Biological Invasions in Marine Systems

Picture: Karsten Reise, Cartoon: Kochmann et al. 2008

Biological Invasions in Marine Systems

Outline

<u>Pathways in Marine Systems</u>

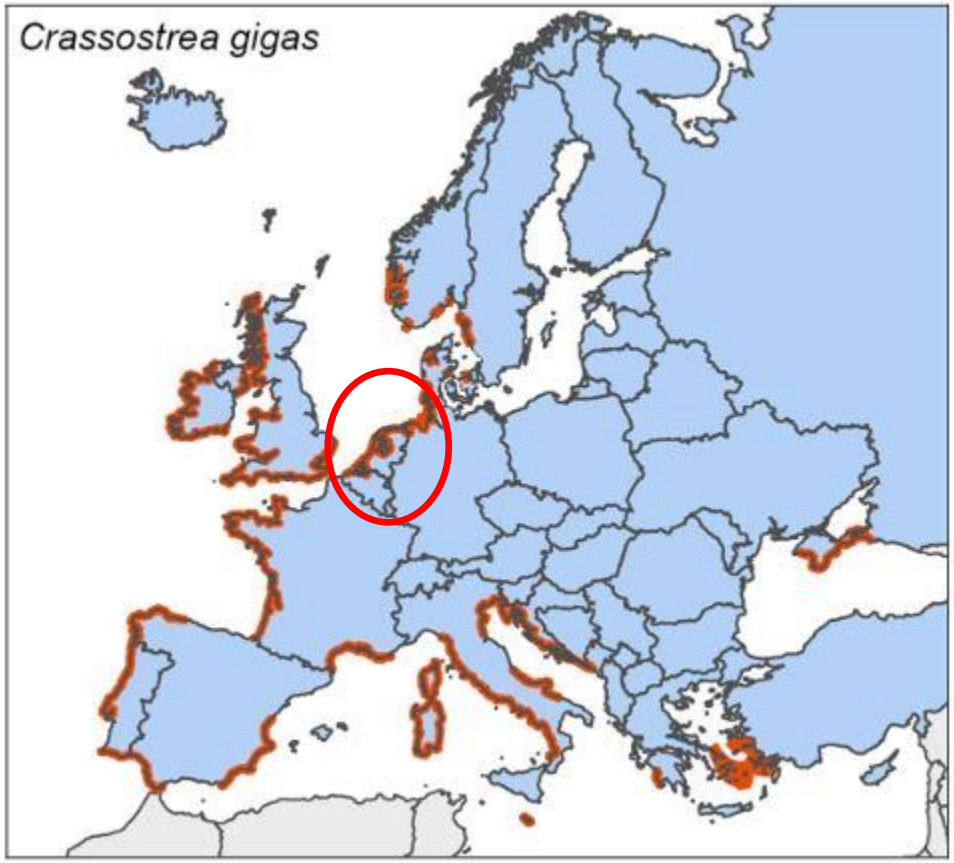
- Shipping (Boring, Fouling, Ballast Water)
- Global Aquaria Trade & Ornamental Escape
- **Aquaculture**
- **Canals**

- **Slides: Course website, juliusaellrich.weebly.com, USB drive**

Oyster On- & Off-bottom Culture

→ Multiple introductions, accidental escapes and releases, dispersal…

European Distribution



Multiple introductions with aquaculture operations on European coasts

Nehring 2011

Oyster Aquaculture in the Wadden Sea

***Crassostrea* aquaculture started:**

Netherlands (in 1964)

Germany (in 1971) & Sylt (in 1986)

(other countries followed)

Crassostrea gigas

The European Oyster *Ostrea edulis* decline:

Netherlands (1940ies – 1950ies)

Germany (1880ies)

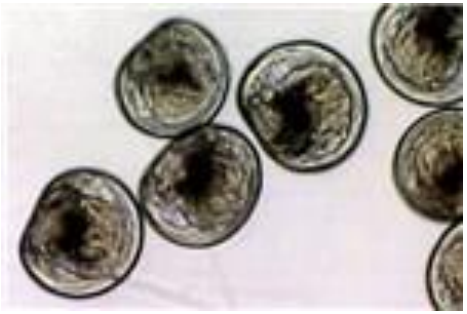
→ caused by overfishing

Ostrea edulis

Crassostrea Dispersal

Larval development: 3 weeks

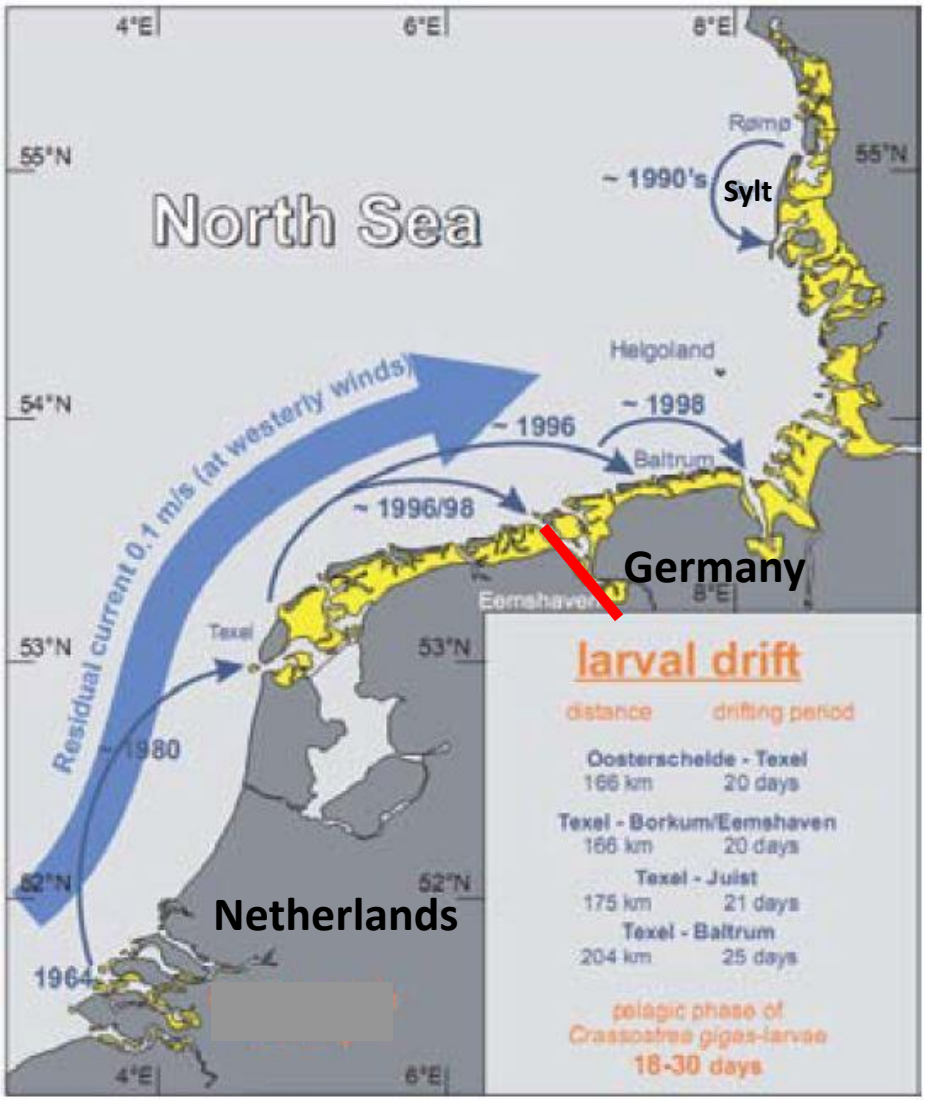
Veligers



Pediveliger

Recruitment: July & August

Troost 2010



Nehls et al. 2009


North Sea
THE WADDEN SEA
Waddenzee · Wattenmeer · Vadehavet
United Nations Educational, Scientific and Cultural Organization
The Wadden Sea World Heritage Site since 2009
WADDEN SEA
WORLD HERITAGE


Mudflats

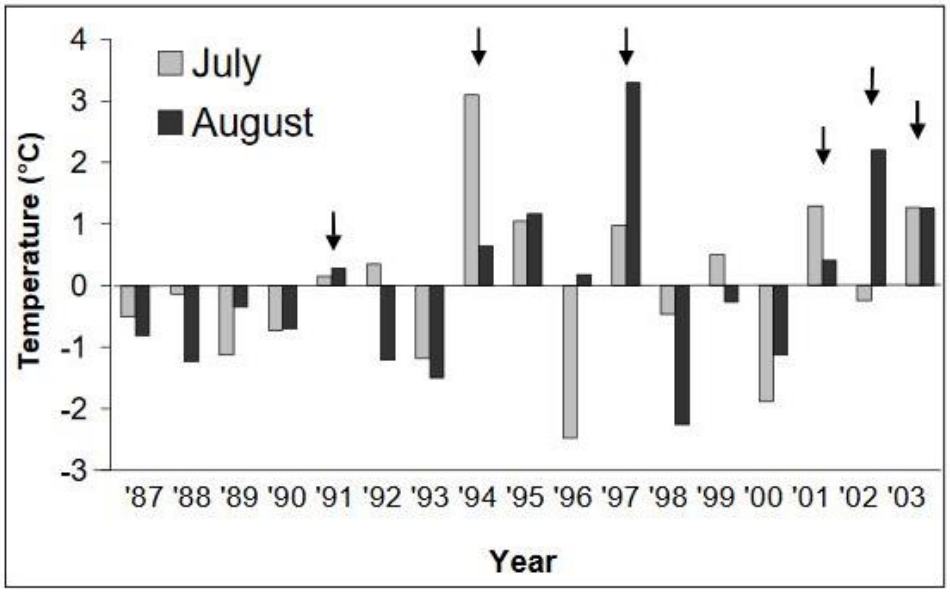
Mussel Beds are the Main Hard Substrates for Oyster Settlement

Kochmann et al. 2008

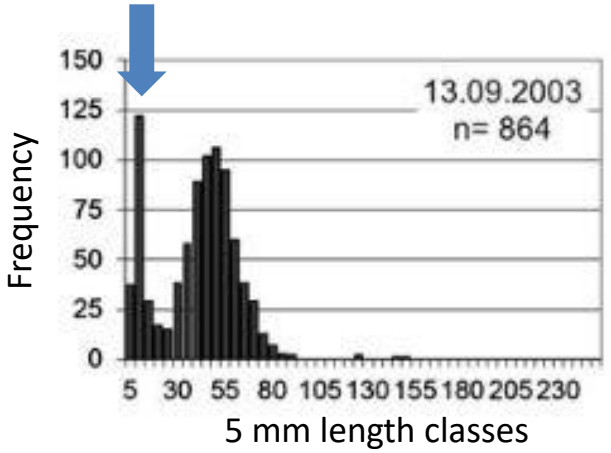
Mytilus edulis

Byssal threads

Warm Summers Favor *Crassostrea* Recruitment



Oyster recruits



Length-frequency distribution of Pacific oysters, n= number of oysters measured (Büttger et al. 2011)

Fig. 20: Deviation of mean monthly water temperature in July and August from the long-term mean (1987 - 2003). Arrows mark years with high *C. gigas* recruitment (1991, 1994, 1997, 2001, 2002, 2003) (Diederich et al. 2005).

Oyster Settlement & Recruitment

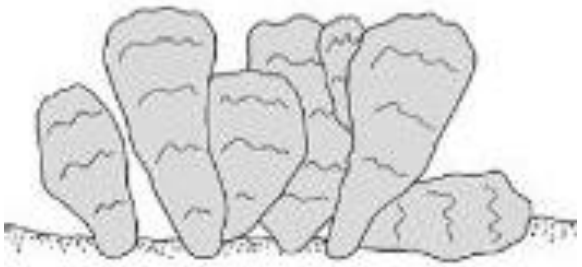
Mussel Bed

Mixed Bed

→ Changes in habitat structure

Cartoon: Kochmann et al. 2008

Oyster Recruitment on Conspecifics



Oyster Reef

→ Oysters are Ecosystem Engineers: Formation of Oyster Reefs

Left picture: Troost 2010, Cartoon: Kochmann et al. 2008

Changes in Community Structure With Decreasing Mussel Density

Mussel Bed | Mixed Bed | Oyster Reef

Overall: oysters decreased mussel density & biomass, competition for food, oysters are the superior competitors

Cartoon: Kochmann et al. 2008, Nehls et al. 2009

Establishment

- Predation **(biotic barrier)**
- Individual Growth **(species trait)**
- Ecosystem Engineering **(species trait)**
- Temperature **(abiotic barrier)**

Oyster Predators Native to the Wadden Sea

Oystercatcher
occur only locally

Haematopus ostralegus

Crabs
prefer mussels

Carcinus maenas & *Cancer magister*

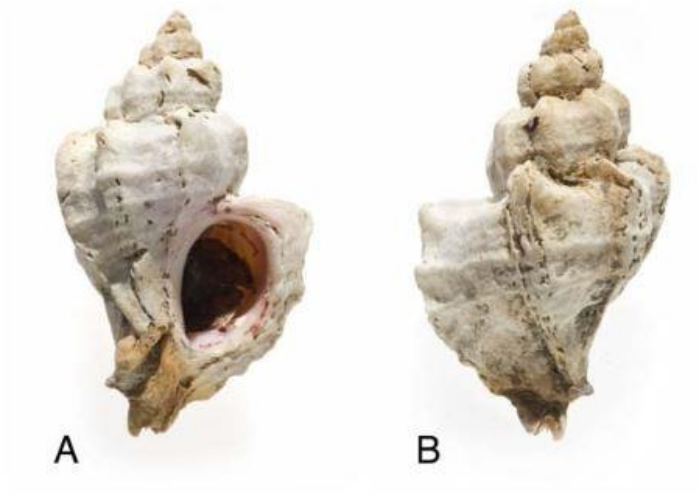
Sea stars prefer mussels

Asterias rubens

Diederich 2005, Cadée 2008

Oyster Predators Introduced to the Wadden Sea

Ocinebrellus inornatus



occur very locally

Urosalpinx cinerea

occur very locally

→ Predation on *C. gigas* is low

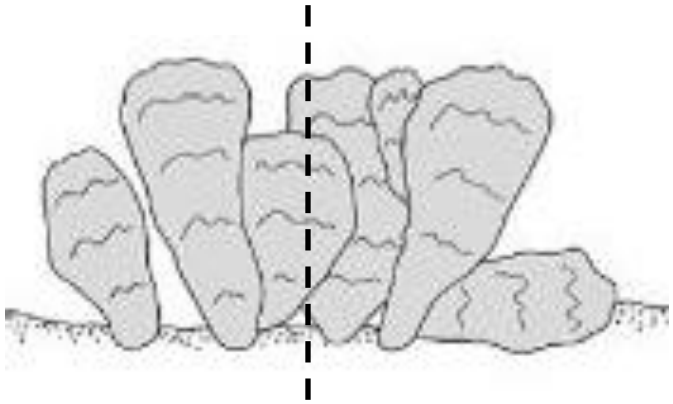
Fast Growth in Oyster Individuals

2 year old individuals: 30 mm to 80 mm length

→ size refuge from low predation

Ecosystem Engineering

less complex



complex

<u>Reef complexity may decrease:</u>

water flow

heat & desiccation

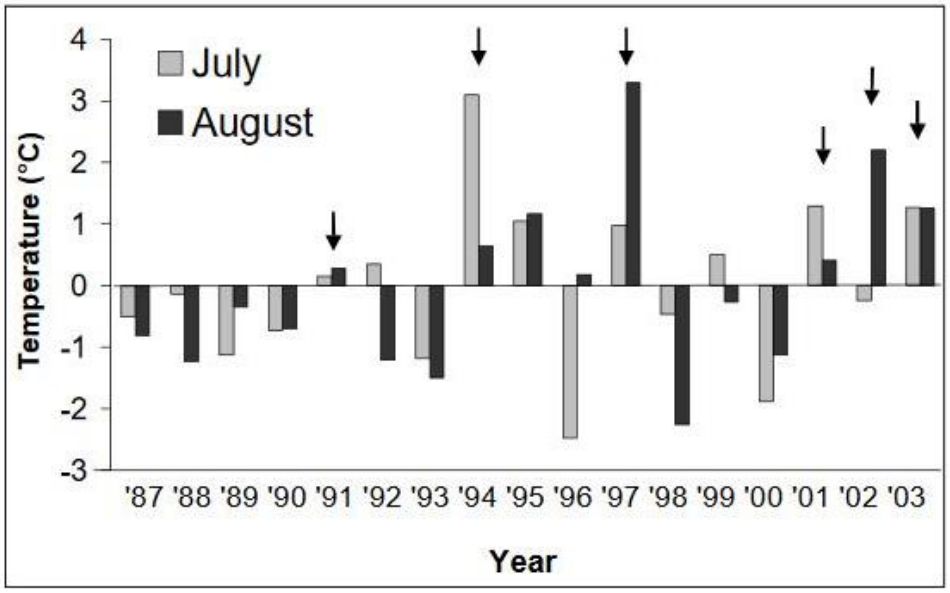
predation

<u>Reef complexity may increase:</u>

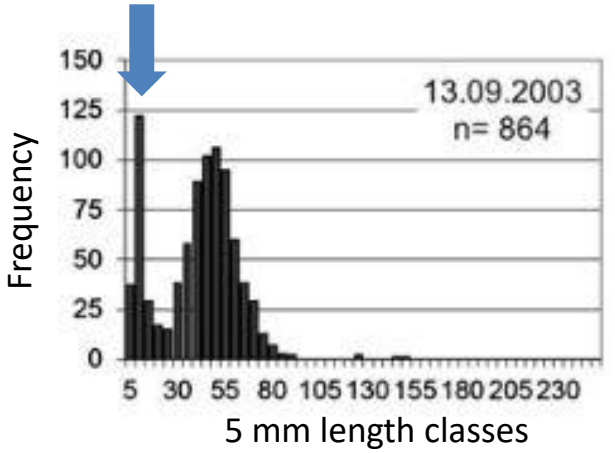
gregarious settlement

→ more oyster recruitment

Temperature:
Warm Summers Favor *Crassostrea* Recruitment



Oyster recruits



Length-frequency distribution
of Pacific oysters (Büttger et al. 2011)

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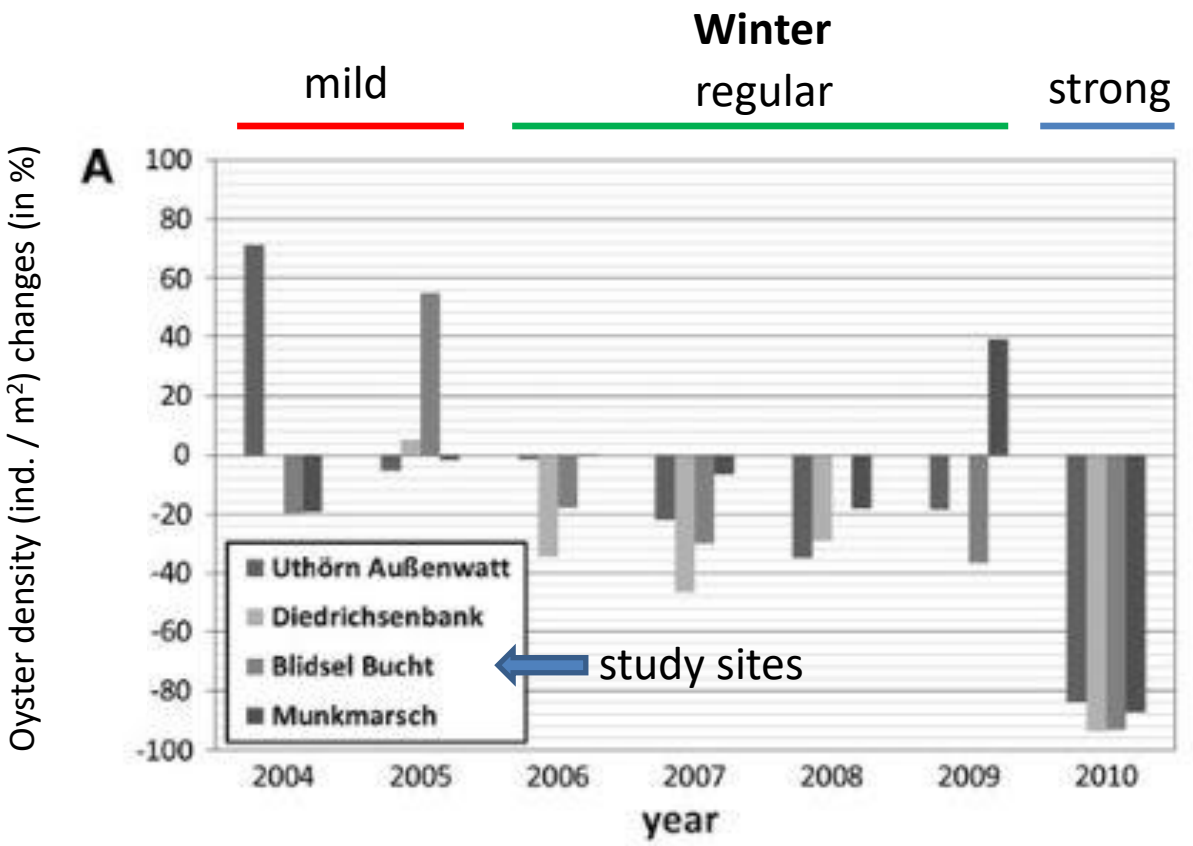
Temperature:
Cold Winters Decimate *Crassostrea* Populations



Oyster density changes (in %) over the winters from 2004 to 2010
(e.g. year 2004: autumn 2003 – spring 2004), modified after Büttger et al. 2011)

Species Introduced with *Crassostrea*

Seaweed, *Sargassum muticum*

Slipper Limpet, *Crepidula fornicata*

Oysters Benefit Local Economy

Oyster Impacts on Human Health

Wadden Sea

Biological Invasions in Marine Systems

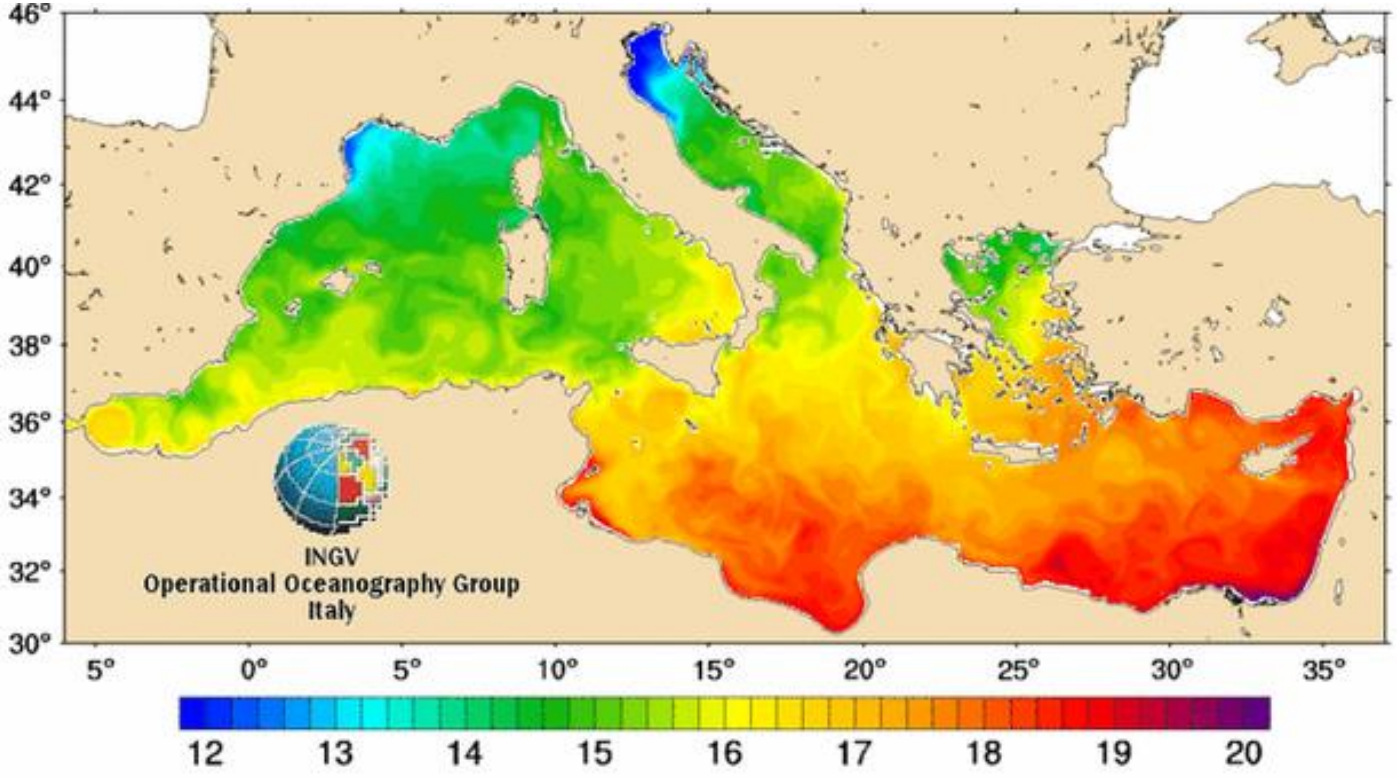
- Canals -

Mediterranean Sea

Temperature in the Mediterranean Sea

Sea Surface Temperature in Summer

W



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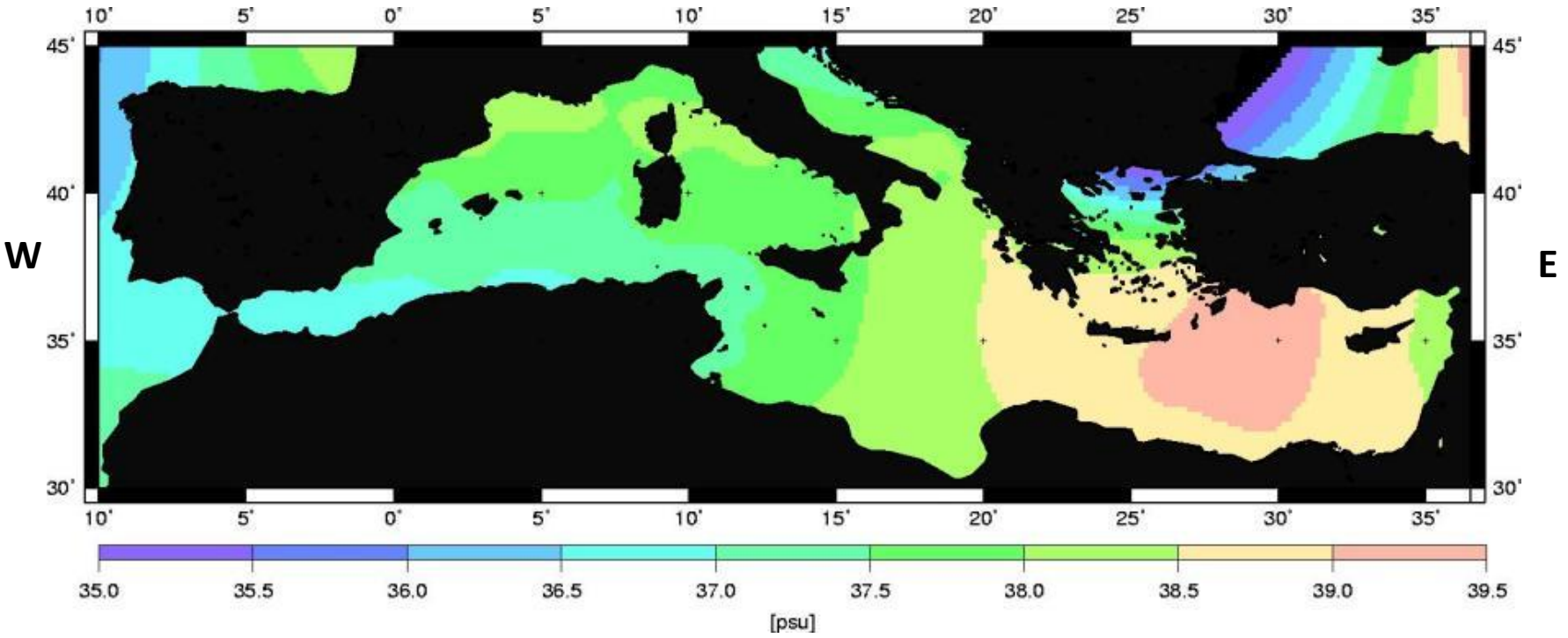
Temperature increases from West to East

Salinity in the Mediterranean Sea

Salinity



psu = practical salt unit

Salinity increases from West to East

Species Richness of Native Fish & Invertebrates in the Mediterranean Sea

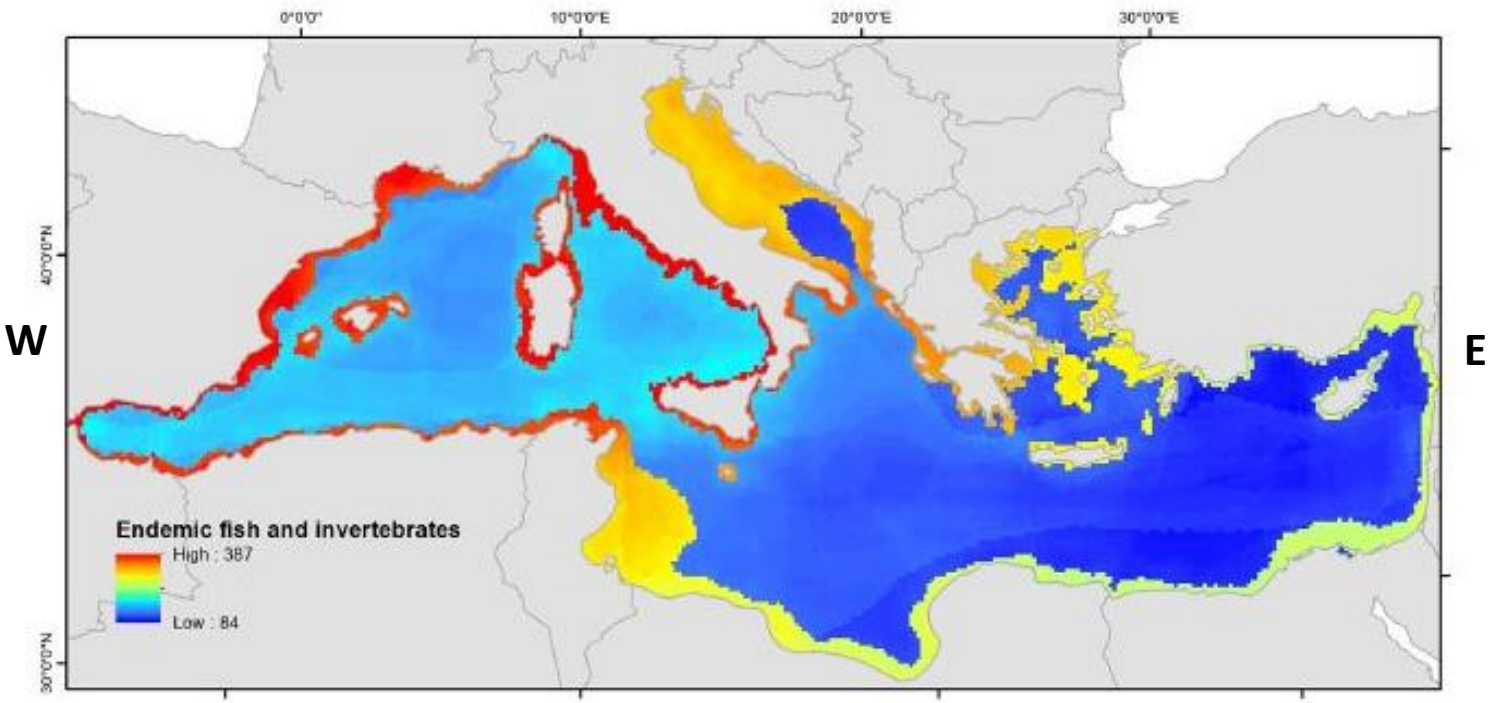


FIGURE 7 | Richness (number of species in a 10 × 10 km grid) of native fish and invertebrates in the Mediterranean Sea. The data are plotted using a linear scale from minimum to maximum values.

>17,000 marine species, Atlantic origin, one fifth are endemic species

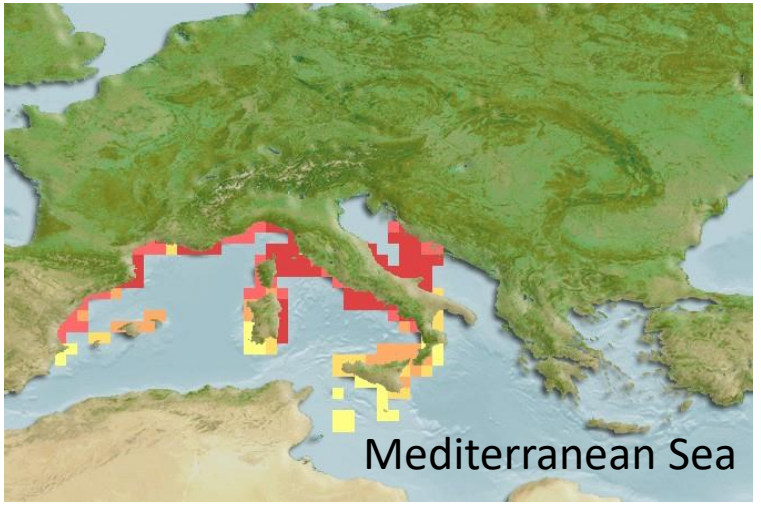
Species richness decreases from West to East

Katsanevakis et al. 2014

Endemic Species

A species being unique to a defined geographic area

A goby,
Buenia affinis, Iljin 1930,
endemic to the Mediterranean Sea



B. affinis, distribution

http://www.fishbase.ca/

FishBase

Invasive Species Impacts in the Mediterranean Sea

Ecological Impacts

- Displacement of native (& endemic) species
- Changes in community structure
- Effects on food web structure
- Modification of habitats

Economic Loss

Human health

Katsanevakis et al. 2014

Pathways into the Mediterranean Sea

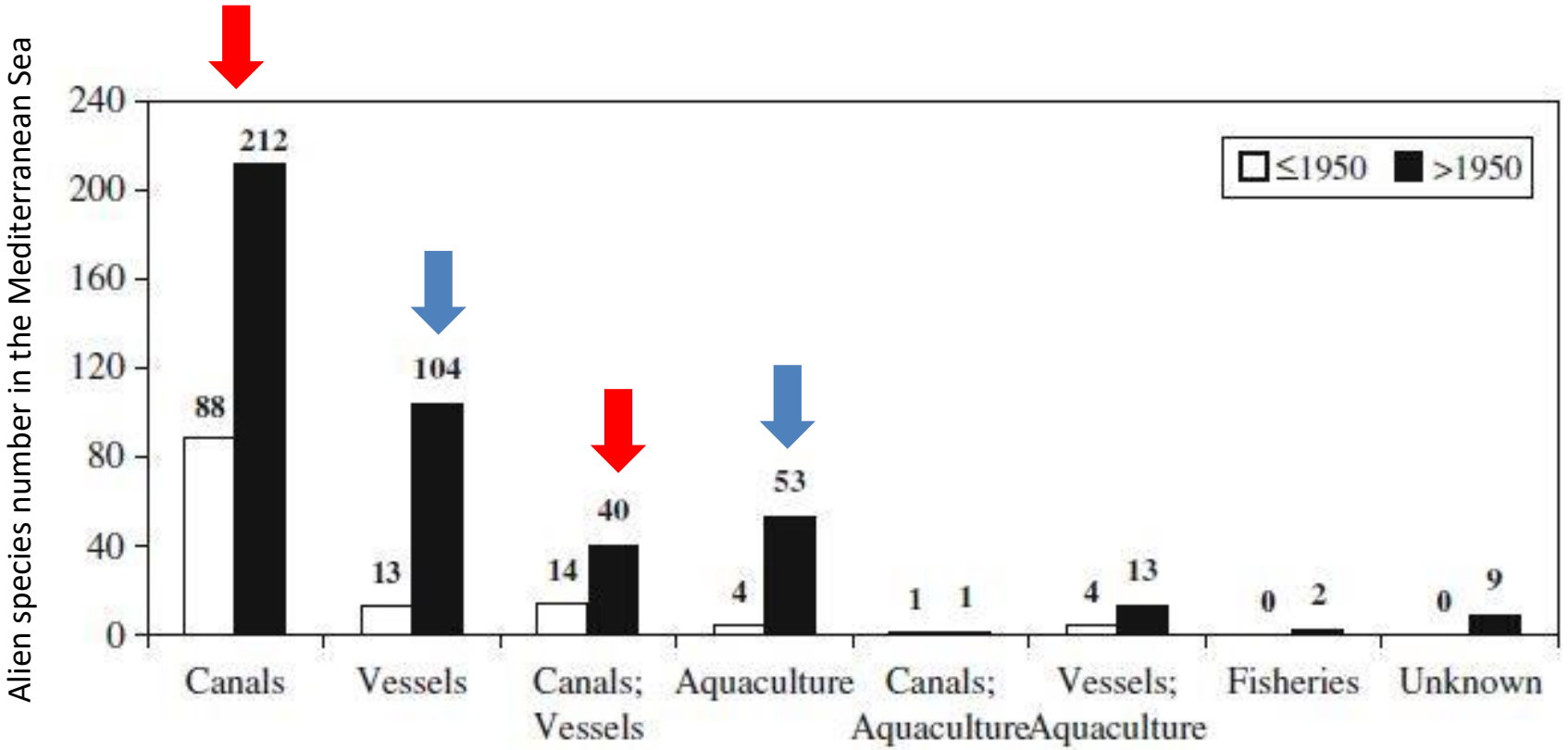
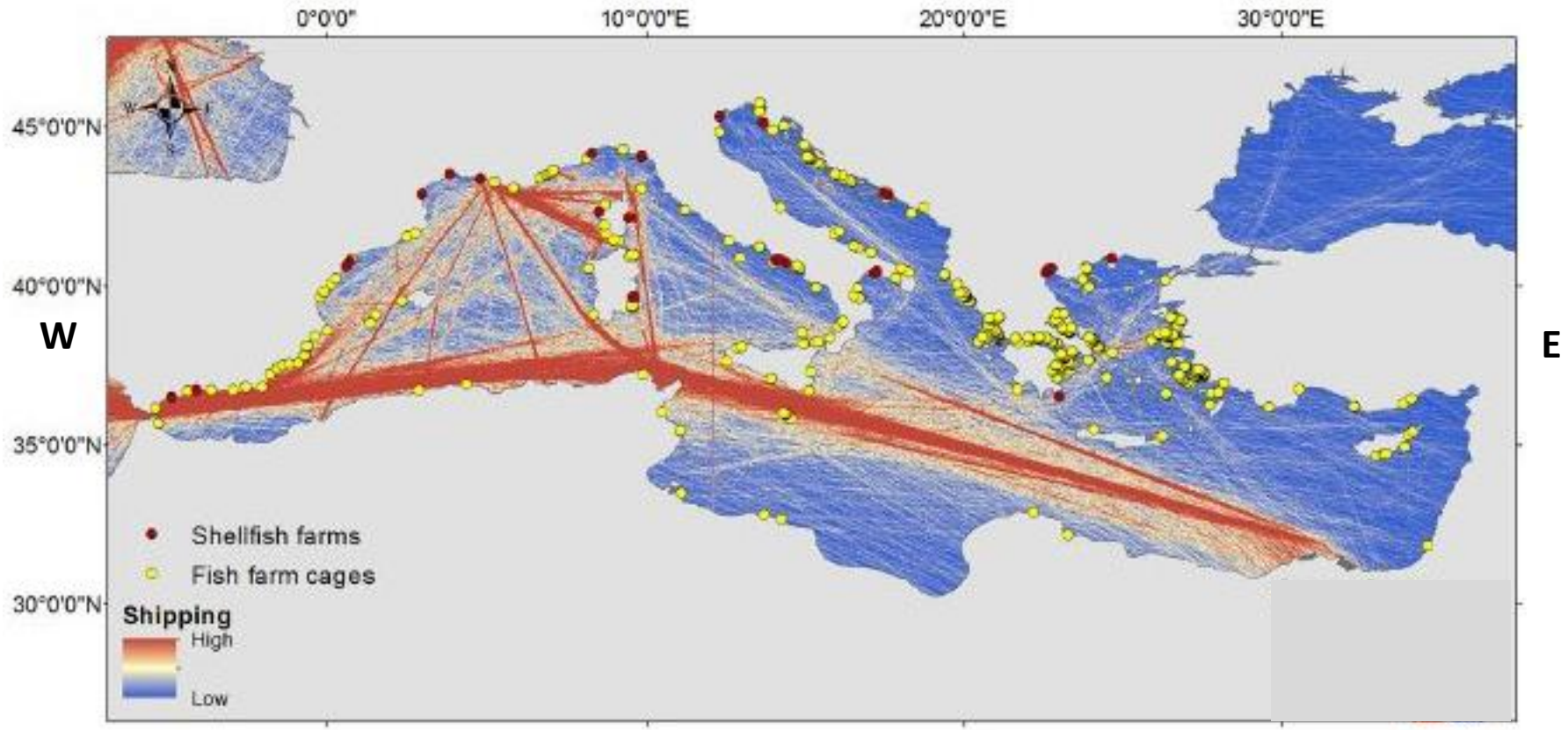


Fig. 6 Number of alien species in the Mediterranean Sea, presented by means of introduction, before and after 1950

Galil 2008, Hydrobiologia

Vessels & Aquaculture



Katsanevakis et al. 2014

Mediterranean Sea: The Suez Canal

Suez Canal

The Suez Canal connects the Mediterranean Sea with the Red sea across the Isthmus of Suez

Suez Canal as Trade Route

Suez Canal passage duration (today): 13 - 14 h

Construction of the Suez Canal

Ferdinand de Lesseps
(1805-1894)

Hofrichter 2002, Tardent 2005

1859-1869:
Construction

Length:
161 km

Average Depth:
13 m

Width:
80 – 150 m

one way traffic

no locks

Lessepsian Migration

Red Sea & Indo-Pacific species invading the Mediterranean via the Suez Canal

Ferdinand de Lesseps
(1805-1894)

Removal of a geographic barrier → Natural range expansion (larval drift, dispersal)

Hofrichter 2002, Galil et al. 2015

Lessepsian Migration: 4 Drivers

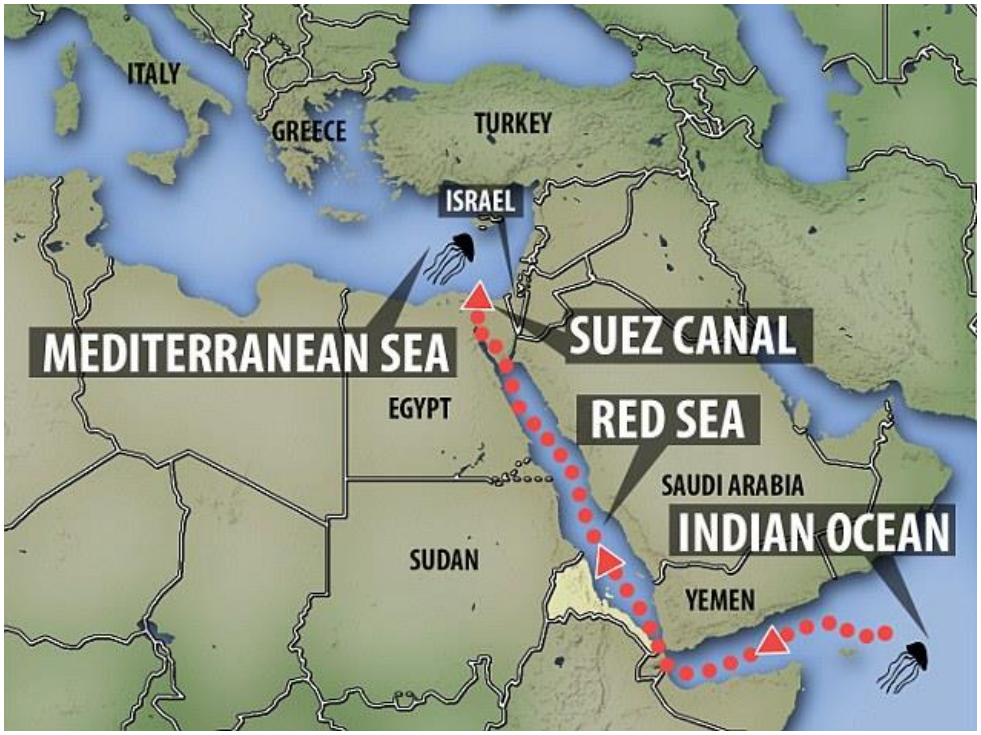
- Salinity
- Temperature
- Water Flow
- Wind Direction

Hofrichter 2002, Tardent 2005, Zakaria 2015, Hafner & Rudolf 2016

Salinity

Eastern Mediterranean:

38.5 psu



Northern Red Sea:

> 41 psu

Red Sea species tolerate higher salinities

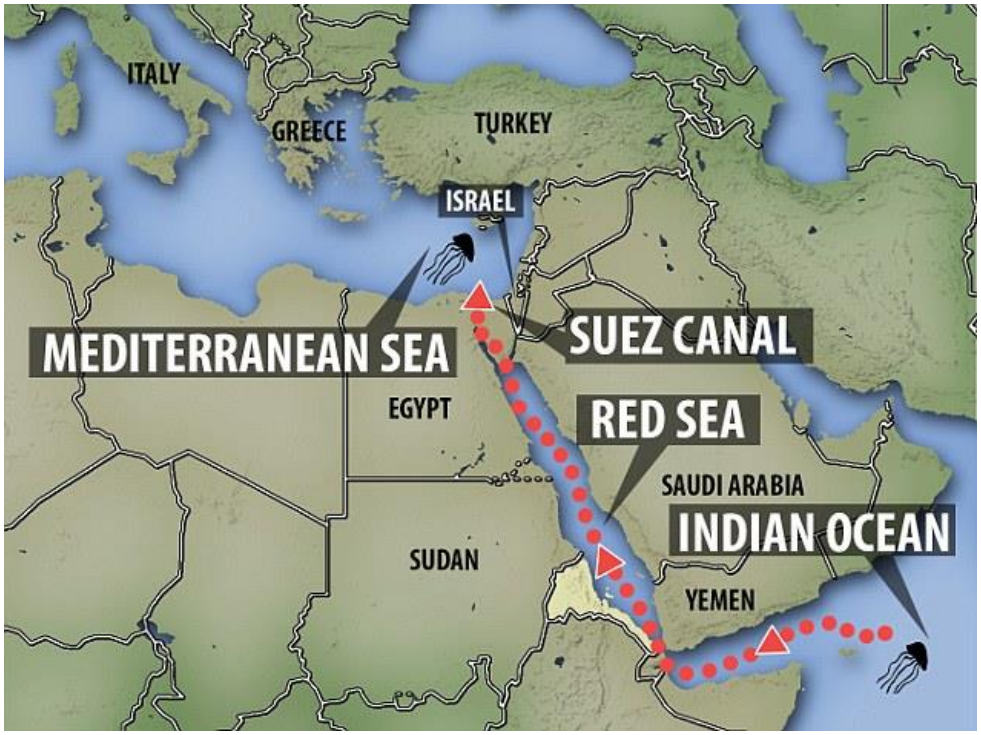
→ Red Sea species can migrate into the Mediterranean Sea

Zakaria 2015

Temperature

Eastern Mediterranean:

Summer:
20 °C



Northern Red Sea:

Summer:
28 °C

Red Sea species tolerate higher temperatures

→ Red Sea species can migrate into the Mediterranean Sea

Zakaria 2015

Prevailing Water Flow

The Red Sea surface is 25 – 40 cm higher than the Mediterranean Sea surface.

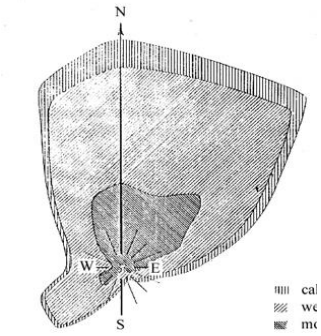
→ Water flows primarily northwards

→ Prevailing water flow enhances immigration into the Mediterranean Sea.

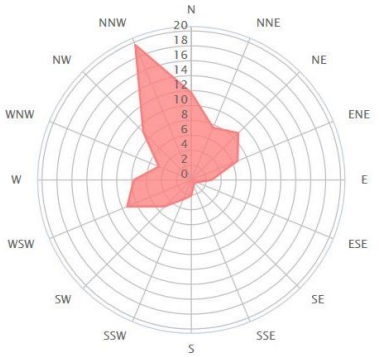
Hafner & Rudolf 2016

Prevailing Wind Direction

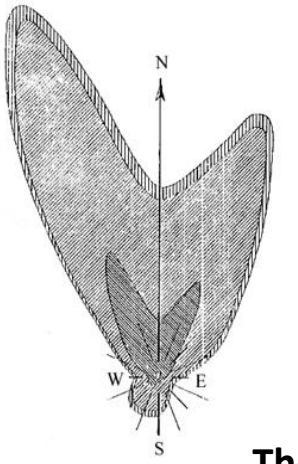
Port Said



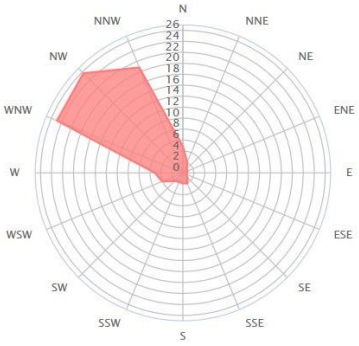
Port Said

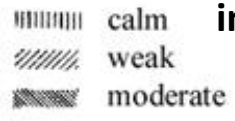


Port Taufiq



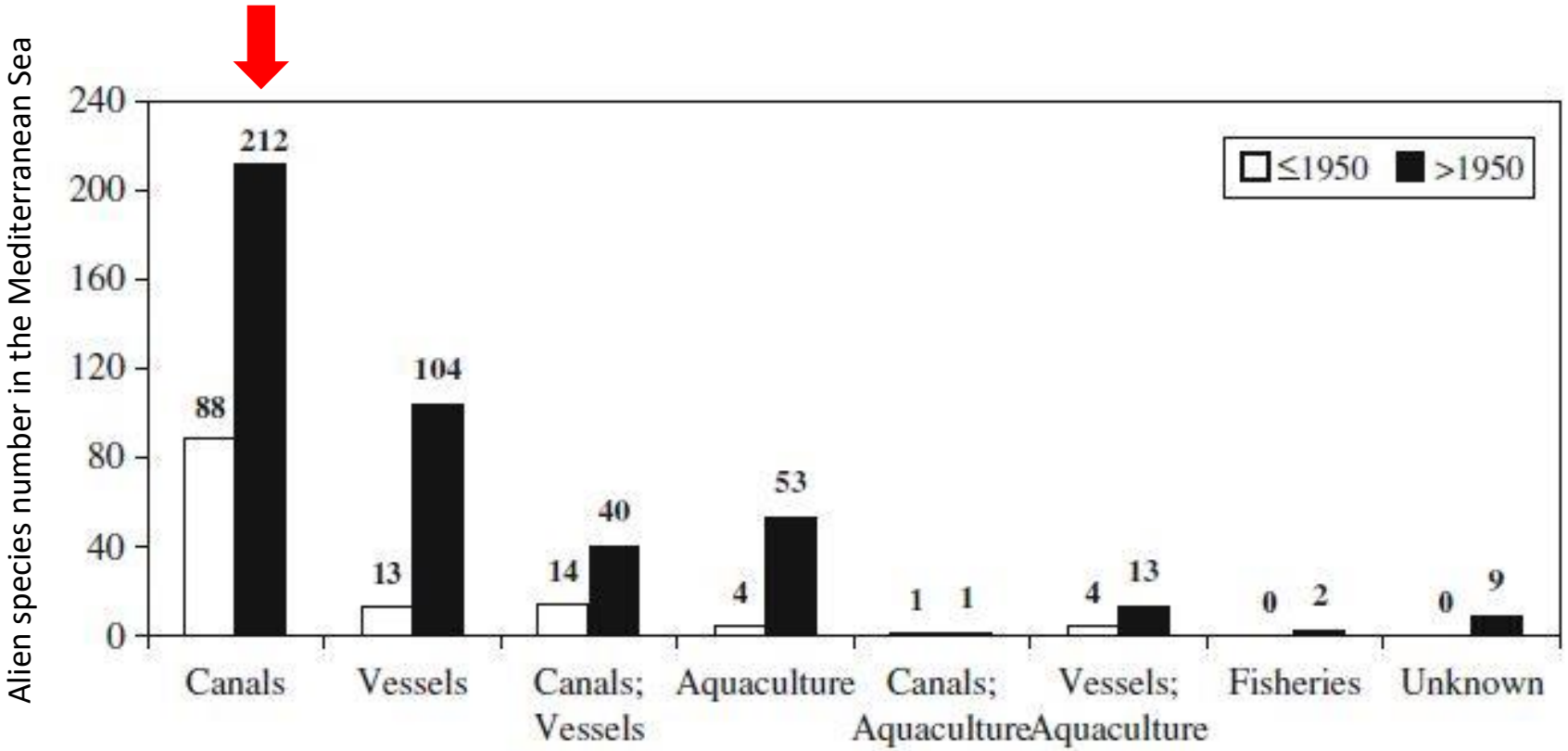
Ras Sudr





The prevailing wind direction supports immigration to the Mediterranean Sea.

Invasion Increase > 1950



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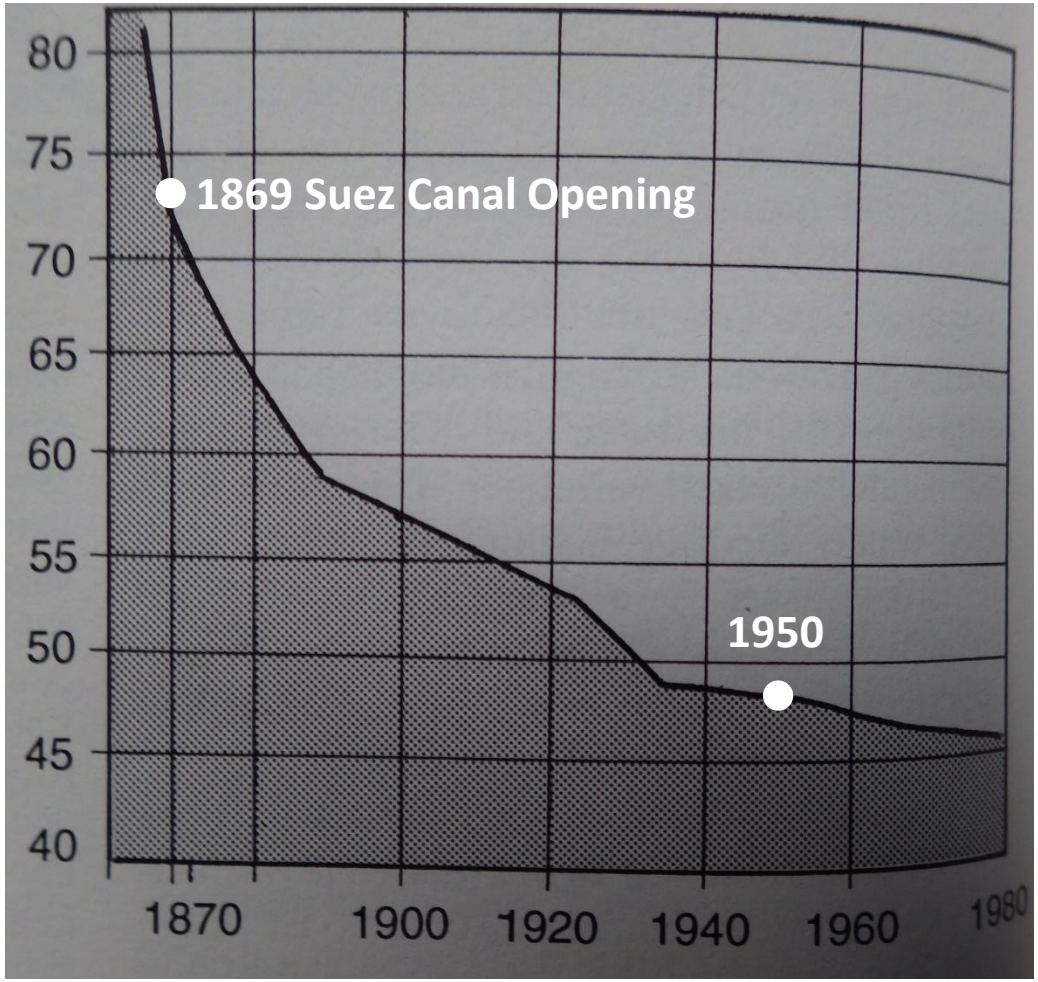
Galil 2008

The Bitter Lake Salt Valley

a Salt Valley

The Bitter Lake Salinity Barrier Over Time



ca. 40 psu
(currently)

→ **Facilitation of Lessepsian Migration**

Tardent 2005

The Nile Delta Outflow Before 1966

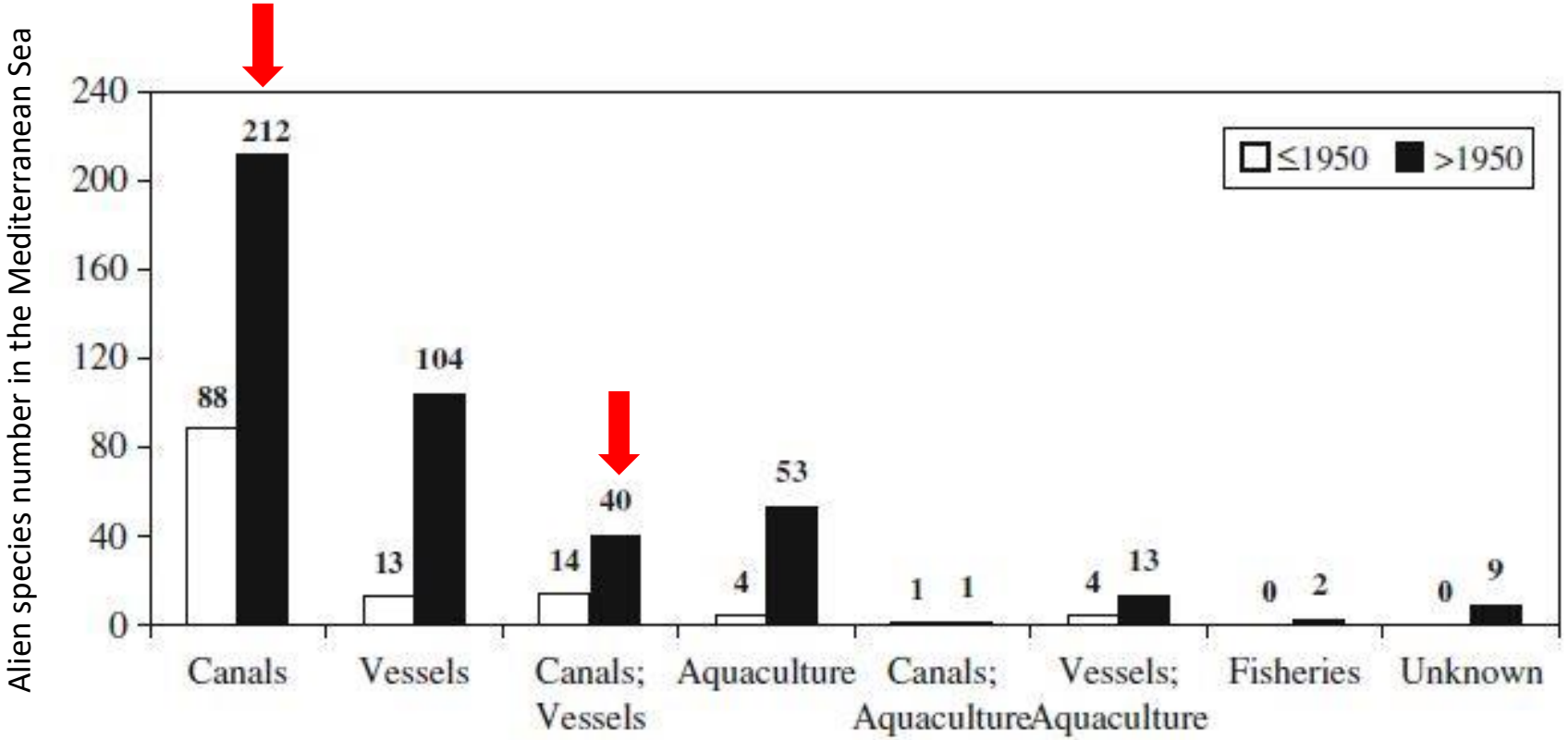
→ **Freshwater Barrier (33 psu)**

Hafner & Rudolf 2016

The Aswan Dam Construction: 1960 - 1970

The Aswan Dam limited the Nile River delta freshwater barrier

Invasion Increase > 1950



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The Bitter Lake desalination & the Nile river delta manipulation facilitated the Lessepsian migration.

Galil 2008, Hydrobiologia

Shipping Increase Through the Suez Canal

Ships (per year)

468 (1870)

1.600 (1879)

3.389 (1890)

12.168 (1952)

21.250 (1966)

21.999 (1978)

17.317 (1993)

11.748 (2000)

17.483 (2015)

Ships in Port Said, 1880

Ship, recent

Dry ballast → Ballast water

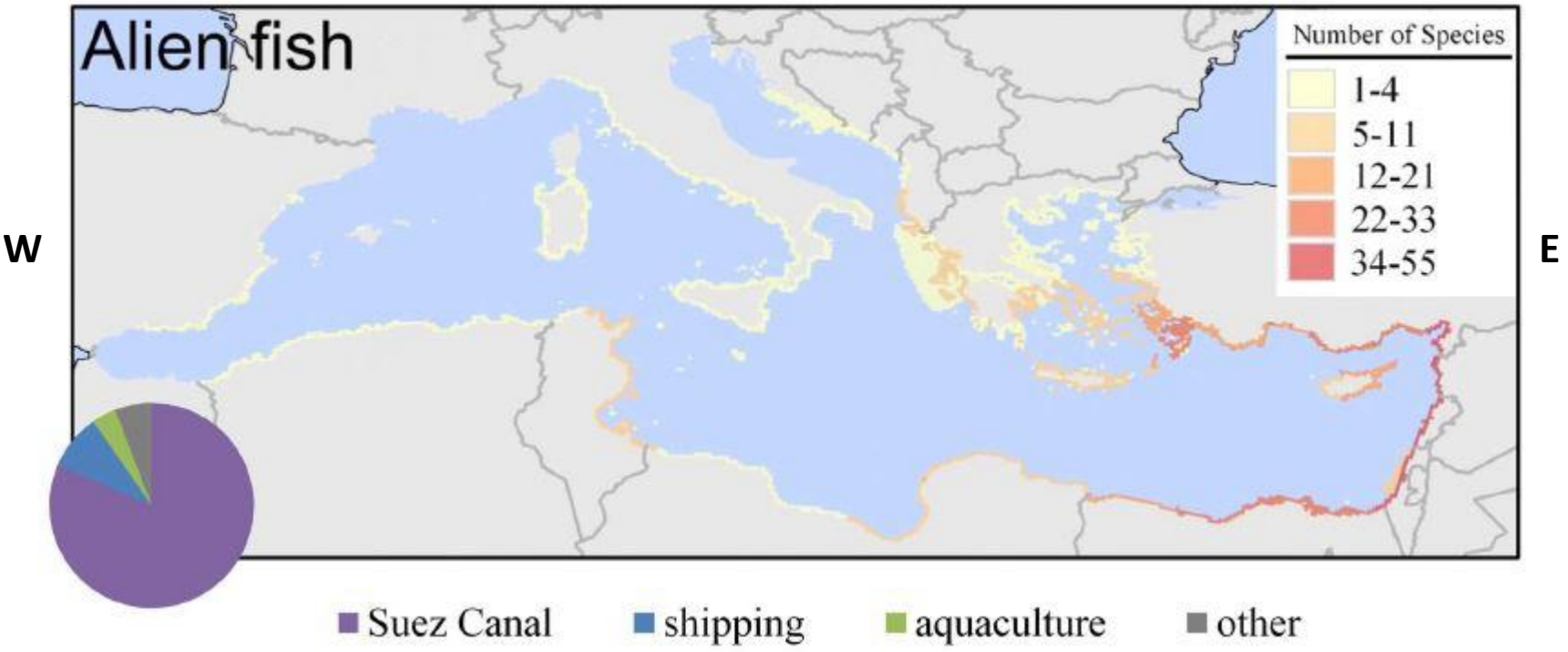
Ship size & ballast water increase

Port water quality improvements

Travelling time reduction

Results:

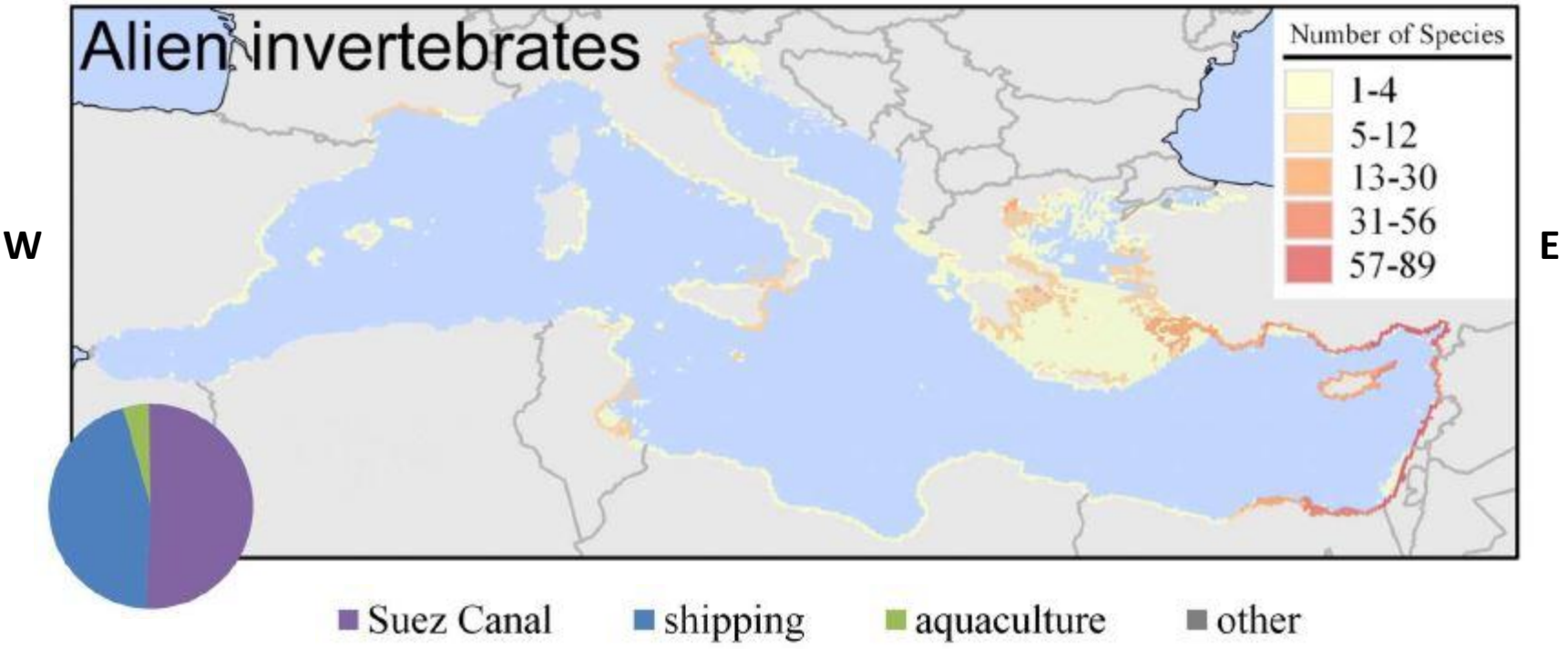
Species Richness in Introduced Fish



W E

Katsanevakis et al. 2014

Species Richness of Introduced Invertebrates

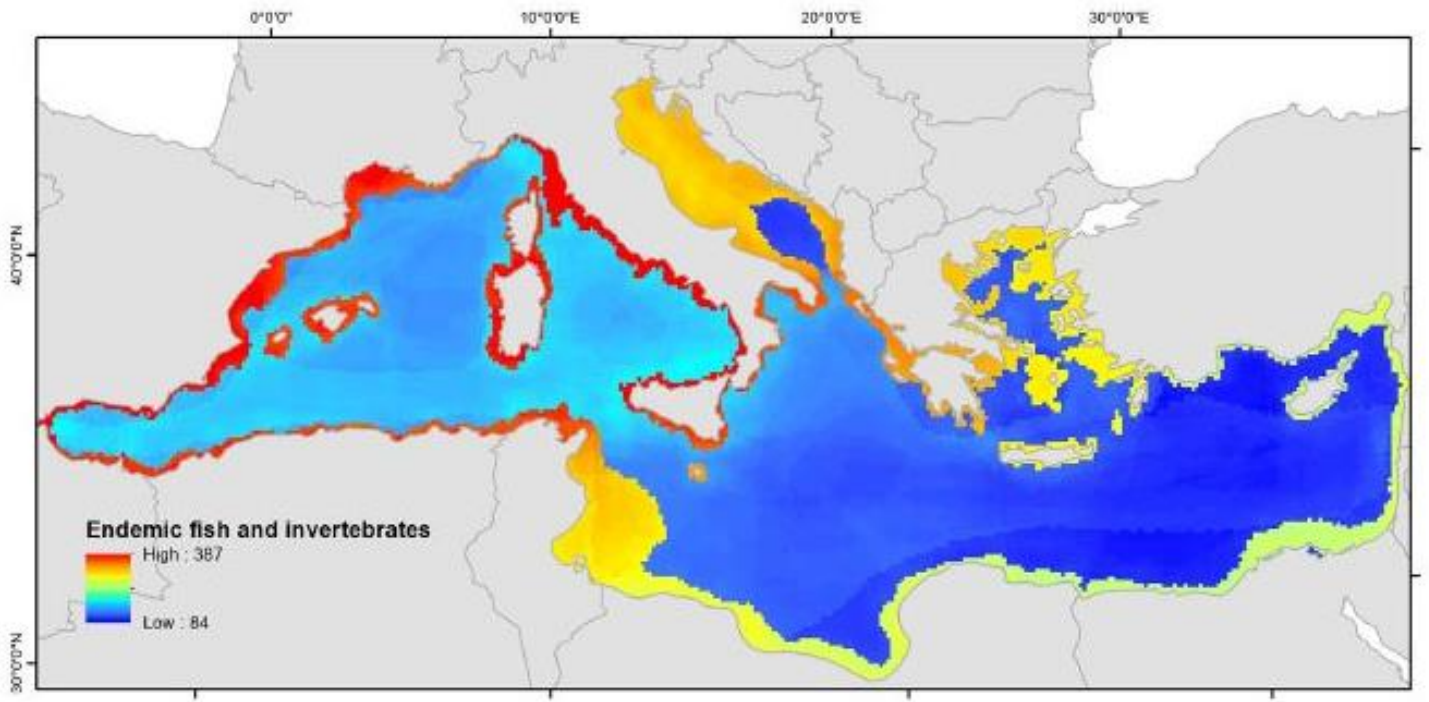


W E

Katsanevakis et al. 2014

Species Richness of Native Fish & Invertebrates

W



E

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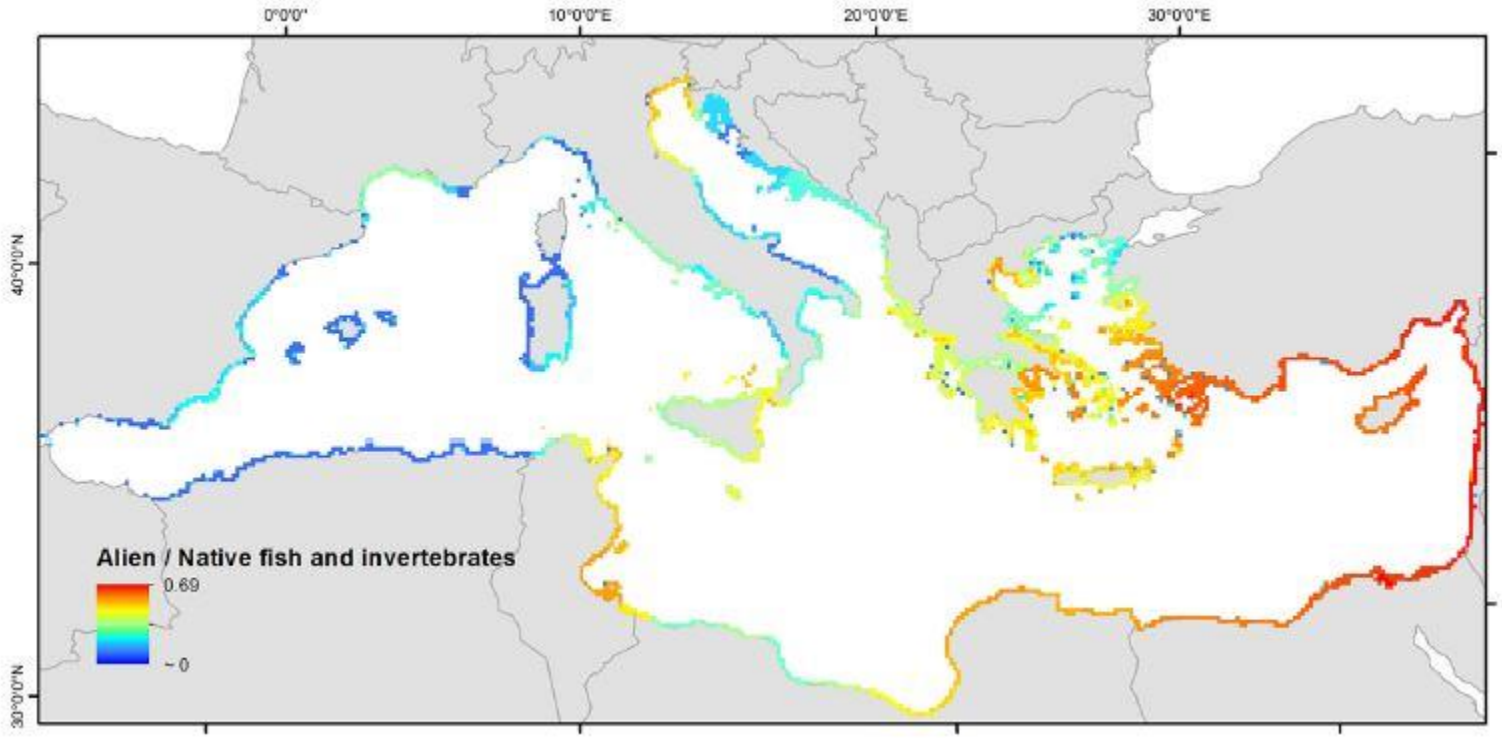
Species richness decreases from West to East

Katsanevakis et al. 2014

Introduced / Native fish & Invertebrate Ratio

W



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→ **Indication of change in community composition**

Introduced Species from the Red Sea

Fish

Family	Species
Acropomatidae	*Synagrops japonicus*
Apogonidae	*Apogon nigripinnis*
Atherinidae	*Atherinomorus lacunosus*
Belonidae	*Tylosurus choram*
Blenniidae	*Petroscirtes ancylodon*
Callionymidae	*Callionymus filamentosus*
Carangidae	*Alepes djedaba*
Clupeidae	*Dussumieria elopsoides, Etrumeus teres, Herklotsichthys punctatus, Spratelloides delicatulus*
Congridae	*Rhynchoconger trewavasae*
Cynoglossidae	*Cynoglossus sinusarabici*
Dasyatidae	*Himantura uarnak*
Diodontidae	*Chilomycterus spilostylus*
Exocoetidae	*Parexocoetus mento*
Fistularidae	*Fistularia commersonii*
Gobiidae	*Coryogalops ochetica, Oxyurichthys petersi, Silhouetta aegyptia*
Haemulidae	*Pomadasys stridens*
Hemiramphidae	*Hemiramphus far, Hyporhamphus affinis*
Holocentridae	*Sargocentron rubrum*
Istiophoridae	*Makaira indica*
Labridae	*Pteragogus pelycus*
Leiognathidae	*Leiognathus klunzingeri*
Lutjanidae	*Lutjanus argentimaculatus*
Monacanthidae	*Stephanolepis diaspros*
Mugilidae	*Liza carinata, Mugil soiuy*
Mullidae	*Upeneus moluccensis, U. pori*
Muraenesocidae	*Muraenesox cinereus*
Ostraciidae	*Tetrosomus gibbosus*
Pempheridae	*Pempheris vanicolensis*
Platycephalidae	*Papilloculiceps longiceps, Platycephalus indicus, Sorsogona prionota*
Pomacentridae	*Abudefduf vaigiensis*
Rachycentridae	*Rachycentron canadum*
Scombridae	*Rastrelliger kanagurta, Scomberomorus commerson*
Scorpaenidae	*Pterois miles*
Serranidae	*Epinephelus coioides, E. malabaricus*
Siganidae	*Siganus luridus, S. rivulatus*
Sillaginidae	*Sillago sihama*
Sparidae	*Crenidens crenidens, Rhabdosargus haffara*
Sphyraenidae	*Sphyraena chrysotaenia, S. flavicauda*
Synodontidae	*Saurida undosquamis*
Teraponidae	*Pelates quadrilineatus, Terapon puta*
Tetraodontidae	*Lagocephalus spadiceus, L. suezensis, Torquigener flavimaculosus*

Crustaceans

Decapoda Macrura	
Alpheidae	*Alpheus edwardsii, A. lobidens, A. migrans, A. rapacida*
Luciferidae	*Lucifer hanseni*
Ogyrididae	*Ogyrides mjoebergi*
Palaemonidae	*Palaemonella rotumana, Periclimenes calmani*
Palinuridae	*Panulirus ornatus*
Pasiphaeidae	*Leptochela aculeocaudata, L. pugnax*
Penaeidae	*Marsupenaeus japonicus, Melicertus hathor, Metapenaeopsis aegyptia, M. mogiensis consobrina, Metapenaeus monoceros, M. stebbingi, Penaeus semisulcatus, Trachysalambria curvirostris*
Solenoceridae	*Solenocera crassicornis*
Decapoda Brachyura	
Calappidae	*Ashtoret lunaris*
Euryplacidae	*Eucrate crenata*
Grapsidae	*Plagusia tuberculata*
Leucosiidae	*Ixa monodi, Leucosia signata, Myra subgranulata*
Majidae	*Hyastenus hilgendorfi, Micippa thalia*
Ocypodidae	*Macrophthalmus graeffei*
Pilumnidae	*Halimeda tyche, Heteropanope laevis, Pilumnopeus vauquelini, Pilumnus hirsutus*
Portunidae	*Charybdis helleri, Ch. longicollis, Portunus pelagicus, Thalamita gloriensis, T. poissonii*
Raninidae	*Notopus dorsipes*
Xanthidae	*Atergatis roseus, Daira perlata, Sphaerozius nitidus*
Stomatopoda	
Squillidae	*Erugosquilla massavensis*

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Molluscs

Bivalvia, Pteromorpha	
Arcidae	*Acar plicata, Anadara demiri, A. inaequivalvis, A. natalensis*
Glycymeridae	*Glycymeris arabicus*
Limopsidae	*Limopsis multistriata*
Malleidae	*Malleus regulus*
Mytilidae	*Brachidontes pharaonis, Musculista perfragilis, M. senhousia, Modiolus auriculatus, Xenostrobus securis*
Ostreidae	*Crassostrea gigas, Saccostrea cucullata*
Pteriidae	*Pinctada margaritifera, P. radiata*
Spondylidae	*Spondylus spinosus, S. groschi*
Bivalvia, Heterodonta	
Cardiidae	*Fulvia australis, F. fragilis*
Chamidae	*Chama pacifica, Pseudochama corbieri*
Gastrochaenidae	*Gastrochaena cymbium*
Lucinidae	*Divalinga arabica*
Mactridae	*Mactra olorina*
Mesodesmatidae	*Atactodea glabrata*
Myidae	*Sphenia rueppelli*
Psammobiidae	*Hiatula ruppelliana*
Tellinidae	*Psammotreta praerupta, Tellina valtonis*
Trapeziidae	*Trapezium oblongum*
Veneridae	*Antigona lamellaris, Circenita callipyga, Clementia papyracea, Dosinia erythraea, Gafrarium pectinatum, Paphia textile, Tapes philippinarum*
Bivalvia, Anomalodesmata	
Laternulidae	*Laternula anatina*
Gastropoda, Opisthobranchia	
Aeolidioidea	*Aeolidiella indica*
Aglajidae	*Chelidonura fulvipunctata*
Aplysiidae	*Bursatella leachi*
Bullidae	*Bulla ampulla*
Chromodoridae	*Chromodoris quadricolor, Hypselodoris infucata*
Cylichnidae	*Acteocina mucronata, Cylichnina girardi*
Dendrodoridae	*Dendrodoris fumata*
Flabellinidae	*Flabellina rubrolineata*
Glaucidae	*Caloria indica*
Pleurobranchidae	*Pleurobranchus forskali*
Polyceridae / Triophidae	*Plocamopherus ocellatus*
Retusidae	*Pyrunculus fourierii*
Tergipedidae	*Cuthona perca*
Tethyidae	*Melibe fimbriata*

Gastropoda, Prosobranchia	
Cerithiidae	*Cerithium nesioticum, C. nodulosum, C. scabridum, Clypeomorus bifasciatus, Rhinoclavis kochi*
Cerithiopsidae	*Cerithiopsis pulvis, C. tenthrenois*
Columbellidae	*Anachis savignyi, A. selasphora*
Conidae	*Conus fumigatus*
Costellariidae	*Pusia depexa*
Cypraeidae	*Erosaria turdus, Palmadusta lentiginosa lentiginosa, Purpuradusta gracilis notata*
Dialidae	*Diala varia*
Epitoniidae	*Cycloscala hyalina*
Eulimidae	*Sticteulima lentiginosa*
Fasciolariidae	*Fusinus marmoratus*
Fissurellidae	*Diodora ruppellii*
Haliotidae	*Haliotis pustulata cruenta*
Hipponicidae	*Sabia conica*
Litiopidae	*Alaba punctostriata*
Muricidae	*Ergalatax obscura, Murex forskoehlii, Rapana venosa, Rapana rapiformis, Thais lacerus*
Nacellidae	*Cellana rota*
Nassariidae	*Nassarius arcularius plicatus*
Naticidae	*Natica gualteriana*
Neritidae	*Nerita sanguinolenta, Smaragdia souverbiana*
Obtortionidae	*Clathrofenella ferruginea, Finella pupoides*
Planaxidae	*Angiola punctostriata, Planaxis savignyi*
Rissoidae	*Alvania dorbignyi, Rissoina bertholleti, R. spirata, Woorwindia tiberiana*
Strombidae	*Strombus persicus*
Triphoridae	*Metaxia bacillum*
Trochidae	*Trochus erythraeus, Pseudominolia nedyma*
Vasidae	*Vasum turbinellus*
Gastropoda, Heterobranchia	
Anisocyclidae	*Murchisonella columna*
Pyramidellidae	*Adelactaeon fulvus, A. amoenus, Chrysallida fischeri, C. maiae, C. pirintella, Cingulina isseli, Iolaea neofelixoides, Odostomia lorioli, Oscilla jocosa, Styloptygma beatrix, Syrnola fasciata, S. cinctella, Turbonilla edgarii*
Gastropoda, Divasibranchia	
Siphonariidae	*Siphonaria kurracheensis*
Polyplacophora	
Chitonidae	*Chiton hululensis*

Tabelle 8.11 *In das Mittelmeer eingewanderte Mollusken (Lesseps'sche Migranten). Angaben nach CIESM (Atlas of Exotic Species in the Mediterranean Sea).*

Hofrichter 2002 → http://www.ciesm.org/online/atlas/intro.htm

Introduction: Mobility & Salinity Tolerance

Charybdis helleri, (A. Milne-Edwards 1867)

Charybdis longicollis, Leene 1938

Swimcrabs:

early invaders

active swimmers

strong osmoregulators

→established in benthic habitats of the eastern Mediterranean coast

Hofrichter 2002

Establishment: Activity Patterns

Introduced from the Red Sea:

Red soldierfish
Sargocentron rubrum
(Forsskål, 1775)

Bullseye cardinalfish
Apogon nigripinnis
Cuvier, 1828

Vanikolo sweeper
Pempheris vanicolensis
Cuvier, 1831

No native nocturnal fish (active during the night) in the eastern Mediterranean

Hofrichter 2002

Establishment: Ecosystem Engineering

Oysters: *Saccostrea cucullata*

Ecosystem engineering of oyster reefs

→ Habitat modification facilitating oyster establishment

Nawrot et al. 2015, Cartoon: Kochmann et al. 2008

Establishment: Low Competition

Native to the Mediterranean

Sarpa salpa (Linnaeus, 1758)

Sparisoma cretense (Linnaeus, 1758)

Introduced from the Red Sea

Siganus luridus (Rüppell, 1829)

Siganus rivulatus Forsskål, 1775

Hofrichter 2002, Hafner & Rudolf 2016

Establishment: Distribution Partitioning

Goatfish:

Upenus moluccensis,
(Bleeker, 1855)

Introduced from the Red Sea,
10 - 30 m depth

Upenus pori
Ben-Tuvia & Golani, 1989

Introduced from the Red Sea,
40 – 55 m depth

Mullus barbatus,
Linnaeus, 1758

Native to the Mediterranean,
deeper than introduced
goatfish species

Hofrichter 2002

Concerns: Recent Additions & Deepening of the Suez Canal

Costs: $8.5 billion

Revenue: $5.3 billion (in 2015) to
$13.2 billion (by 2023)

→ Canal additions & deepening likely contributes to invasion increase

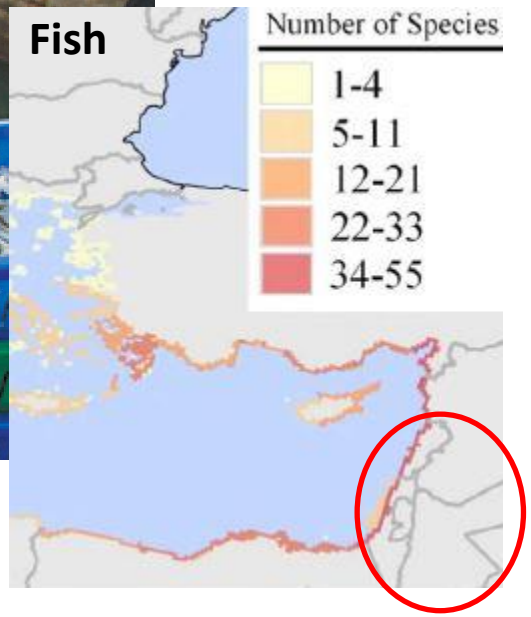
Biol Invasions (2015) 17:973–976
DOI 10.1007/s10530-014-0778-y

LETTER TO THE EDITOR

'Double trouble': the expansion of the Suez Canal and marine bioinvasions in the Mediterranean Sea

Economic Impact

Siganus sp.



Israel: Red Sea fish & prawns provide ca. 50 % of the Mediterranean catch

Hofrichter 2002, Katsanevakis et al. 2014, Hafner & Rudolf 2016

Negative Economic Impact

Disrupting Fisheries: Costs: $10 Million damage (Turkey, in 2014)

Pufferfish *Lagocephalus sceleratus* (Gmelin, 1789)

Nader et al. 2012

Negative Economic Impact

BBC NEWS

Jellyfish threaten Israeli power plant

5 July 2011 Last updated at 23:54 BST

Venomous
Disrupting Fisheries & Tourism
Clogging Power plants: $50,000
(in 2001)

Nomadic jellyfish
Rhopilema nomadica
Galil, 1990

www.cabi.org

Negative Ecological Impact: “Bunniefish”

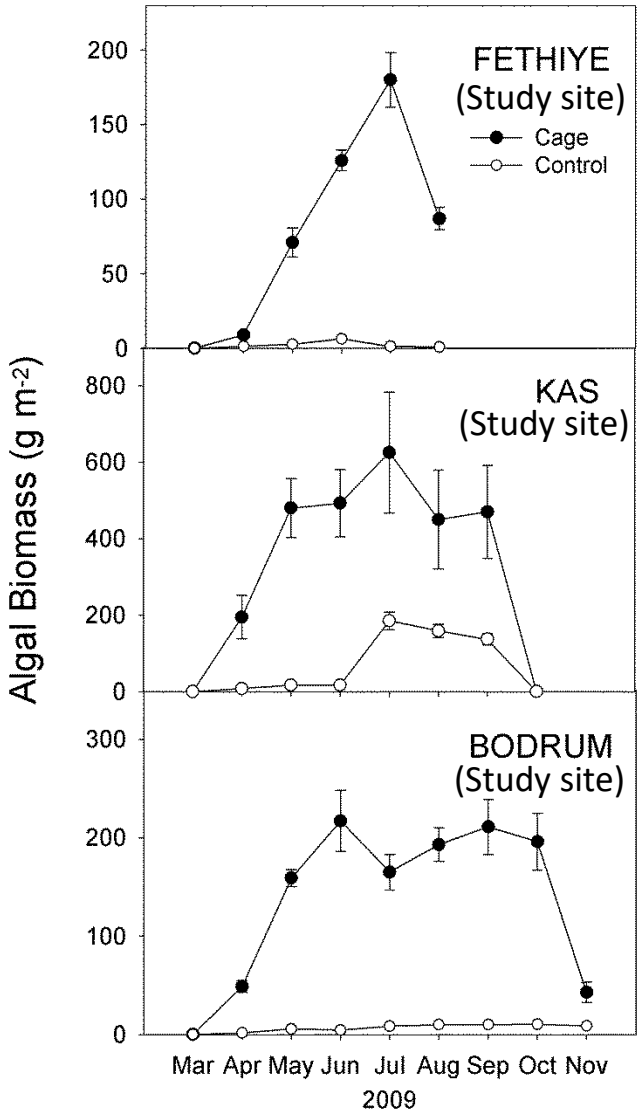
Figure 4. An exclusion cage at Kas in August 2009, five months after the beginning of the experiment.

Sala et al. 2011

Negative Ecological Impact: “Bunniefish”

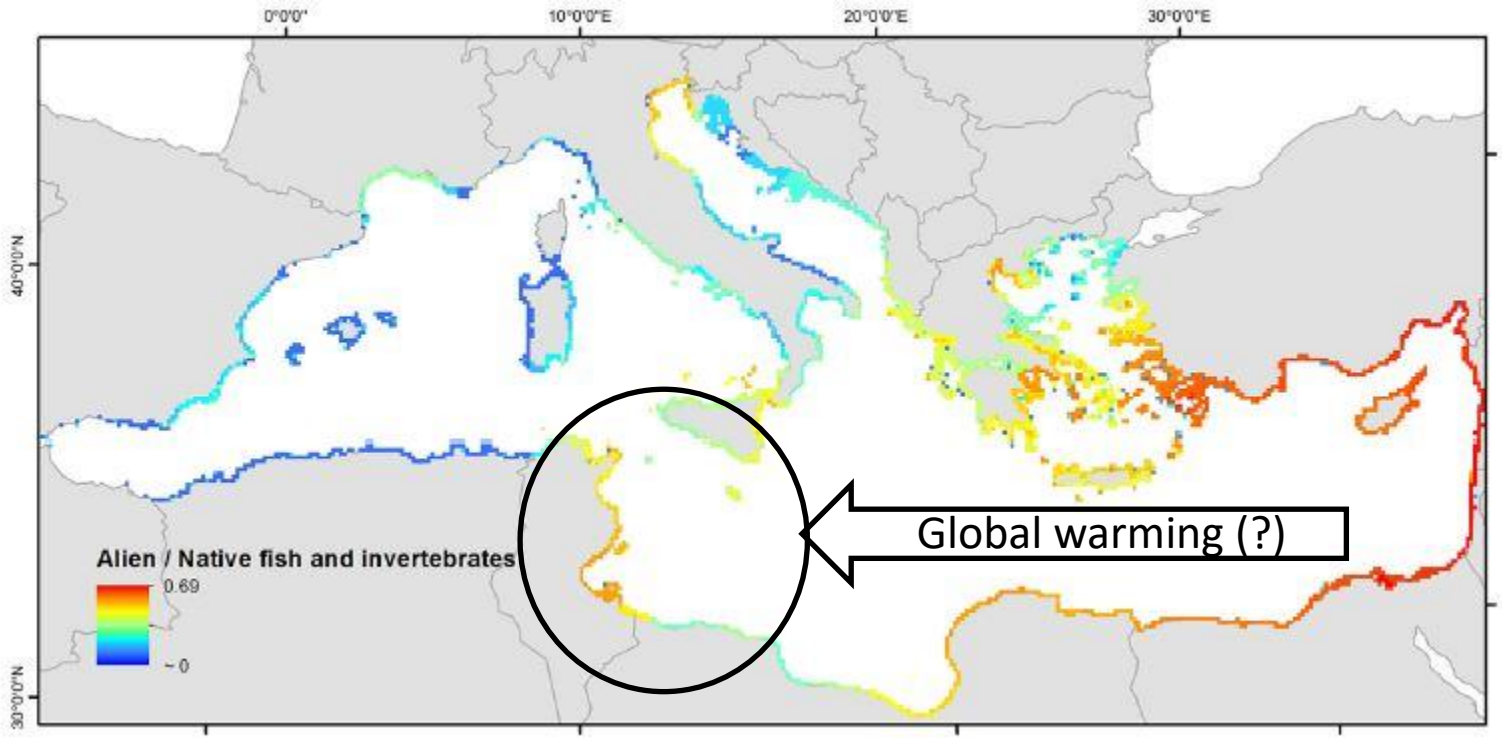
Siganus luridus

Cage: fish exclusion



Sala et al. 2011

Concerns: Red Sea Species Spread Across the Mediterranean



Health Impact

(e.g. Galil 2009)

Monday, May 18, 2015, 10:38

Poisonous fish found in Malta for the first time

Pufferfish *Lagocephalus sceleratus* (Gmelin, 1789)

Venomous, Tetrodotoxin
Disrupting Fisheries & Tourism
Deaths reported from Egypt & Israel

How to limit the invasion through the Suez Canal?

New York Times, 29 Jan 2016

Salt

Artificial salt barriers may substitute the Bitter Lake salinity barrier

https://www.nytimes.com/2016/01/30/opinion/our-mediterranean-our-survival.html?_r=0
https://www.nytimes.com/2014/11/13/opinion/under-the-ships-in-the-suez-canal.html
http://www.economist.com/news/technology-quarterly/21651921-how-prevent-egypts-enlargement-suez-canal-making-it-easier-red-sea

Anti-Lessepsian Migration

Mediterranean species immigrating the Red Sea is comparatively rare

Spotted Seabass
Dicentrarchus punctatus
(Bloch, 1792)

Cerastoderma edule
(Linnaeus, 1758)

→ Low tolerance of hypersaline conditions in Mediterranean species

Ben-Tuvia 1977

Hofrichter 2002

Transoceanic Canals

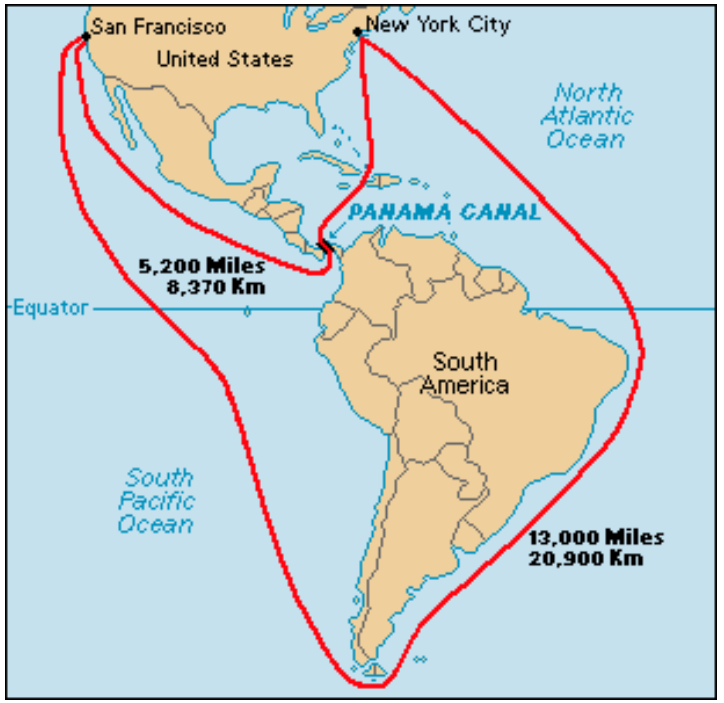
Suez Canal

1859-1869: Construction

161 km length

No locks

Panama Canal



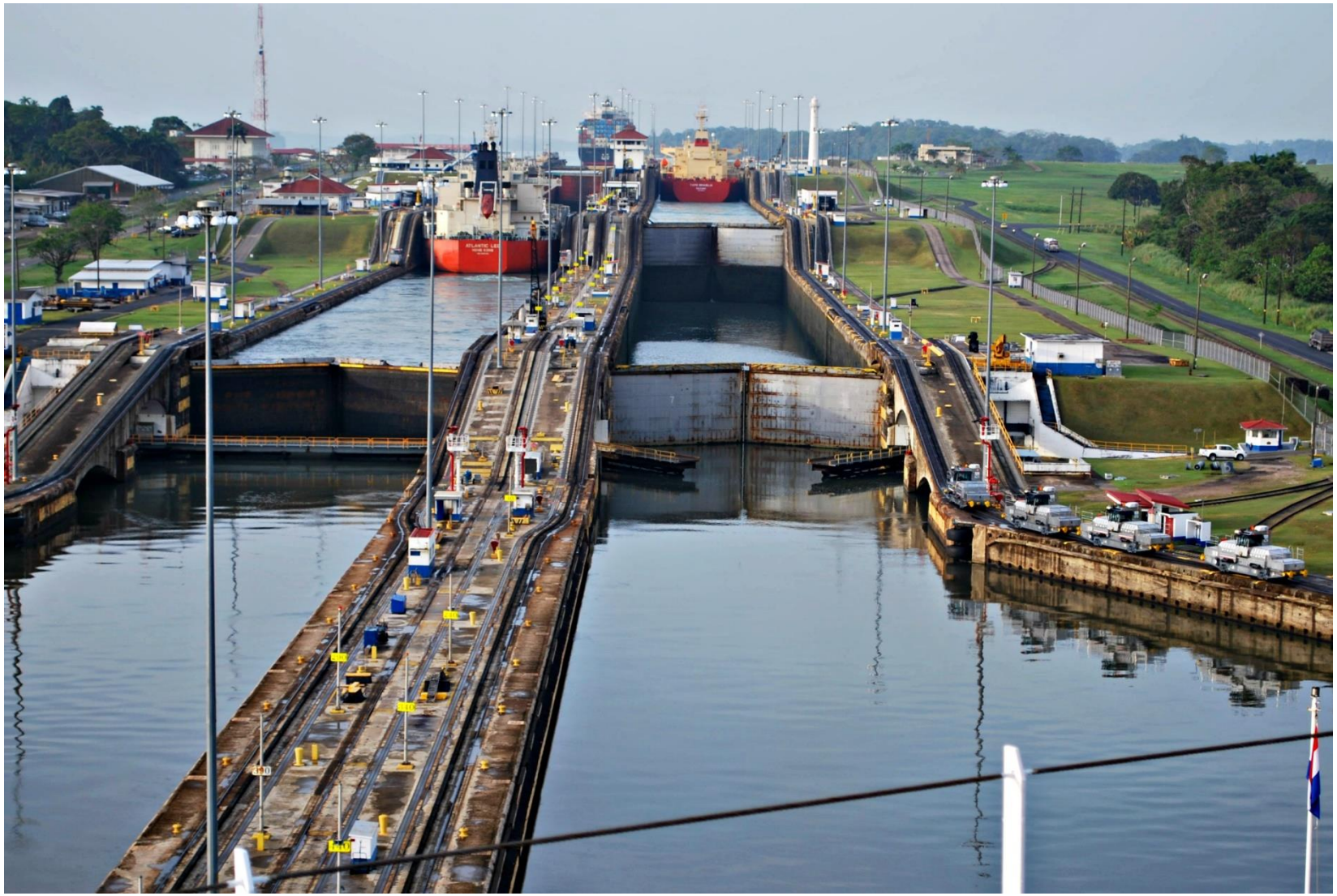
1904-1914: Construction

82 km length

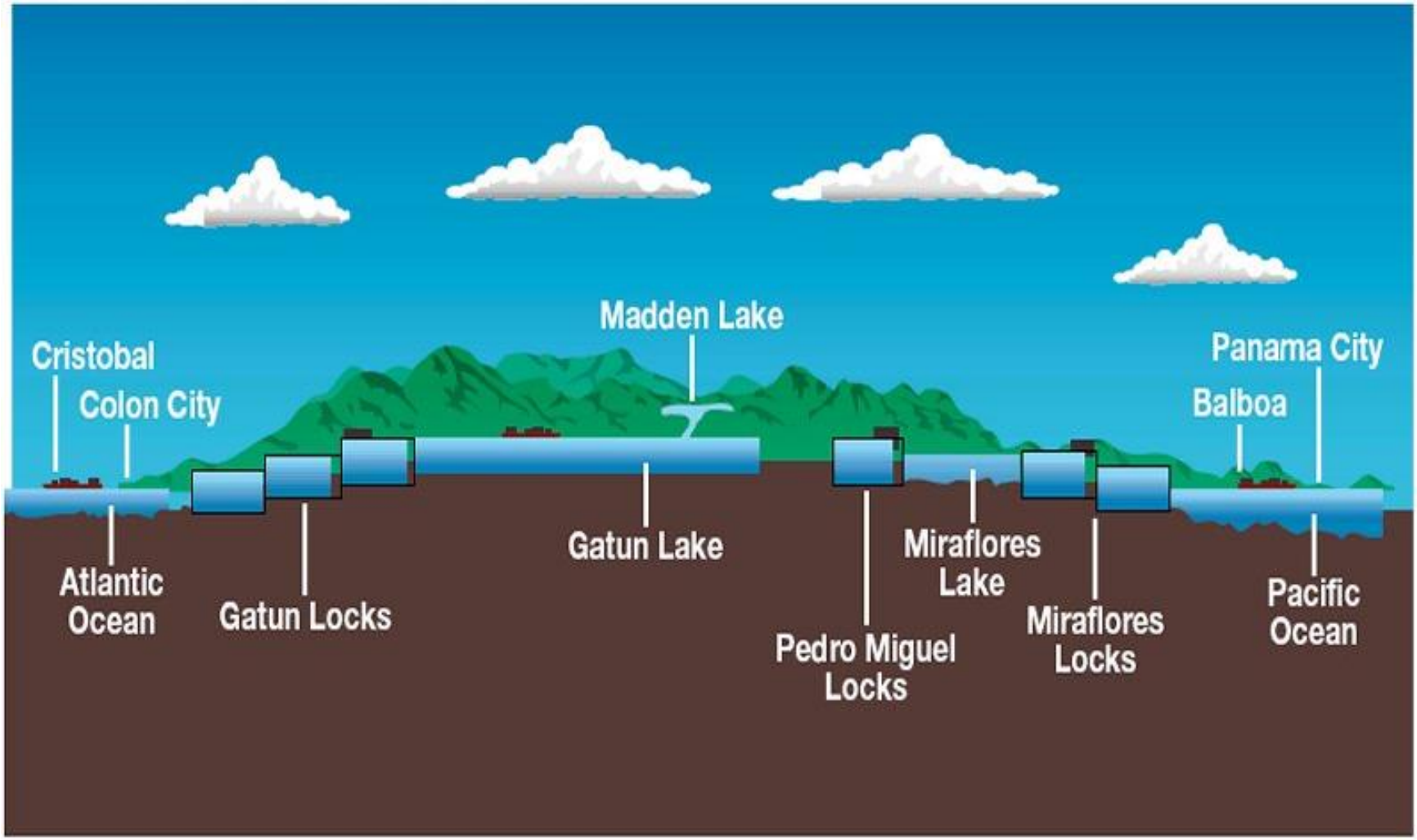
3 locks

Panama Canal Locks

Panama Canal Locks



Panama Canal Profile



28 m height difference

Gatun Lake

Gatun Lake & the Panama canal are freshwater barriers

Trans-Panama Canal Migration is Relatively Little

Crabs: 7 species: Atlantic to Pacific
1 species: Pacific to Atlantic

Fish: 7 species: Atlantic to Pacific
3 species: Pacific to Atlantic

} reported in the canal

Atlantic tarpon (*Megalops atlanticus*), Valenciennes 1847

→ The Freshwater of the Panama Canal is an effective barrier to migrating species

Galil et al. 2007

Thank you!