simplistic method of summing up reported actual or putative costs, without much inquiry into their contribution to actual net outcomes. Admittedly, this requires much more knowledge on the effects of NIS than we presently have, yet it does not justify using these numbers for weighing the risks and harms involved, let alone using them for engaging in potentially feckless and wasteful eradication and control initiatives (Hershner and Havens 2008). As noticed by Vimercati et al. (2020), quantifying positive impacts "should not be seen as an attempt to outweigh or discount deleterious impacts of alien taxa, but rather as an opportunity to provide an additional piece of information for scientists, managers, and policymakers".

This said, we should make it clear that we do not favor biological introductions. We agree with the widely held tenet that the risks involved are too high, and the results sometimes disastrous. Nevertheless, once a NIS has managed to enter and become established, the option to do nothing or invest in its control cannot be based on its putative or demonstrated negative impacts only. In this respect, its positive effects are as important as the negative ones, and, if control programs are deemed necessary, the economic and ecosystem-service benefits must obviously outweigh the investments involved. Further, when the eradication of a clearly damaging NIS is unviable, efforts should be focused on alternatives to beneficially use it (Howard 2019).

Acknowledgements This work was supported by grant UNDEFI (Argentina) 273/2020 to NC. The suggestions of two anonymous reviewers, as well as comments by Mark Davis on an earlier version of the manuscript, are greatly appreciated.

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