A Sea, a Canal, a Disaster: The Suez Canal and the Transformation of the Mediterranean Biota

Bella S. Galil

Abstract The introduction of non-native species is among the main direct drivers of biodiversity change. Off the Israeli coast 445 non-native species were recorded thus far, more than anywhere in the Mediterranean Sea. The number of recorded introductions has been rising inexorably, tripling since the 1970s. Nearly all have been introduced through the ever-enlarged Suez Canal. Worldwide there is no other vector of marine bioinvasions that delivers as high a propagule supply for so long to a certain locale. Once established, the non-native species are unlikely to be contained or controlled and their impacts are irreversible. The Canal-introduced species form prominent micro-communities and biological facies in most littoral habitats, some have been documented to displace or reduce populations of native species, alter community structure and food webs, change ecosystem functioning and the consequent provision of goods and services—profound ecological impacts that undermine the goals of sustainable *blue economy* in the *Mediterranean* Sea.

B. S. Galil (✉)
Curator (Emerita) of Crustacea, Steinhardt Museum of Natural History, Tel Aviv, Israel
e-mail: bgalil@tauex.tau.ac.il

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These species have been spreading throughout the Mediterranean Sea while the Israeli shelf serves as a hotspot, beachhead, and dispersal hub. Their spatial and temporal spread has advanced concurrently with successive enlargements of the Suez Canal, rise in mean seawater temperature, and prevalence, duration, and severity of marine heat waves increase. The invasion poses a challenge to the environmental ethics and policies of the Mediterranean countries. As signatories to the Convention on Biological Diversity these countries are required to prevent the introduction of, control or eradicate alien species which threaten ecosystems, habitats or species (Article 8(h)), and ensure that the environmental consequences of their policies that are likely to have significant adverse effects on biological diversity are taken into account (Article 14.1). The present Egyptian government is in a position to reduce future introductions. Egypt announced the development of 35 desalination plants, of which the first 17 plants will add 2.8 million m^3 daily capacity. It is suggested that an environmental impact assessment evaluates the environmental and economic consequences of utilizing the brine effluents from the large-scale desalination plants constructed in the vicinity of the Suez Canal to restore the salinity barrier once posed by the Bitter Lakes.

Keywords Convention on Biological Diversity · Desalination brine effluent · Erythraean invasion · Non-indigenous species · Invasive marine species · Salinity barrier · United Nations Convention on the Law of the Sea

The Mediterranean Sea

The Mediterranean Sea, a remnant of the Tethys Ocean, was disconnected from the Atlantic Ocean approximately six million years ago with the sealing of the precursor of the Strait of Gibraltar. At its nadir, termed the "Messinian salinity crisis," the isolation led to desiccation and the creation of evaporitic basins, and its once high level of biodiversity was severely reduced. With the re-opening of the strait approximately five million years ago, the sea was repopulated by Atlantic biota. Subsequent changes in climate, sea level, salinity levels, and oxygen levels resulted in alternate entries of boreal and subtropical Atlantic biota.

The sea's main hydrologic features are a microtidal regime, scarce freshwater inputs, and evaporation compensated by inflow of Atlantic surface water, high salinity (38–39.5) in the eastern basin, oligotrophy, with organic carbon inputs 15–80 times lower in the eastern than in the western basin and extremely low concentrations of chlorophyll-a in surface offshore waters (ca 0.05 $\mu g\ l^{-1}$), high homeothermy from approximately 300–500 m downward, bottom temperatures about 12.8–13.5 °C in the western basin and 13.5–15.5 °C in the eastern basin. With an average depth of around 1500 m, climate-driven thermohaline circulation and short water residency (75–100 years), the Mediterranean Sea is more vulnerable to climate change.

More than 17,000 marine species were recorded from the Mediterranean Sea, comprising an estimated 7% of the world's marine biodiversity.[1] However, recent rapid human population growth of coastal residents and transient recreational populations (the latter 244 million in 2000, 342 million in 2014, 590 million expected in 2050),[2] coupled with intensification of anthropogenic activities, are driving unprecedented changes.[3] Symptoms of complex and fundamental alterations to native species populations, habitats, and ecosystems proliferate, including increases in non-indigenous species (NIS). Much of the Mediterranean shelf ecosystems lack resilience and are so heavily impacted by stressors that they change in unexpected and undesirable ways. The biota across wide stretches of the sea, including marine protected areas, has already been altered with significant ecological, economical, and human health impacts.[4]

The Suez Canal

A Very Brief History

A French engineer, Linant-Bey (Linant de Bellefonds), was enlisted by Mehemet Ali Pasha, the Ottoman governor of Egypt, to build the Mahmoudieh Canal, from Alexandria to the Nile, allowing navigation upstream to Cairo. Linant surveyed the Suez Isthmus and was confident of the feasibility of a direct isthmian canal traversing Lake Timsah and the Bitter Lakes and communicated his plans to the French consul, Mimaut, and his vice-consul, de Lesseps, then newly arrived in Egypt. In 1846, a European Study Group was formed, and the next year visited Egypt closely instructed by Luigi Negrelli, a noted civil engineer. In 1854, when Mohammed Said acceded to the viceroyalty, de Lesseps presented him with the detailed maps of the Isthmus prepared by Linant de Bellefonds and the plan for a direct trans-isthmian canal, and by the end of 1854 the initial concession to build a canal, with a port at each end, was approved and signed. A Scientific Commission, convened in 1855, and charged with the examination of the plans for the Canal, favored Linant's proposal for a "direct route" canal across the Suez Isthmus with locks at each end of the canal and the canalization of the lakes. Negrelli argued strongly against canalization and locks, and the Commission adopted his 1847 plans for a "direct route" canal without locks—a fateful decision that determined the environmental impact of the Suez Canal.[5] The Universal Company of the Maritime Suez Canal, formed in 1858 under de Lesseps's direction, raised, by popular subscription in France, more than half the capital needed, and much of the rest was invested by Said himself. Twenty thousand conscripted *fellahin* and prisoners, working in shifts, formed the bulk of the laborers, later replaced by steam-powered bucket dredgers. The canal was 8 m deep, 58–90 m wide at the surface, cross-sectional area 304 square meters, and 160 km long, and along its banks three new cities were built: Suez, Ismailia, and Port Said. Its construction was completed in 1869.

The Expansion of the Suez Canal

The *Compagnie Universelle du Canal Maritime de Suez* embarked on major improvements including the widening and deepening of the channel in 1876, and by 1880 the number of ships transiting the Canal was 2026. In 1955, 14,666 ships traversed the canal, and a plan to enlarge the canal was announced. The events of the summer and autumn of 1956—the nationalization of the Suez Canal Company, followed by the Anglo-French invasion of the Canal Zone, the Arab-Israeli war, and the blockage of the Canal by the Egyptians—derailed those plans. During the months of closure and blockage sand had accumulated, reducing the permissible navigable depth. The first stage of the "Nasser Plan" entailed doubling the canal's width along its entire length, and deepening it to 15.5 m, to a cross-sectional area of 1800 square meters. In 1966, a six-year program, the second stage of the "Nasser Plan" was launched. Its object was to allow the navigation of 110,000 ton loaded tankers and 125,000 tons of partially loaded vessels by 1972. The Six-Day War forced the Suez Canal to close in June 1967, blocking it for the second time in ten years. The canal remained inoperative until June 1975, when maintenance work was recommenced to clear the sand that filled the channel bed. By that time the Canal was incapable of handling half of the world's tanker fleet, with Very Large Crude Carriers (VLCC) (200,000–300,000 dead weight tons [DWT]) plying alternate sea routes.[6] In 1980, its depth was increased to 19.5 m, and its cross-sectional area to 3600 square meters. The Canal was doubled in five parts (Port Said, Ballah, Timsah, Deversoir, Kabret) for a total of 77 kms, to allow transit in both directions. In 2001, its depth increased to 22.5 m, and the cross-sectional area to 4800 square meters in order to maintain the Canal's market share against the inexorable increase in the size of ships. In 2010, it increased yet again to 24 m, and the cross-sectional area to 5200 square meters. In 2015, the Canal was doubled along 113.3 kms.[7]

A Disaster

The introduction of non-indigenous species (NIS) is an important element of global change in marine ecosystems. This phenomenon is considered to be among the main direct drivers of biodiversity change, exacerbated as it is by climate change, pollution, habitat loss, and other human-induced disturbances. Many introduced marine species have been documented to displace or reduce native species populations, alter community structure and food webs, change ecosystem functioning and the consequent provision of goods and services. Once established, they are unlikely to be contained or controlled and their impacts are irreversible. NIS have become a concern in virtually all marine coastal ecosystems around the world, but nowhere more than in the Mediterranean Sea.[8]

The Suez Canal is the main pathway of NIS introduction into the Mediterranean Sea. Its successive enlargements have raised concern over increasing propagule pressure resulting in continuous introductions of new Erythraean species and associated degradation and loss of native populations, habitats, and ecosystem services.[9] The concern harks back to the mid-nineteenth century: even before the Canal was fully excavated, a French malacologist argued that the breaching of the Suez Isthmus would cause the mixing of faunas, advocated what today would be considered a "baseline study," and raised provocative and prescient questions.[10] The opening of the Suez Canal engendered debates on its impact on the Red

Sea and Mediterranean biotas, yet for the next 50 years the documentation of the biota in the Canal itself and the changes in the adjacent marine environments were largely left to learned amateurs, for example, Arthur René Jean Baptiste Bavay and Jean Baptiste Tillier, employees of the Compagnie du canal maritime, are to be thanked for assiduously collecting mollusks and fish.[11] In the first decade of the twentieth century, 13 of the 14 NIS recorded for the first time in the Mediterranean entered through the Suez Canal.[12] A century ago, Walter Steinitz, another learned amateur, recognized the scientific significance of the movement of biota through the Canal and noted that no scientific institute had taken on a comprehensive study of biotic transfer.[13] He raised questions as to the changes caused by Red Sea in the fauna of the eastern basin of the Mediterranean. Yet the sole multidisciplinary, multitaxa survey to investigate the spread of the Erythraean biota in the Levant Sea was a joint program by the Smithsonian Institution, the Hebrew University of Jerusalem, and the Sea Fisheries Research Station (Haifa) in the late 1960s. The resulting list enumerated 140 Erythraean species,[14] forming the base for the compendium prepared by Francis D. Por.[15]

For much of the previous century little attention had been paid to Erythraean NIS in the Mediterranean Sea. As long as their impacts were inconspicuous, confined to the Levant, induced no direct economic cost or impinged on human welfare, Erythraean NIS were ignored by scientists, conservationists, policymakers, and managers. However, in the 1980s the rapid spread and injurious impacts of invasive Erythraean NIS helped raise awareness of the insidious invasion.[16] Since the Levant Sea was recognized early on as vulnerable to bioinvasion,[17] it was *ipso facto* considered to have been "biologically enriched" by it,[18] being "biologically underexploited by marine life... a sort of ecological vacuum where many ecological niches are available."[19] Por postulated that "[t]he Lessepsian migration is therefore, a phenomenon with a rather clearly set frame which is rapidly approaching its fulfilment,"[20] and "[t]he Lessepsian migrants may be considered, in a figurative sense 'welcome guests' in the impoverished, subtropical cul-de-sac."[21] He was proved wrong on both counts when scientists realized that the number of Erythraean NIS had greatly increased over time and profoundly altered the composition of the biota of the eastern Mediterranean Sea, impoverishing native species richness, and causing major shifts in community structure, function, and services. It is now widely believed that "If we do not understand and mitigate the ecological risks associated with the expansion of the Suez Canal, the integrity of a large part of the Mediterranean ecosystem could be in jeopardy."[22]

Erythraean algae, invertebrates, and fish have profoundly marked the composition of the biota of the southeastern Mediterranean Sea,[23] their impacts are determined, in part, by their demographic success (abundance and spread). With few exceptions, the ecological impact of NIS on the native Mediterranean biota have not been scientifically studied. Where populations of native Mediterranean species appear to have been outcompeted or displaced by an NIS, these could be part of a profound anthropogenic alteration of the marine environment. Still, a number of Mediterranean NIS have drawn the attention of scientists, management, and media, for the conspicuous impacts on the native biota attributed to them.

Two species of rabbitfish, *Siganus rivulatus* and *S. luridus*, entered the Mediterranean through the Suez Canal, were first recorded off the southern Levantine coast in 1924 and 1955, respectively.[24] The species were later recorded as far west as France and Tunisia.[25] The schooling, herbivorous fishes form thriving populations in the Levant Sea where "millions of young abound over a rocky outcropping grazing on the relatively abundant early summer algal cover."[26] The siganids comprise a third of the fish biomass in rocky habitats in Israel,[27] 80% of the abundance of herbivorous fish in shallow coastal sites in Lebanon,[28] 83–95% of the biomass of herbivorous fish at sites on the Mediterranean coast of Turkey[29]; and have replaced native herbivorous fish.[30] Their diet has had a significant impact on the structure of the algal community: by selectively feeding, the siganids have nearly extirpated some of their favorite algae locally[31]; "once flourishing algal forests have disappeared to leave space to sponges and wide areas of bare substratum... The shift from well-developed native algal assemblages to 'barrens' implies a dramatic decline in biogenic habitat complexity, biodiversity and biomass... with effects that may move up the food chain to the local fisheries."[32] A survey along one thousand kilometers of Greek and Turkish coasts found that in regions with abundant siganids canopy algae were 65% less abundant, benthic biomass was reduced by 60%, and species richness by 40%.[33]

The small Erythraean mytilid mussel, *Brachidontes pharaonis*, in the early 1970s was "250 times rarer" than the native mytilid *Mytilaster minimus*, that formed dense *Mytilaster* beds on intertidal rocky ledges along the Israeli coastline.[34] More recently "the same rocks are... completely covered with the Erythrean *B. pharaonis*, while *M. minimus* is only rarely encountered."[35] The Erythraean mytilid has spread westward to Italy, where in the south it forms dense populations with over 25,000 specimens/m^2,[36] and to Corsica, France.[37] The Erythraean Spiny oyster, *Spondylus spinosus,* and jewel box oyster, *Chama pacifica*, have supplanted their native congeners *S. gaederopus* and *C. gryphoides*. The Erythraean dragonet, *Callionymus filamentosus*, replaced the native callionymids *C. pusillus* and *C. risso*.[38]

The Levant Sea is unique in hosting six Erythraean scyphozoan jellyfish: *Cassiopea andromeda*, *Chrysaora pseudoocellata*, *Cotylorhiza erythraea*, *Marivagia stellata*, *Phyllorhiza punctata*, and *Rhopilema nomadica*. *Rhopilema nomadica*, first recorded in the Mediterranean in the 1970s, is notorious for the large swarms it has formed each summer since the early 1980s along the southeastern Levantine coast.[39] They periodically clog seawater intake pipes of coastal powerplants, and disrupt coastal fisheries by clogging nets: "It is not uncommon that fishermen, especially purse seines, discard entire hauls due to the overwhelming presence of poisonous medusae in their nets."[40] Gelatinous plankton outbreaks affect production cycles and food webs that are more significant than their obvious impacts in economic and human health terms. Indeed, *R. nomadica* is but one of a dozen venomous or poisonous Erythraean NIS that have drawn the attention of scientists, managers, media, and the public for their conspicuous human health impacts.[41]

The venomous devil lionfish, *Pterois miles*, an Erythraean NIS, has spread throughout the eastern Mediterranean in the past decade.[42] An opportunistic piscivore, it preys on small fish inhabiting rocky reefs and as well as foraging in nearby soft bottom habitats. A recent study revealed a diet comprising a great variety of native species.[43] Its populations inhabit natural and anthropogenic structures (i.e., wrecks, breakwaters), as well as shallow sandy bottoms frequented by bathers. It was recently observed at shelf-edge mesophotic reefs—patchy assemblages of large arborescent anthozoans and sponges that attract highly diverse biota. The occurrence of the piscivorous and highly fecund lionfish at these depths threatens the unique mesophotic assemblages.[44] The lionfish is not unique in establishing populations beyond the shelf edge. Whereas in the 1970s, Erythraean biota was largely limited to habitats shallower than 50 m,[45] recent findings increasingly document them on the deeper shelf, beyond the shelf break and well into the upper slope to a depth of 200 m and beyond.[46]

What may have caused thermophilic Erythraean NIS to descend into the lower shelf and upper slope? The successive enlargements of the Suez Canal[47] have likely increased propagule pressure—increasing the delivery of multiple species, including epipelagic larvae/juveniles of deeper living species. At the same time the Levantine surface waters (LSW) and Levantine intermediate waters (LIW) masses in the southeastern Mediterranean have displayed increasing long-term trends in salinity of $+0.008 \pm 0.006$ and $+0.005 \pm 0.003$ year^{-1}, respectively, and temperature of $+0.12 \pm 0.07$ and $+0.03 \pm 0.02$ °C year^{-1}, respectively.[48] A wider thermal niche confers advantages to thermophilic NIS, as they are more likely to colonize, establish viable populations, and spread in novel habitats. It seems that the climatic niche of some Erythraean NIS is wider than accounted for and is likely to facilitate bathymetric range expansion, as well as higher invasion risk into a wider geographic range. This phenomenon exacerbates the inherent risk in "invasion debt" that may last decades, when the population is not in equilibrium within its novel habitat, nor reached its final distributional extent.

Based on the results from global climate change projection scenarios, the Mediterranean is one of the regions most responsive to climate change, literally a "Hot-spot." Analysis of the largest time series (1982–2019) of deseasonalized sea surface temperature (SST) revealed a consistent warming trend of 0.035 °C/year across the Mediterranean Sea with noticeable spatial variability, the highest values are in the easternmost Mediterranean, along the Levant coast (about 0.040 °C/year). The warming trend is boosted by ever more frequent Marine heatwaves (MHWs). The MHWs resulted in the most catastrophic mass mortality events, covering ever larger areas, affecting emblematic communities, crucial habitat-forming species—scleractinian corals, gorgonians, sponges, and seagrasses—major contributors to the ecosystem structure and functioning (i.e., through the provision of habitat, food, shelter or via facilitation processes). A progressive loss was noted in overall taxonomic biodiversity. Yet only recently did scientists realize that MHWs-triggered degradation and functional shifts provide "resource opportunities" (e.g. nutrients, space) for thermally tolerant species adapted to warmer waters, native as well as non-native. Climate change projections suggest increased frequency and duration of MHWs in the Mediterranean Sea: by 2100 MHWs are projected to occur more frequently, last longer, and affect at peak the entire basin.[49] Bearing in mind that climatic models predict that the Mediterranean Sea will be most affected by warming and MHWs, the synergic and additive effects of warming and Erythraean invasion, augur degradation of the native communities on the Mediterranean shelf, and even upper slope. It is likely native stenothermal biota unable to shift their range to deeper or colder water, endure increasing stress and demographic attrition, and plausibly replaced by Erythraean aliens.[50]

Legislative Response, But No Action, to Erythraean Invasions in the Mediterranean Sea

Vector/pathway management is the most effective strategy for preventing translocation of species, thereby reducing introduction and spread of marine NIS. Lack of effective control on propagule transfer, reduces management to frequently futile eradication/removal and control efforts. Once NIS have spread widely, eradication/removal is virtually impossible, and attempts for long-term reduction of the population to an economically or ecologically acceptable level are rarely successful.

The United Nations Convention on the Law of the Sea (UNCLOS) was the first global legally binding instrument dealing with the intentional or unintentional introduction of marine species and called for "States... take all measures necessary to prevent, reduce and control... the intentional or accidental introduction of species, alien or new, to a particular part of the marine environment, which may cause significant and harmful changes thereto."[51] Article 8(h) of the Convention on Biological Diversity (CBD) requires parties, as possible and as appropriate "to prevent the introduction of, control or eradicate those alien species which threaten ecosystems, habitats or species."[52] The Convention for the Protection of the Marine Environment and the Coastal Region of the Mediterranean came into force in 2004. The Barcelona Convention and its protocols, together with the Mediterranean Action Plan (MAP), form part of the United Nations Environment Programme (UNEP) Regional Seas Programme. The signatories to the convention adopted an "Action Plan concerning species introductions and invasive species in the Mediterranean Sea" in 2003.[53] A Draft Guidelines for controlling the vectors of introduction into the Mediterranean of non-indigenous species and invasive marine species[54] states that "...the greatest influx of invaders resulted from the opening of the Suez Canal in 1869 that allowed entry of Indo-Pacific and Erythraean biota."[55] The recent Action Plan concerning Species Introductions and Invasive Species in the Mediterranean Sea UN Environment/MAP Athens, Greece 2017 acknowledges

> "The trend of new introductions of alien species in the Mediterranean has been increasing. About 1000 marine alien species have been reported in the Mediterranean Sea up to now, of which more than half are considered established. Many of these species have become invasive with serious negative impacts on biodiversity, human health, and ecosystem services [and pledges] . . . to promote the development of coordinated efforts and management measures throughout the Mediterranean region in order to prevent as appropriate, minimize and limit, monitor, and control marine biological invasions and their impacts on biodiversity, human health, and ecosystem services."[56]

Meanwhile, many Erythraean species have become the most conspicuous denizens in Marine Protected Areas across the Levant, having displaced and replaced native species, thereby reversing marine conservation efforts and hampering stock recovery of key economically and ecologically important species.[57] Yet, the ample scientific documentation of Erythraean bioinvasions in the Mediterranean Sea failed to elicit the implementation of effective management policies.

Egypt nationalized the Universal Company of the Suez Maritime Canal in 1956, undertaking all its assets, rights, and obligations. Egypt is a signatory to UNCLOS, signed and ratified CBD, and is a Contracting Party of the Barcelona Convention, but it has made no attempt to curb the influx of Erythraean biota into the Mediterranean. As most of the canal shipping originates from and destined to European ports, it is in the best interest of the EU and the Barcelona Convention signatories to proactively promote biosecurity and work together with Egypt and the international maritime industry to address the threat to the Mediterranean biota, and by extension, to the economic and social wellbeing of the coastal populations.

In fact, the Egyptian government is in a position to reduce future introductions. In 2021 Egypt issued tenders for 17 new desalination plants adding 2.8 million m^3 daily capacity, and plans to increase to 6.4 million m^3 by 2050—the hypersaline brine effluent will establish a formidable salinity barrier if discharged into the canal, recreating the Bitter Lakes. Construction of locks would decrease the transit of current-borne propagules.

Commemorative stamps issued by Egypt on the occasion of the inauguration of the "New Suez Canal" depict a pair of locks. The Suez Canal Authority ought to turn this image into reality—for the sake of the Mediterranean and its inhabitants.

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