Modeling ballast water management strategies for slowing the secondary spread of aquatic invasive species on the Laurentian Great Lakes

Jake Kvistad, Dr. Jonathan Bossenbroek[1], W. Lindsay Chadderton[2]

University of Toledo[1], The Nature Conservancy[2]

Network centrality as a potential method for prioritizing ports for aquatic invasive species surveillance and response in the Laurentian Great LakesJT Kvistad, WL Chadderton, JM Bossenbroek
Management of Biological Invasions 10 (3), 403-427

LAKE ERIE CENTER

Acknowledgements

- Dr. Patrick Kocovsky – USGS
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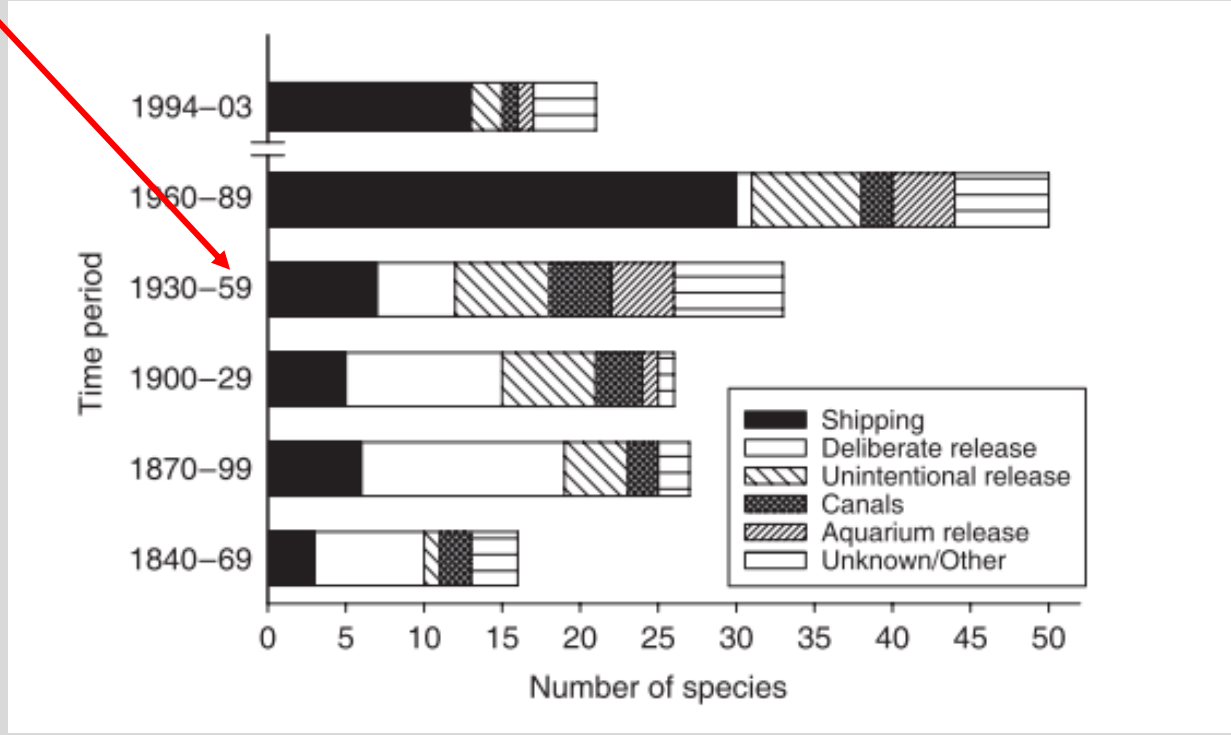
- Funding– Michigan Dept. of Natural Resources Invasive Species Grant Program

Ballast water is the dominant vector for species introductions and spread in the Great Lakes

- 182 recognized non-native species in the Great Lakes
- ~ 2/3 of invasive species in Great Lakes introduced through ballast

St. Lawrence Seaway opens



Ricciardi (2006)

Some of our worst invaders were introduced through ballast water

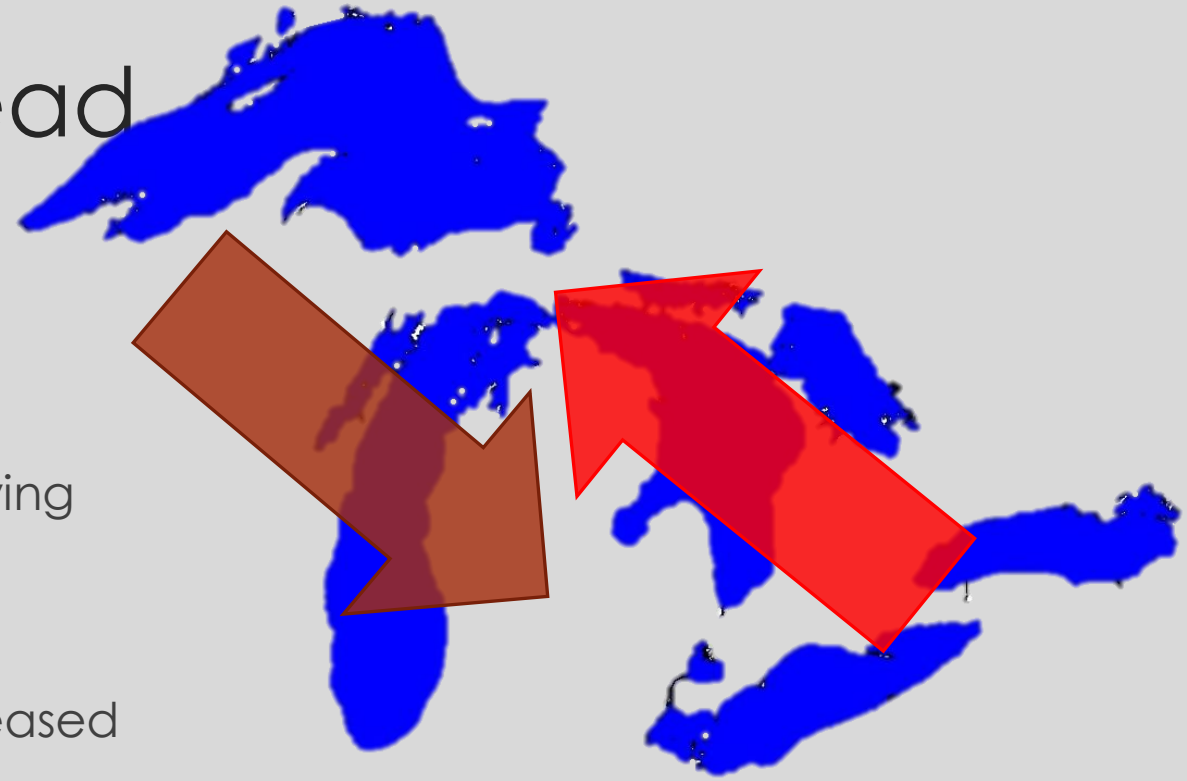
VHSV; nas.usgs.gov

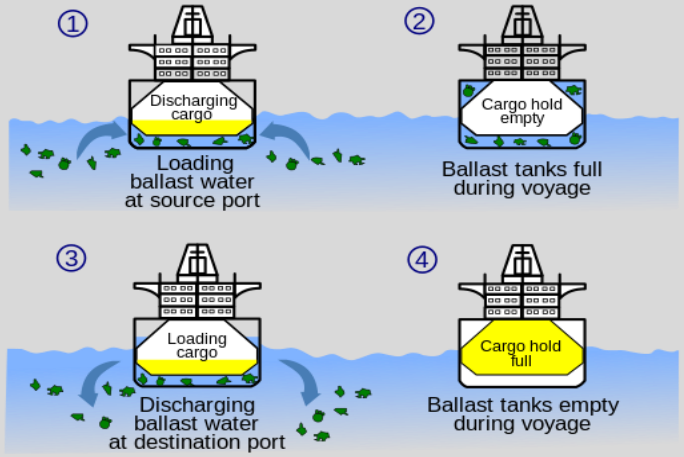
Quagga mussel; newscientist.com

Spiny water flea; bugguide.net

Secondary spread

- Large domestic shipping network- “Lakers”
- Ships empty of cargo travel upstream- carrying ballast water
- Cargo transported downstream- ballast released upon loading cargo
- Net ballast transport upstream





wikipedia.org

Lakers exempt from most ballast water regulations set by IMO

- Short intraregional trips
- Old ships- up to 60 years in some cases
- Exclusively freshwater- ballast tanks not lined with anticorrosive paint
- 15,000 – 30,000 m^3 ballast capacity
- How can risk be minimized?

Shoreside ballast water management

- Ships deballast at ballast reception facilities
- ‘Clean’ ballast can be loaded, ‘dirty’ ballast can be treated
- Significant investment in construction
- So which ports should construct these facilities?

dhigroup.com

Goals/Objectives

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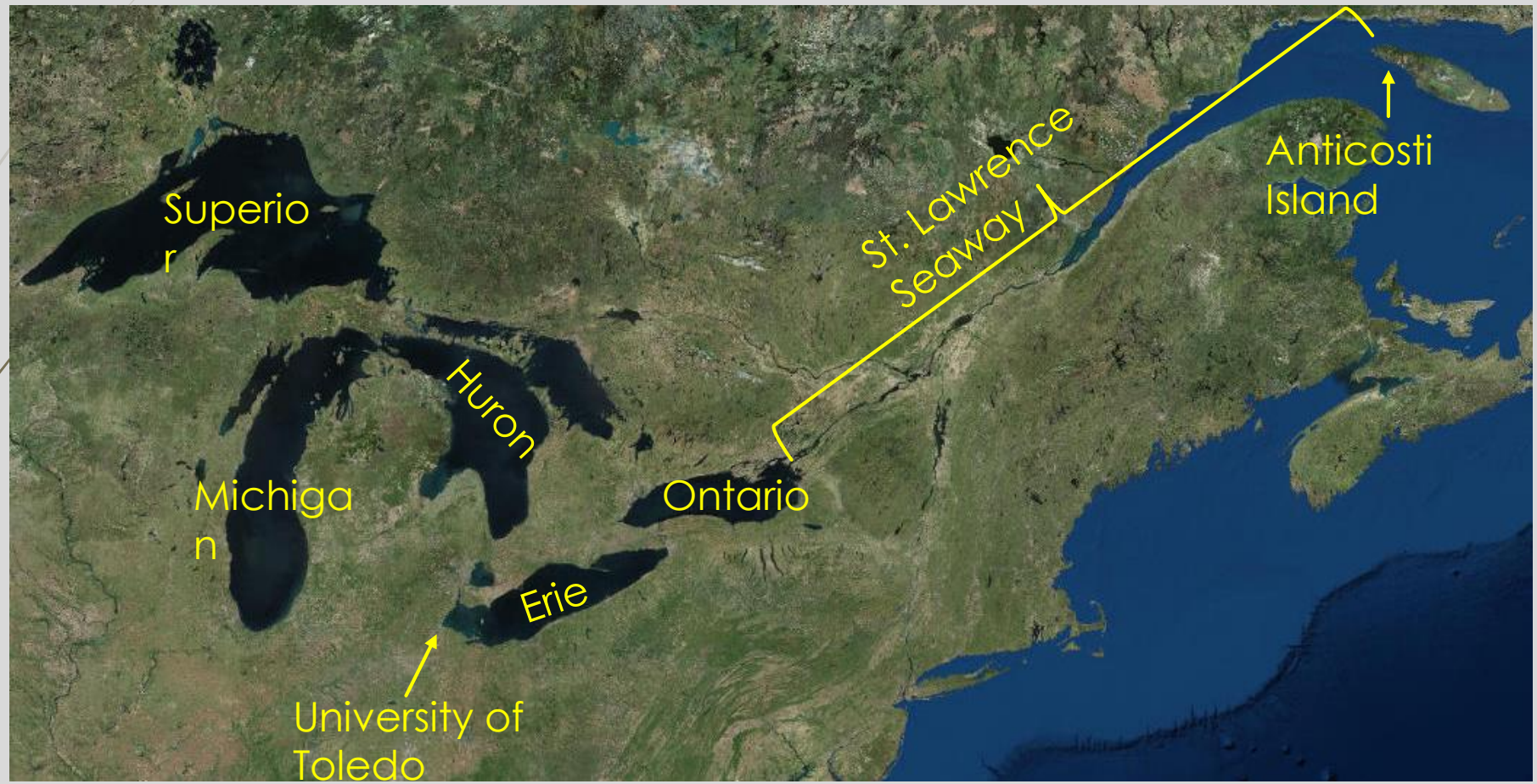
Study area


Superio
r
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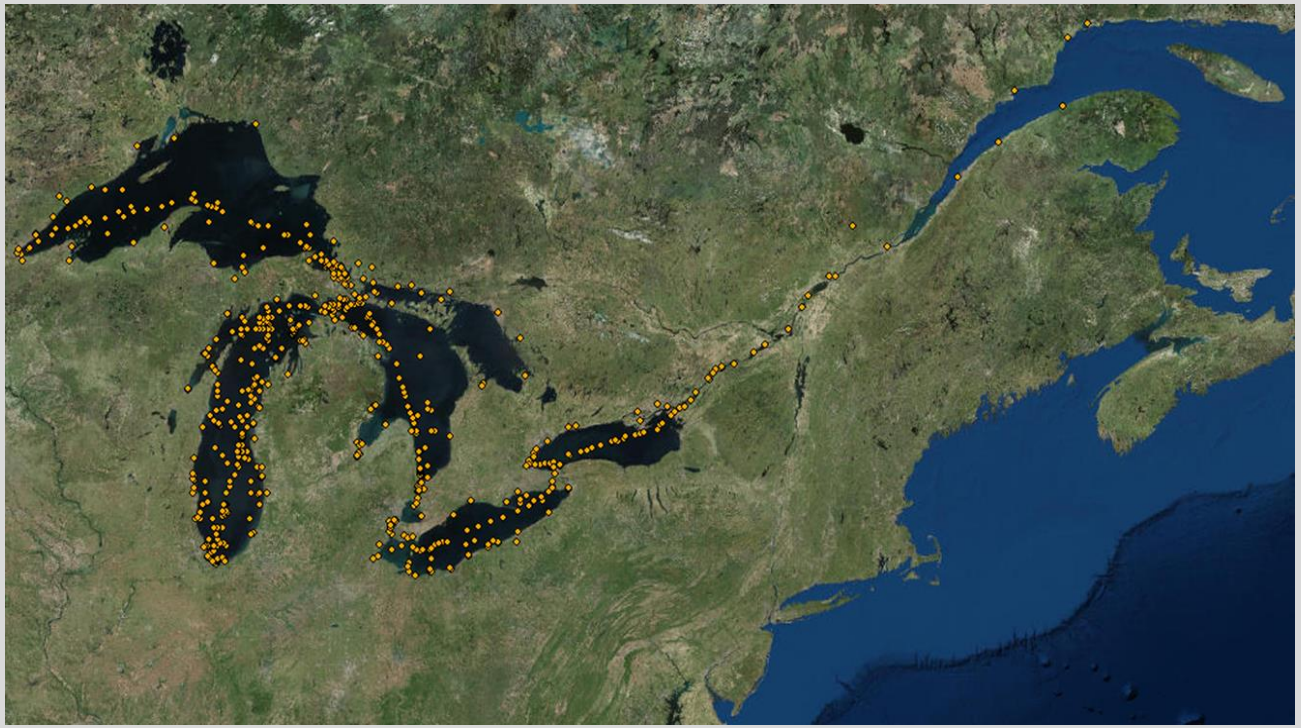
Huron
Erie
Ontario
St. Lawrence
Seaway
Anticosti
Island
University of
Toledo

Data description

- Public records from National Ballast Information Clearinghouse (NBIC)
  - 2005-2015
  - Contains detailed records of ballast activity
- Dataset from Fisheries and Oceans Canada
  - 2005-2007
  - Ship movements
- Matrix of average ballast water movements between port pairs

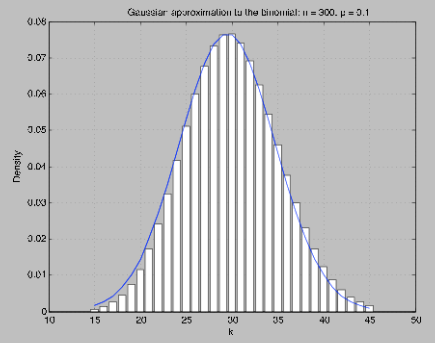


Source \ Destination	A	B	C	D
A	0	62	12	34
B	45	0	21	56
C	78	21	0	125
D	12	65	3	0

$* \chi$

Source \ Destination	A	B	C	D
A	0	.25	.03	.18
B	.12	0	.15	.20
C	.33	.1	0	.95
D	.03	.26	.01	0

Year 1



Infested?

D	A	B	C	D
	0	1	0	1

Source \ Destination	A	B	C	D
A	0	.25	.03	.18
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Year 2

Source \ Destination	A	B	C	D
A	0	.25	.03	.18
B	.12	0	.15	.20
C	.33	.1	0	.95
D	.03	.26	.01	0

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Golden mussel (*Limnoperna fortunei*)

- Mytilid mussel native to SE Asia
  - ~ 25 – 30mm
- Invasive in South America
- Similar consequences as dreissenids in North America
- Sieracki et al. (2014) predicted Bay City, MI as potential initial infestation

Monkey goby (*Neogobius fluviatilis*)

- Ponto-Caspian species
- Invasive in parts of Western Europe
- Likely to invade Great Lakes (Stepien and Tumeo, 2006)
- Initial infestation chosen at ports along St. Clair-Detroit Rivers

Needed to parameterize model to accurately reflect likely spread patterns

- Existing examples that could be used?
  - Zebra mussel
  - Round goby
- Once parameterized, realistic scenarios could be forecast

nas.usgs.gov

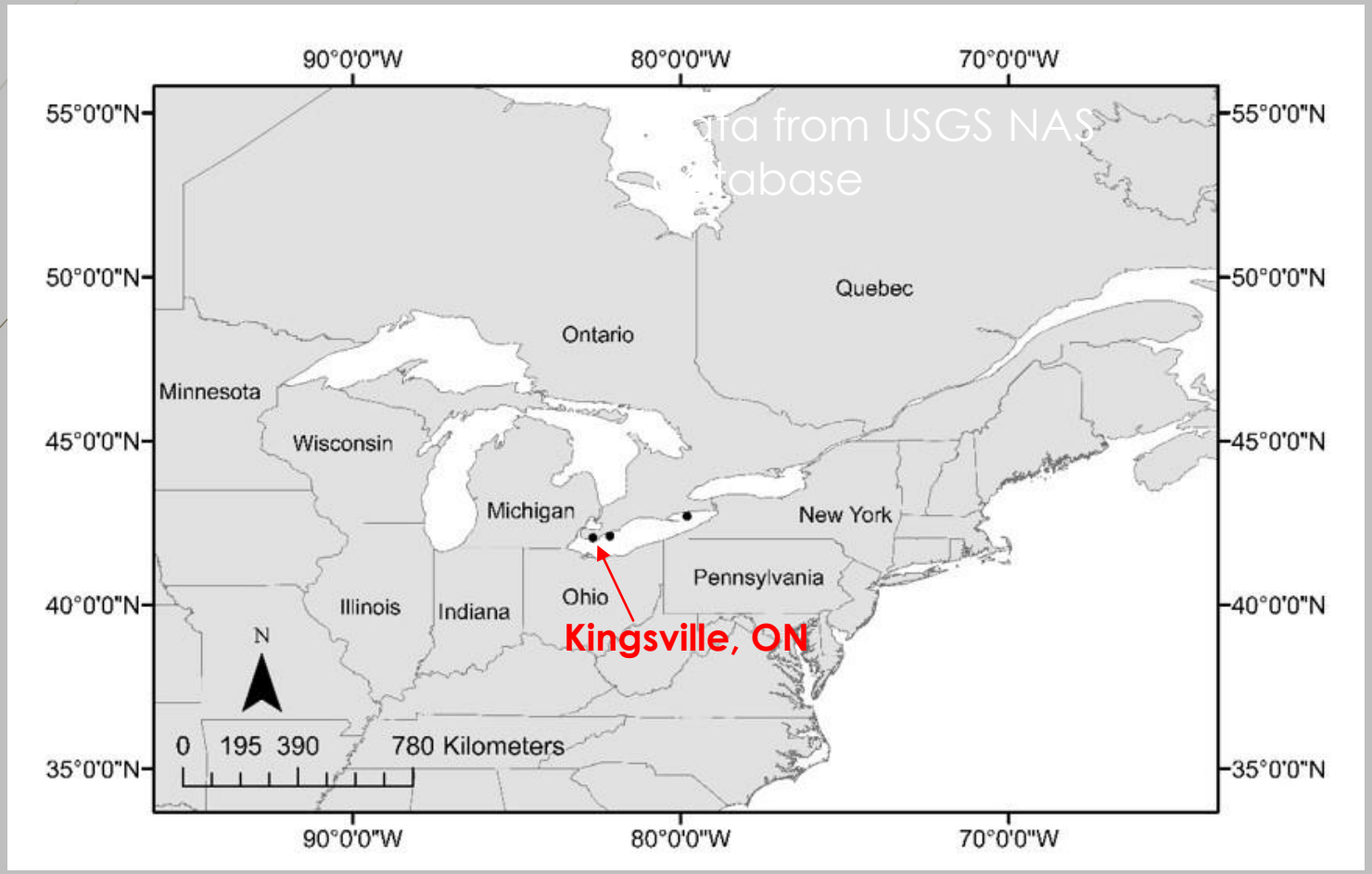
uwindsor.ca

Zebra mussel (*Dreissena polymorpha*)

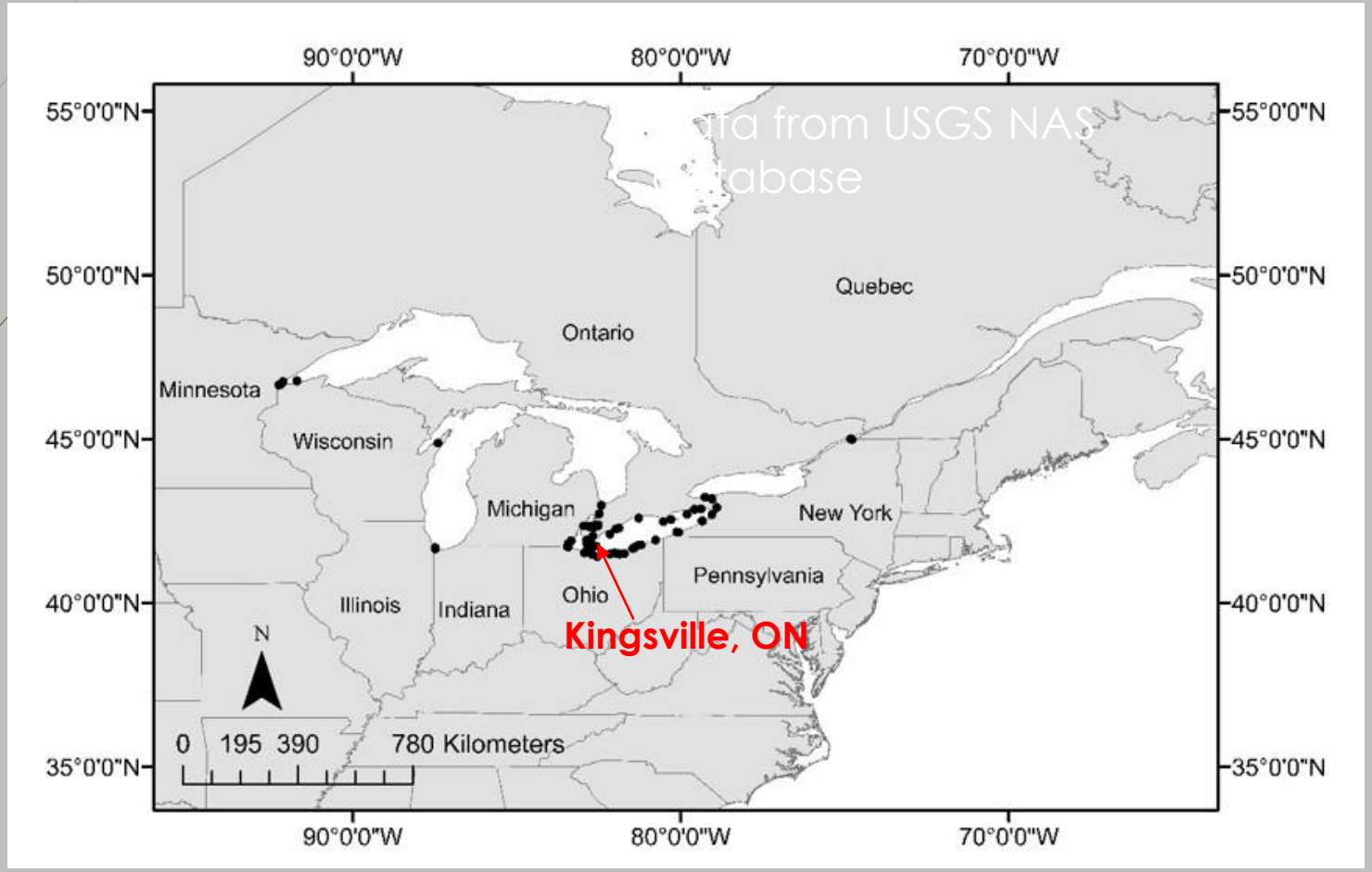
- Introduced in ballast by ocean-going freighters from Black Sea
- Enormous ecological and economic damage
- Rapid secondary spread in the Great Lakes primarily through ballast water

nas.usgs.gov

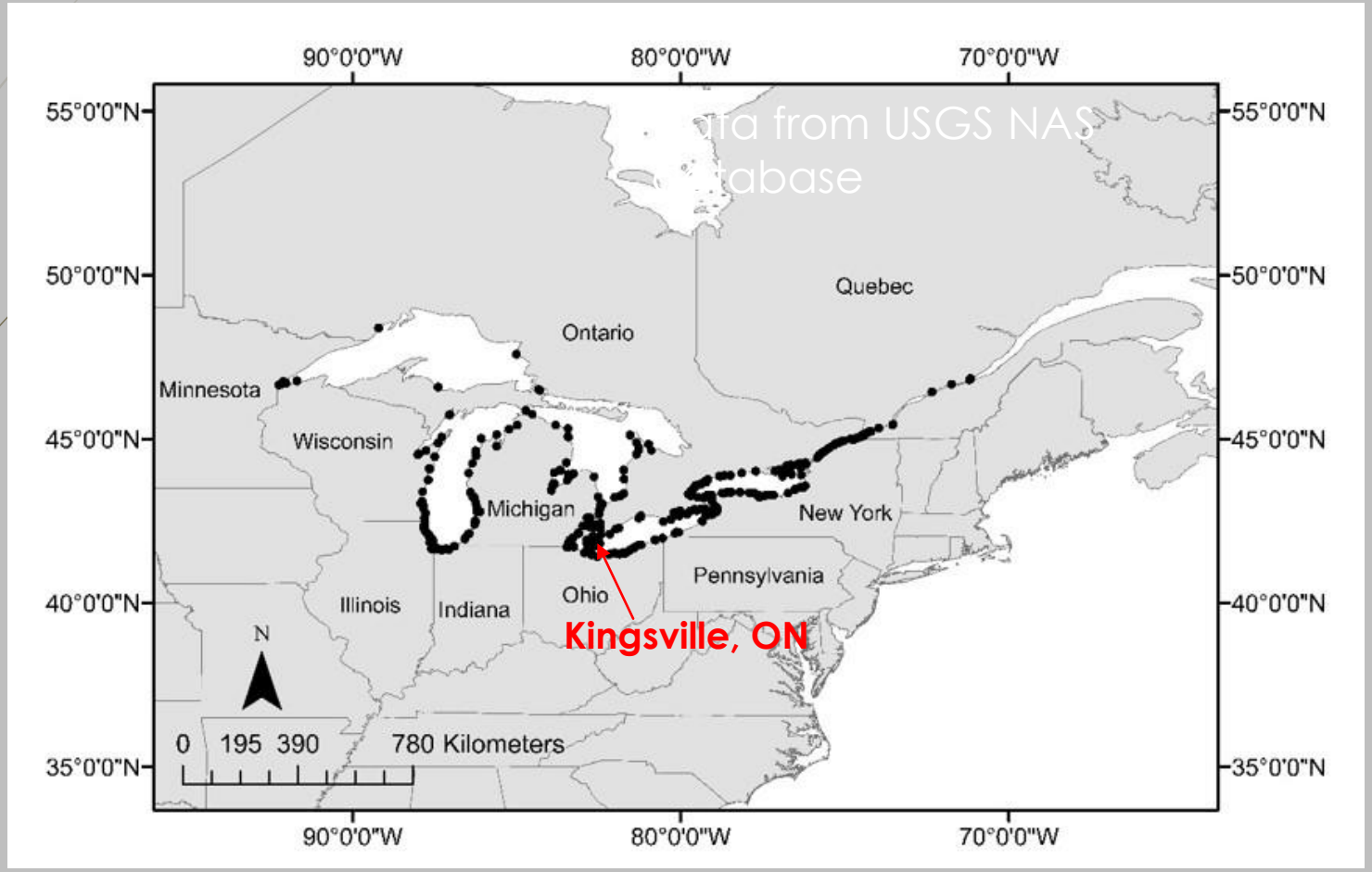
Zebra mussel 1987



Zebra mussel 1989



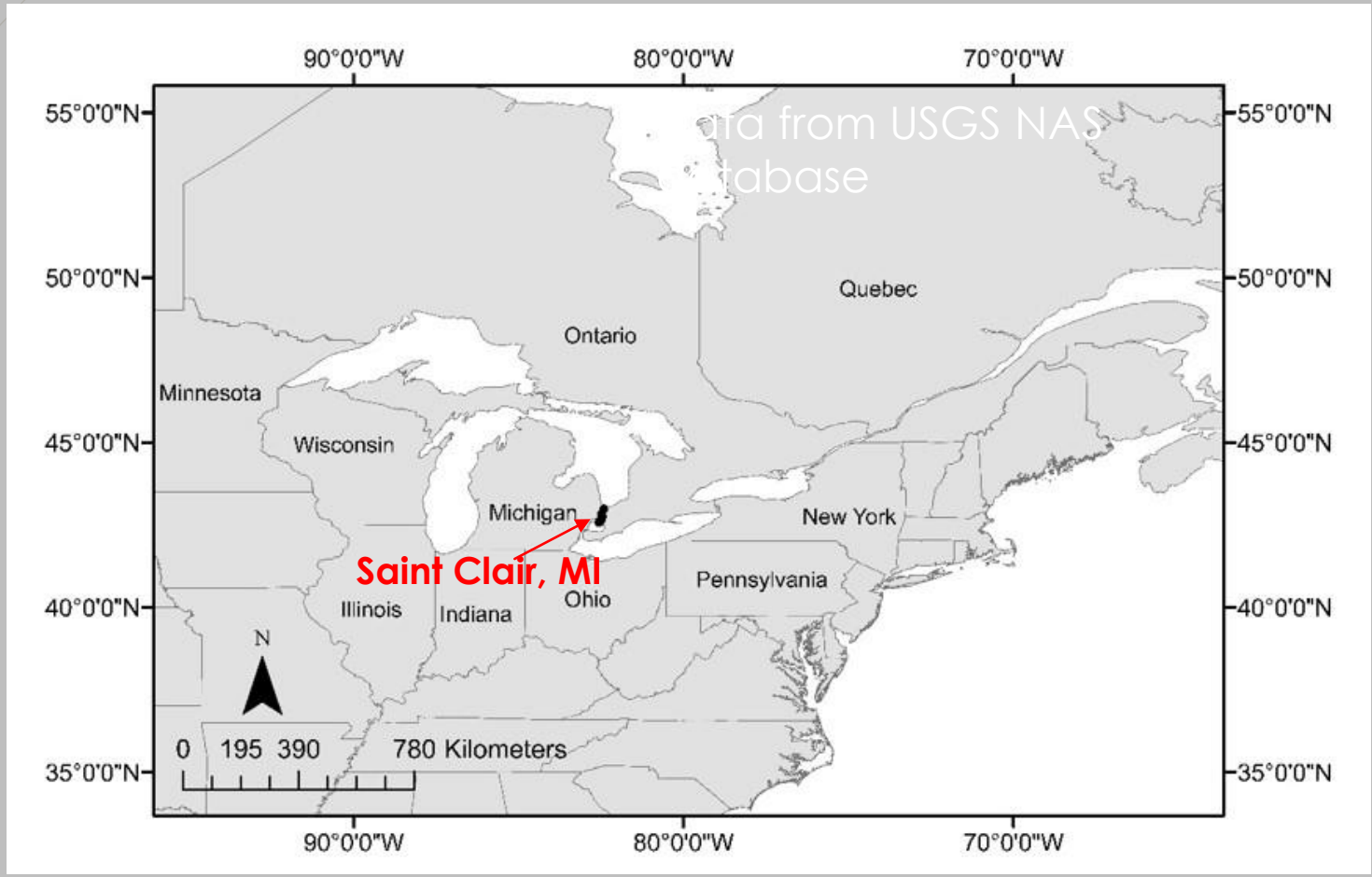
Zebra mussel 1992



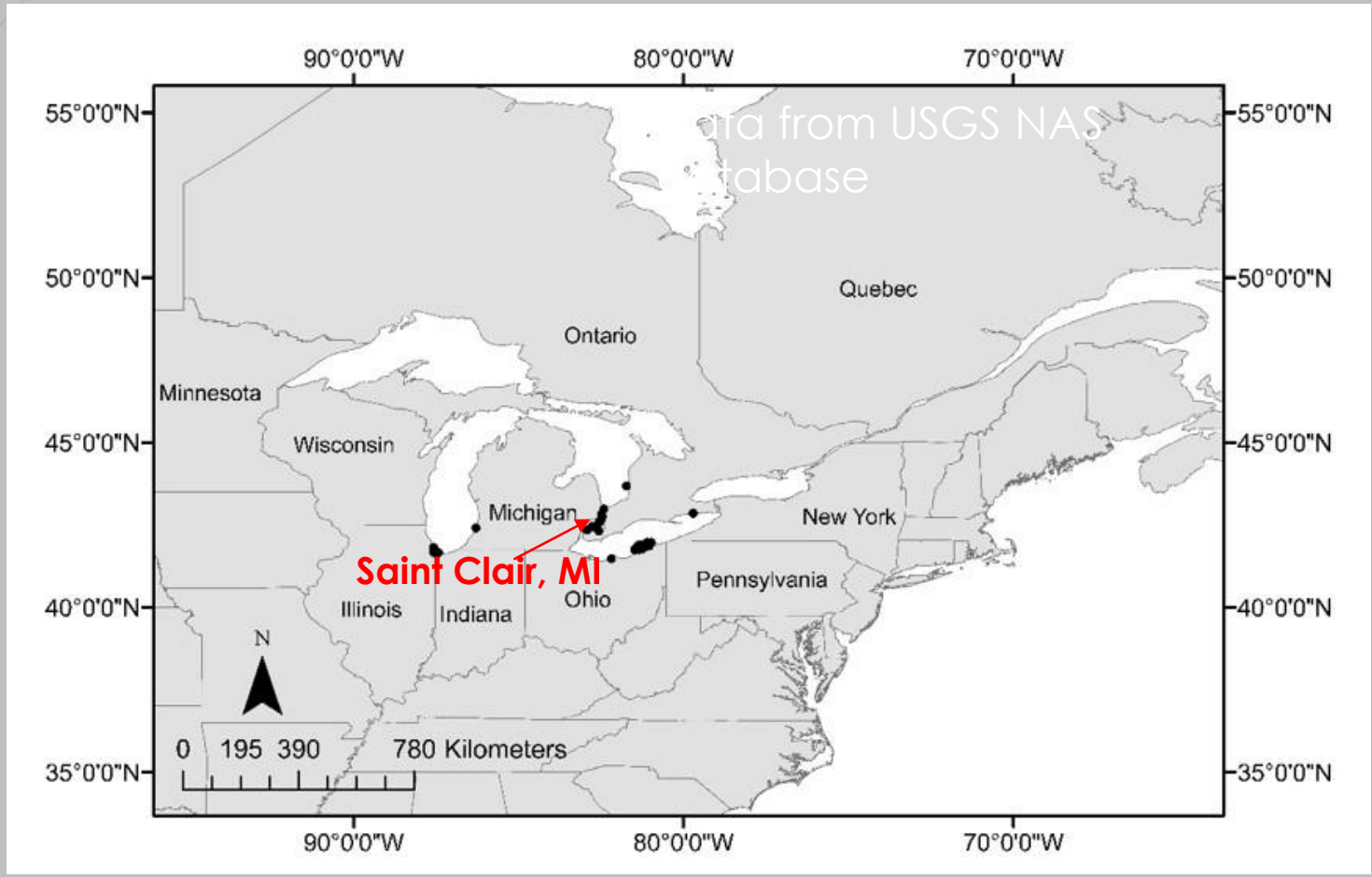
Round goby (*Neogobius melanostomus*)

- Introduced by ballast water from the Baltics
- Ballast water largely responsible for secondary spread
  - Genetic evidence for multiple introductions
- Found throughout Great Lakes

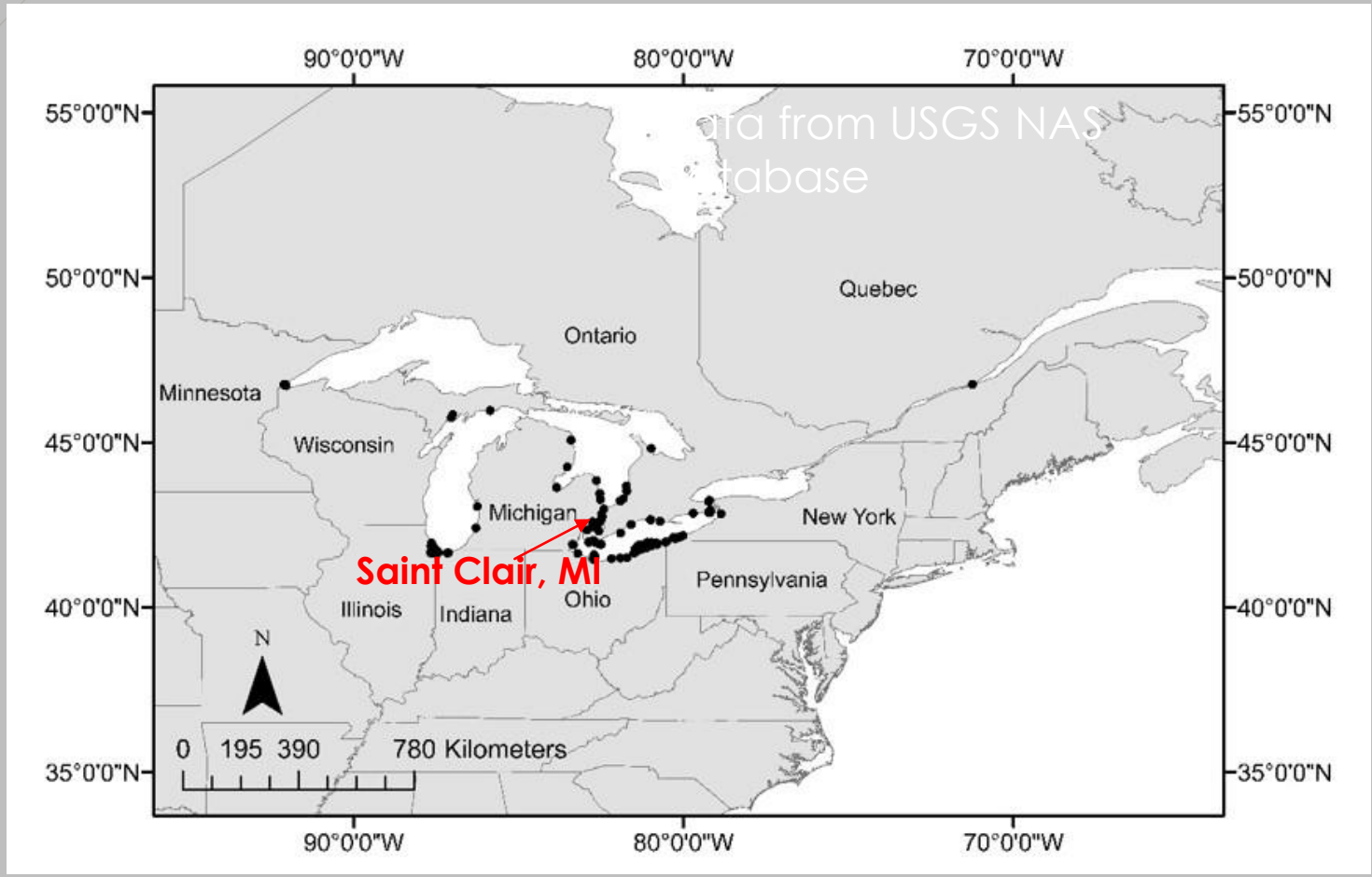
Round goby 1990



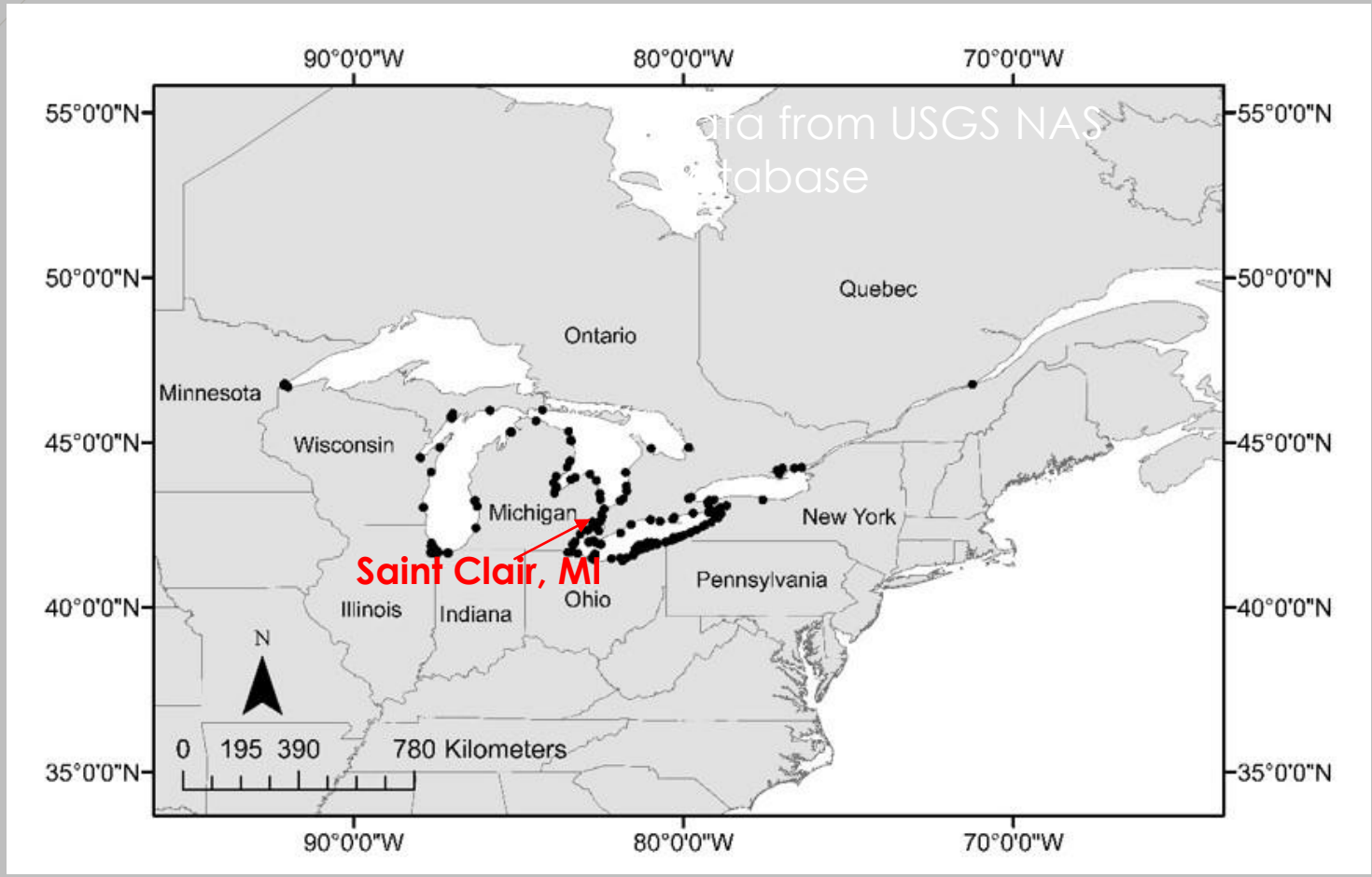
Round goby 1994



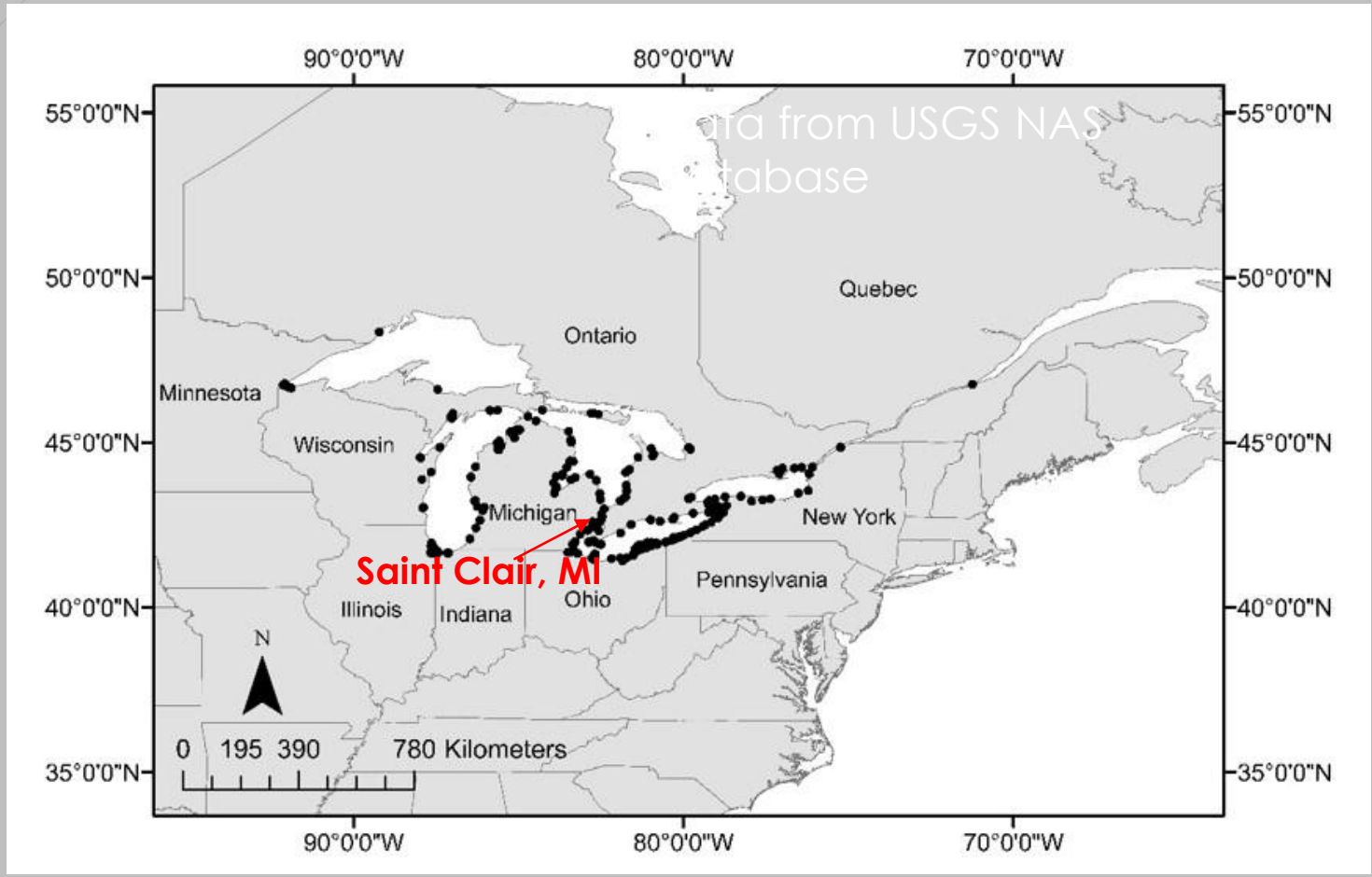
Round goby 1998



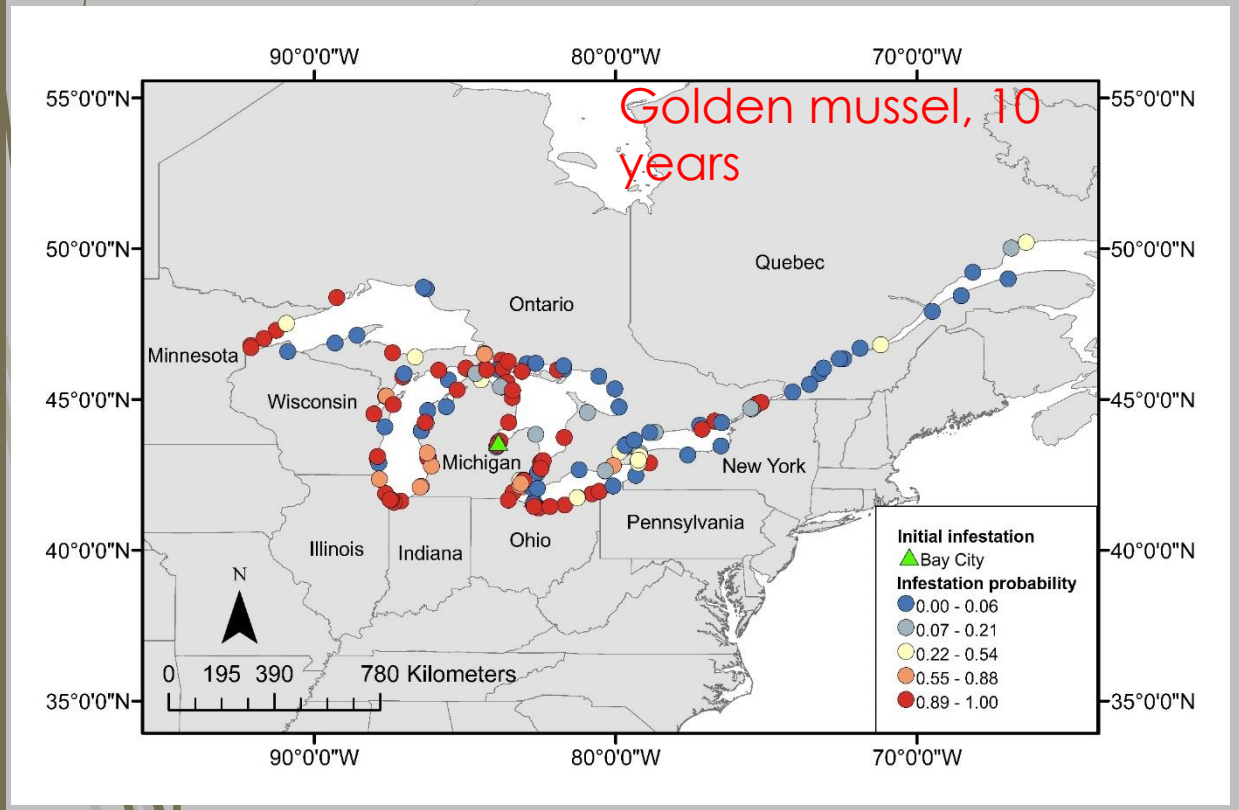
Round goby 2002

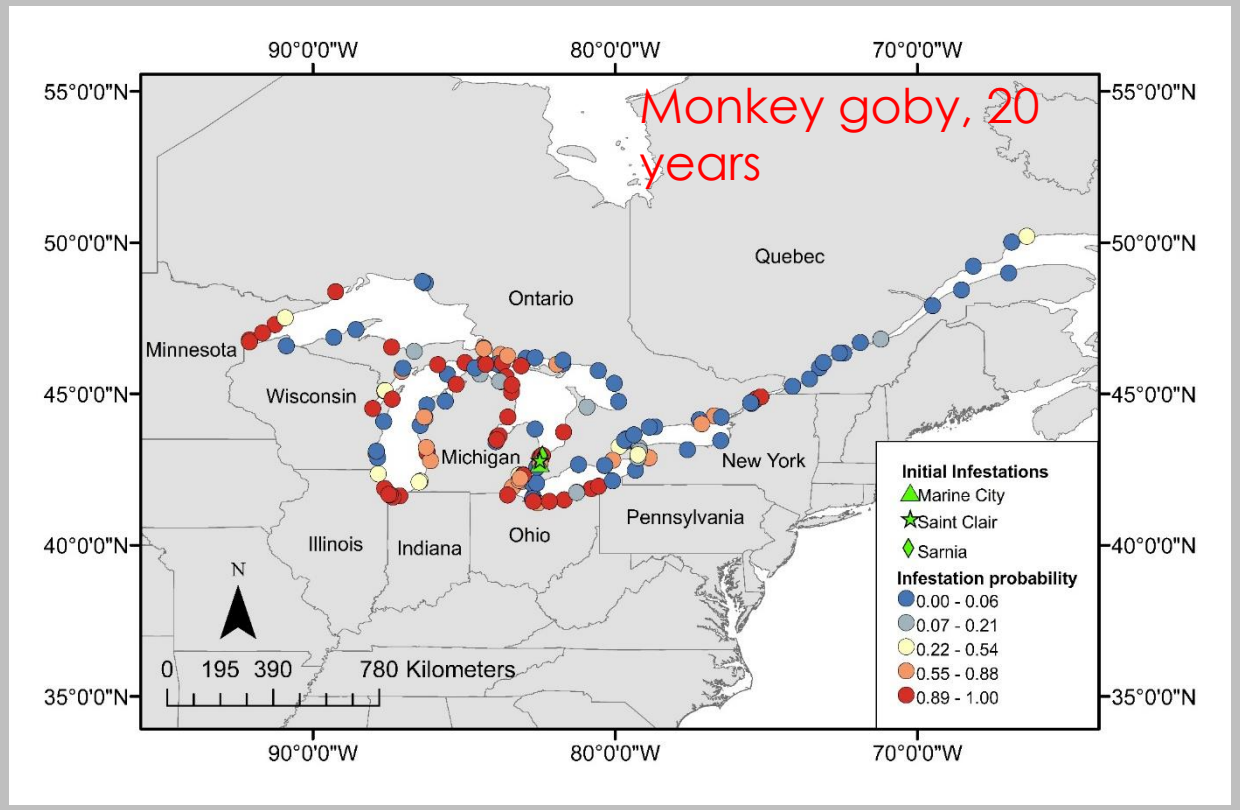


Round goby 2006



Secondary spread forecasts





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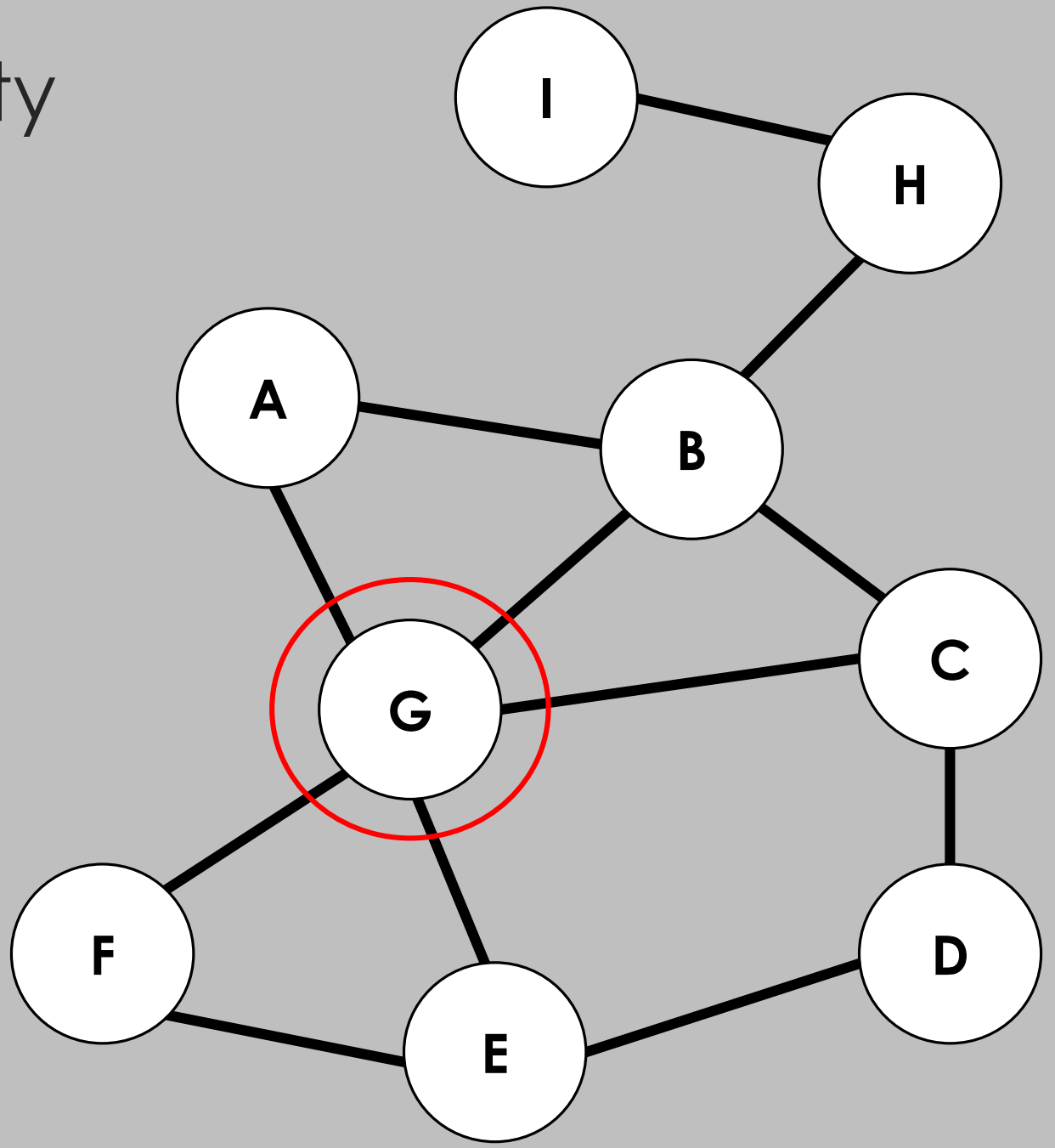
How do you quantify importance?

Tonnage handled at the top 10 U.S. Great Lakes ports in 2010.
Data from www.midamericafreight.org

PORT NAME	Total Tonnage (U.S. Tons)	Domestic (U.S. Tons)
Duluth-Superior, MN and WI	36,598,247	26,936,111
Chicago, IL	18,534,237	15,381,973
Two Harbors, MN	13,877,097	13,391,512
Detroit, MI	13,406,493	10,792,960
Cleveland, OH	10,791,326	9,218,274
Toledo, OH	10,720,187	3,927,139
Indiana Harbor, IN	10,168,960	9,901,838
Presque Isle, MI	8,720,506	6,447,080
St. Clair, MI	7,988,201	7,988,201
Gary, IN	7,831,215	7,607,812

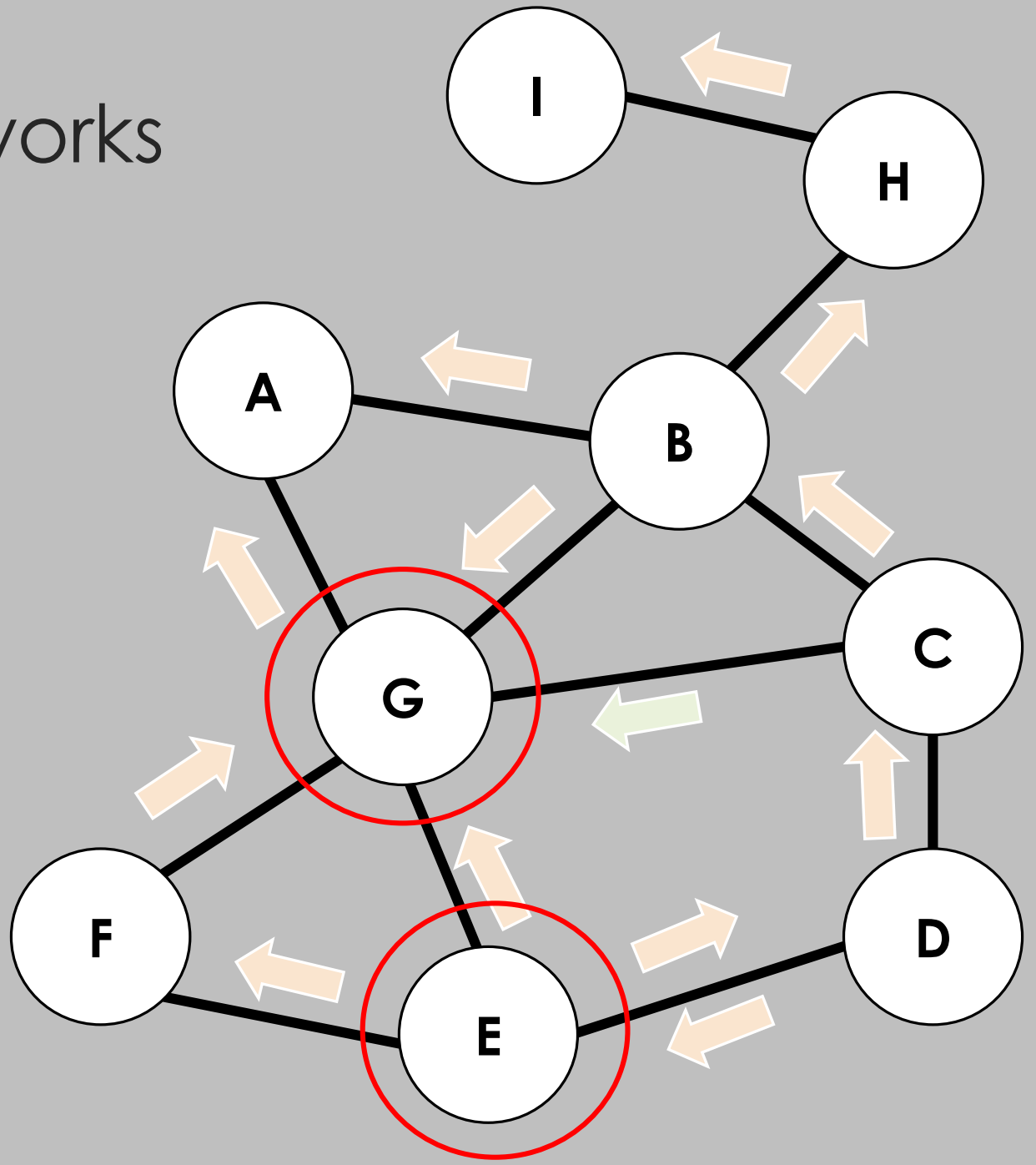
Network centrality

- Most influential?
- Identify key ‘actors’ in the shipping network.
- More central nodes have greater influence over network
  - Many ways to define this
  - Always context dependent
- Most basic: Freeman’s degree centrality



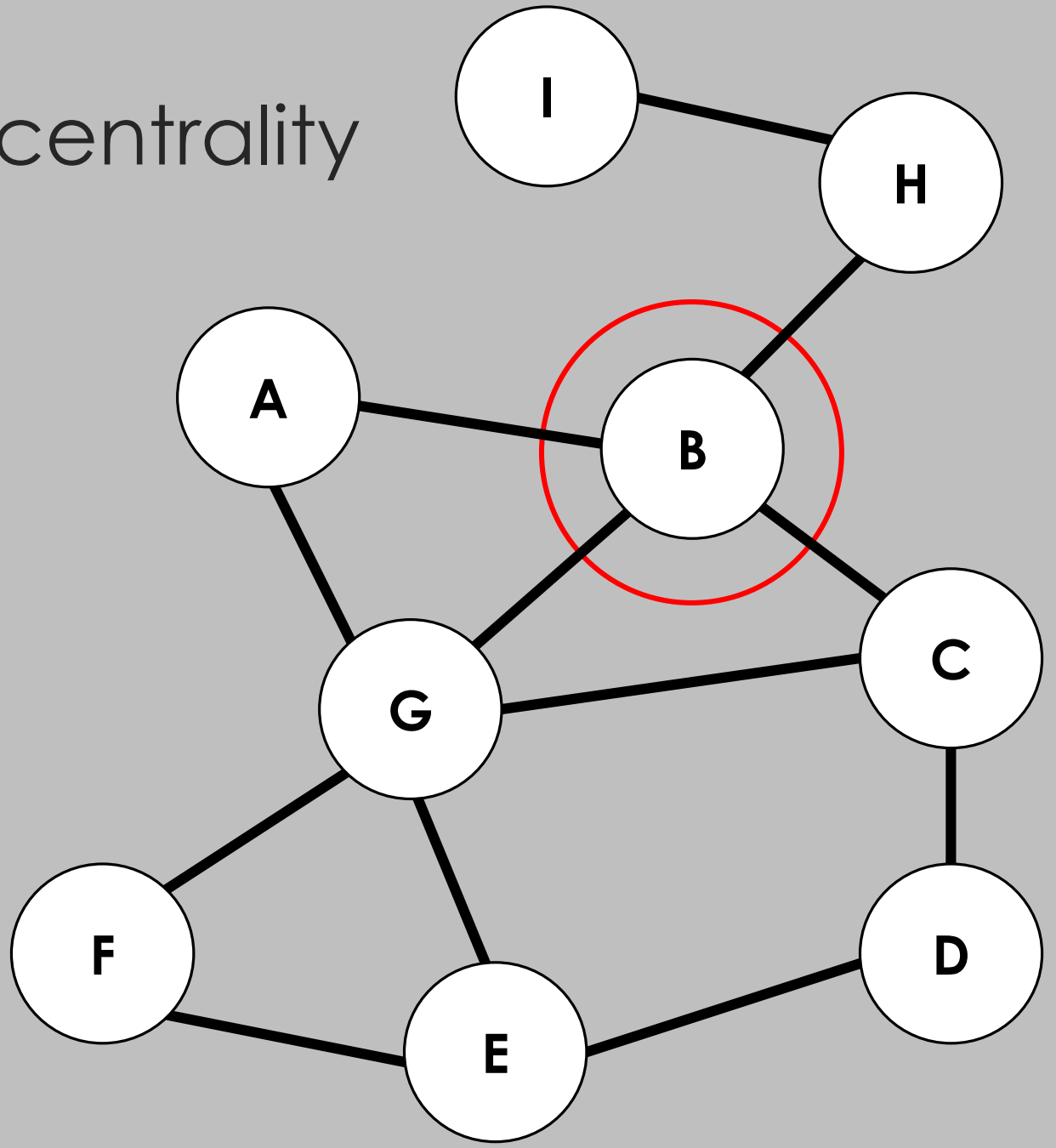
Directed networks

- Direction of connections is important to consider
- Indegree (incoming connections)
  - Receivers
- Outdegree (outgoing connections)
  - Distributors



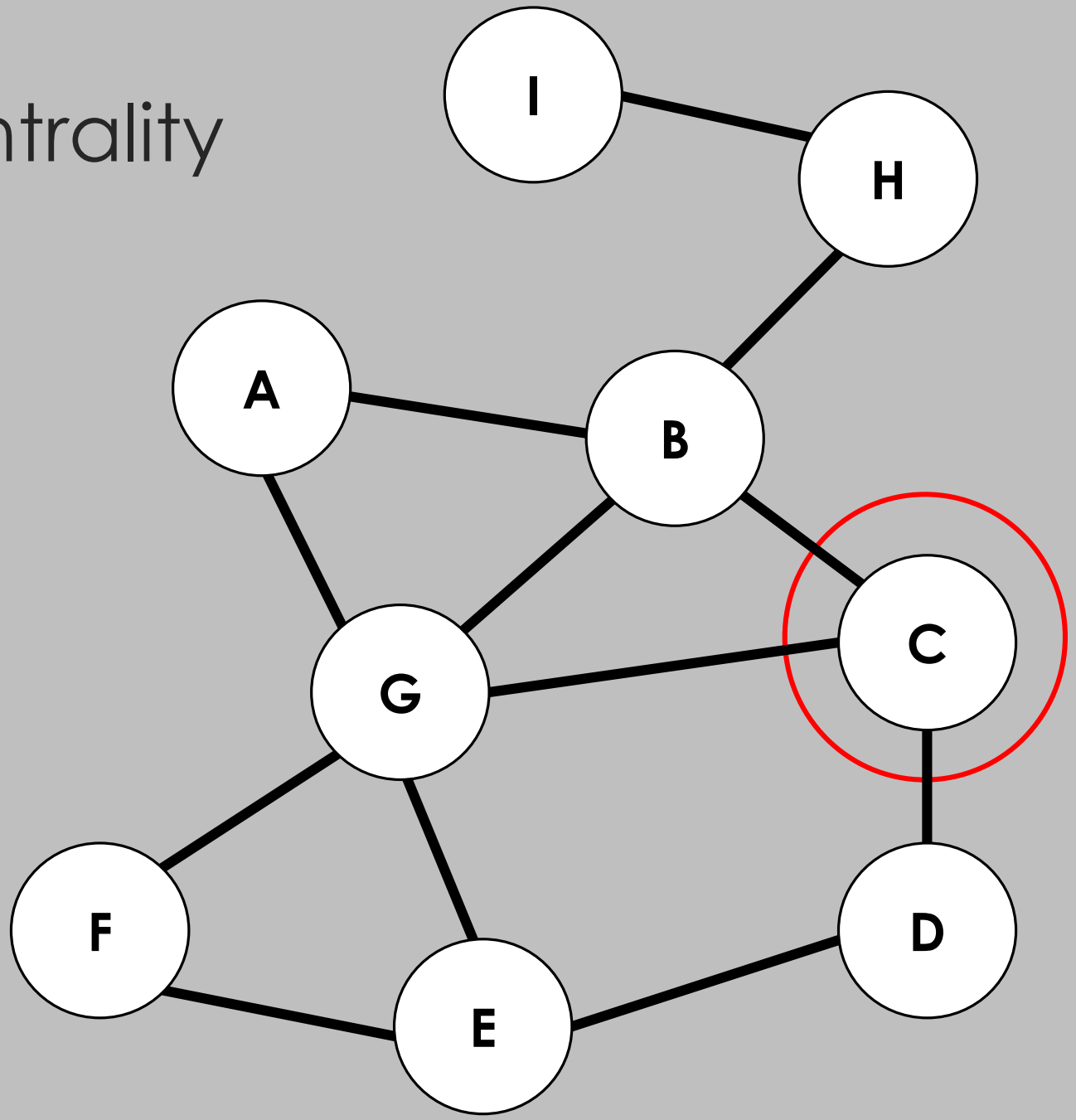
Betweenness centrality

- Which nodes act as bridges along the shortest paths to all other nodes?
- Critical links in the network
- Can determine fate of entire sections of the network
  - Gateways



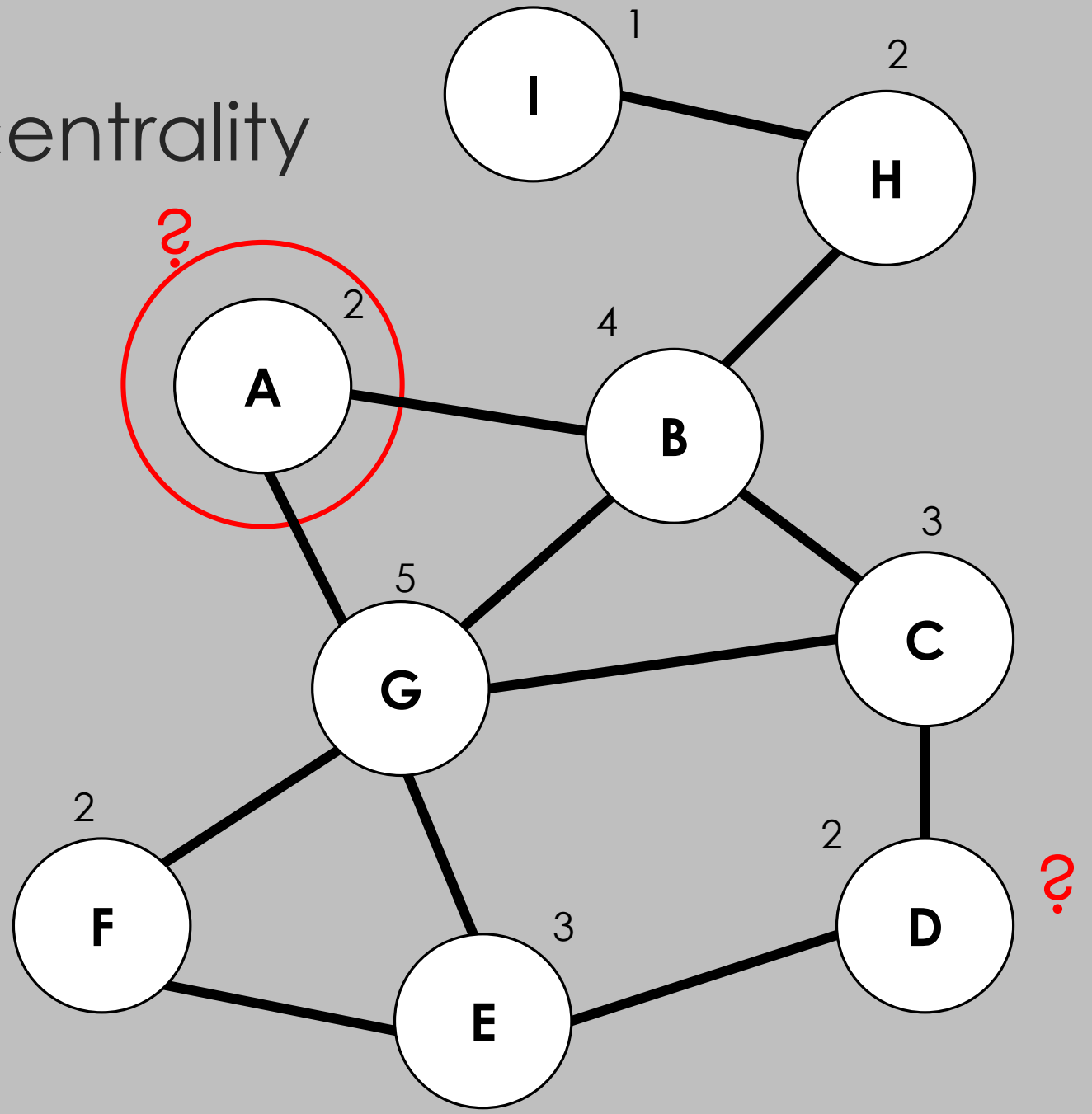
Closeness centrality

- Lowest number of steps to reach other nodes
- Facilitates rapid transport within the network
  - Sort of like geographic centers



Eigenvector centrality

- Nodes that are connected to nodes with high connections, which in turn share many connections and so on…
- Consider two nodes with 2 ties each



Simulating management scenarios

- 6 network centrality metrics plus busiest ports, total of 7 scenarios
  1. Freeman's degree – total connections
  2. Indegree – receivers
  3. Outdegree – distributors
  4. Closeness – central hubs
  5. Betweenness – gateways
  6. Eigenvector – prestige
  7. Busiest ports by ship arrivals

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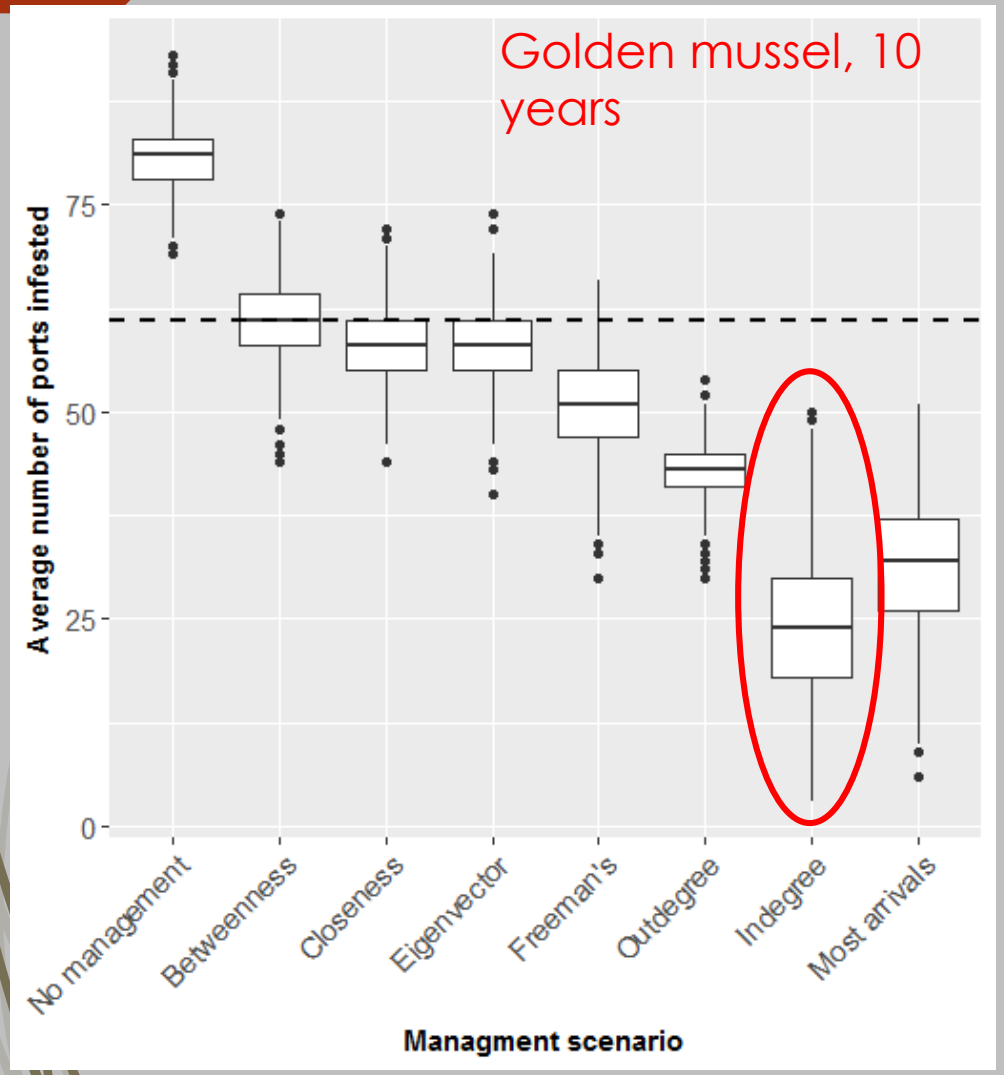
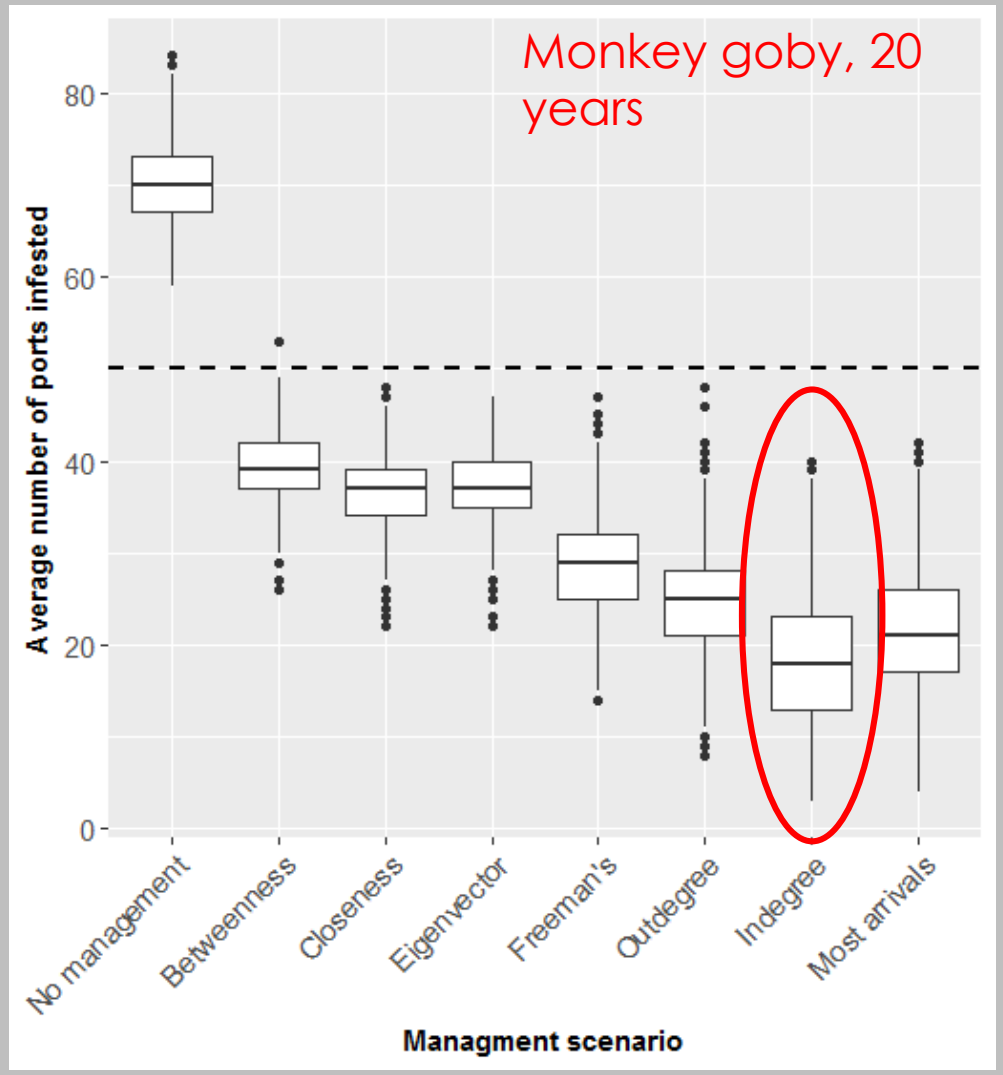
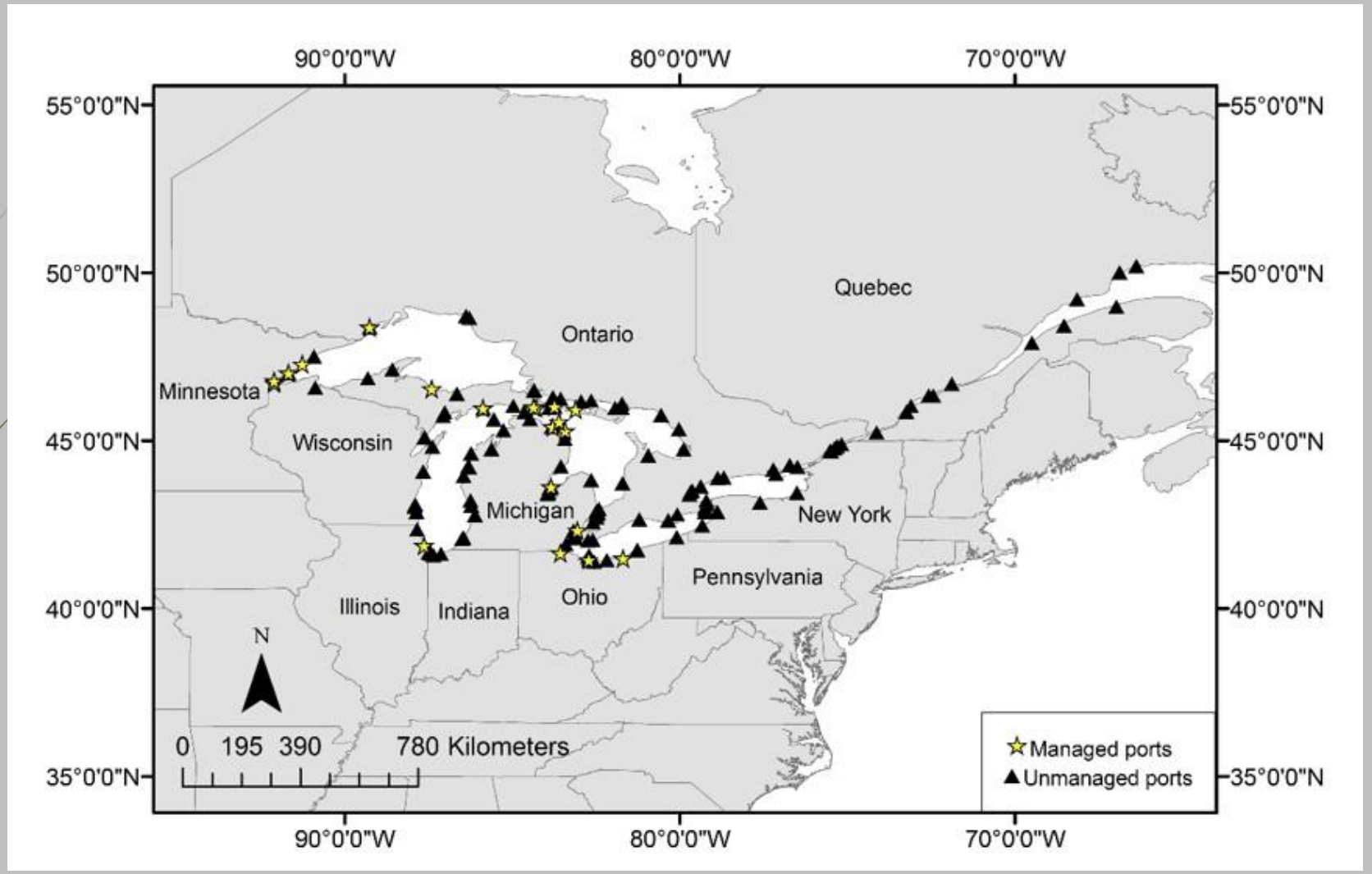
  5. Betweenness – gateways
  6. Eigenvector – prestige
  7. Most arrivals (general measure of business)
- Modeled management at top 20 scoring ports in each metric; assumed 0% infestation probability
- 1000 times at 10 years of spread for golden mussel, 20 years for monkey goby

Management at top 20 scoring ports for each species produced similar results





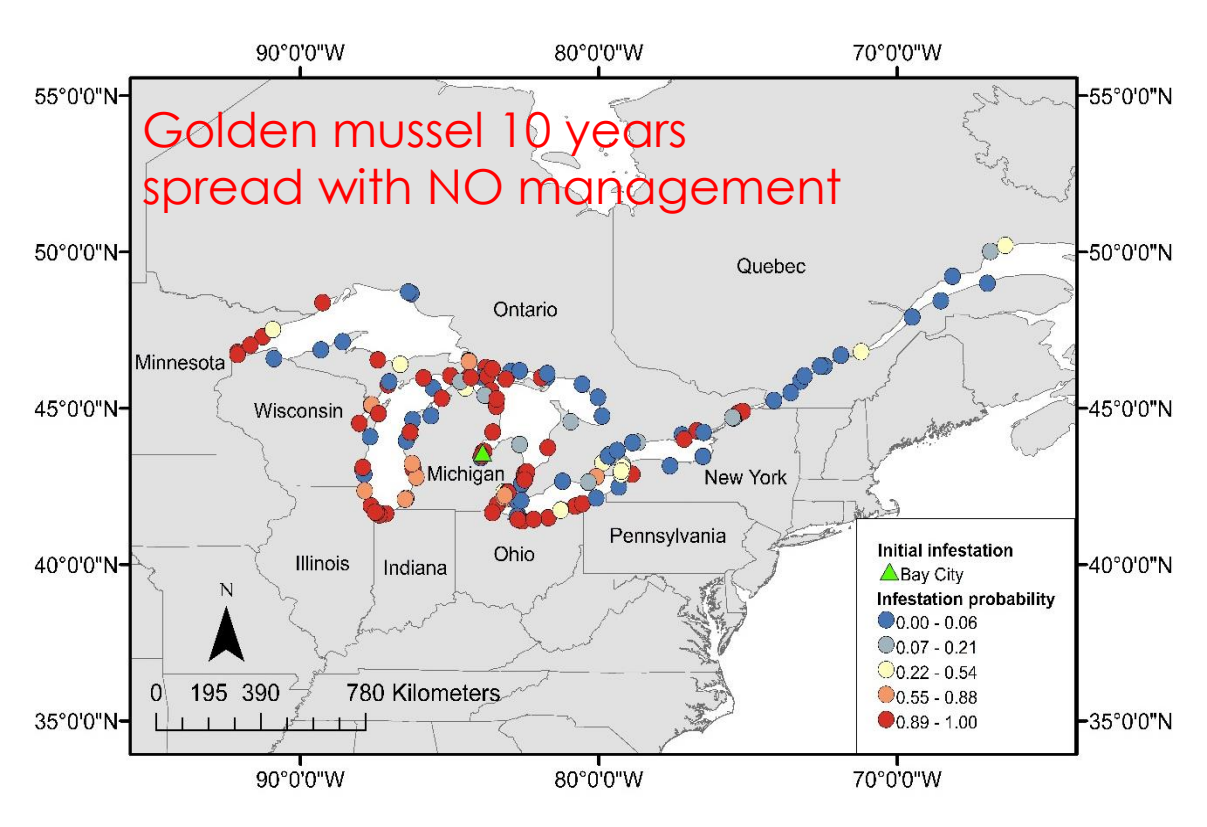

90°0'0"W
80°0'0"W
70°0'0"W
55°0'0"N
50°0'0"N
45°0'0"N
40°0'0"N
35°0'0"N
Quebec
Ontario
Minnesota
Wisconsin
Michigan
New York
Pennsylvania
Illinois
Indiana
Ohio
N
0 195 390 780 Kilometers
Managed ports
Unmanaged ports

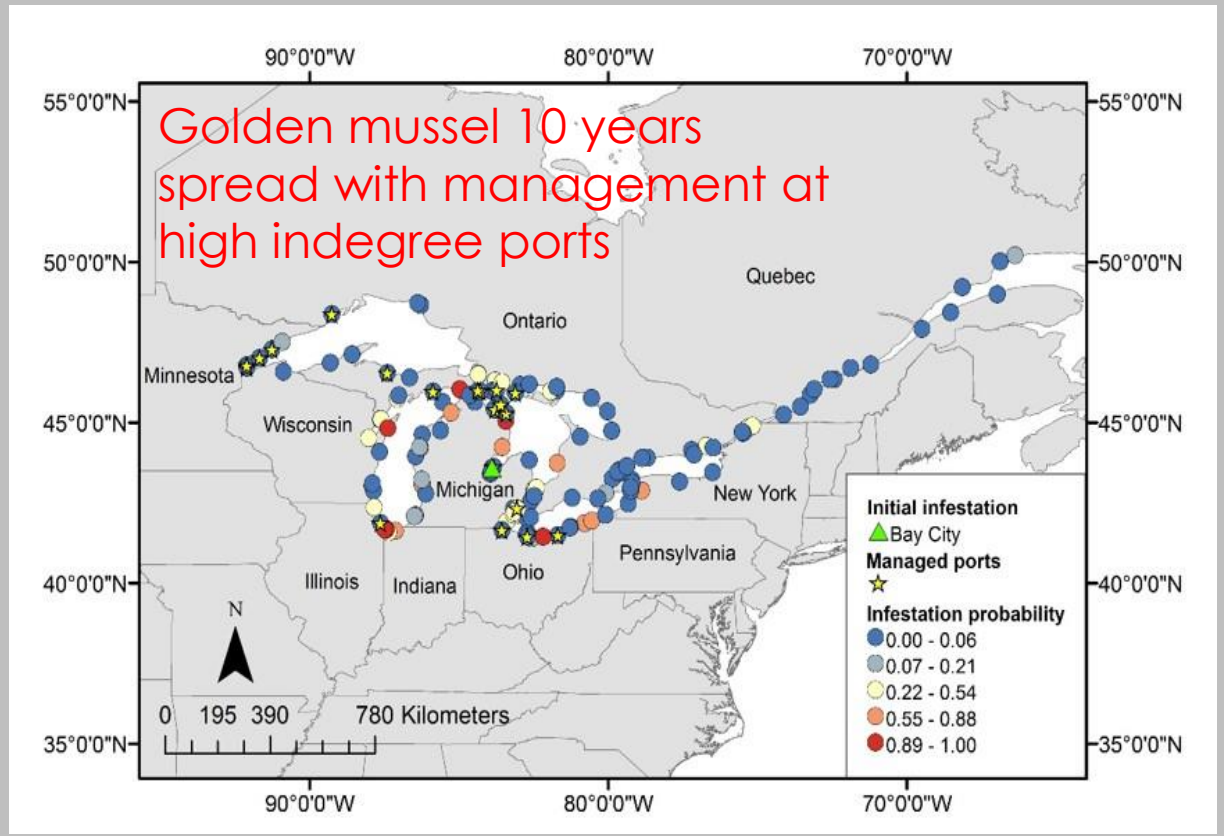
Secondary spread results

Average number of ports infested: 82.01

62%!

Average number of ports infested: 23.62

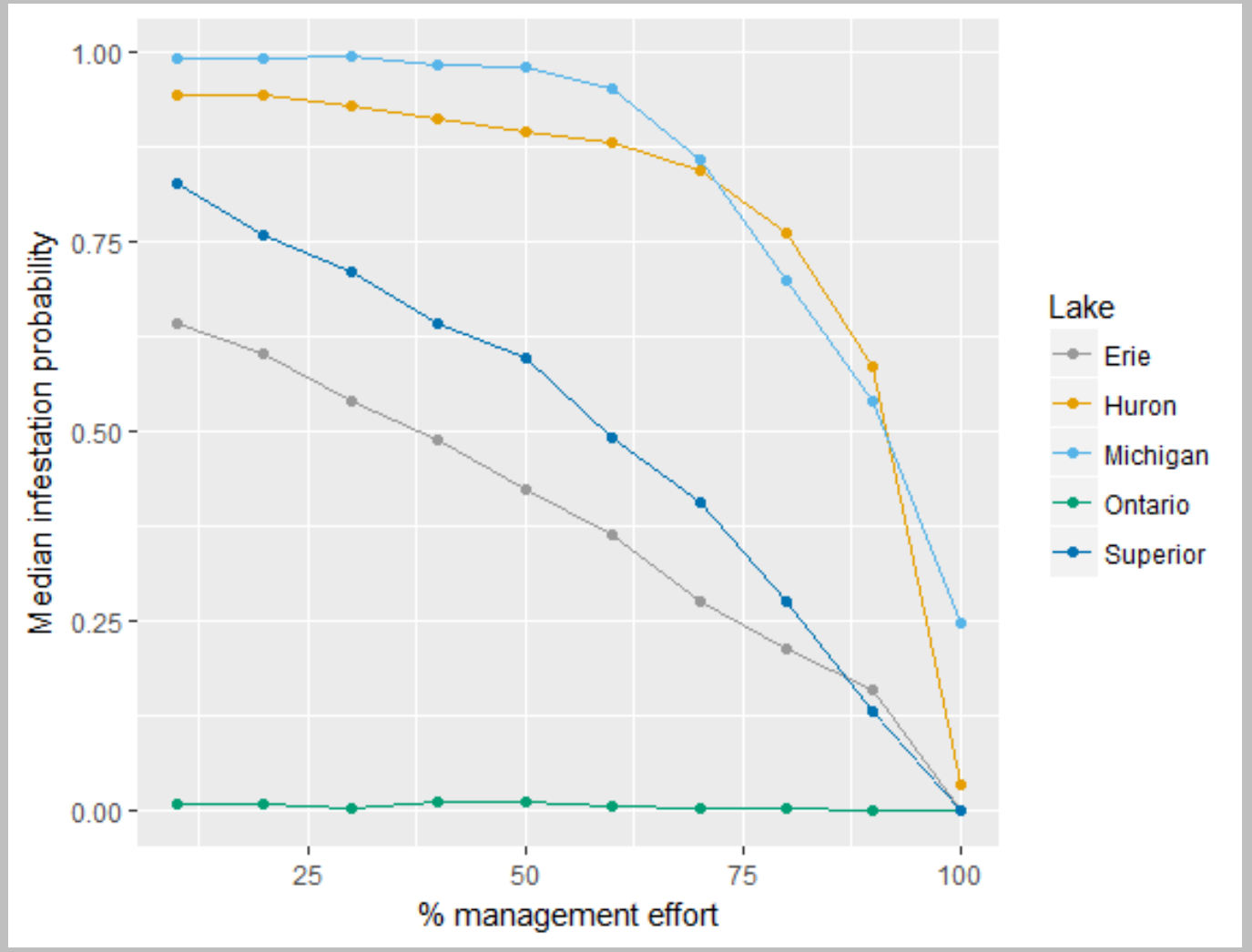




How much effort is needed to make a difference?

- Tested effort in two ways:
  - How intensely do ports need to be managed?
  - How many ports need to be managed?
- Simulated range of management intensity scenarios
- Simulated spread by adding management incrementally
  - Mann-Whitney U test to determine when number of ports infested became significantly different from ‘No management’

Management should be intensive and the effects of management are not even between lakes



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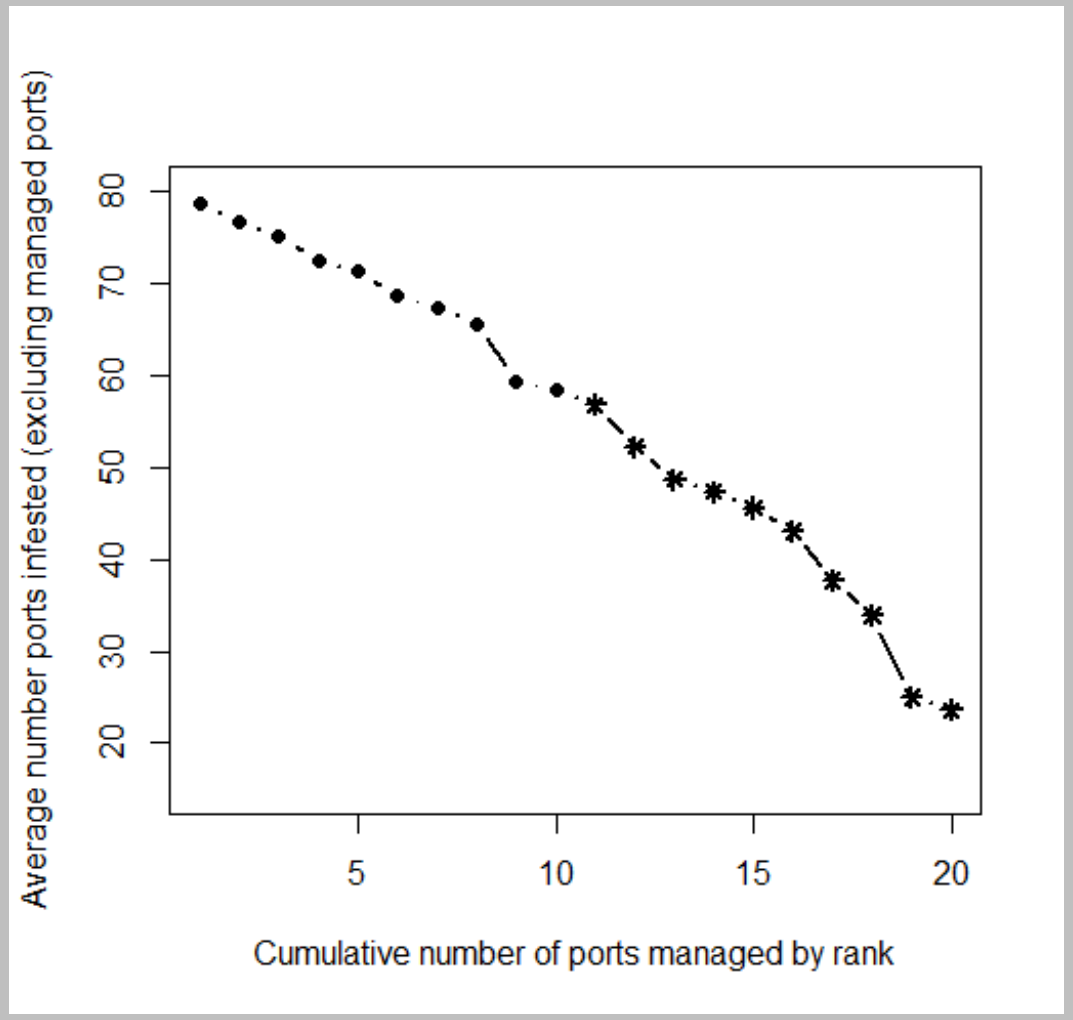
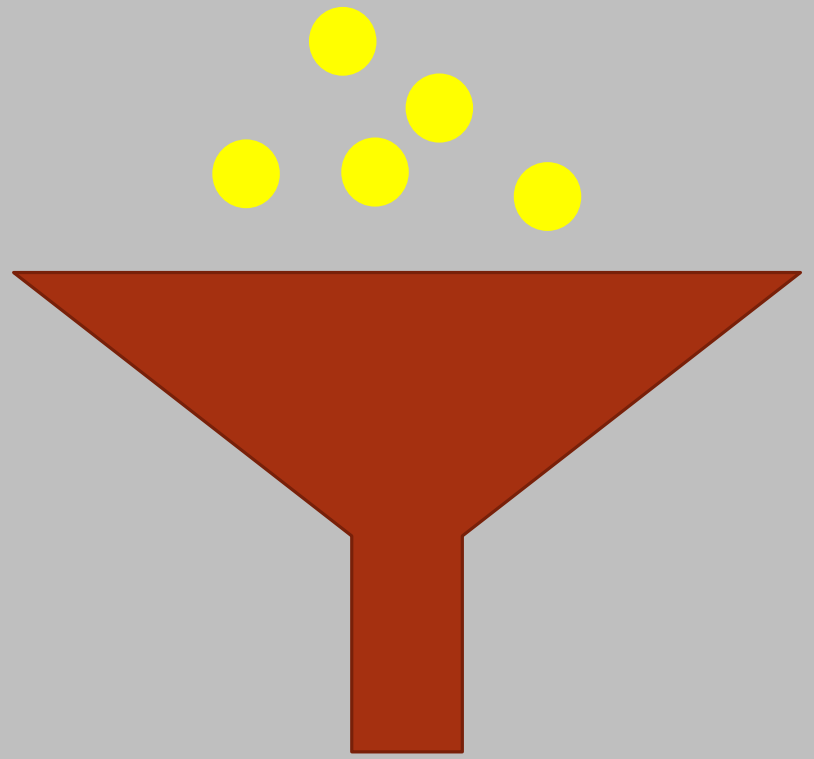


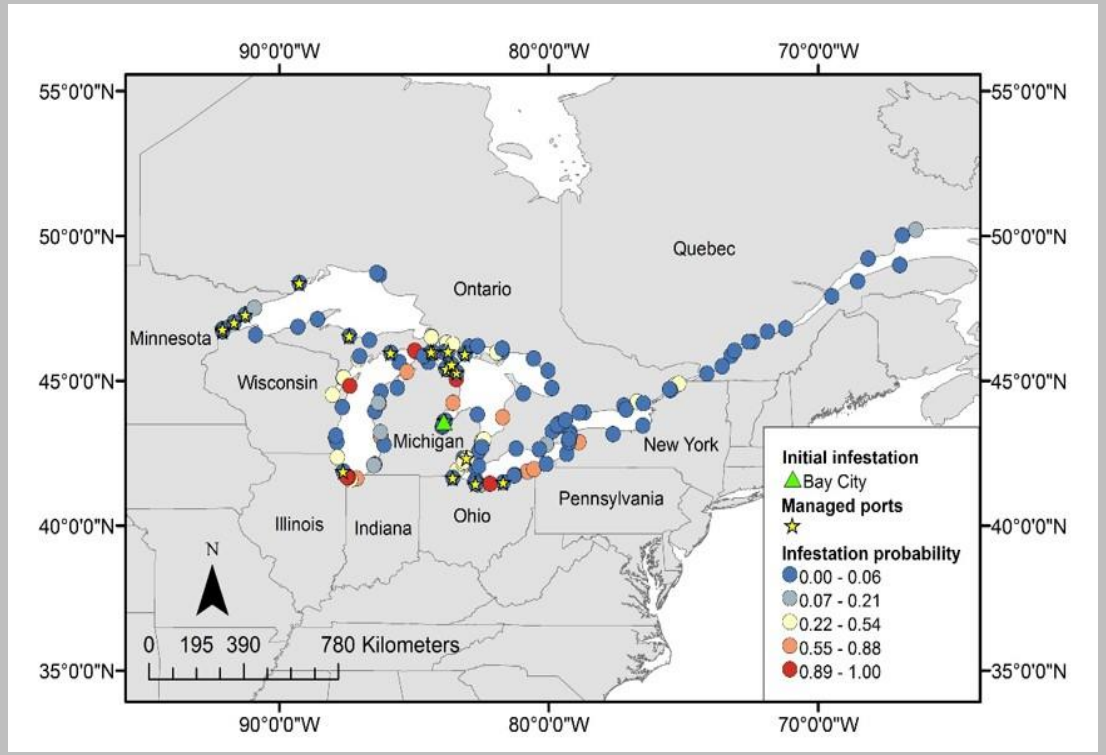
High indegree ports are like a funnels for AIS

- The higher the indegree score, the bigger the funnel
- Therefore provide the greatest chance to encounter and stop new AIS early in the invasion process
- Once they are through the funnel, they become hard to contain

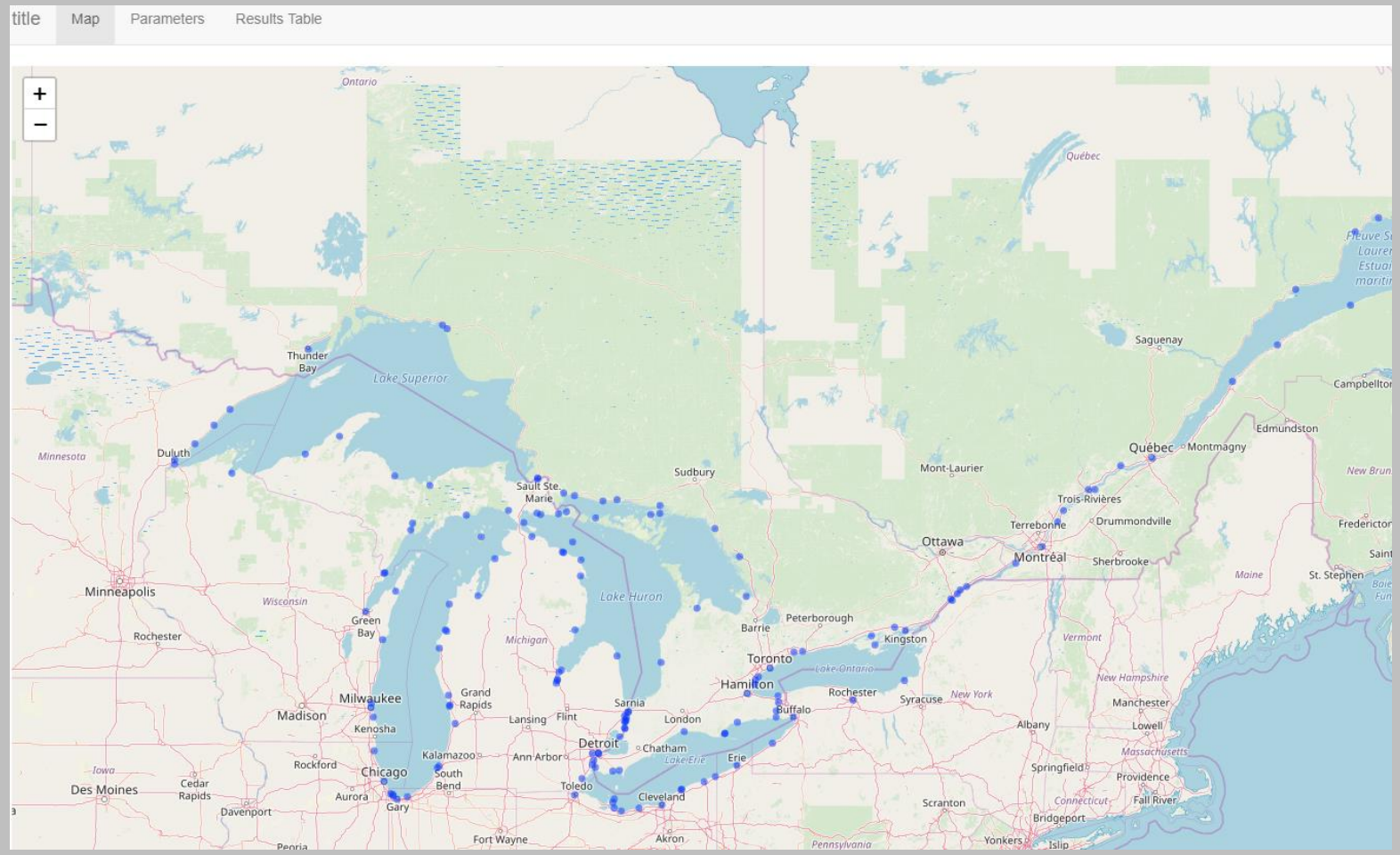


Conclusions

- Model capable of predicting secondary spread through ballast water
  - Best available data from U.S. and Canada
  - Parameterized for a range of taxa
- Demonstrated the utility of network centrality for AIS management
- Management should be both:
  - Intensive
  - Collaborative



User Friendly Model – RCloud, Shiny Package



/cloud/project - Shiny - Google Chrome

https://jonathan-bossenbroek.rstudio.cloud/c3a301c4ec5640

title | Map | Parameters | Results Table

Choose a Port

Ashtabula

Years of spread?

1 — 10 — 20

1 3 5 7 9 11 13 15 17 19 20

Species scalar (Example: Round goby = 0.003, zebra mussel = 0.014)

0.0001 — 0.02

0.0001 0.0041 0.0081 0.0121 0.0161 0.02

Environmental distance scalar

0 — 1.000

0 100 200 300 400 500 600 700 800 900 1,000

Which ports will be managed?

How effective?

0 — 1

0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1

Spread range (km)

0 — 30

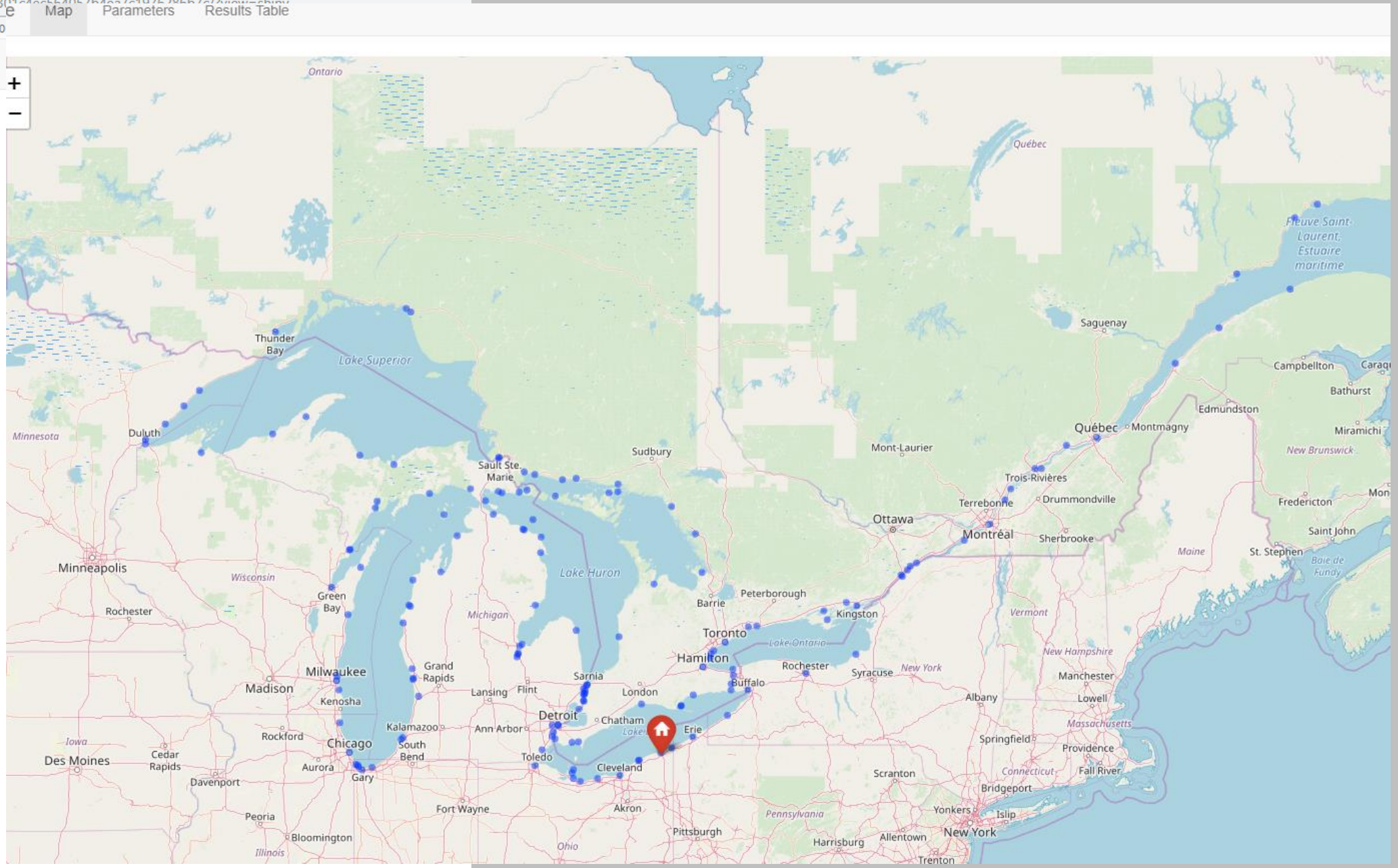
0 3 6 9 12 15 18 21 24 27 30

Change shipping rate?

0 — 1 — 2

0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2

Run



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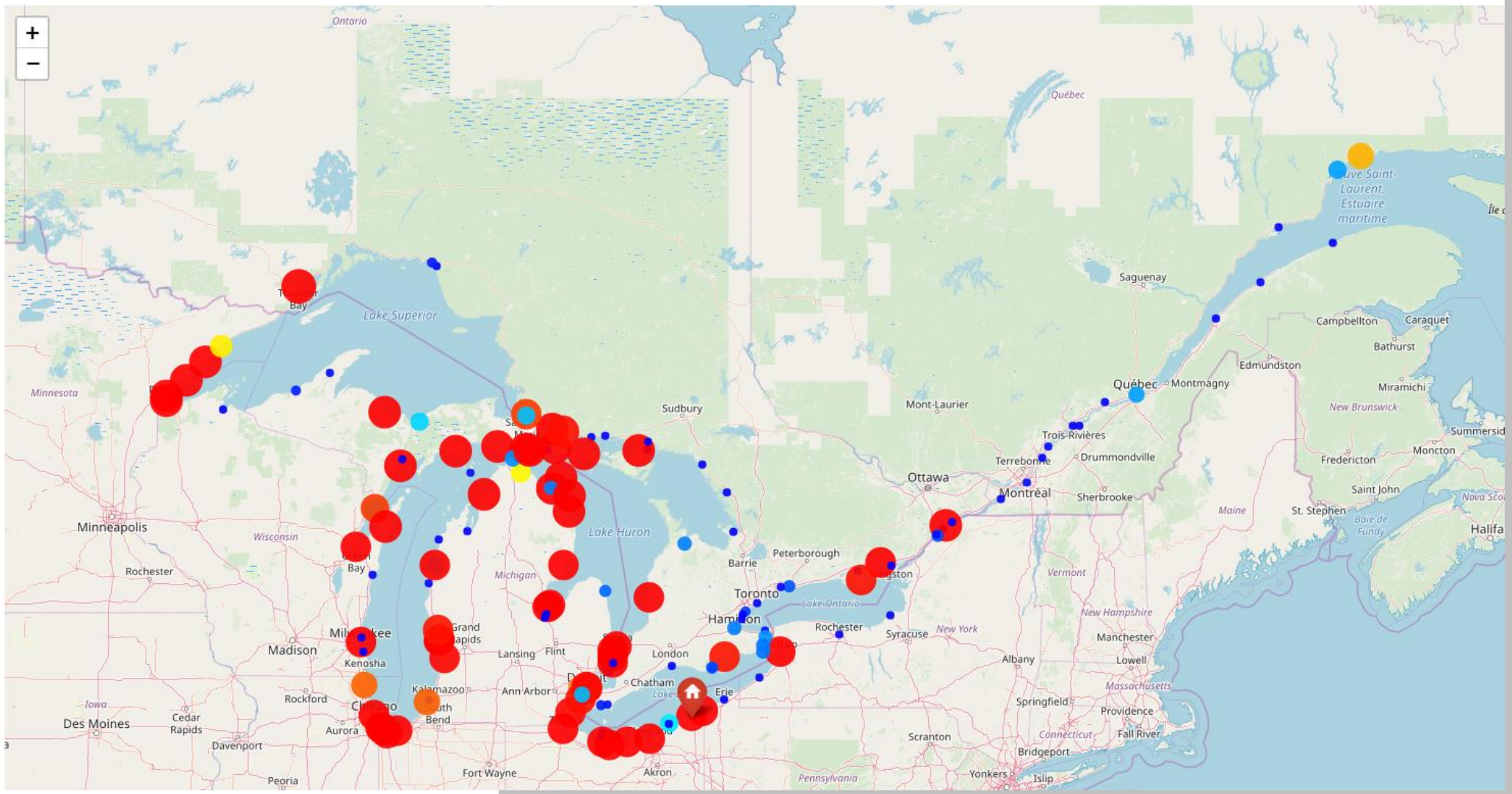

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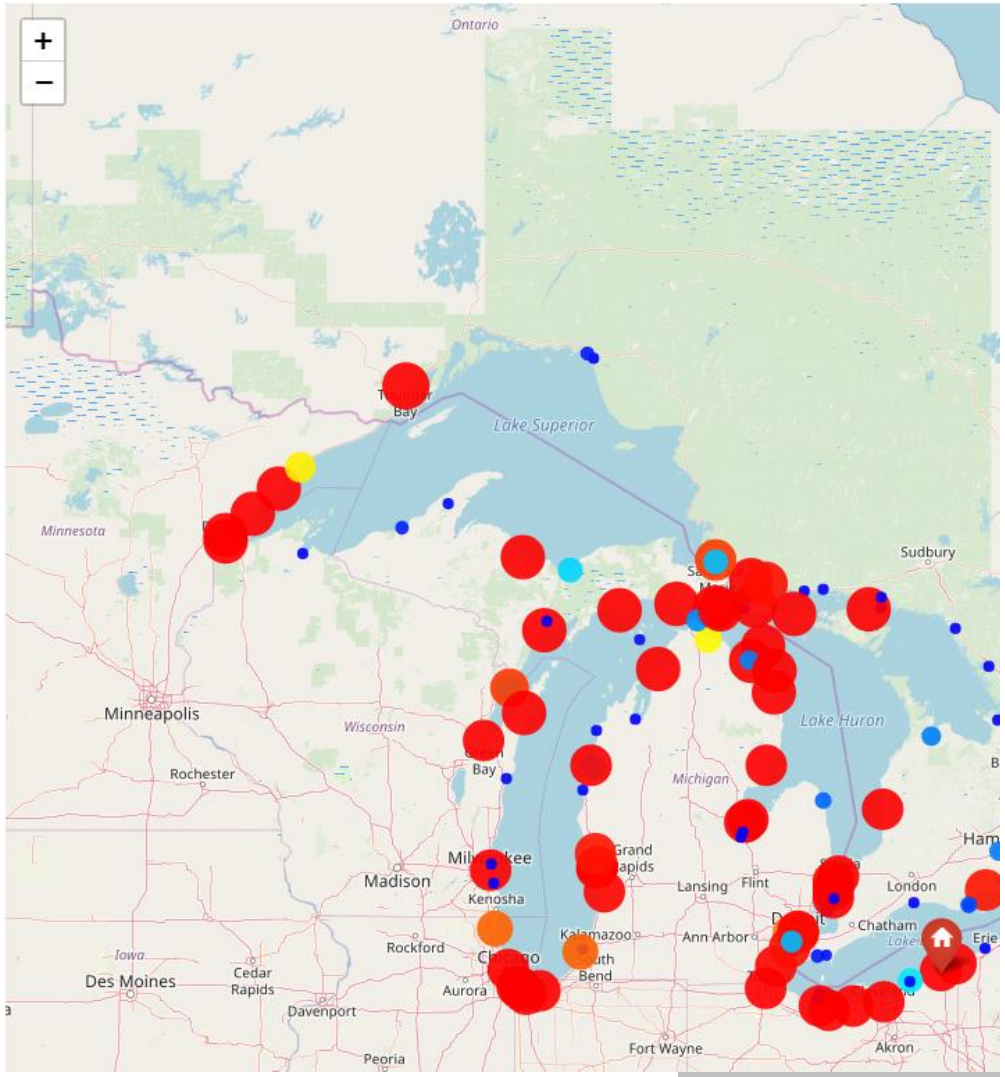
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2

Run



title | Map | Parameters | Results Table

Port	Probability	lat	long	Lake	State_code
Alpena	1.00	45.06	-83.43	Huron	MI
Ashtabula	1.00	41.87	-80.79	Erie	OH
Bath	1.00	44.28	-76.72	Ontario	CAN
BayCity	1.00	43.59	-83.89	Huron	MI
Brevort	1.00	46.04	-84.97	Michigan	MI
BruceMines	1.00	46.30	-83.79	Huron	CAN
Buffalo	1.00	42.89	-78.88	Erie	NY
Buffington	1.00	41.64	-87.43	Michigan	IN
BurnsHarbor	1.00	41.63	-87.13	Michigan	IN
Calcite	1.00	45.41	-83.79	Huron	MI
Cedarville	1.00	46.00	-84.36	Huron	MI
Charlevoix	1.00	45.32	-85.26	Michigan	MI
Chicago	1.00	41.88	-87.63	Michigan	IL
Cleveland	1.00	41.50	-81.69	Erie	OH
Conneaut	1.00	41.95	-80.55	Erie	OH
Detroit	1.00	42.33	-83.05	LakeStClair	MI
Drummond	1.00	46.02	-83.73	Huron	MI
Duluth	1.00	46.79	-92.10	Superior	MN
Escanaba	1.00	45.75	-87.06	Michigan	MI
Essexville	1.00	43.62	-83.84	Huron	MI
Ferrysburg	1.00	43.08	-86.22	Michigan	MI
Gary	1.00	41.59	-87.35	Michigan	IN
Goderich	1.00	43.74	-81.71	Huron	CAN
GreenBay	1.00	44.52	-88.02	Michigan	WI
IndianaHarbor	1.00	41.67	-87.44	Michigan	IN

title Map Parameters Results Table

e Map Parameters Results Table

Choose a Port

Ashtabula

Years of spread?

1 10 20

1 3 5 7 9 11 13 15 17 19 20

Species scalar (Example: Round goby = 0.003, zebra mussel = 0.014)

0.0001 0.02

0.0001 0.0041 0.0081 0.0121 0.0161 0.02

Environmental distance scalar

0 1,000

0 100 200 300 400 500 600 700 800 900 1,000

Which ports will be managed?

Calcite Cleveland Duluth Marquette
PresqueIsle Sandusky SilverBay
Superior TwoHarbors Toledo

How effective?

0 1

0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1

Spread range (km)

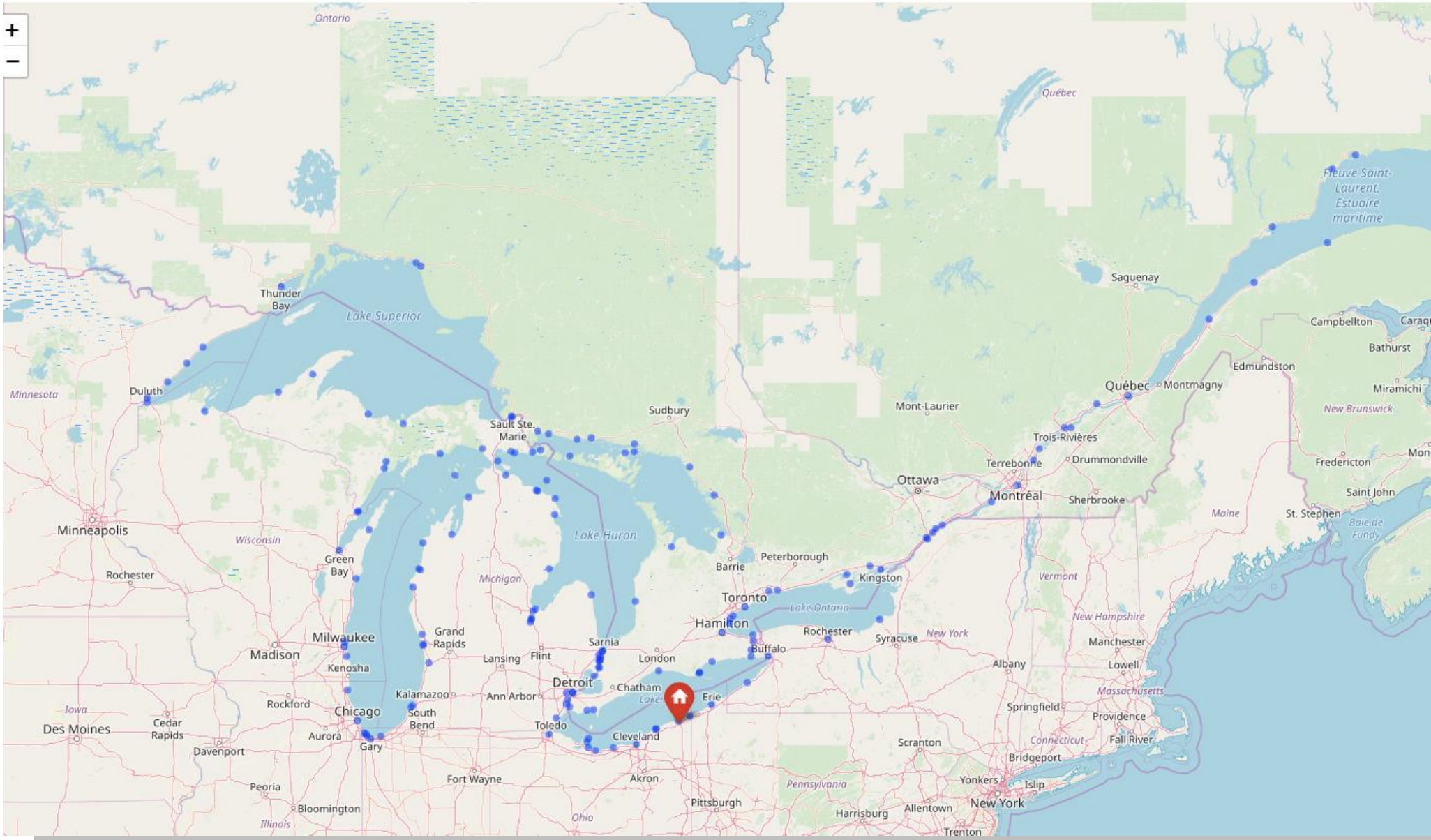
0 30

0 3 6 9 12 15 18 21 24 27 30

Change shipping rate?

0 1 2

0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2



title | Map | Parameters | Results Table

Choose a Port

Ashtabula

Years of spread?

1 — 10

1 3 5 7 9 11 13 15 17

Species scalar (Example: Round goby = 0.003, zebra mussel = 0.014)

0.0001

0.0001 0.0041 0.0081 0.0121 0.0161

Environmental distance scalar

0

0 100 200 300 400 500 600 700 800 90

Which ports will be managed?

Calcite | Cleveland | Duluth | Marquette | PresqueIsle | Sandusky | SilverBay | Superior | TwoHarbors | Toledo

How effective?

0

0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.

Spread range (km)

0

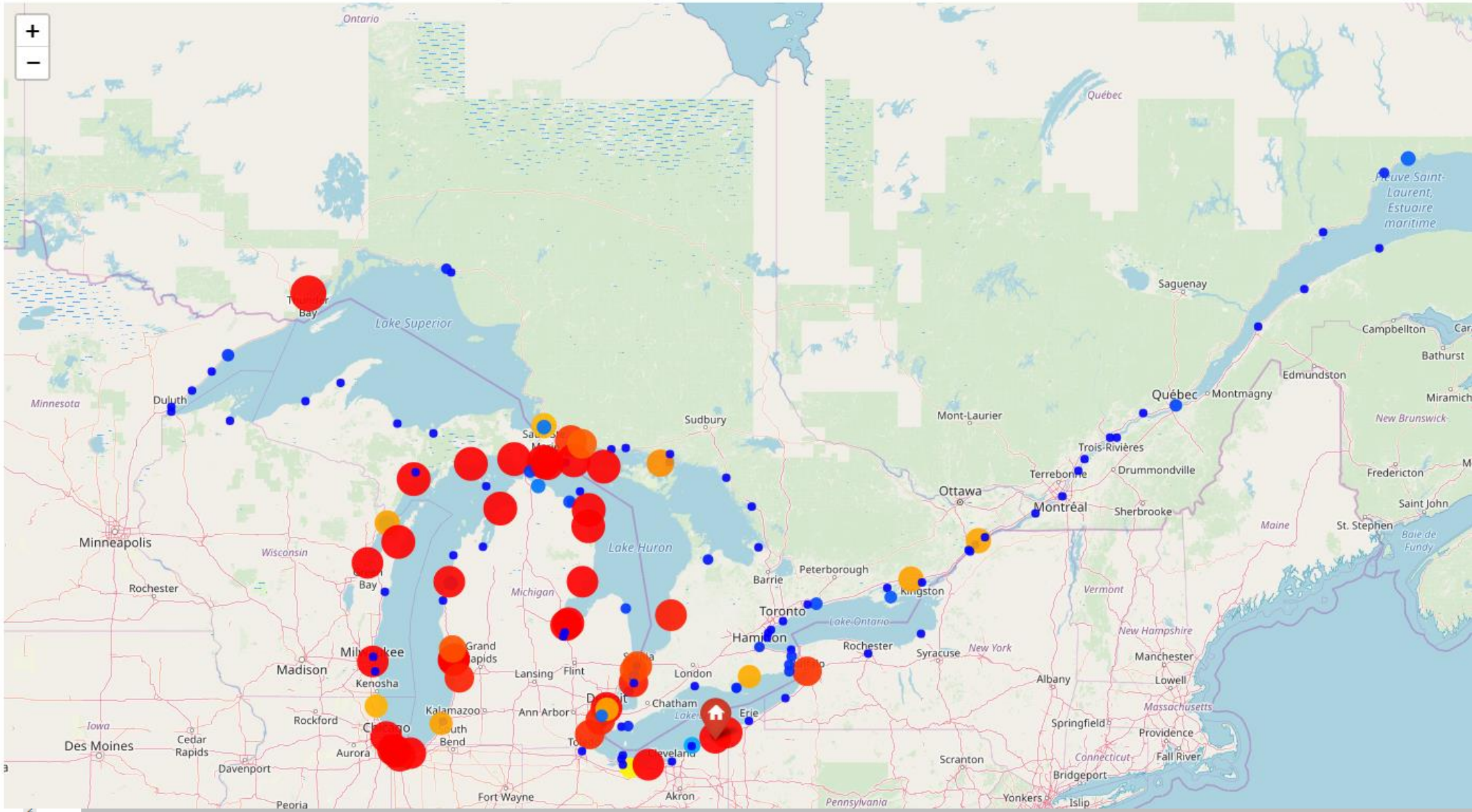
0 3 6 9 12 15 18 21 24 27

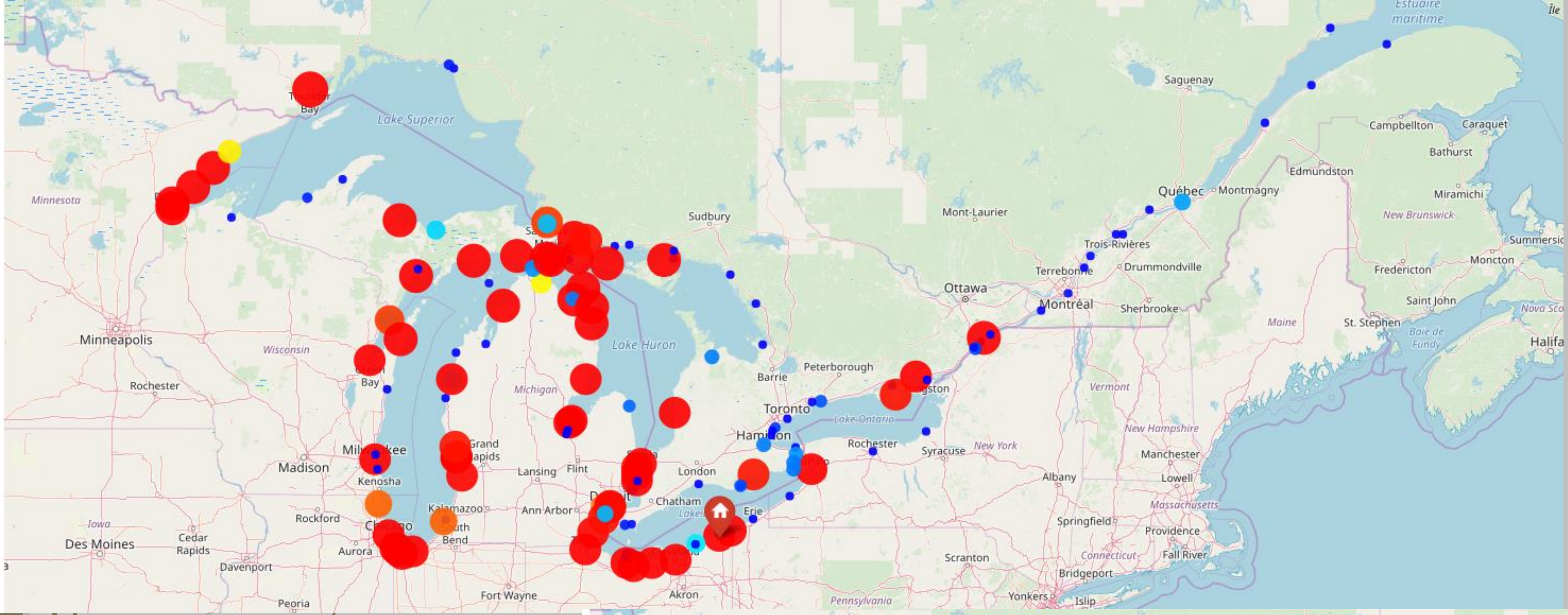
Change shipping rate?

0 — 1

0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2

title | Map | Parameters | Results Table




Lake Superior
Minnesota
Minneapolis
Wisconsin
Rochester
Madison
Kenosha
Rockford
Iowa
Des Moines
Cedar Rapids
Davenport
Aurora
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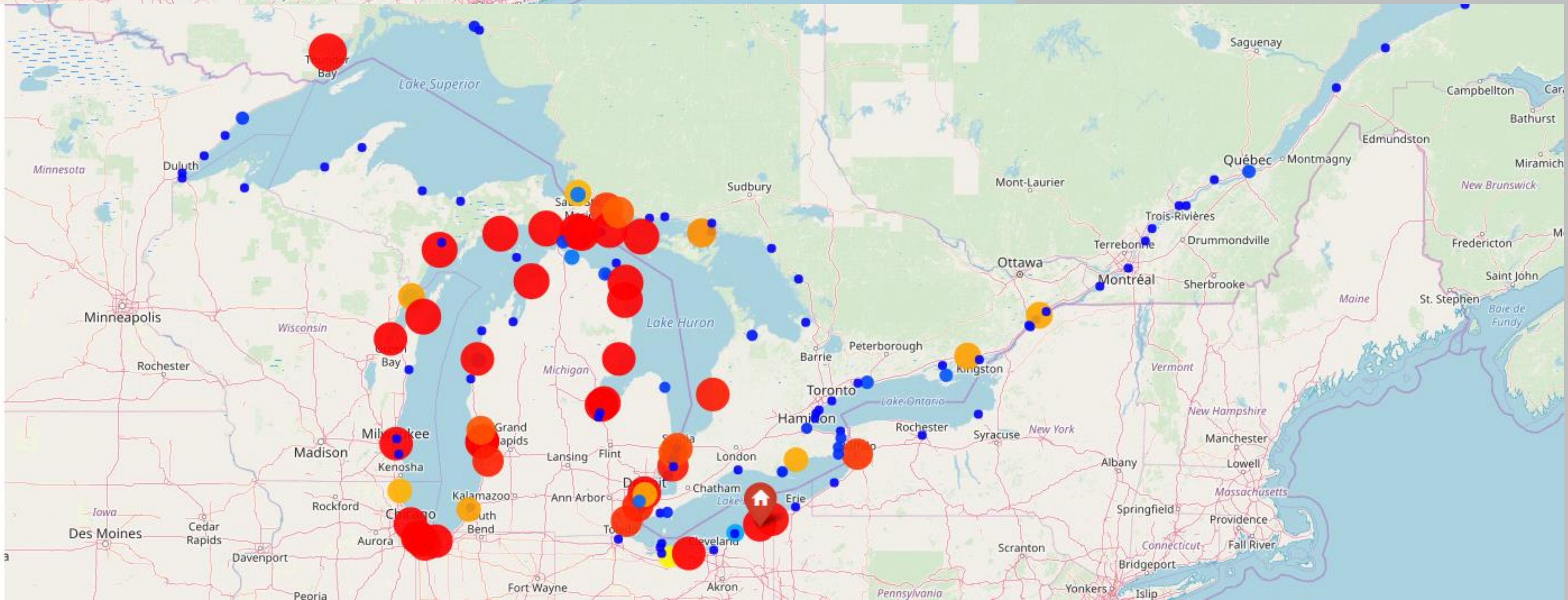
Kalamazoo
Grand Rapids
Lansing
Flint
Ann Arbor
Michigan
Fort Wayne
Akron
Lake Huron
Sudbury
Barrie
Peterborough
Toronto
London
Chatham
Erie
Lake Ontario
Rochester
Syracuse
New York
Pennsylvania
Scranton
Albany
Ottawa
Mont-Laurier
Terrebonne
Montréal
Trois-Rivières
Drummondville
Sherbrooke
Québec
Montmagny
Saguenay
Vermont
New Hampshire
Manchester
Lowell
Massachusetts
Springfield
Providence
Connecticut
Fall River
Bridgeport
Yonkers
Islip
Maine
Campbellton
Caraquet
Bathurst
Edmundston
Miramichi
New Brunswick
Fredericton
Moncton
Saint John
St. Stephen
Baie de Fundy
Estuaire maritime


Lake Superior
Duluth
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Wisconsin
Rochester
Madison
Kenosha
Rockford
Iowa
Des Moines
Cedar Rapids
Davenport
Aurora
Peoria
Kalamazoo
Grand Rapids
Lansing
Flint
Ann Arbor
Michigan
Fort Wayne
Akron
Lake Huron
Sudbury
Barrie
Peterborough
Toronto
Hamilton
London
Chatham
Erie
Lake Ontario
Rochester
Syracuse
Kingston
New York
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Scranton
Albany
Ottawa
Mont-Laurier
Terrebonne
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Trois-Rivières
Drummondville
Sherbrooke
Québec
Montmagny
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Vermont
New Hampshire
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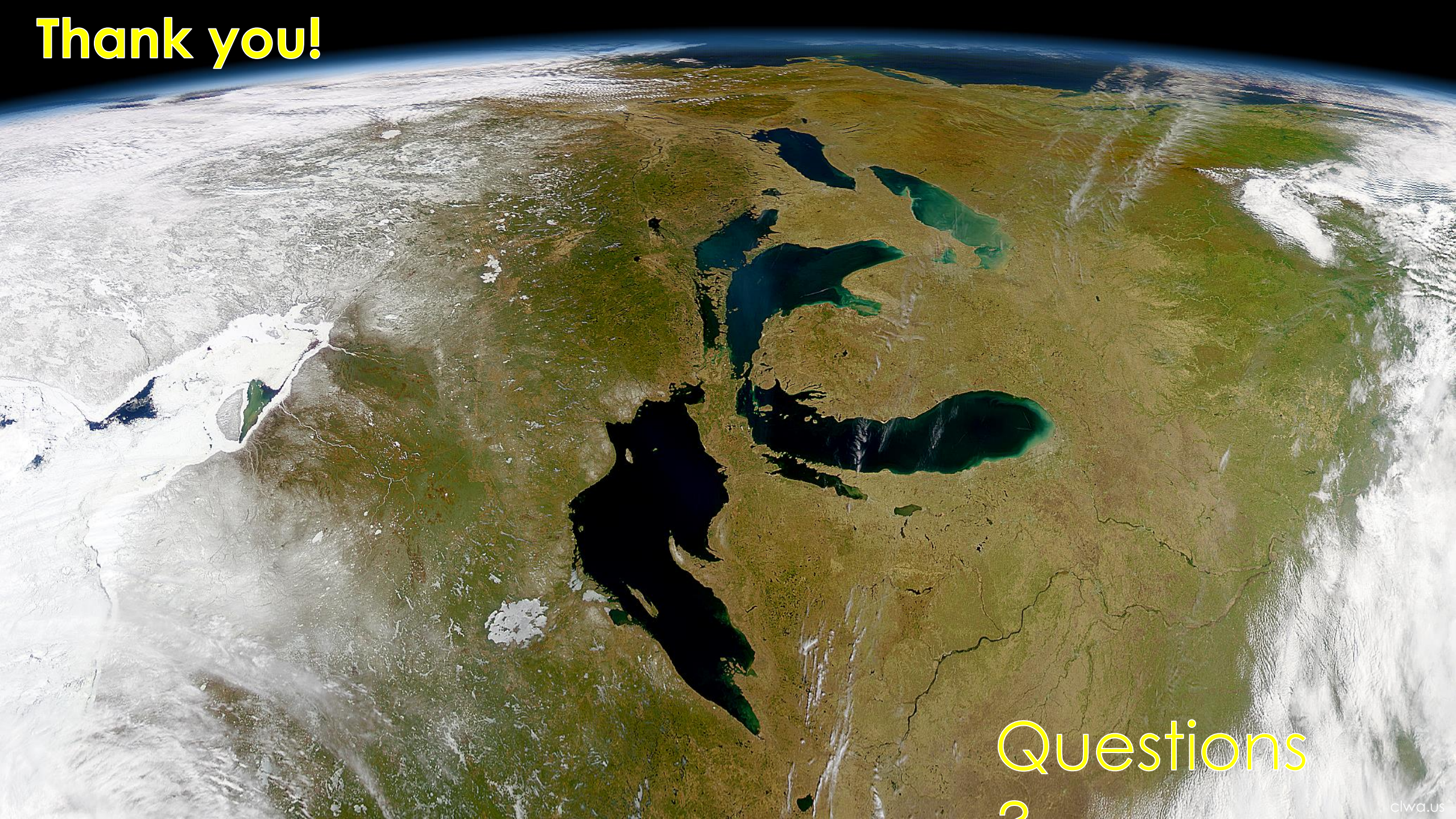
Lowell
Massachusetts
Springfield
Providence
Connecticut
Fall River
Bridgeport
Yonkers
Islip
Maine
Campbellton
Bathurst
Edmundston
New Brunswick
Fredericton
Saint John
St. Stephen

User Friendly Model – RCloud, Shiny Package

- Useful for hypothetical scenarios
- Can incorporate environmental similarity.
- Working with TNC to determine where to host.

Thank you!



Questions
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clwa.us