Ballast water management in the Great Lakes and beyond

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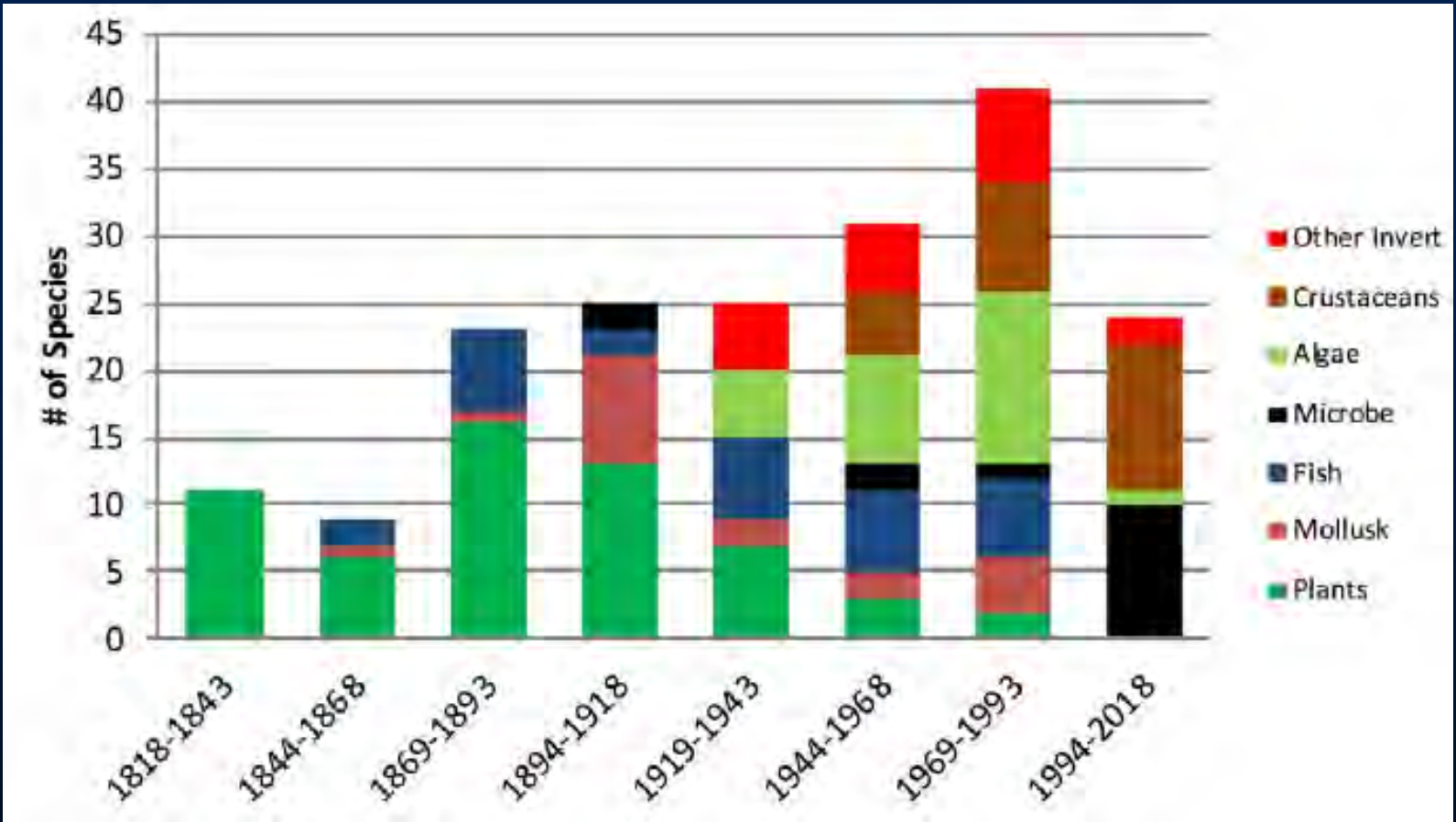
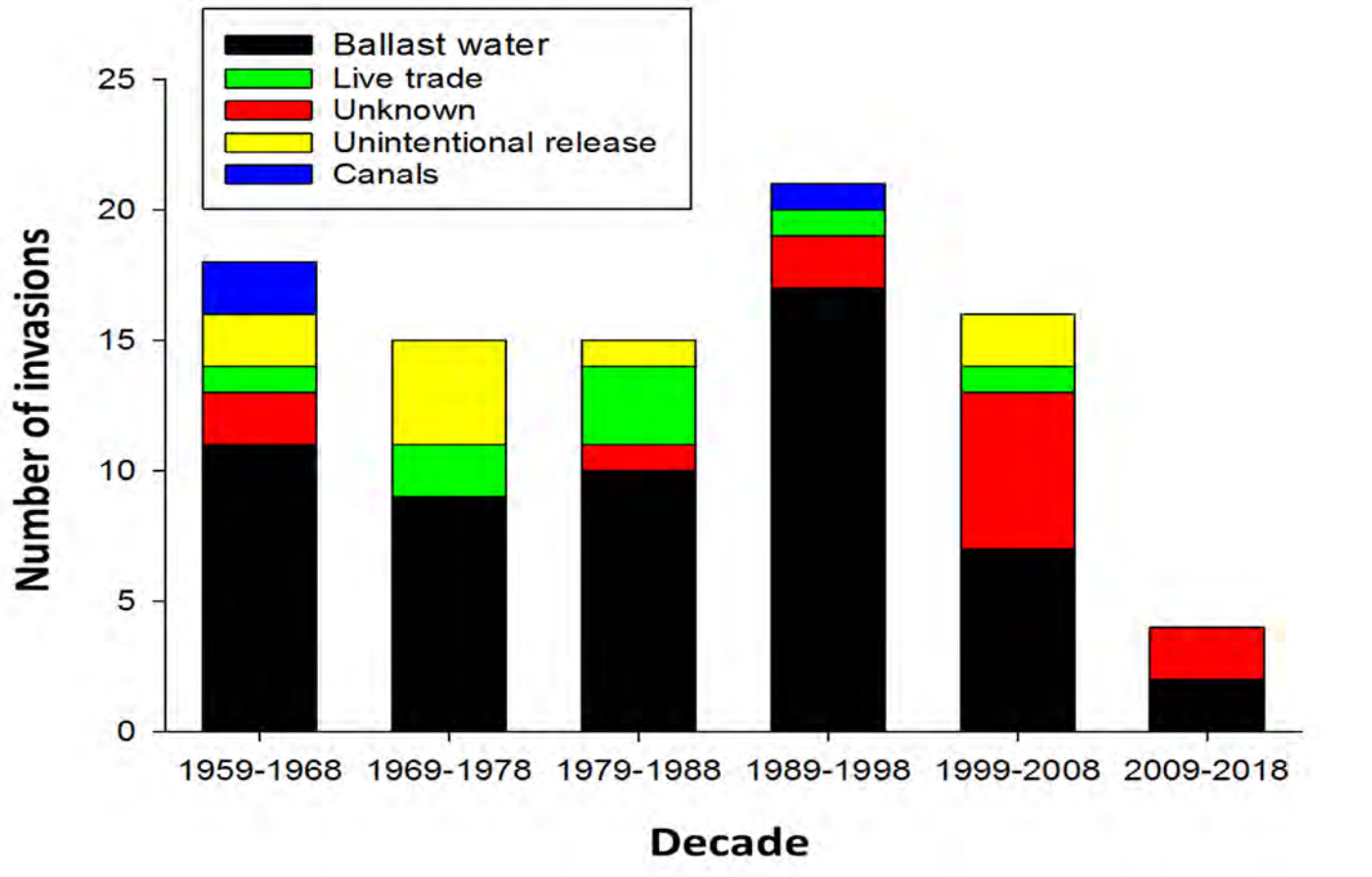
Reported Invasions in the Great Lakes



- Plants and fish dominant until after opening of modern Seaway in 1959
- Recent domination by invertebrates, algae and microbes

Sturtevant et al. 2019 JGLR

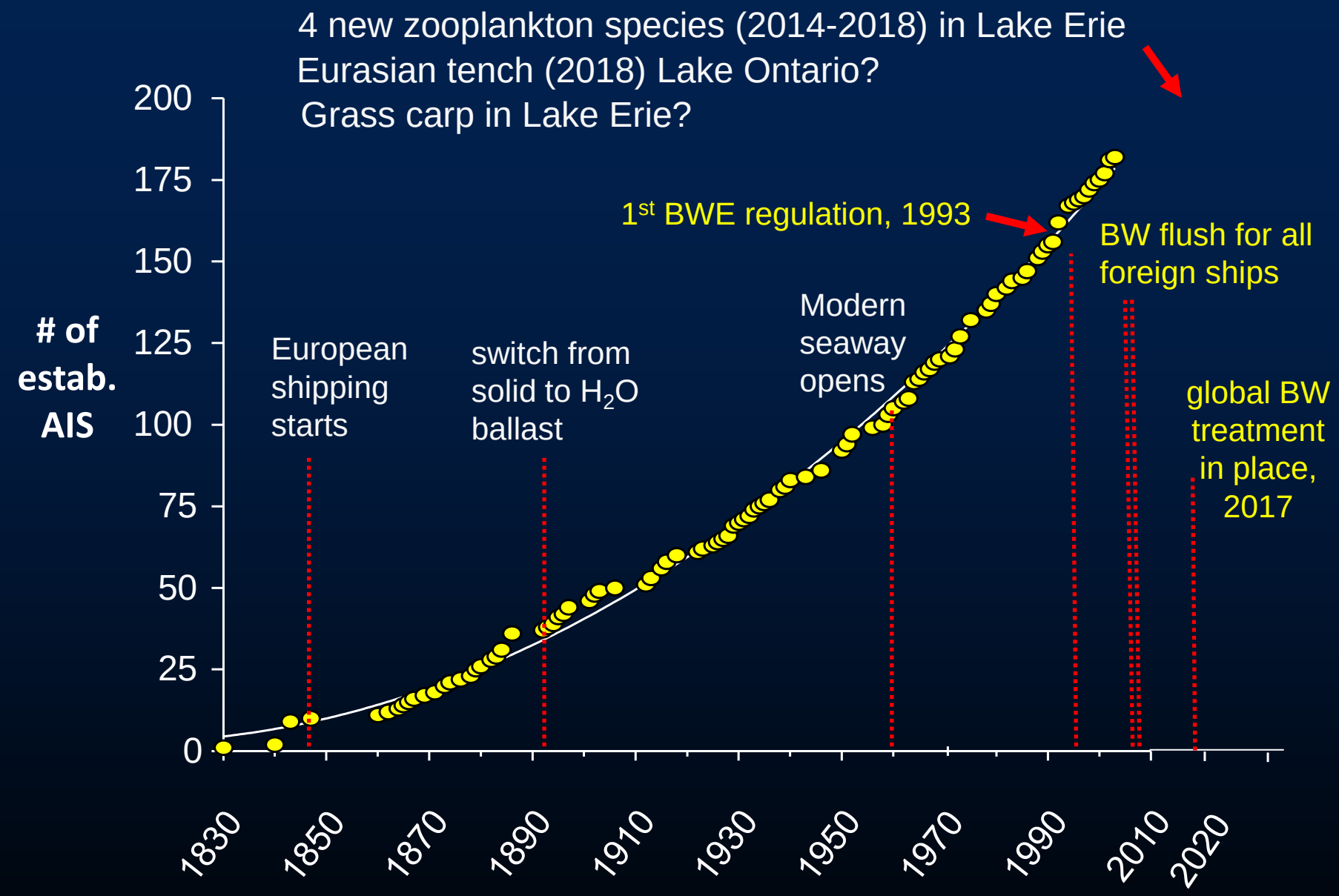
Vectors of Introduction



- Shipping has been dominant vector since the modern Seaway opened
- Troubling number of cases of unknown vector

Ricciardi and MacIsaac, unpubl. data

AIS established in the Great Lakes



Mills et al. (1993); Ricciardi (2001); GLANSIS (NOAA; 2019); Connolly et al. (2017, 2018, 2019)

New AIS zooplankton in Lake Erie

Thermocyclops crassus

- First detected in western Lake Erie by EPA in August 2014
- Subsequently detected in 2015 -2016 (Connolly et al. 2017)
- Considered established
- Also found in Lake Champlain
- Found previously in ballast water of NOBOB ship (Johengen et al. 2005)
- Salinity tolerance up to 7.2‰

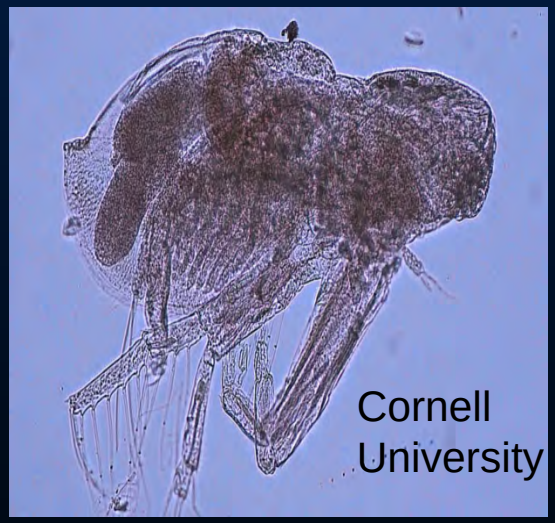
Brachionus leydigii

- A single individual detected in western Lake Erie by EPA in April 2016 (Connolly et al. 2018)
- Not considered established (2018)
- Found previously in ballast water & sediment (Bailey et al. 2005; Johengen et al. 2005)
- Euryhaline

New AIS zooplankton in Lake Erie

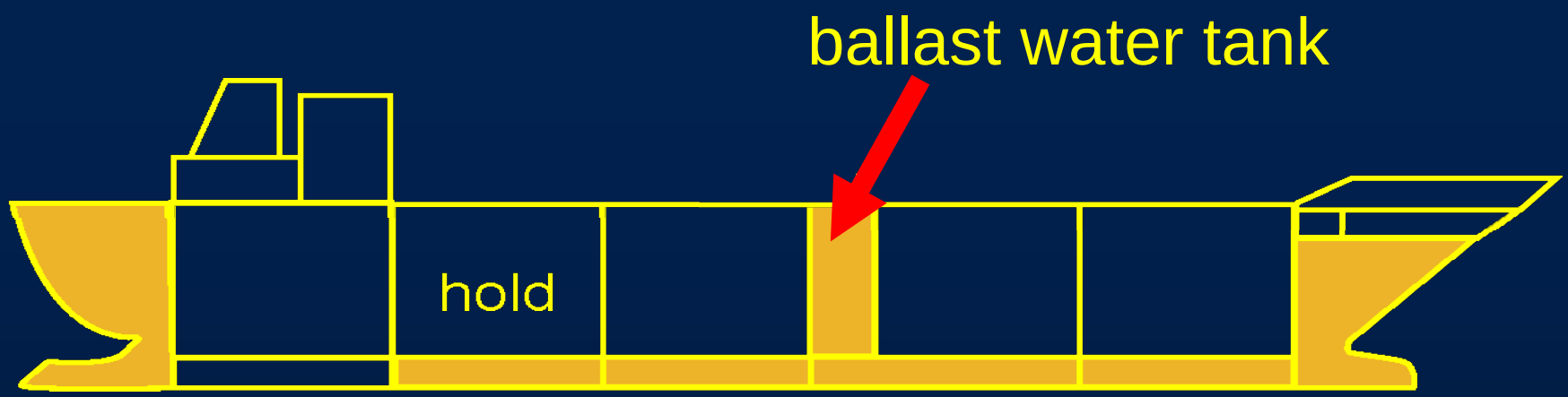
Mesocyclops pehpeiensis

- Collected in western Lake Erie 2016-2018 (Connolly et al. 2019)
- Likely established
- Suspected aquaculture introduction
- Freshwater only



Diaphanosoma fluviatile

- Collected (2015) in Maumee River and later in western Lake Erie by EPA (Lower and Sturtevant 2019)
- Also collected in lakes Michigan and Superior (2018)
- Established (Lower and Daniel 2019)
- Genus found in ballast water of NOBOB (Johengen et al. 2005)
- Freshwater, estuarine



Ballast on Board ships regulated in 1993 (BW exchange at sea)

- These vessels only accounted for ~5% of total tank transits

No Ballast on Board ships carry cargo and only residual ballast;

- Studies suggested they could still introduce species, thus USA and Canada required flushing at sea beginning in 2006-2008

2017 IMO-D2 Convention requires all ships to have treatment by 2024 implemented

International Maritime Organization (IMO) D-2 discharge standards for viable organisms

Organism category	Permissible Density
Zooplankton, >50 µm in minimum dimension	< 10 organisms / m^3
Phytoplankton, 10-50 µm	< 10 cells / ml
Toxicogenic *Vibrio cholera*	< 1 cfu* / 100 ml
Escherichia coli	< 250 cfu* / 100 ml
Intestinal *Enterococcus*	< 100 cfu* / 100 ml

* colony forming unit

Notice the plankton are numerical, community-based standards

What Factors Affect Invasion Success?

1) Propagule Pressure (PP)

- Number of introduction events
- Number of propagules introduced per event

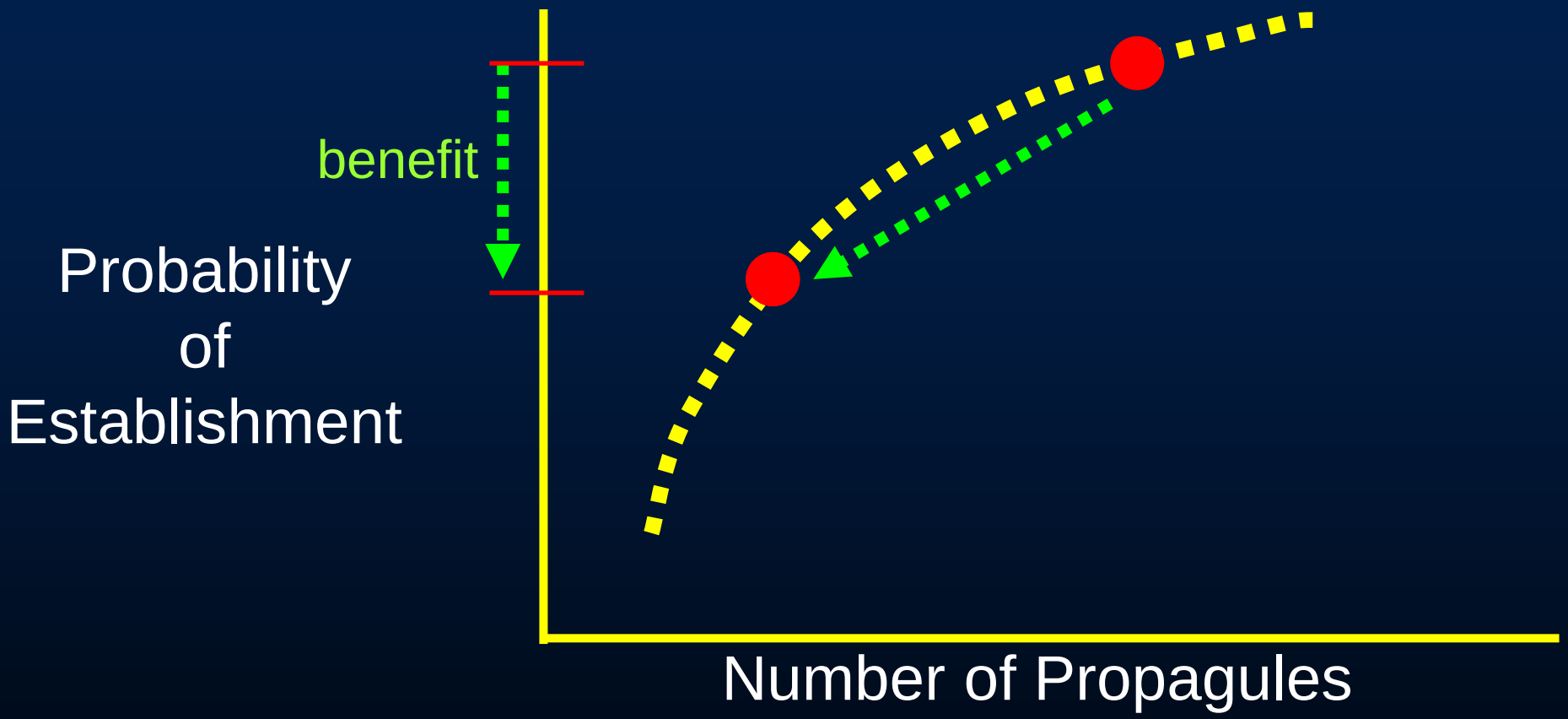
Greater PP reduces severity of Allee effects

2) Colonization Pressure (CP)

- Number of species introduced

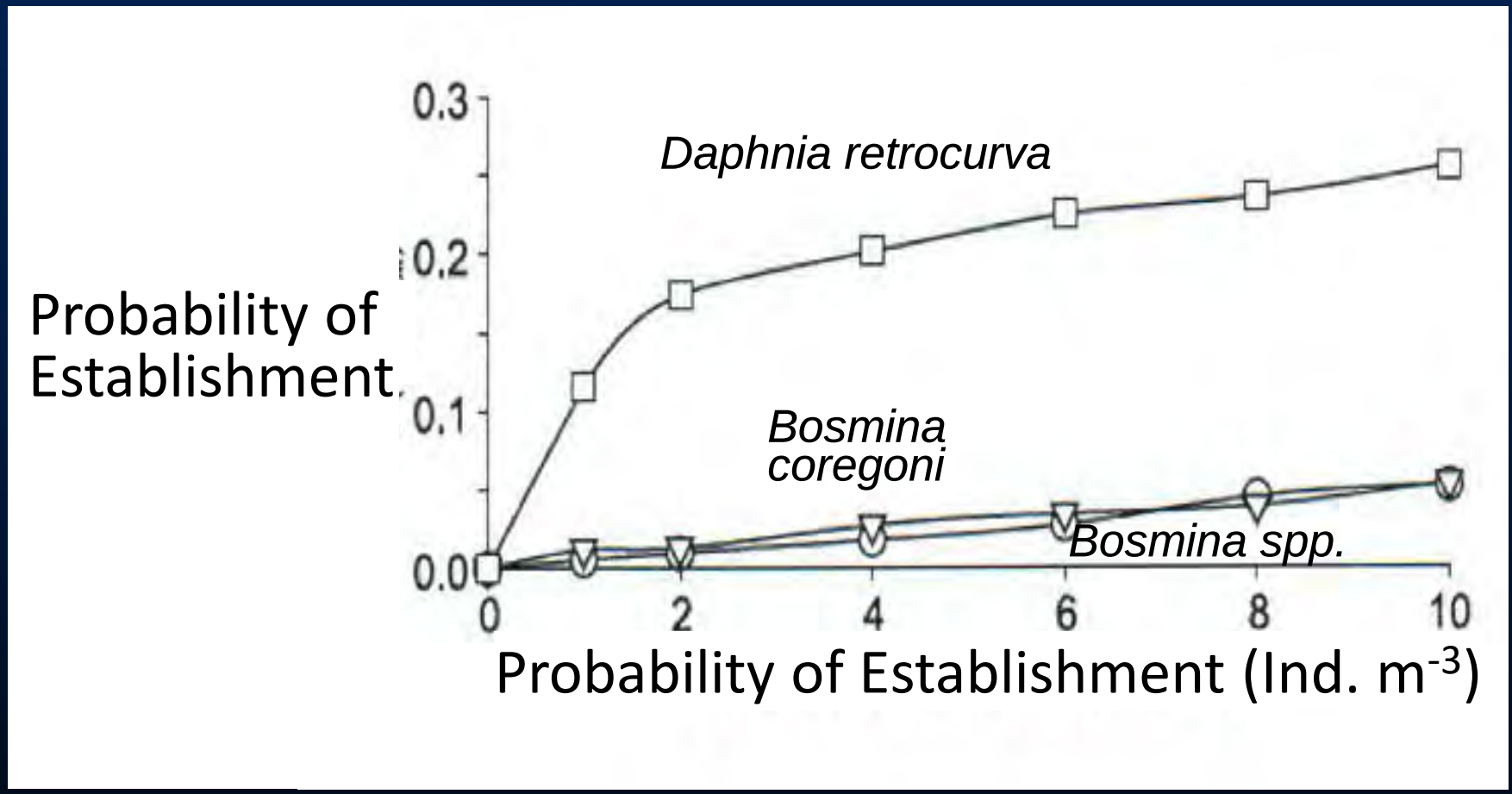
Greater CP assures that at least one species meets environmental requirements to establish

Reducing Propagule Pressure Reduces Risk



Modified from National Research Council (2011)

Zooplankton respond to Propagule Pressure



National Research Council (2011). Modified from Bailey et al. (2009) CJFAS

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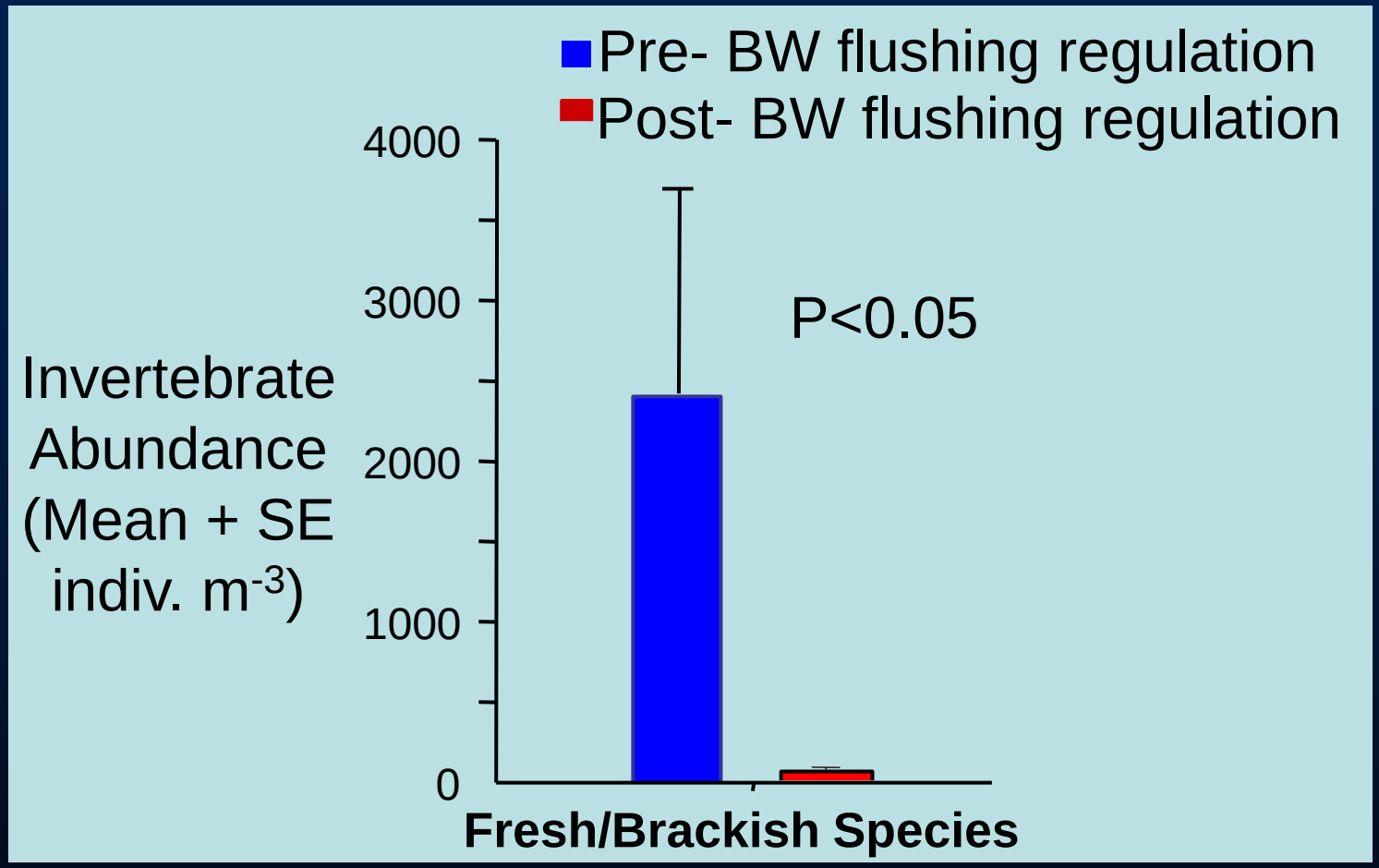
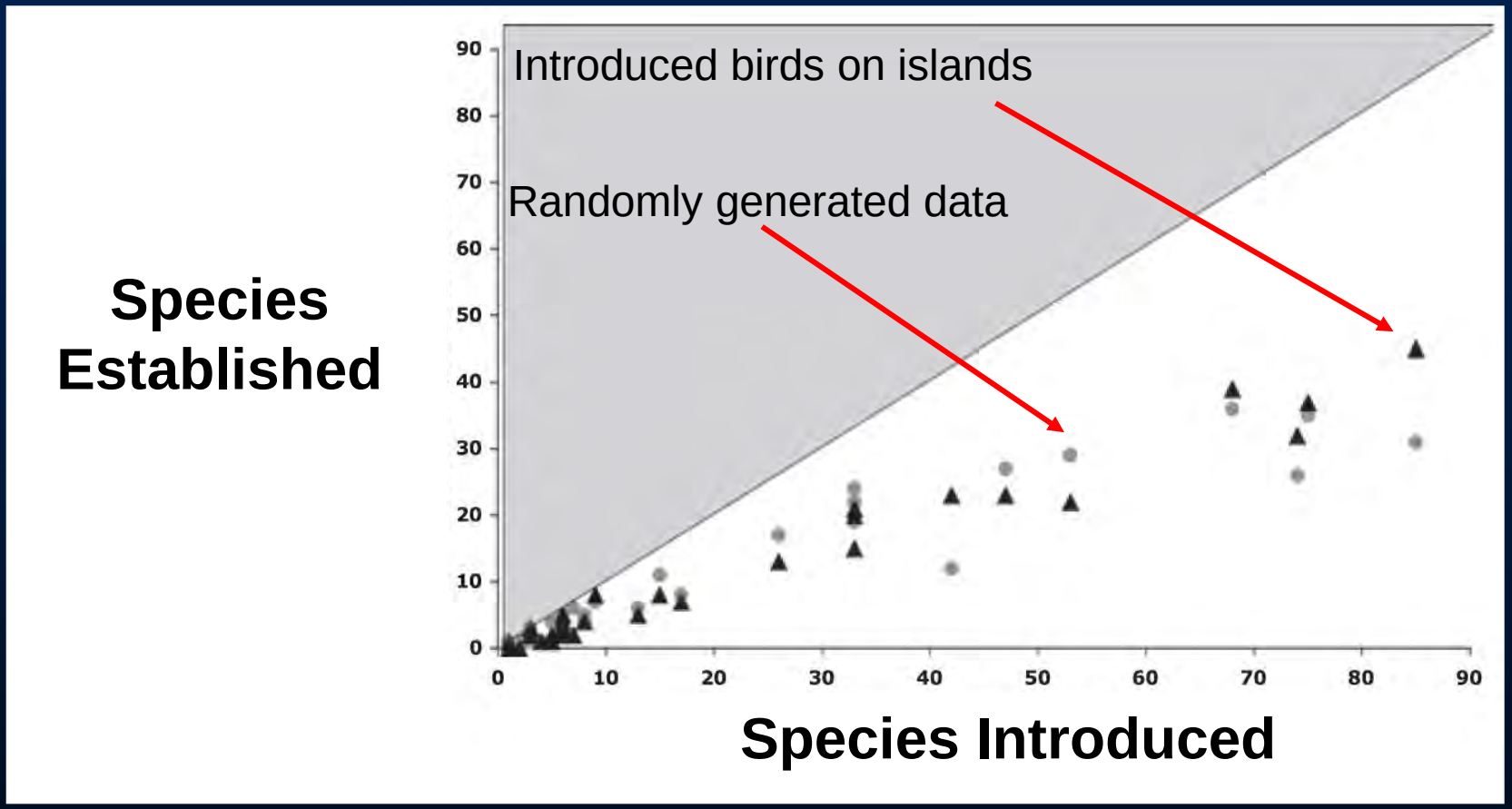


Community Propagule Pressure of risky species in ballast tanks of ships entering the Great Lakes declined significantly

Bailey et al. (2011) Environmental Science & Technology

Why is Colonization Pressure Important?



Introducing more than one species increases overall risk of establishment

Lockwood et al. (2009) Div. Dist.

Freshwater Ballast Water Flushing (BWE)

Zooplankton Colonization Pressure

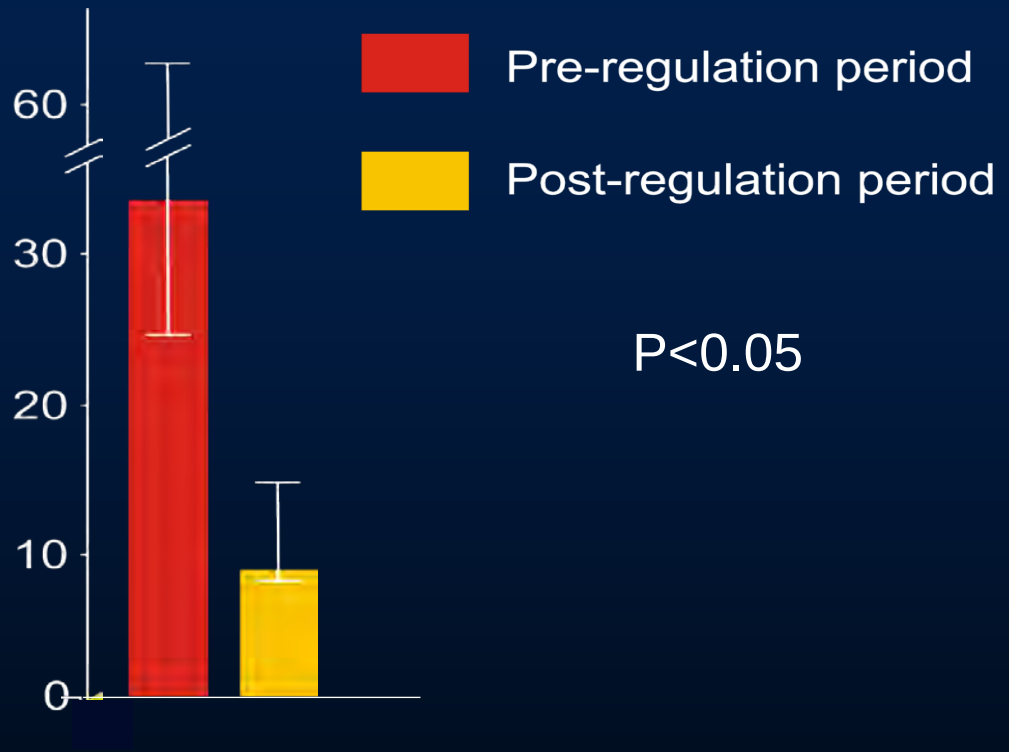
	Before BWE		After BWE	
	Control	Flushed	Control	Flushed
Cladocera	8	9	9	3
Copepoda	5	7	7	1
Rotifera	20	19	19	3
Total CP	33	35	35	7

Colonization Pressure reduced significantly following BW flushing for ships leaving the Great Lakes for Europe

Gray et al. (2007) Limnology & Oceanography

Colonization Pressure of AIS Invertebrates in ships' ballast sediments

Colonization Pressure



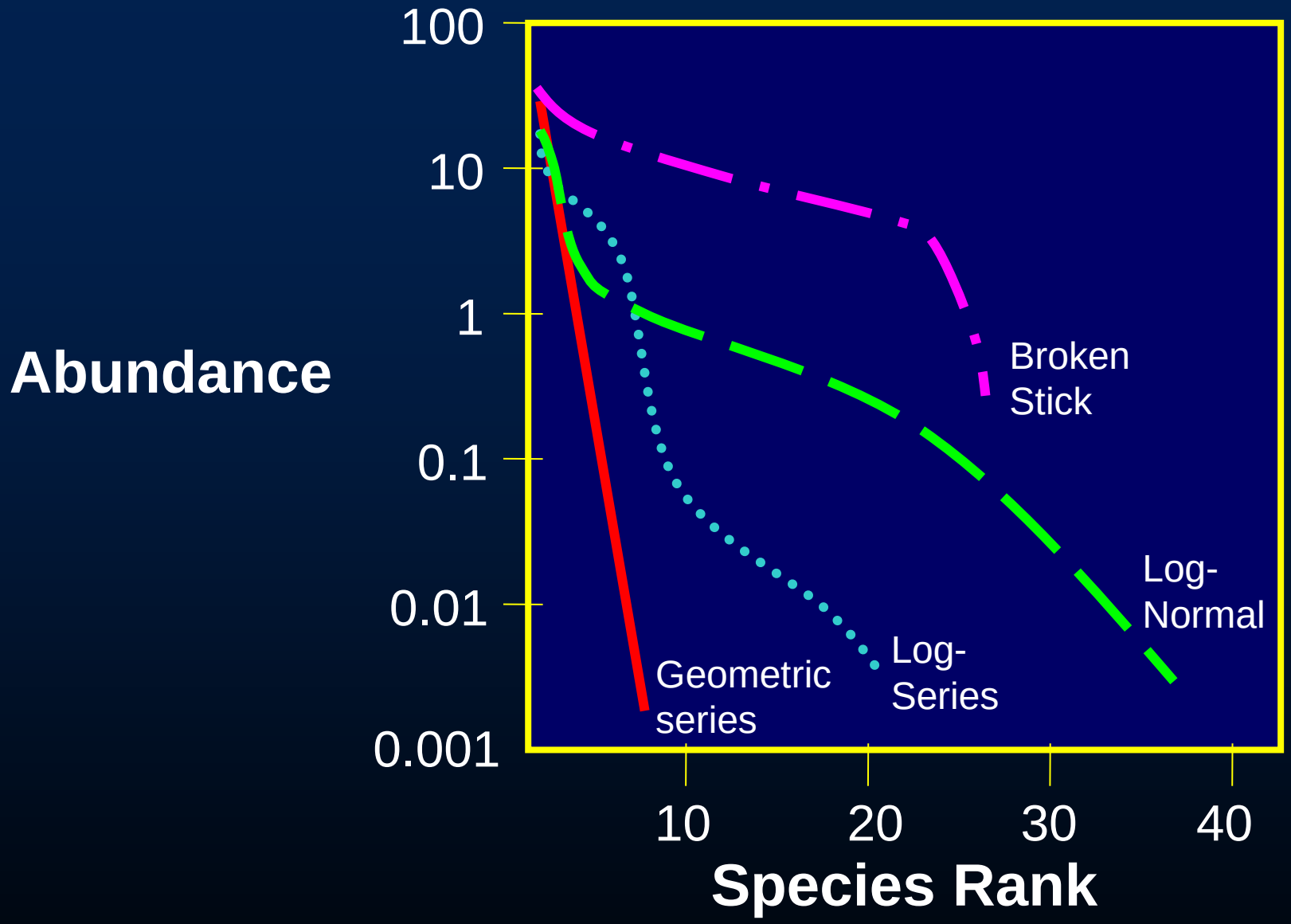
P<0.05

Briski et al. (2010) Freshwater Biology

IMO D-2 Ballast Water standards are not fool-proof

- International Maritime Organization Global Convention on Ballast Water and Sediments (2004) came into force September 2017
- New build ships must come equipped with water treatment systems now
- Existing vessels have until 2024 to implement treatment, and will use IMO D-1 (BWE) standard until then
- Even vessels with treatment systems pose some risk
- Risk reduction focuses on Total Community Propagule Pressure for invertebrate- and phytoplankton-sized organisms only (**D-2 performance standard**)

Species Rank-Abundance Distributions in Communities



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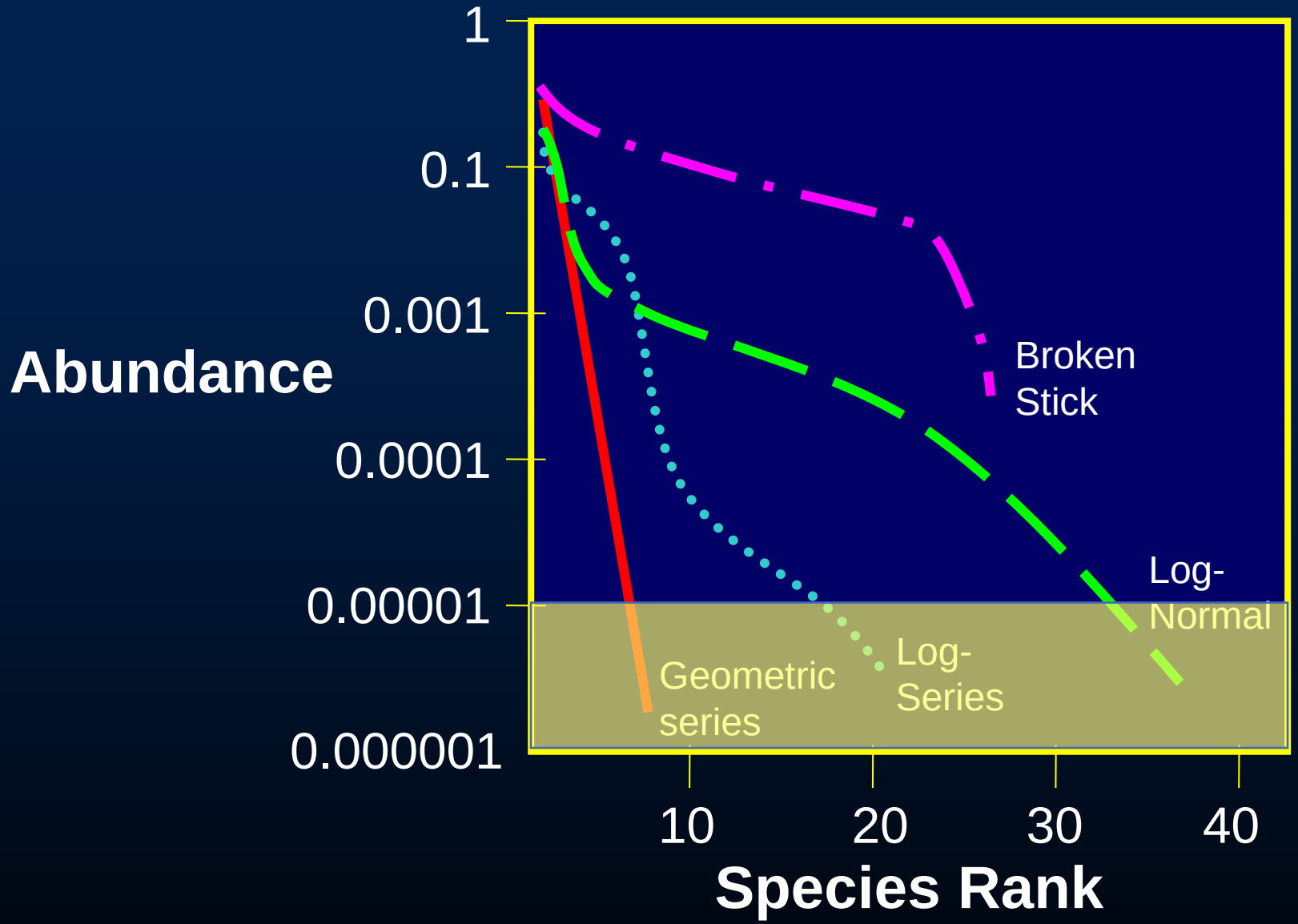

BW treatment should sharply reduce PP and possibly CP but inoculum will likely still have many species.

New IMO D-2 Ballast Water regulation addresses community propagule pressure only

We do not know the relative risk associated with different assemblages that differ in number of species and mean abundance of those species.

Species Number	Max. Density Each* (organisms m^{-3})
1	10
2	5
5	2
10	1

* Maximum density is <10 viable ind. m^{-3}

Increasing the number of species increases chance that one of them finds conditions suitable for establishment but it comes at the expense of possibly higher Allee effects.