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AQUATIC INVASIVE SPECIES: THE ECONOMIC COST-BENEFIT BALANCE OF HUMAN-MADE INFRASTRUCTURE

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Keywors
Introduced species
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Spread
Impacts
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Abstract Human-made facilities and major construction projects, like navigation canals and water-transfer canals and pipelines, can facilitate the spread of aquatic alien species, some of which may have negative impacts on the habitats invaded, and on the economy. However, the positive economic impacts of such facilities are usually much higher than their costs, and their ecosystem-service values are usually mixed, with both positive and negative ecological impacts being common.

Palabras clave
Especies introducidas
Construcciones humanas
Canales
Dispersión
Impactos
Economía

Resumen Especies acuáticas invasoras: los costos-bene cios de las obras de infraestructura humanas. Las construcciones humanas, como canales para navegación y transferencia de agua dulce, facilitan la distribución de especies introducidas, algunas de las cuales pueden tener impactos negativos importantes sobre los hábitats invadidos y sobre la economía. Sin embargo, en términos económicos los impactos positivos de estas obras son normalmente muy superiores a los negativos, y sus efectos ecológicos son generalmente mixtos, con resultados tanto negativos como positivos.

1. Introduction

From the dawn of humankind, in efforts to guarantee its subsistence our species has been reshaping the planet. Although all plants and animals modify their environment to suit their needs, because of humankind's spread and abilities, its interventions went far beyond those of other organisms. From the point of view of introduced or non-indigenous species (NIS; i.e., species that, aided by humans, colonize areas outside of the range where they emerged, rather than by their own means or the intervention of "natural" vectors, such as wind, currents, other non-human organisms, etc.), while most of them have little or no influence on the communities and habitats invaded, and many have at least some beneficial impacts (Boltovskoy et al. 2021), a few (probably 1 in 1000) of those that are transported become invasive pests thriving in the new habitats, monopolizing resources, and strongly affecting native communities and, often, human interests (Williamson and Brown 1986, Jeschke et al. 2012).

Aside from deliberate introductions (and, occasionally, their subsequent escapes or releases into the wild), among the most salient human activities that facilitate the transport of species from their native geographic ranges to otherwise inaccessible areas is the creation of pathways that facilitate their dispersal. These pathways include (but are not restricted to) (1) The accidental transport as "contaminants" associated with the trade of goods and travel, including the ballast water and hull fouling of freshwater, coastal and transoceanic vessels (Minchin and Gollasch 2003, Sayinli et al. 2022); and (2) The dispersal corridors created ad hoc in terrestrial systems to increase areal connectivity and favor the subsistence of native species, as well the incidental ones represented by road and railroad verges, tunnels (connecting mountain valleys) and bridges (between islands and mainlands) (Hulme et al. 2008, Haddad et al. 2014, Resasco et al. 2014, Phillips et al. 2020). For aquatic species, these dispersal corridors are chiefly represented by navigation canals and water-transfer infrastructure linking previously isolated watersheds (Galil et al. 2008, Zhan et al. 2015, Shumilova et al. 2018).

Although introduced species and their effects on the systems invaded have been the focus of much research during the last few decades (Hui and Richardson 2017, Vilà and Hulme 2017, Jeschke and Heger 2018), assessments of their impacts on the economy and human wellbeing are relatively scarce (Perrings et al. 2001, Pimentel 2011, Diagne et al. 2021). Further, many of the estimates produced have been heavily criticized for their unfounded assumptions and poorly supported figures (Davis 2009, Thompson 2014, Boltovskoy et al. 2022). In relation to biological invasions fostered by the above-mentioned pathways, a major - but usually ignored - issue is whether from the point of view of the economy and human wellbeing these human-made connections have brought about more harm than benefits.

In this short overview we offer a few examples of the impacts that some of the human-made connections have on aquatic organisms worldwide, and the negative impacts and economic benefits brought about by such facilities and construction projects.

2. Major canals and water-transfer facilities

River improvement and construction of artificial waterways have been undertaken since the 23rd century BC, chiefly in Asia and northern Africa (Galil et al. 2008), and have been increasing worldwide due to the uneven distribution and rising scarcity of freshwater, as well as to facilitate regional and international water-borne trade (Fig. 1).

Worldwide, there currently are several thousand human-made canals, many of which are based on pre-existing river stretches. Among the busiest ones in terms of ship traffic are the Suez Canal, the Panama Canal, the Great Lakes-St. Lawrence region canals (Fig. 1), and several canals linking the

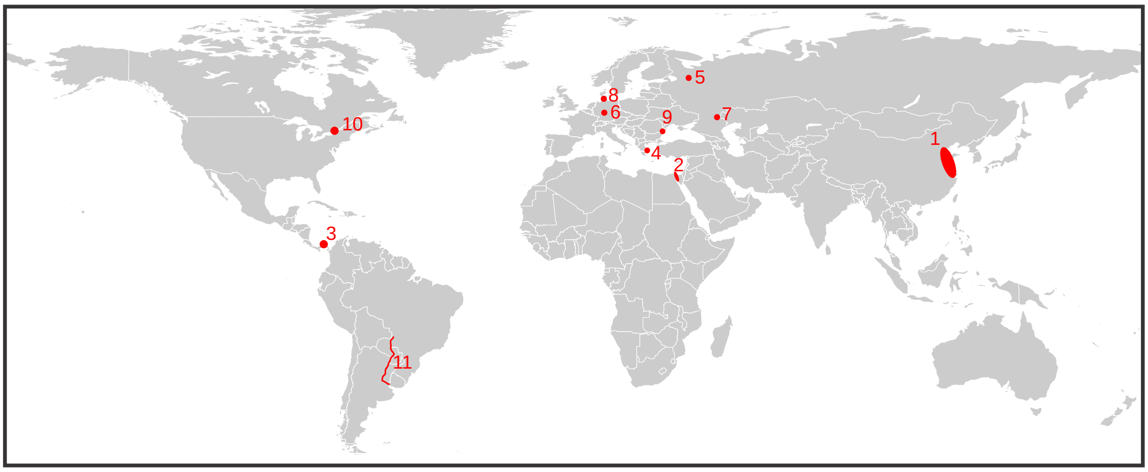

Fig. 1. Some major human-made navigation canals, waterbodies connected, and year of completion. 1: Beijing-Hangzhou Grand Canal (Yellow River-Yangtze River, 6th-7th centuries BC, currently part of the South-to-North Water Transfer Project); 2: Suez Canal (Mediterranean Sea-Red Sea, 1869); 3: Panama Canal (Atlantic Ocean-Pacific Ocean, 1914); 4: Corinth Canal (Ionian Sea-Aegean Sea, 1893); 5. White Sea-Baltic Sea Canal (White Sea-Baltic Sea, 1933); 6: Rhine-Main-Danube Canal (North Sea-Black Sea, 1976-1987); 7: Volga-Don Canal (Caspian Sea-Azov Sea, 1952); 8: Kiel Canal (North Sea-Baltic Sea, 1895); 9: Danube-Black Sea Canal (North Sea-Black Sea, 1984-1987); 10: Great Lakes-St. Lawrence System (North Atlantic-Great Lakes, 1854-1959); 11: Hidrovía Paraguay-Paraná (Pantanal, Brazil-Atlantic Ocean, 1999-present).

Caspian Sea, the Black Sea, the Mediterranean Sea, the Atlantic Ocean, the North Sea and the Baltic Sea (Figs, 2, 3).

Over 80 major water-transfer projects are presently completed or under construction (Zhan et al. 2015), and many more are in the planning stages, mostly for agricultural and hydropower purposes (Shumilova et al. 2018; see below). Although a few of these artificial constructions are restricted to a single watershed, most connect previously totally or partially isolated basins, thus allowing the interchange of their flora and fauna. Some salient examples are listed below.

2.1. The Great Lakes-St. Lawrence region canals (USA-Canada)

The connection of the North Atlantic and the Great Lakes (Fig. 1) allowed the entry of 187 NIS in the latter (Sturtevant et al. 2019), including some with major economic impacts, like the sea lamprey (*Petromyzon marinus*) (Kitchell et al. 2015). Yet, these man-made connections have had an enormous positive impact on the economy of Canada and the USA, connecting 40 major Great Lakes ports with the North Atlantic. In 2017, the economic activity fostered by these connections was estimated at 116 thousand million US$, and supported almost 800,000 jobs (Martin Associates 2018).

2.2. The Paraguay-Paraná rivers Hidrovía (South America)

In South America, dredging and other works gave rise to the 3,400 km-long Hidrovía Paraguay-Paraná (Fig. 1), a navigable waterway that connects Puerto Cáceres, in Brazil, with the Atlantic Ocean, through the Río de la Plata Estuary. Commercial navigation along this waterway facilitated the fast upstream dispersal of the invasive golden mussel *L. fortunei* (Boltovskoy et al. 2006), whose biofouling of human-made facilities (refineries, water-treatment and power plants, watercraft, etc. has major economic impacts (Boltovskoy et al. 2015, Rebelo et al. 2018). However, on the other hand, the Hidrovía waterway is used for transporting >100 million metric tons of goods annually, and has fostered and enhanced the regional and international trade of Argentina, Bolivia, Brazil and Paraguay immensely.

2.3. The South-to-North Water Transfer Project (China)

A similar case, also involving the golden mussel and other species (Qin et al. 2019), is China's South-to-North Water Transfer Project (Fig. 1). For aquatic NIS in general, this and many other human-made water diversion constructions throughout the world (Gollasch et al. 2006, Zhan et al. 2015, Shumilova et al. 2018) created artificial connections between previously isolated basins and facilitated the spread of many NIS. Although the South-to-North Water Transfer Project has been highly controversial since its inception (partly due to its cost of ~60 billion US$), its net positive impacts on agricultural, forest, and urban systems, plus its overall eco-environmental benefits, have been forecasted to reach >840,000 billion US$ by 2030 (the (Kattel et al. 2019).

2.4. The Suez (Egypt) and the Panama Canals

Interbasin connections, like the Suez Canal (Fig. 1), allowed the entry of hundreds of organisms from the Red Sea to the Mediterranean (Galil et al. 2015). The Panama Canal (Figure 1) has had an impact on the homogenization of biotas on its Atlantic and Pacific sides (Castellanos-Galindo et al. 2020). Although most of these impacts are difficult to monetize, they have had environmental costs, but also benefits (Katsanevakis et al. 2014). Yet, on the other hand, these connections have also had an enormous positive economic impact on international trade, and provided major ecosystem services, such as reduced CO_2 and sulfur emissions due to shorter shipping routes (Castellanos-Galindo et al. 2020). In 2021, >2000 transits through the Panama Canal took place (https://www.pancanal.com/eng/op/transit-stats/, accessed 26 February 2022); for large bulk carriers, tankers and container-ships, the saving per ship range from ~230,000 to 1,000,000 US$ (Zupanovic et al. 2019), and an overall reduction of CO_2 emissions of ~16 million tons due to shorter navigation routes (de Marucci 2012). The recent (March 2021) 6-day blockage of the Suez Canal by the Ever Given container ship is estimated to have costed 400 million US$ per hour (https://www.indiatimes. com/technology/news/suez-canal-container-ship-block-400-million-dollar-per-hour-worldwide-537096.html; accessed 20 September 2021) and ~7000 t of excess CO_2 equivalent emissions by only 12 of the ships re-routed around Africa (https://www.theecoexperts.co.uk/blog/how-much-co2e-the-suez-canal-blockage-caused; accessed 27 February 2022).

2.5. The European canals

Inter-basin canals for navigation, crop irrigation, water supply, hydropower or drainage have been built throughout Europe since Roman times, and especially since the 18-19th centuries (Figs. 2, 3) (Gollasch et al. 2006, Karatayev et al. 2007, Ram and Palazzolo 2008, Leuven et al. 2009), greatly fostering national and international trade and the economic growth of the nations involved. However, they also facilitated the spread of many species, especially from the Ponto-Caspian basins to Western Europe and, occasionally, to the Americas (Leuven et al. 2009, Karatayev et al. 2015). The impacts of these invasive species, however, have been mostly mixed. In a thorough review of marine high-impact invaders in Europe (Katsanevakis et al. 2014) concluded that 17 had only negative and 7 only positive impacts; both negative and positive effects having been reported for the majority (62 species).

3. Alternatives?

The obvious argument is that such human interventions should take into account the potential NIS-related problems involved and anticipate the necessary solutions (Zhan et al. 2015, Castellanos-Galindo et al. 2020).

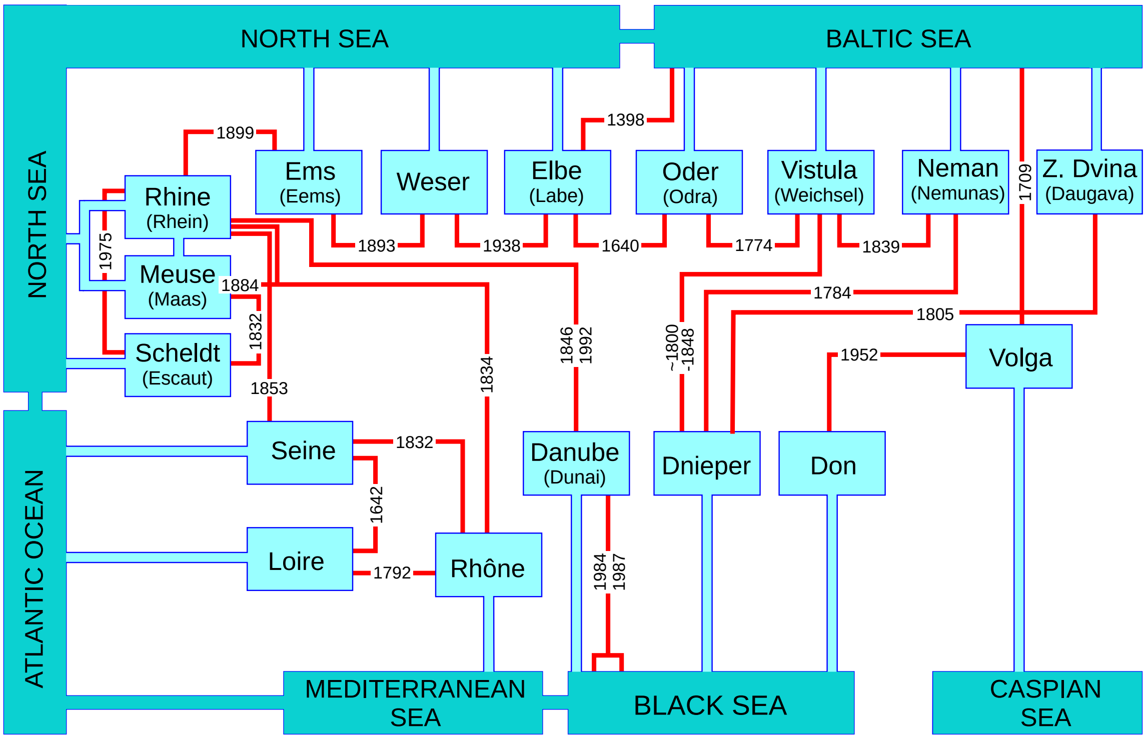

Fig. 2. Human-made connections, chiefly for navigation purposes (red lines), between major European rivers and with their natural discharge basins, and their years of completion, centered on the Rhine River (adapted from Leuven et al. 2009, with additional data from Karatayev et al. 2008).

Fig. 3. Geographic location of the major rivers shown in Fig. 2.

In the case of water-borne species introductions mitigating actions to cull the spread of introduced species are implemented, such as ballast water management regulations (Sayinli et al. 2022). Electric, sound, or air-bubble curtains have been explored as well, although their efficiency is contentious and they have important drawbacks (Gollasch et al. 2006). In some cases the presence of natural obstacles, like the low salinity Gatún Lake between the Atlantic and the Pacific sides of the Panama Canal, mitigate the interoceanic transfer of marine species significantly (Gollasch et al. 2006). The high salinity Bitter Lakes along the Suez Canal have also been an important barrier until their salinity started dropping after the damming of the Nile River (Gollasch et al. 2006). In others, however, salinity gradients are lower, like the network of canals connecting the seas around Europe and the Ponto-Caspian region (Figs. 2, 3) (Gollasch et al. 2006), or nil (the Hidrovía in South America, the Chinese South-to-North Water Transfer Project; Fig. 1). Methods for curtailing the spread of some baneful NIS in water transfer facilities have been proposed (Liu et al. 2017, Zhang et al. 2017, Liu et al. 2020), and they might mitigate the problem, but are unlikely to eliminate it.

4. Concluding remarks

As with most assessments of the impacts (ecological and economic) of invasive species, the overall outcome depends on the side of the coin one looks at. With the exception of human pathogens and parasites, and those of organisms valued by humankind for their contribution to the economy, or for many other reasons which are difficult to monetize (such as aesthetics, people's perceptions, socio-cultural contexts, traditions, practices, companionship, emotional support, sense of purpose, psychological health, etc.) (Hoffmann et al. 2019, Shackleton et al. 2019a), the effects of the invaders are almost

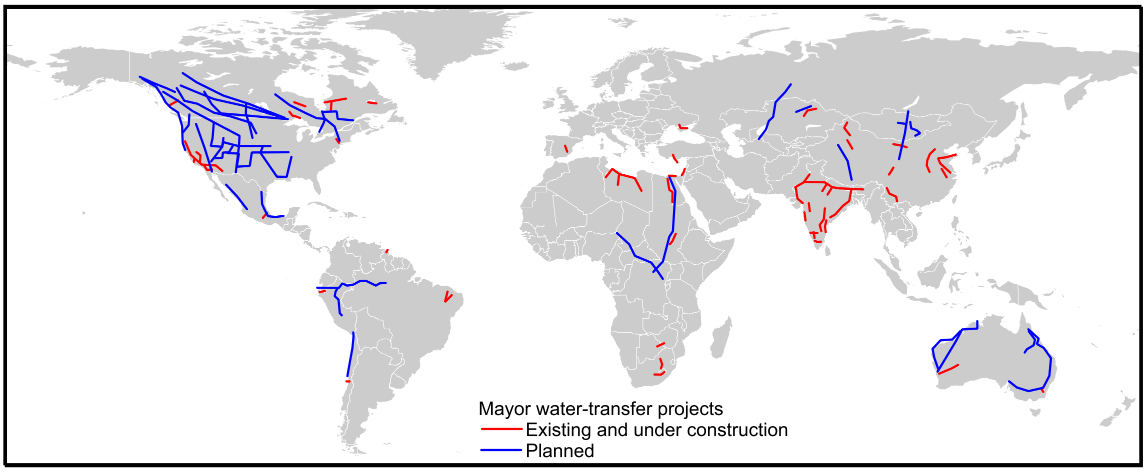

Fig. 4. Major existing, under construction, and planned water-transfer projects (adapted from Shumilova et al. 2018).

invariably multifaceted, highly context-dependent, and very rarely affect a single native species or process. Further, impacts of the same invader are neither static nor permanent, changing widely in time and space (Noordhuis et al. 2016, Strayer et al. 2017, Boltovskoy et al. 2021).

Assessing the impacts of introduced species cannot be based on their negative effects only (Vimercati et al. 2020, Boltovskoy et al. 2022). Aside from the fact that most have mixed impacts, their economic, social, or ecosystem-service assets are often very important (Jernelöv 2017, Shackleton et al. 2019b, Cassini 2020, Guzman-Novoa et al. 2020, Schlaepfer et al. 2020, Valentine et al. 2020, Goedkoop et al. 2021). Canals and water-transfer projects (Fig. 4) have been identified as major drivers of species invasions, loss of habitat, transfer of pollutants, salinization, soil erosion, and destruction of animal migration routes (Zhan et al. 2015, Shumilova et al. 2018). Their costs are staggering: the construction of 76 future large water-transfer projects will require a combined cost of around 2.7 trillion US$ (Shumilova et al. 2018). Further, their selection as the best option for mitigating water shortage is often questionable as they involve multiple issues, including "...who are served and profit from the water transfer, the full costs - financial, environmental, social - and alternative resolutions such as demand reduction, reducing system loses and appropriate water use, particularly agricultural, in drylands" (Sternberg 2015). However, generally their positive effects on the economy and human wellbeing are huge, and such engineering interventions are often unavoidable unless economic growth and social integration are compromised.

Although many scholars in the area of biological invasions tend to focus their attention on the baneful effects of introduced species, and, following the legacy of Charles Elton's seminal work (Elton 1958), often advocate for their complete extirpation with the aim of reverting ecosystems to some ideal "pristine" state, in many - or even most - cases this goal is likely unrealistic (Hobbs et al. 2006, Tait and Larson 2018); but see also (Simberloff 2020). In the last decades a different approach has been suggested, based on the notion of "novel ecosystems", defined as "a system of abiotic, biotic, and social components (and their interactions) that, by virtue of human influence, differ from those that prevailed historically, having a tendency to self-organize and manifest novel qualities without intensive human management" (Hobbs et al. 2013). Obviously, this concept does not negate the need to invest in viable actions to eradicate some clearly baneful invasives (and natives), or to pursue demonstrably successful policies aimed at culling new introductions, assuming that these introductions have obvious negative impacts overall. However, it does support the recognition of the fact that while these systems differ from those that prevailed historically, they are not necessarily worse or less desirable than the latter (Hobbs et al. 2006). Further, there are many examples where these invaders have been responsible for the amelioration of major ecosystems impacted by human activities (Goedkoop et al. 2021, Li et al. 2021), and helped the recovery of declining native species or replaced them functionally (Bruestle et al. 2018, Vizentin-Bugoni et al. 2019, Lundgren et al. 2020).

The "novel ecosystems" outlook also involves viewing the role of alien species more pragmatically, and even considering some "new" species as desirable elements (Hui and Richardson 2017), or the unavoidable cost of major economic and human wellbeing gains.

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