Modeling the Secondary Spread of Invasive Species by Ballast Water in the Laurentian Great Lakes

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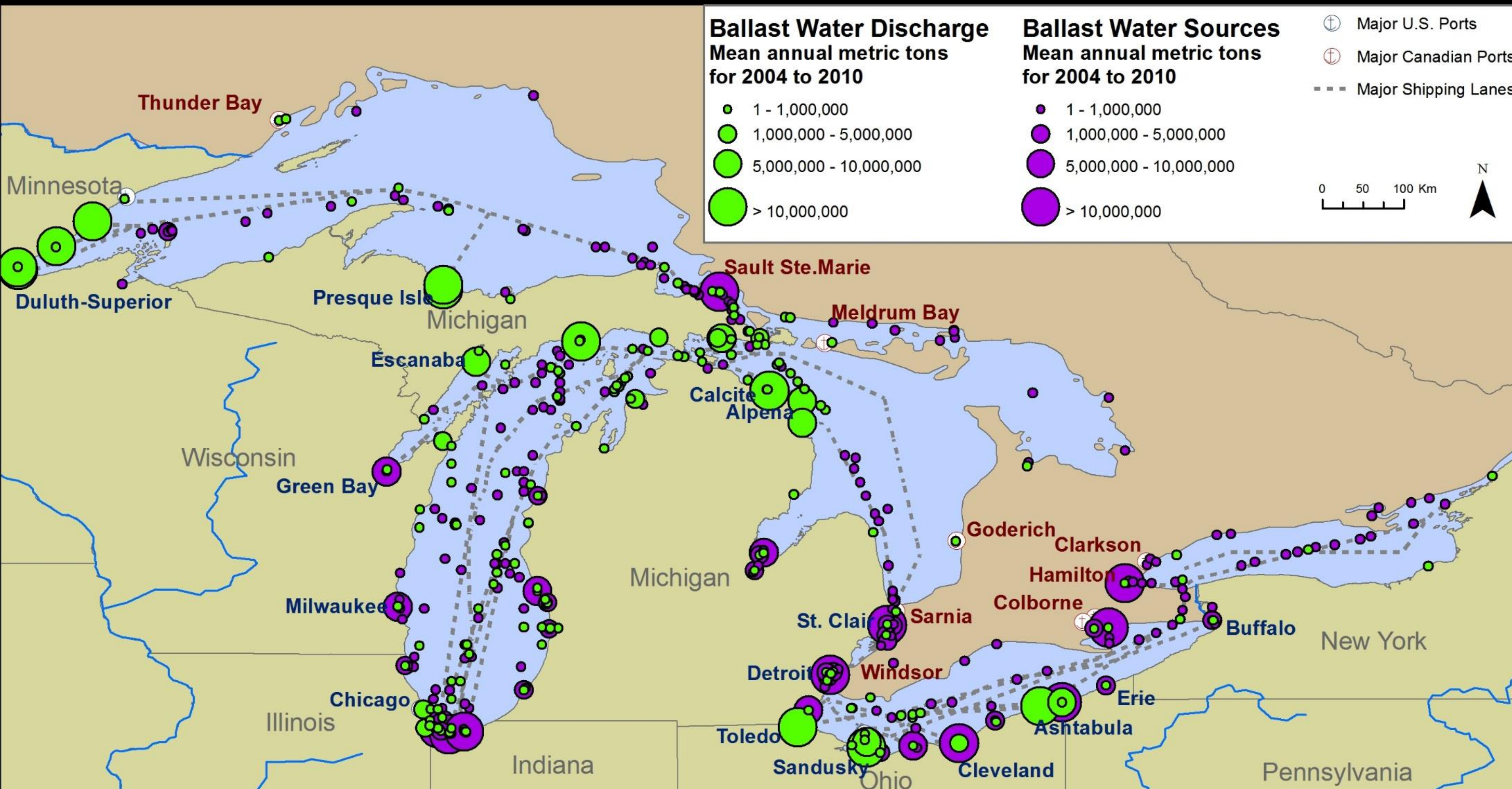
Great Lakes Invaders

- Since the opening of the St. Lawrence Seaway in 1959, ballast water has become the most important vector of spread
  - Between 1840 and 1959, 21% of invasions due to ballast
  - Between 1960 and 2013, 62% due to ballast

Ballast Water and Invasive Species

- Recent research is also finding that ballast water may be playing an important role in "secondary spread"
- It is important to be able to predict spread due to ballast as part of invasive species surveillance and management plans



Ballast Water Discharge
Mean annual metric tons for 2004 to 2010
1 - 1,000,000
1,000,000 - 5,000,000
5,000,000 - 10,000,000
> 10,000,000
Ballast Water Sources
Mean annual metric tons for 2004 to 2010
1 - 1,000,000
1,000,000 - 5,000,000
5,000,000 - 10,000,000
> 10,000,000
Major U.S. Ports
Major Canadian Ports
Major Shipping Lanes
0 50 100 Km
N
Thunder Bay
Minnesota
Duluth-Superior
Presque Isle
Michigan
Sault Ste.Marie
Meldrum Bay
Escanaba
Calcite
Alpena
Wisconsin
Green Bay
Goderich
Clarkson
Hamilton
Colborne
Michigan
Milwaukee
St. Clair
Sarnia
Buffalo
New York
Detroit
Windsor
Erie
Chicago
Illinois
Toledo
Ashtabula
Indiana
Sandusky
Ohio
Cleveland
Pennsylvania

Current Ballast Water Policies

- Since 1993, ocean-going ships with ballast water are required to exchange water in their tanks with seawater
- Since 2008, oceangoing NOBOB vessels must flush their tanks with salt water
- Since Dec 2013, the EPA Vessel General Permit has defined mandatory management practices

Goals and Objectives

- Predict the future spread of an invasive species that already occurs in the Great Lakes, but is not yet widespread
  - Backcast the spread of Eurasian ruffe to predict its future spread
- Predict the future spread of species that may invade the Great Lakes in the future
  - Backcast the spread of zebra mussel to predict the potential spread of killer shrimp and golden mussel

Identifying Best Fit Model

- 3 models were tested to determine if distribution is:
  - Due to chance
  - Related to discharge locations
  - Related to discharge locations weighted that receive the most discharges

Models Needed to Answer Questions

	Random Model	Location Model	Propagule Pressure Model
Discharge locations?	X	X	

Results from the random and location models determined if discharge locations were related to invasions

Models Needed to Answer Questions

	Random Model	Location Model	Propagule Pressure Model
Discharge locations?	X	X	
# of discharge events?		X	X

Results from the location and propagule pressure models determined if invasions occurred in high discharge locations

Models Needed to Answer Questions

	Random Model	Location Model	Propagule Pressure Model
Discharge locations?	X	X	
# of discharge events?		X	X
Spread distance?	X	X	X

All 3 models were used to test localized spread distance values

Models Needed to Answer Questions

	Random Model	Location Model	Propagule Pressure Model
Discharge locations?	X	X	
# of discharge events?		X	X
Spread distance?	X	X	X
Probability of infestation?			X

Test Parameters

- **Spread distance-** potential localized natural spread of a species that could occur after a discharge event
- **Infestation probability-** likelihood of a species being released alive at a discharge location

Test Parameters

- Due to lack of specific information on localized spread distance and probability of infestation, a range of values were tested.
- The probability of infestation decreased with each day spent in the ballast tank
  - More distant ports would be less likely to become invaded during a given discharge event

Input Data

- Ballast water discharge/source data:
  - National Ballast Information Clearinghouse (NBIC)
    - Only collected from ships arriving at U.S. ports
    - Provided:
      - Ballast discharge locations
      - Pattern of ballast movement
      - Median trip length between source and discharge locations were calculated
- Species occurrences
  - USGS Nonindigenous Aquatic Species (NAS) database

Goals and Objectives

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Eurasian Ruffe

- First introduced to Duluth/Superior Harbor in 1986
- Likely introduced by ballast water
- Currently only in Lake Superior and northern portions of Lake Michigan and Lake Huron
- Potential to spread to other parts of the Great Lakes
- Backcasted 1986 to 2011

1986-1988


Lake Superior
Duluth
Ontario
Quebec
Lake Huron
Lake Michigan
Wisconsin
Michigan
Milwaukee
Lake Ontario
Buffalo
New York
Detroit
Lake Erie
Chicago
Illinois
Toledo
Cleveland
Indiana
Ohio
Pennsylvania
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100 Miles

1991

Lake Superior
Duluth
Ontario
Quebec
Lake Huron
Lake Michigan
Wisconsin
Lake Ontario
Milwaukee
Michigan
Buffalo
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New York
Lake Erie
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1992-1994

Lake Superior
Duluth
Ontario
Quebec
Lake Huron
Lake Michigan
Wisconsin
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Lake Ontario
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1995

Lake Superior
Duluth
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1996-2001


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Detroit
New York
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2002

Lake Superior
Duluth
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Buffalo
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New York
Lake Erie
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2003

Lake Superior
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2004-2005

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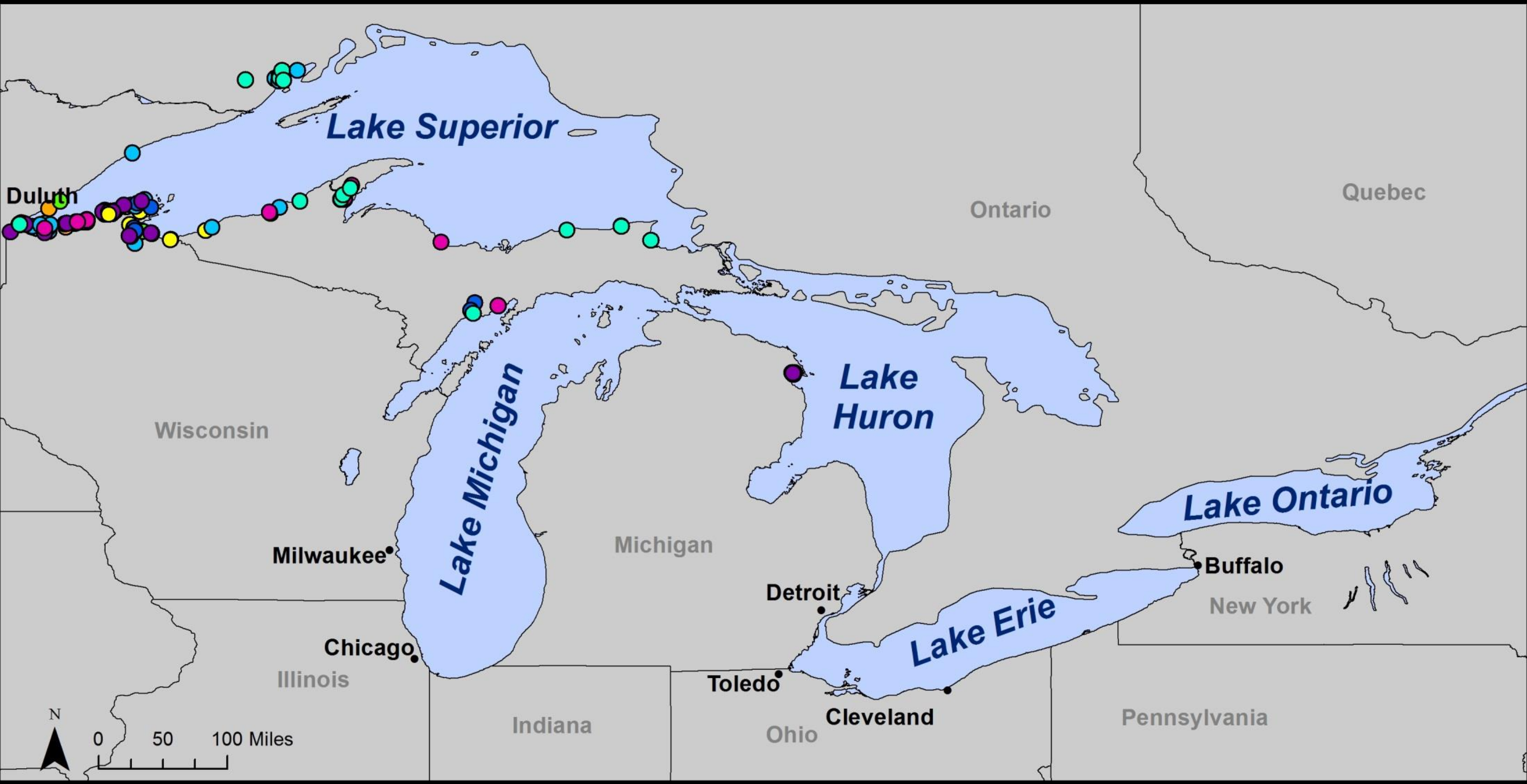
2006



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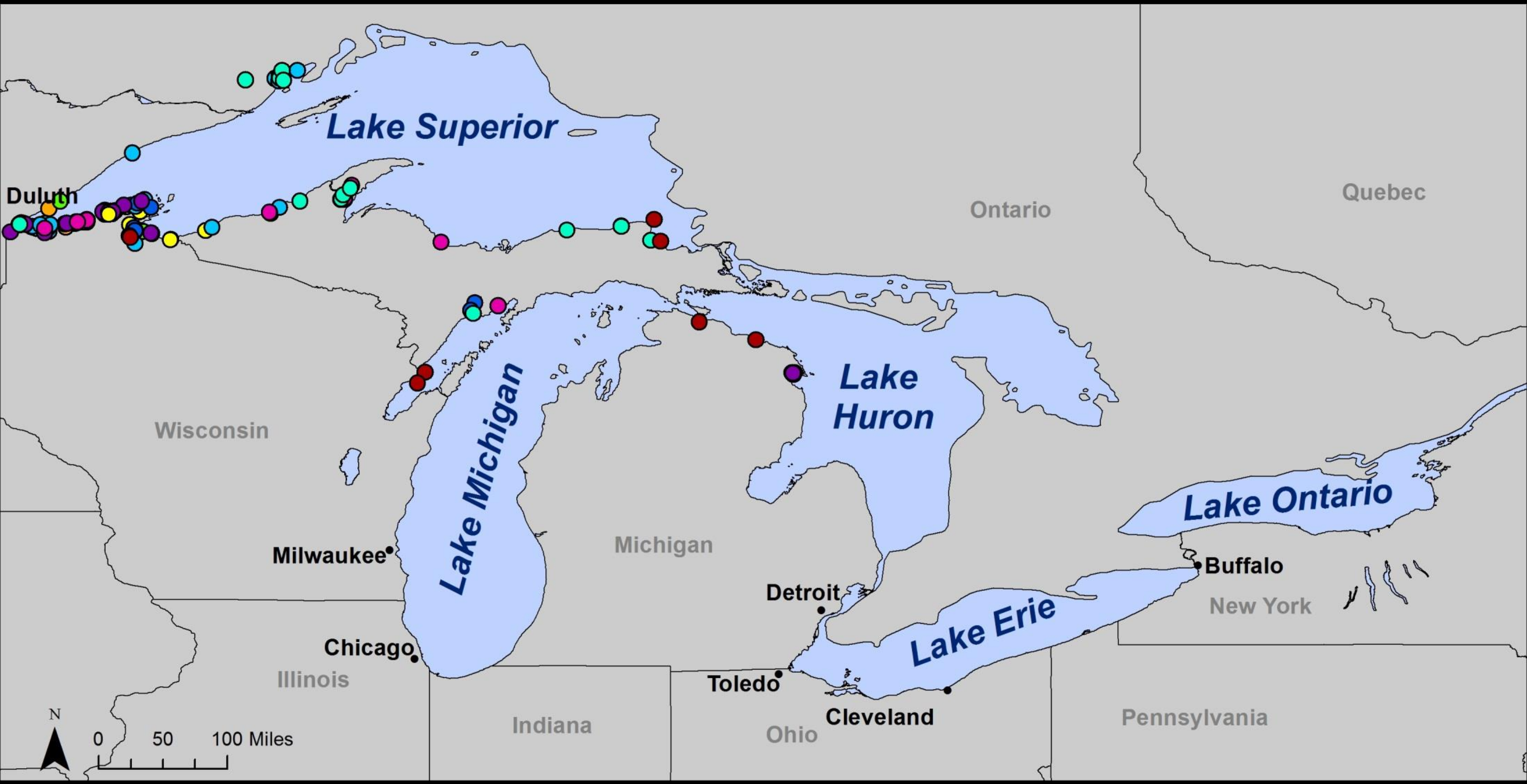
2007-2011



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Illinois
Toledo
Cleveland
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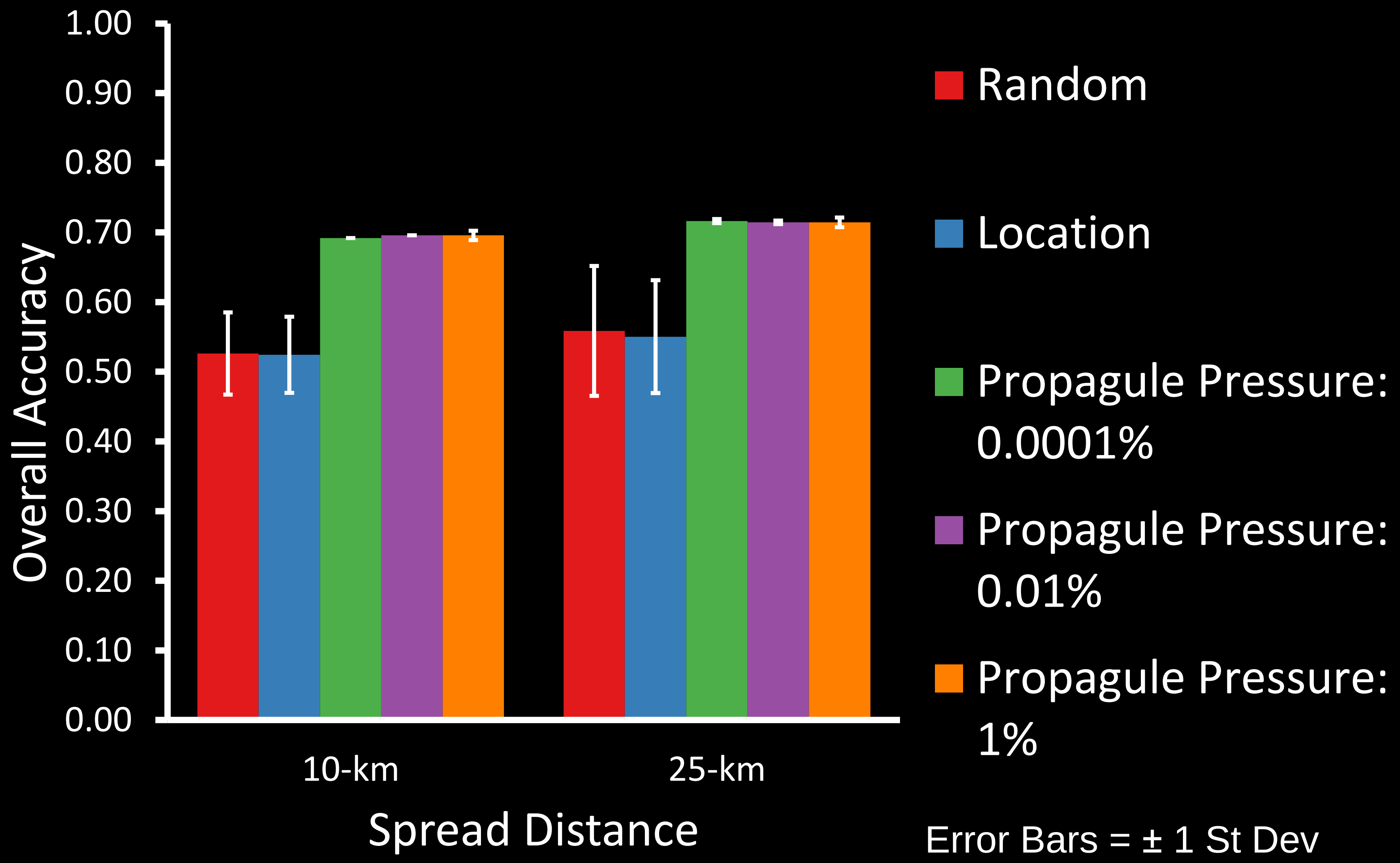
Eurasian Ruffe Test Parameters

- Spread distances tested:
  - 10-km
  - 25-km (based on actual spread distances observed along the southern shore of Lake Superior)
- Probabilities of infestation tested:
  - 0.0001%
  - 0.01%
  - 1%

Photo Credit: Tiit Hunt

Model Testing

- **Three measures used for model testing:**
  - **Presence accuracy**
  - **Absence accuracy**
  - **Overall accuracy**


1.00
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0.70
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0.50
0.40
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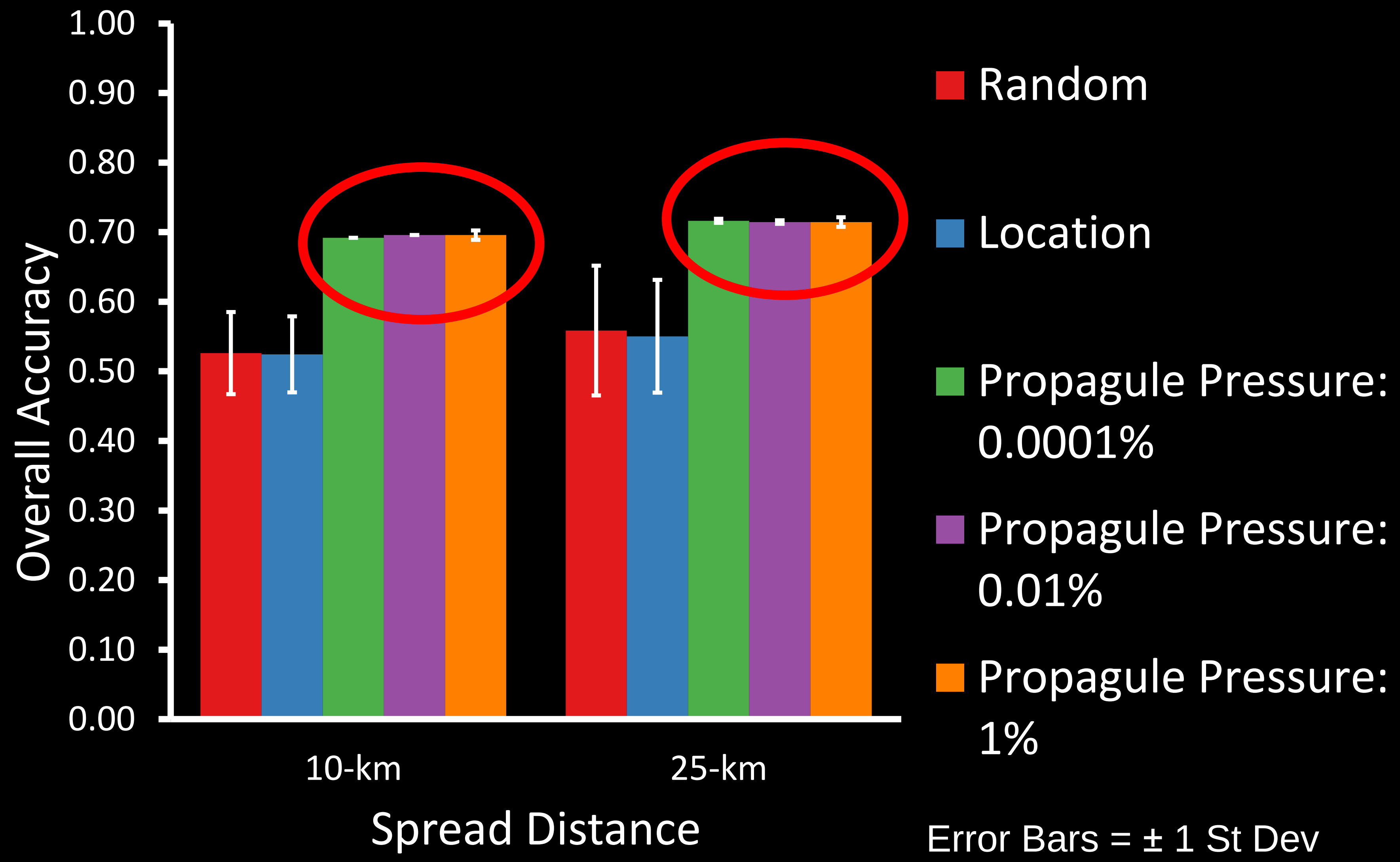
0.20
0.10
0.00
Overall Accuracy
10-km
25-km
Spread Distance
Random
Location
Propagule Pressure: 0.0001%
Propagule Pressure: 0.01%
Propagule Pressure: 1%
Error Bars = ± 1 St Dev

Ruffe Backcasting Conclusions

- Models that included ballast discharge and trip information performed the best



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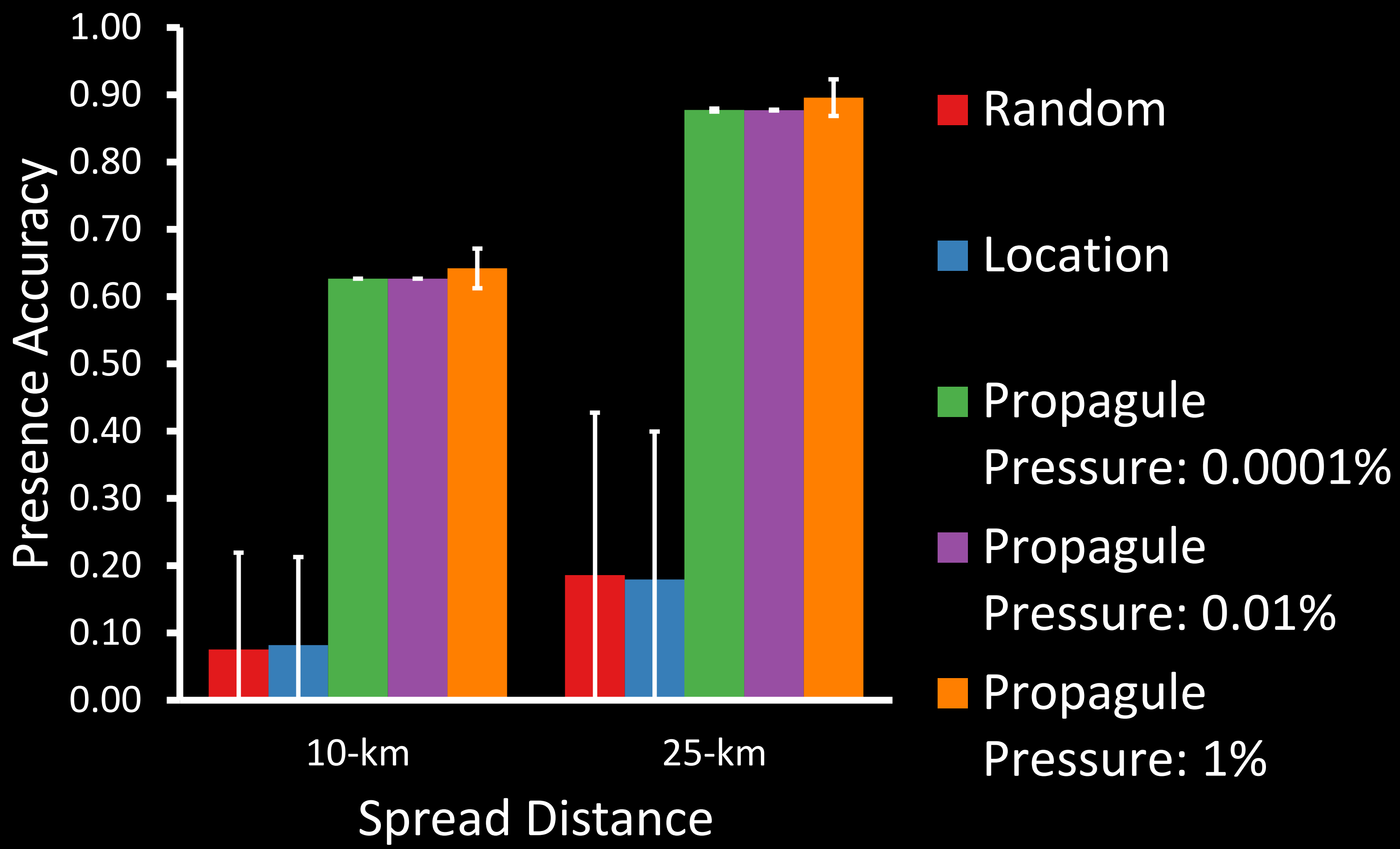
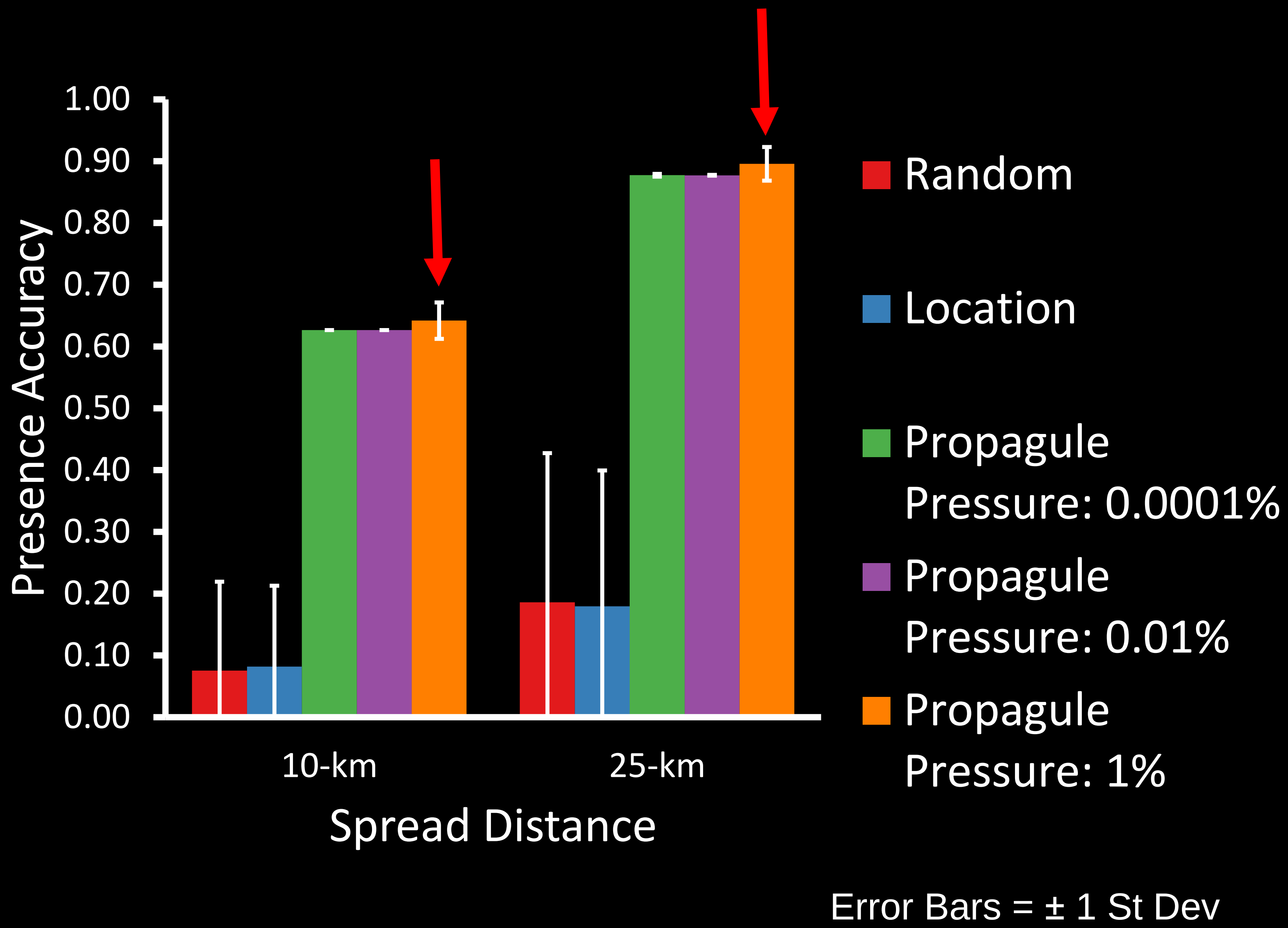


Error Bars = ± 1 St Dev

Ruffe Backcasting Conclusions

- Models that included ballast discharge and trip information performed the best
- Propagule Pressure models with Probability of Infestation = 1% predicted presences better…



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0.10
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10-km
25-km
Spread Distance
Random
Location
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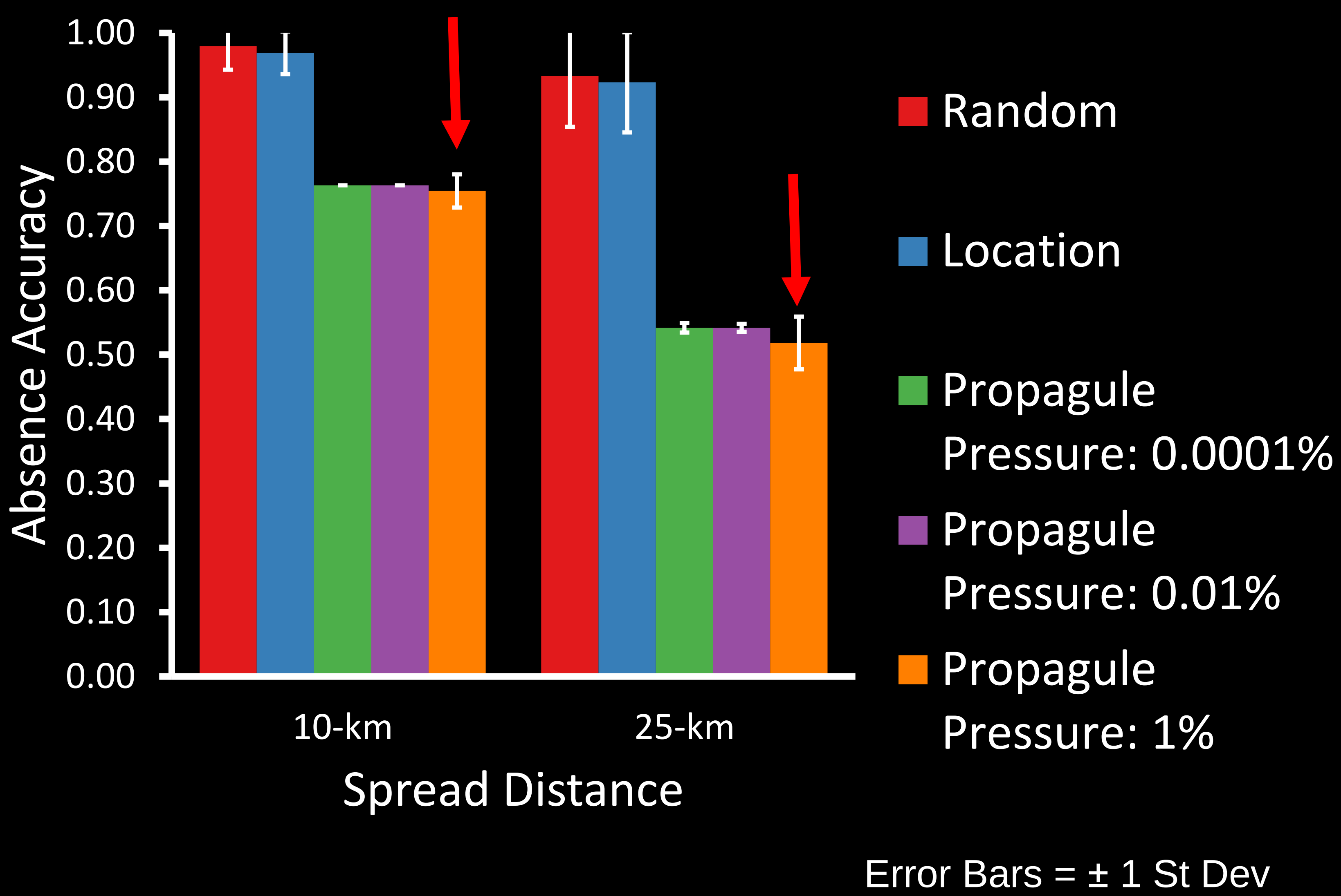
Ruffe Backcasting Conclusions

- Models that included ballast discharge and trip information performed the best
- Propagule Pressure models with Prob of Infestation = 1% predicted presences better…
- …but the 25-km model did not predict absences as well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Absence Accuracy
10-km
25-km
Spread Distance
Random
Location
Propagule Pressure: 0.0001%
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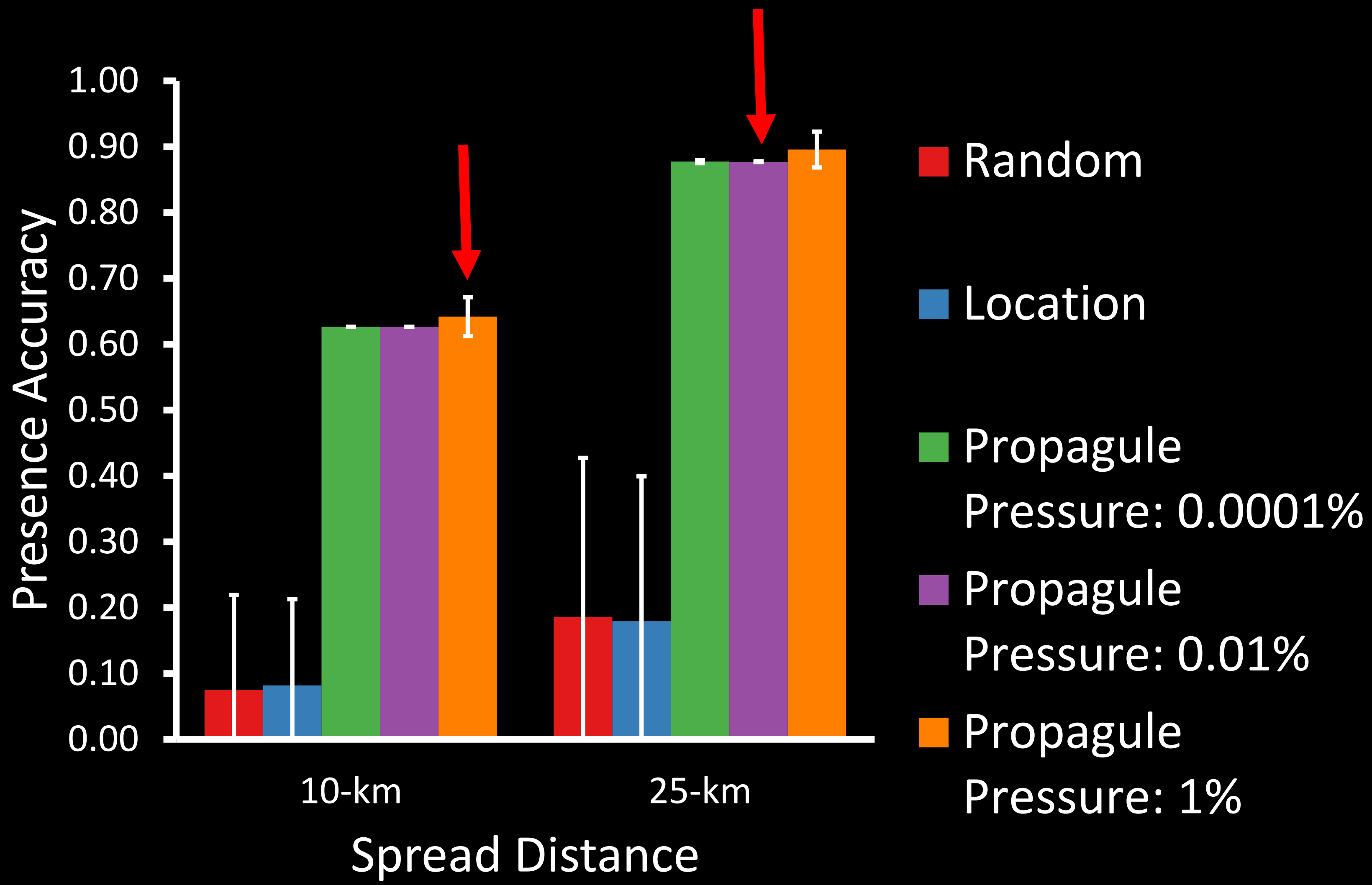
Ruffe Backcasting Conclusions

- Models that included ballast discharge and trip information performed the best
- Propagule Pressure models with Prob of Infestation = 1% predicted presences better…
- …but the 25-km model did not predict absences as well

Two sets of parameter values were used to predict future spread



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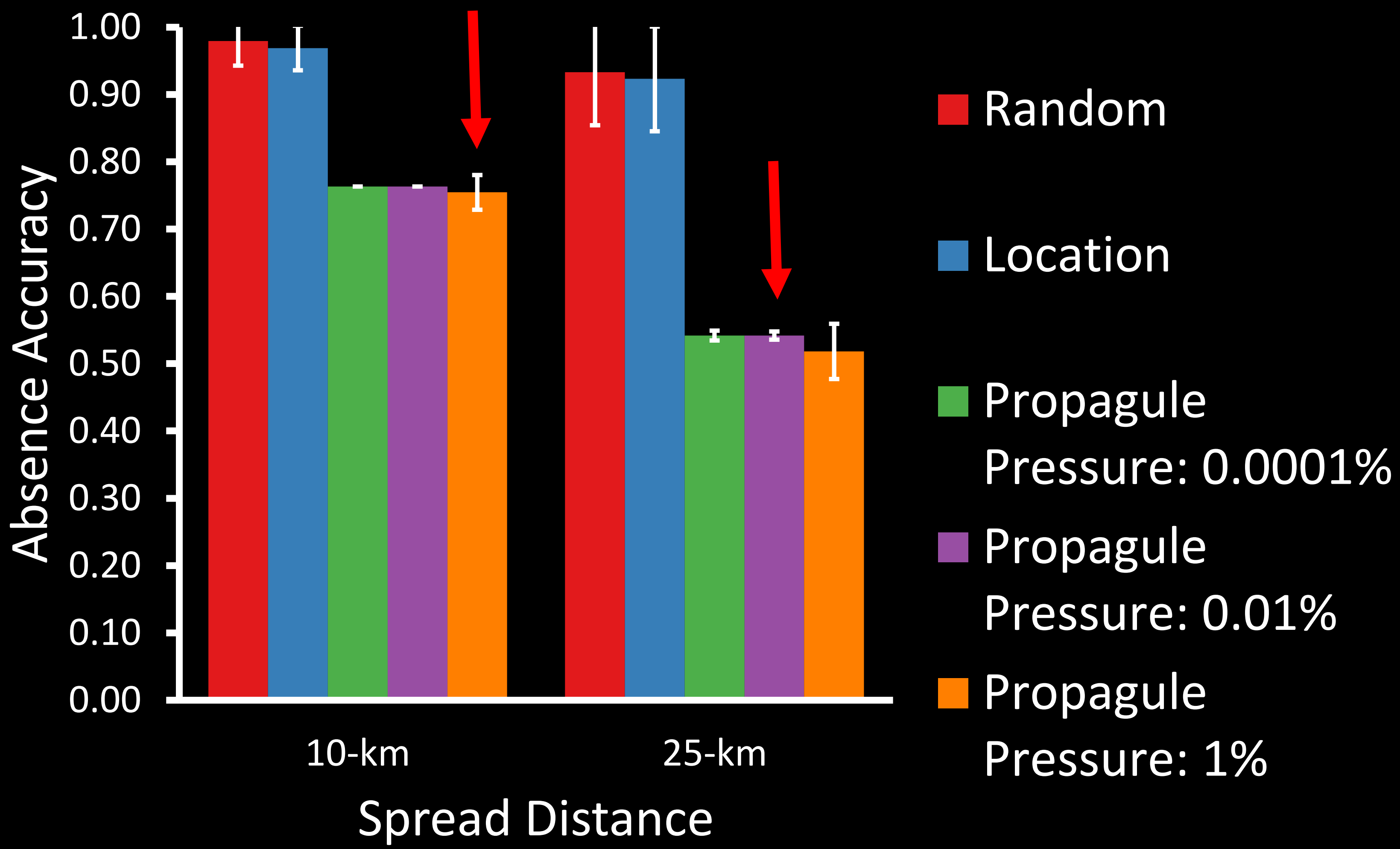

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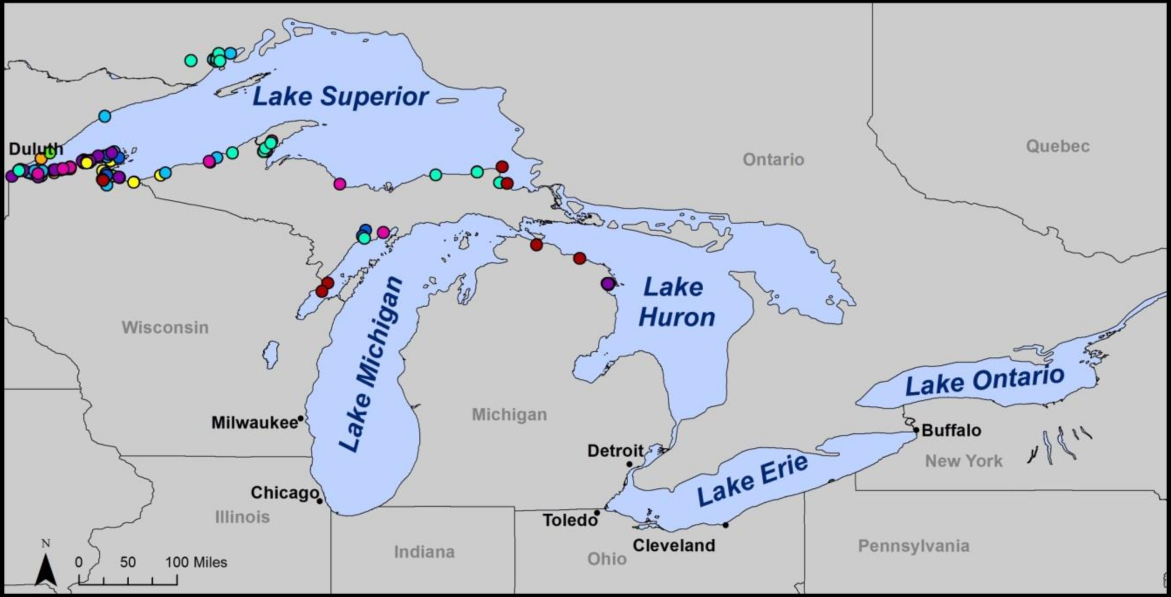
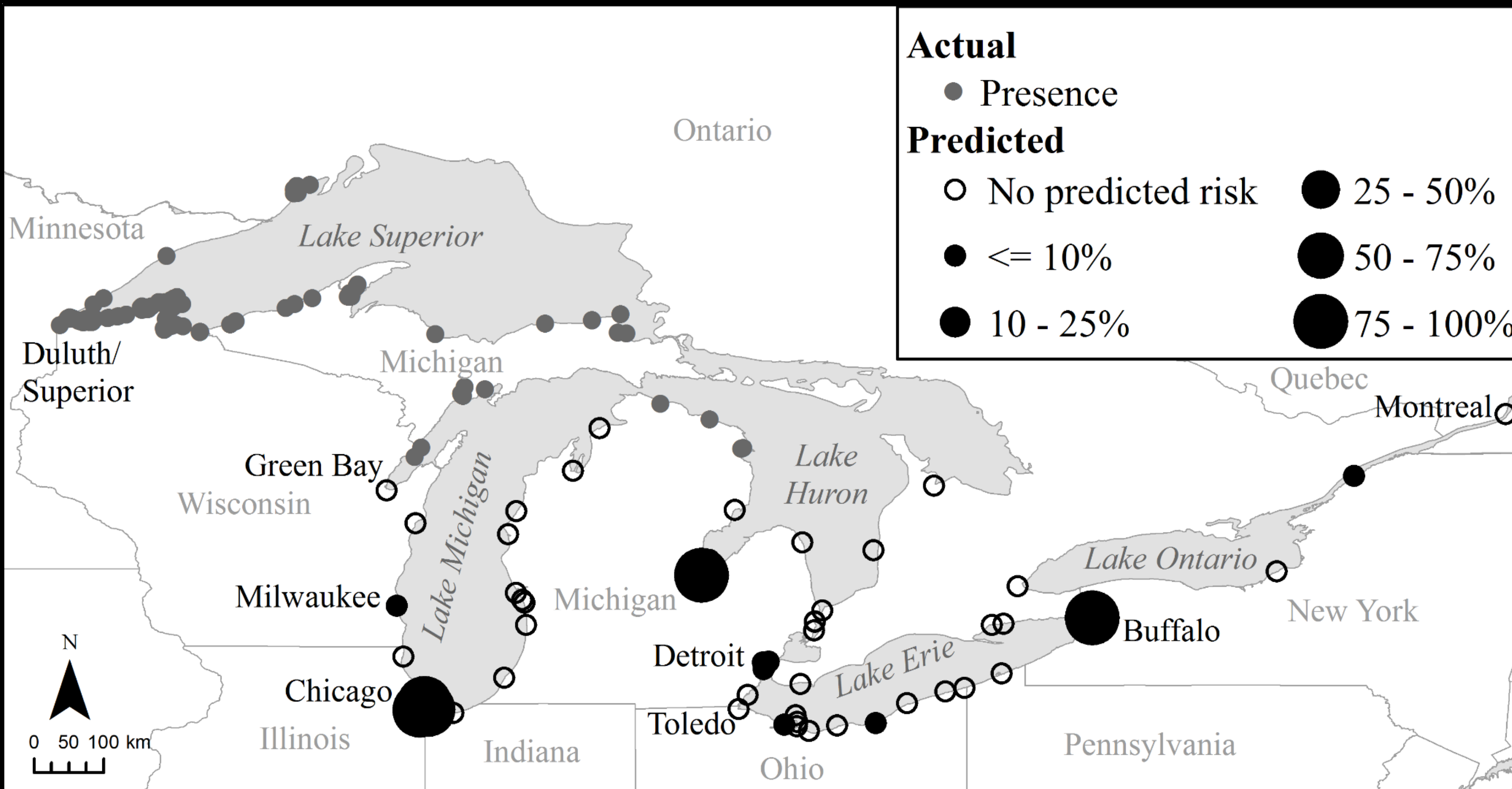
Eurasian Ruffe Predictions

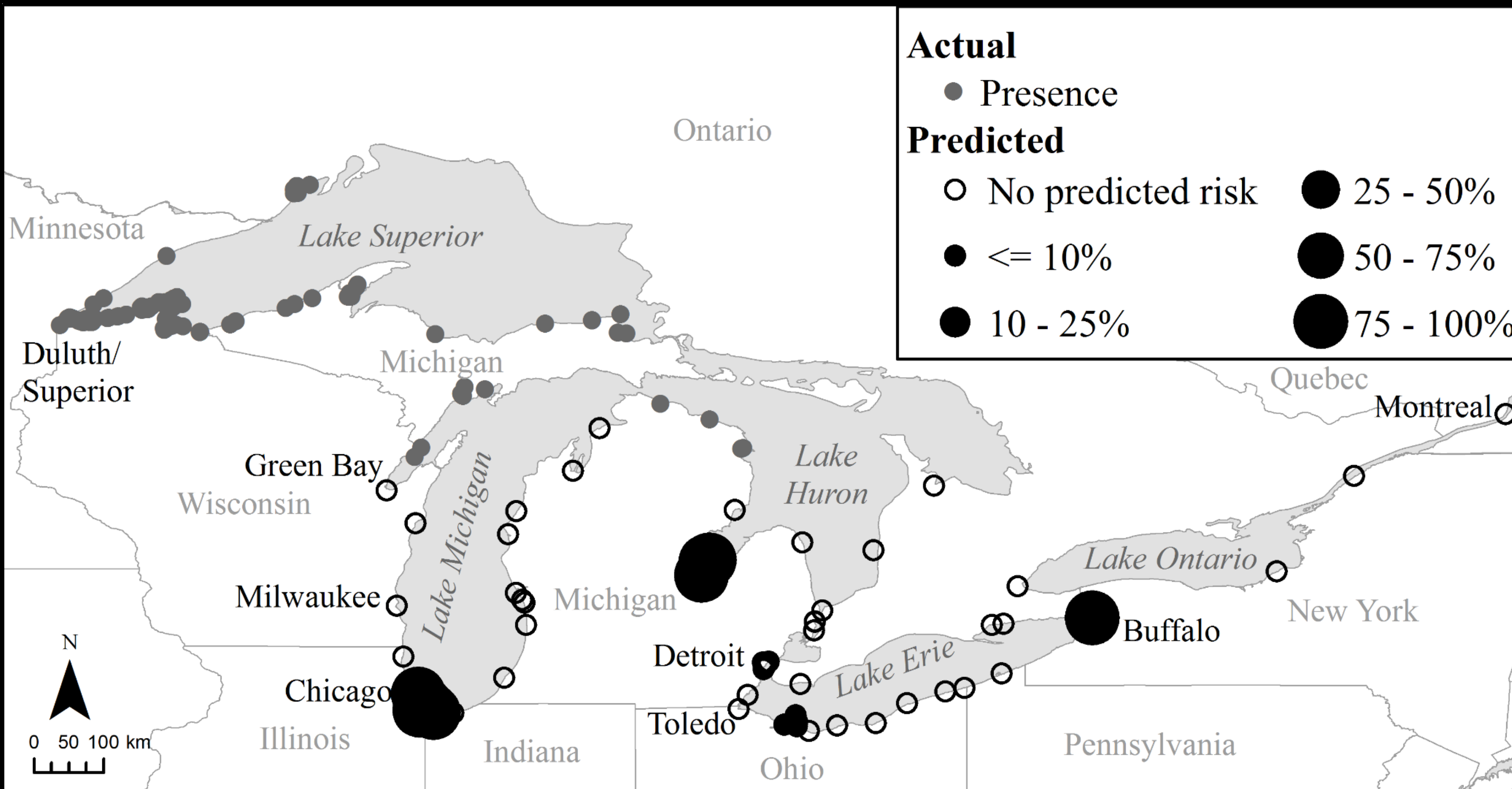
- Introduction sites: Current occurrences
- Parameter Set 1: 10-km, 1%
- Parameter Set 2: 25-km, 0.01%



Ruffe Predictions: 10-km, 1% Model



Ruffe Predictions: 25-km, 0.01% Model



Ruffe Prediction Conclusions

- Chicago, Saginaw Bay, and Buffalo most likely to be invaded next
- Sandusky, Milwaukee, Detroit, and Cleveland also may be at risk
- Results used to inform eDNA detection efforts
- Summer 2013: Positive eDNA detection in Calumet Harbor in Chicago area
  - 95-97% chance of invasion predicted

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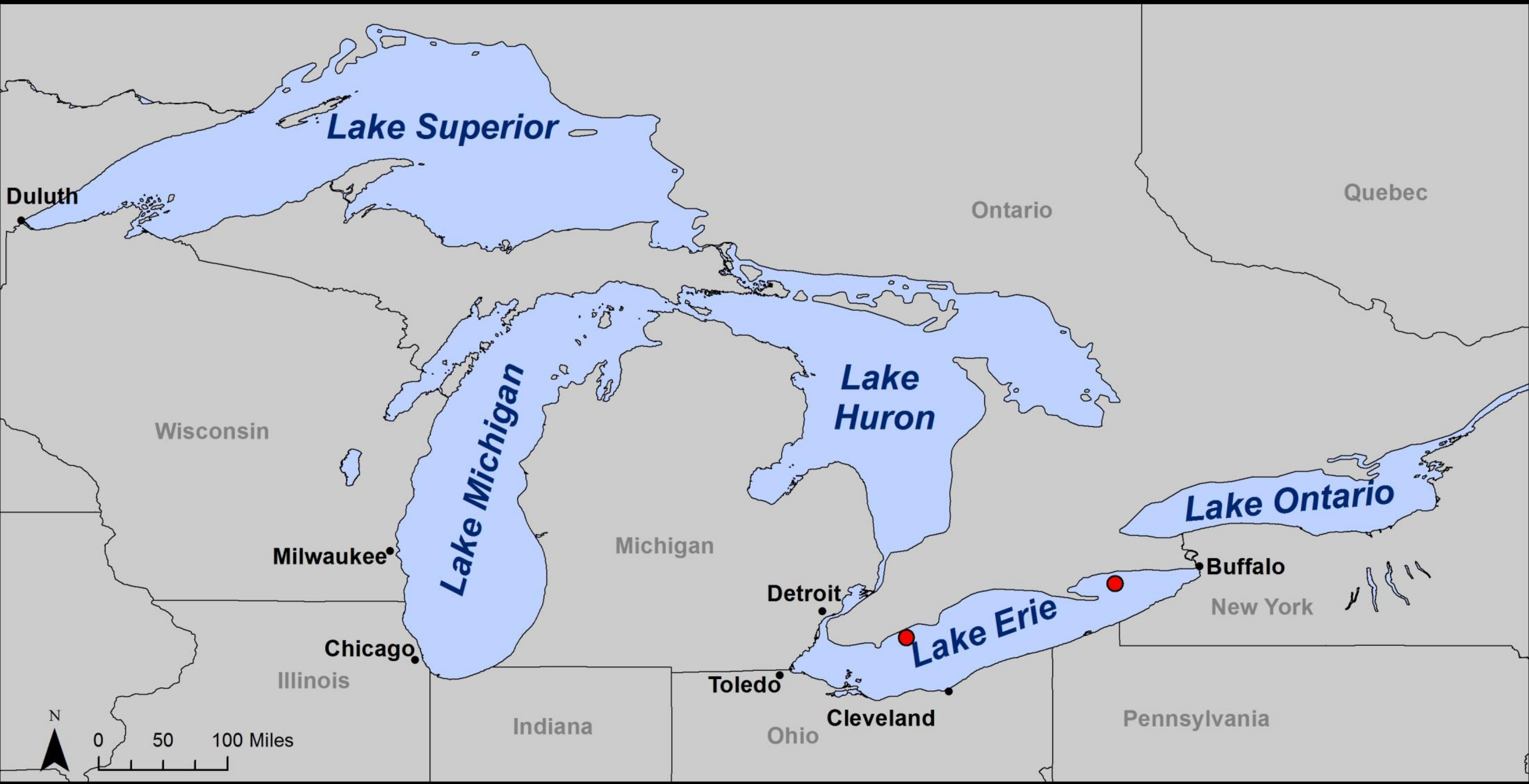
  - Backcast the spread of zebra mussel to predict the potential spread of killer shrimp and golden mussel

Zebra Mussels

- 1986 in Lake Erie was first known introduction
- Ballast water was the likely vector
- Currently widespread in the Great Lakes
- Similar to golden mussels
- Backcasted 1986 to 1992

1986



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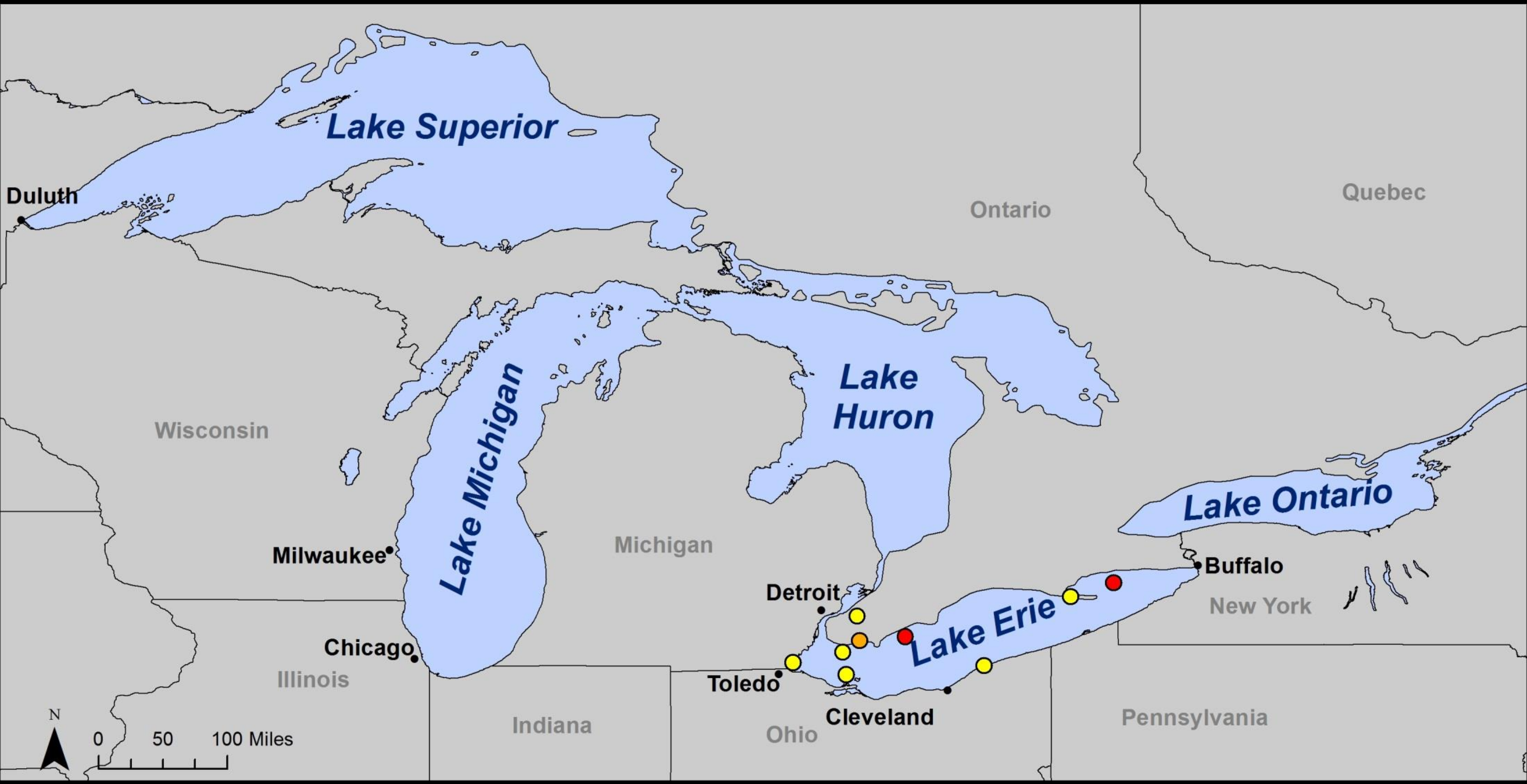

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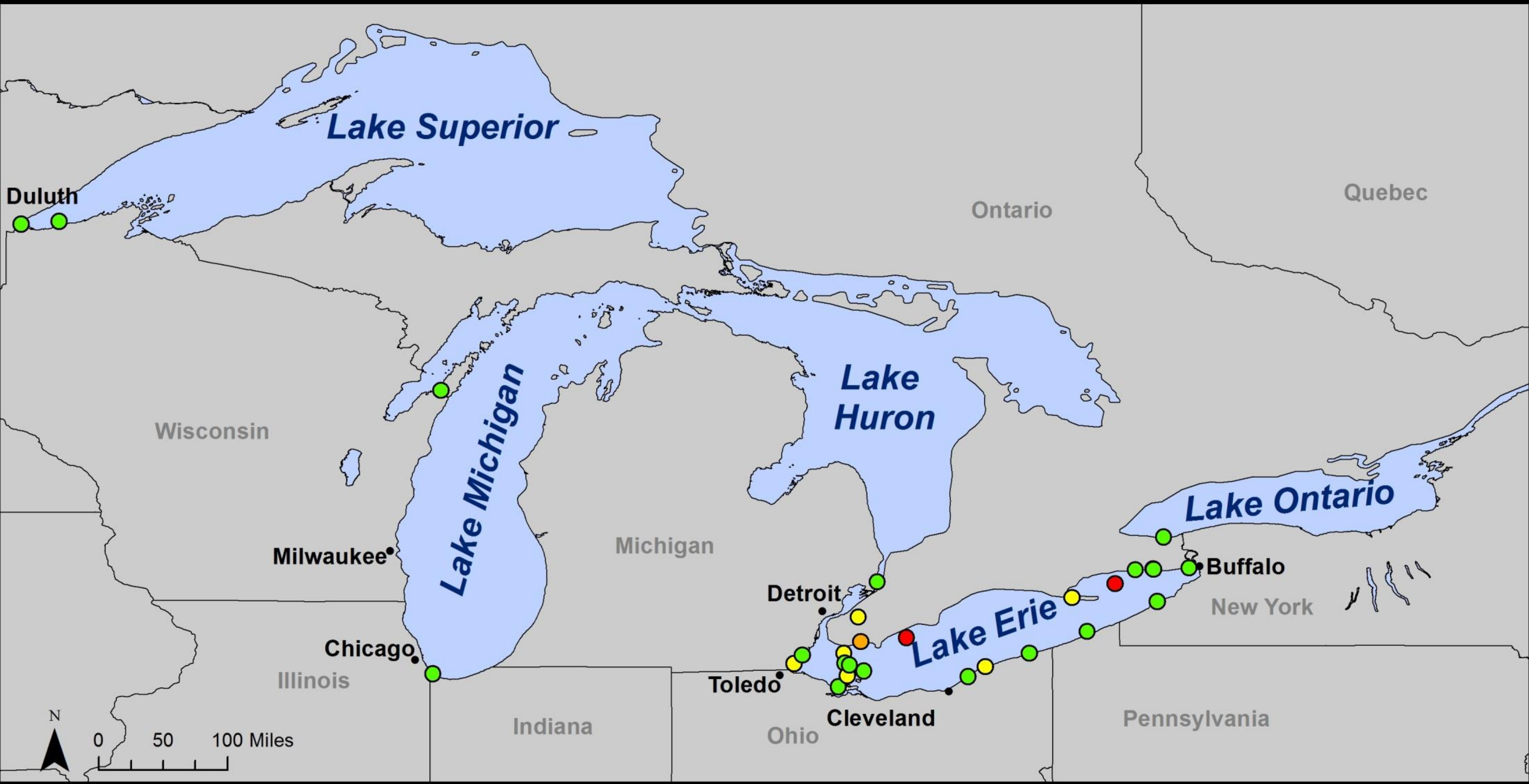
1989



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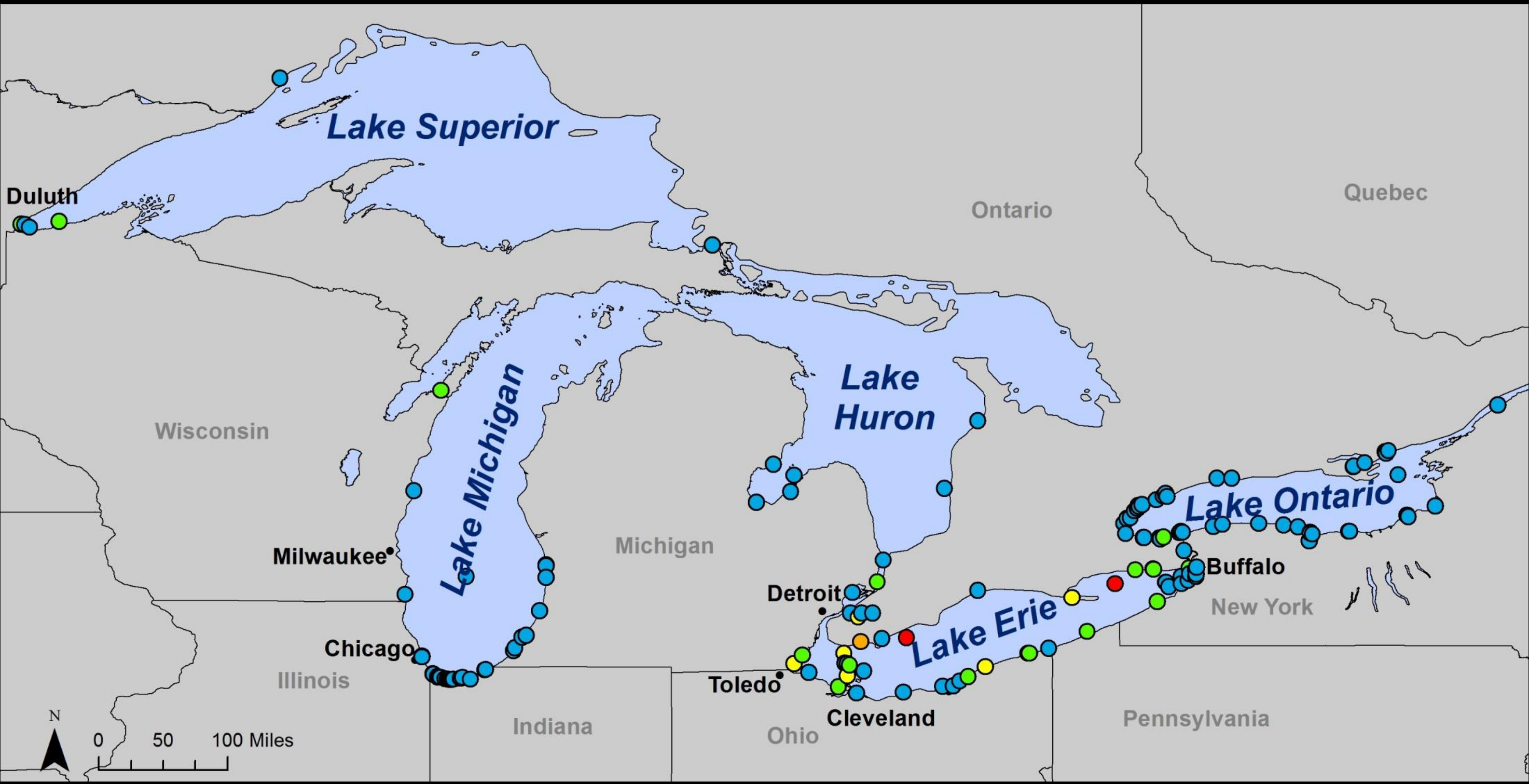

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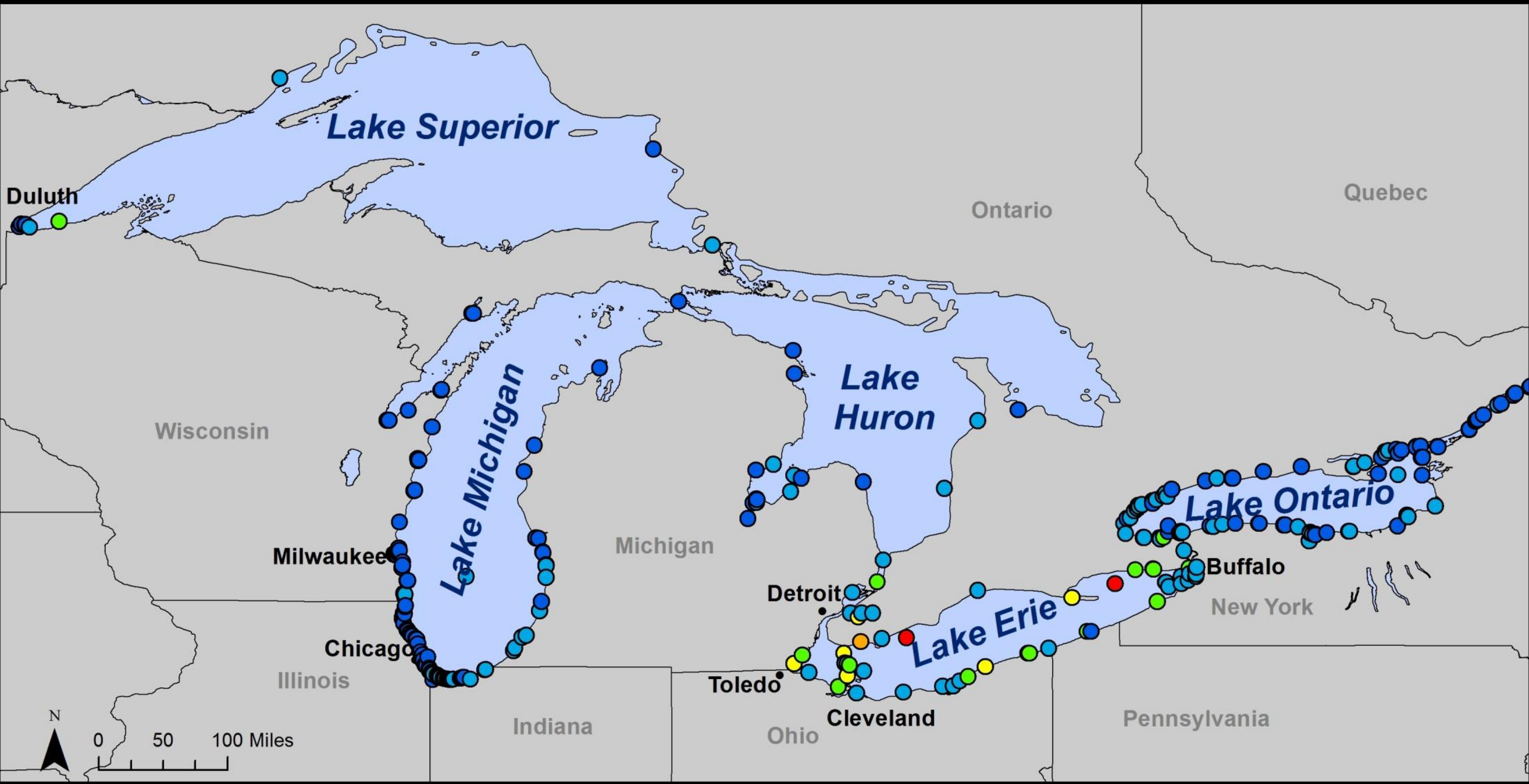
1991



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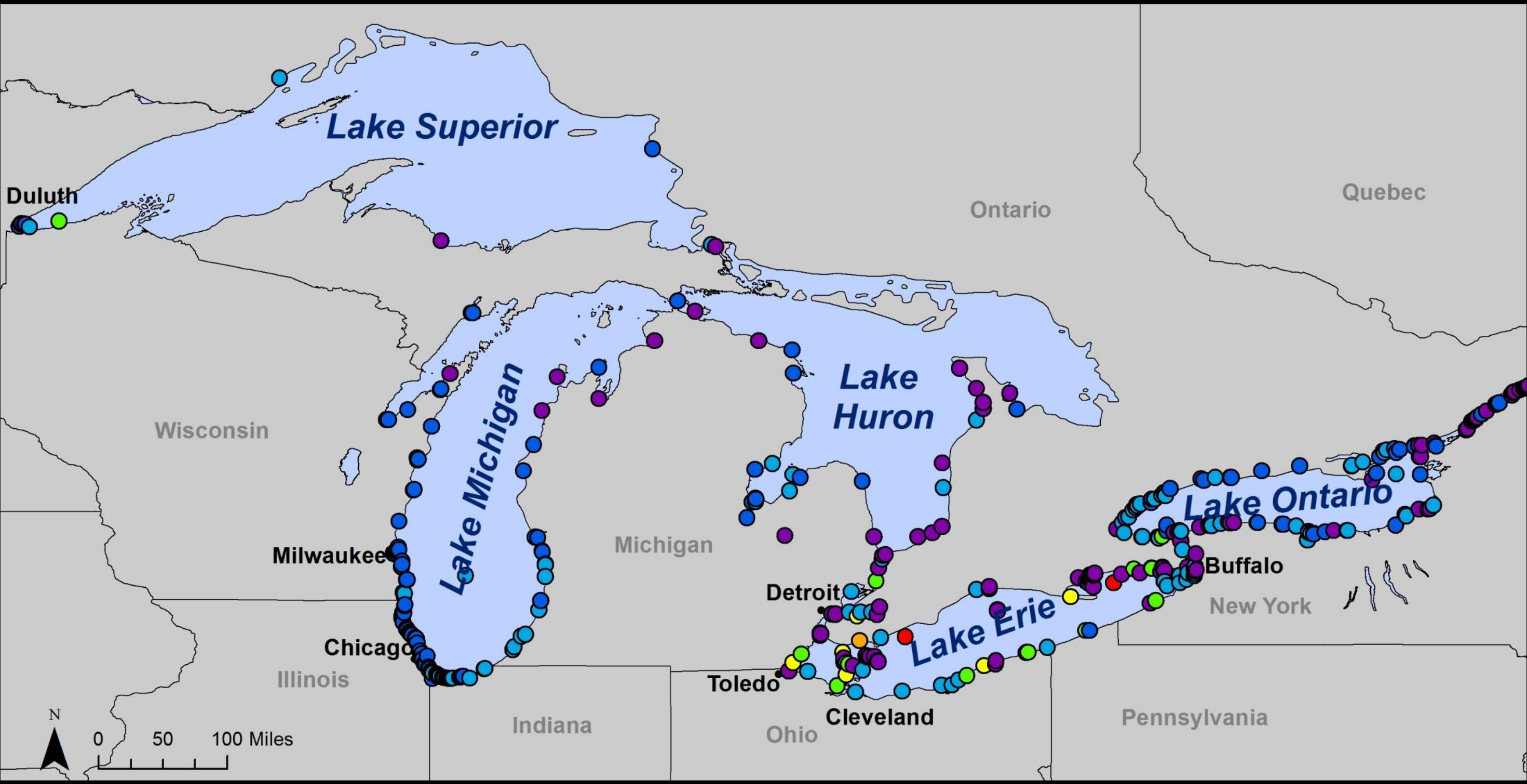
1992



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Pennsylvania
Indiana
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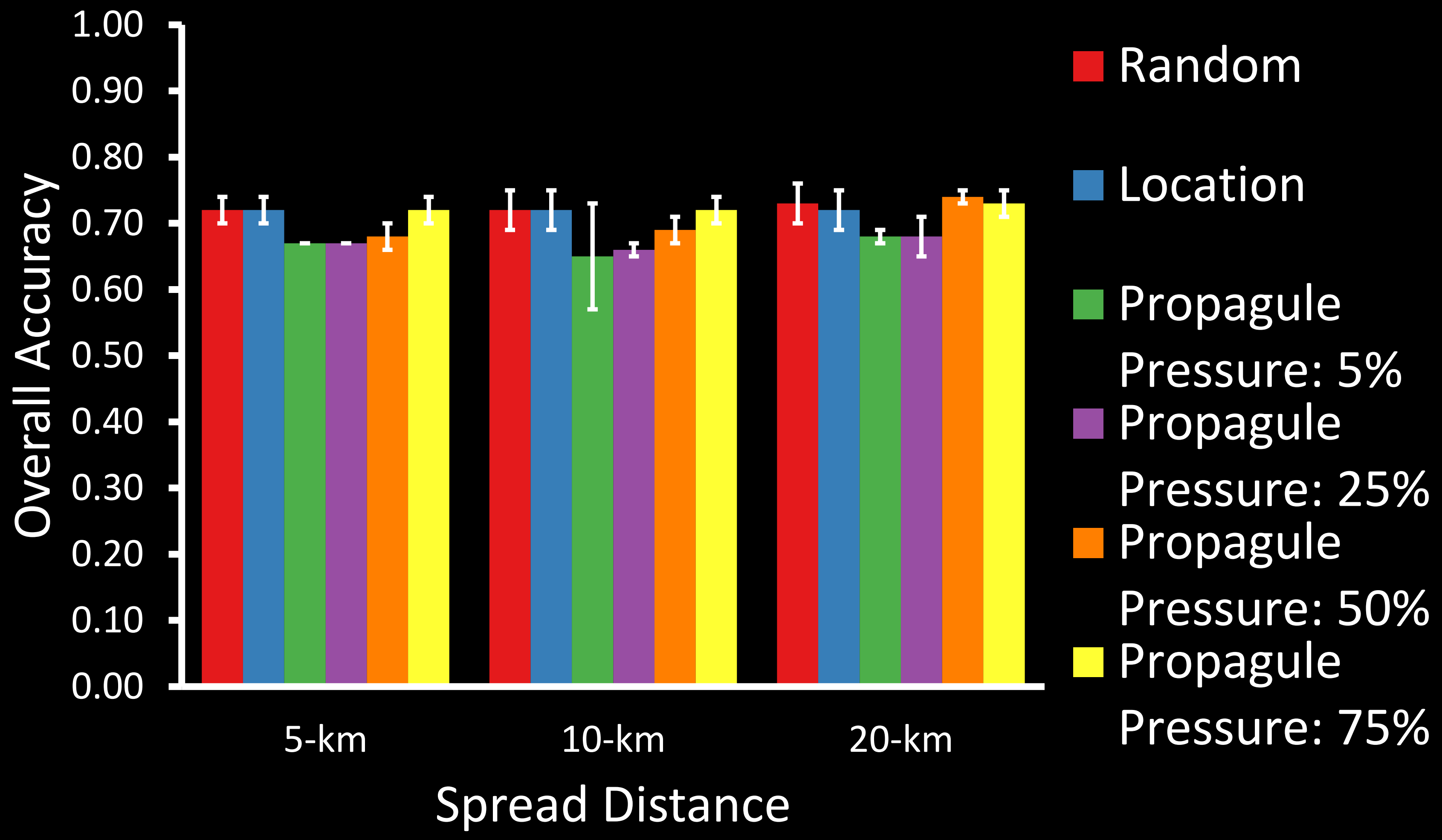
100 Miles

Zebra Mussel Parameters

- Spread distances tested:
  - 5-km
  - 10-km
  - 20-km
- Probabilities of infestation tested:
  - 5%
  - 25%
  - 50%
  - 75%

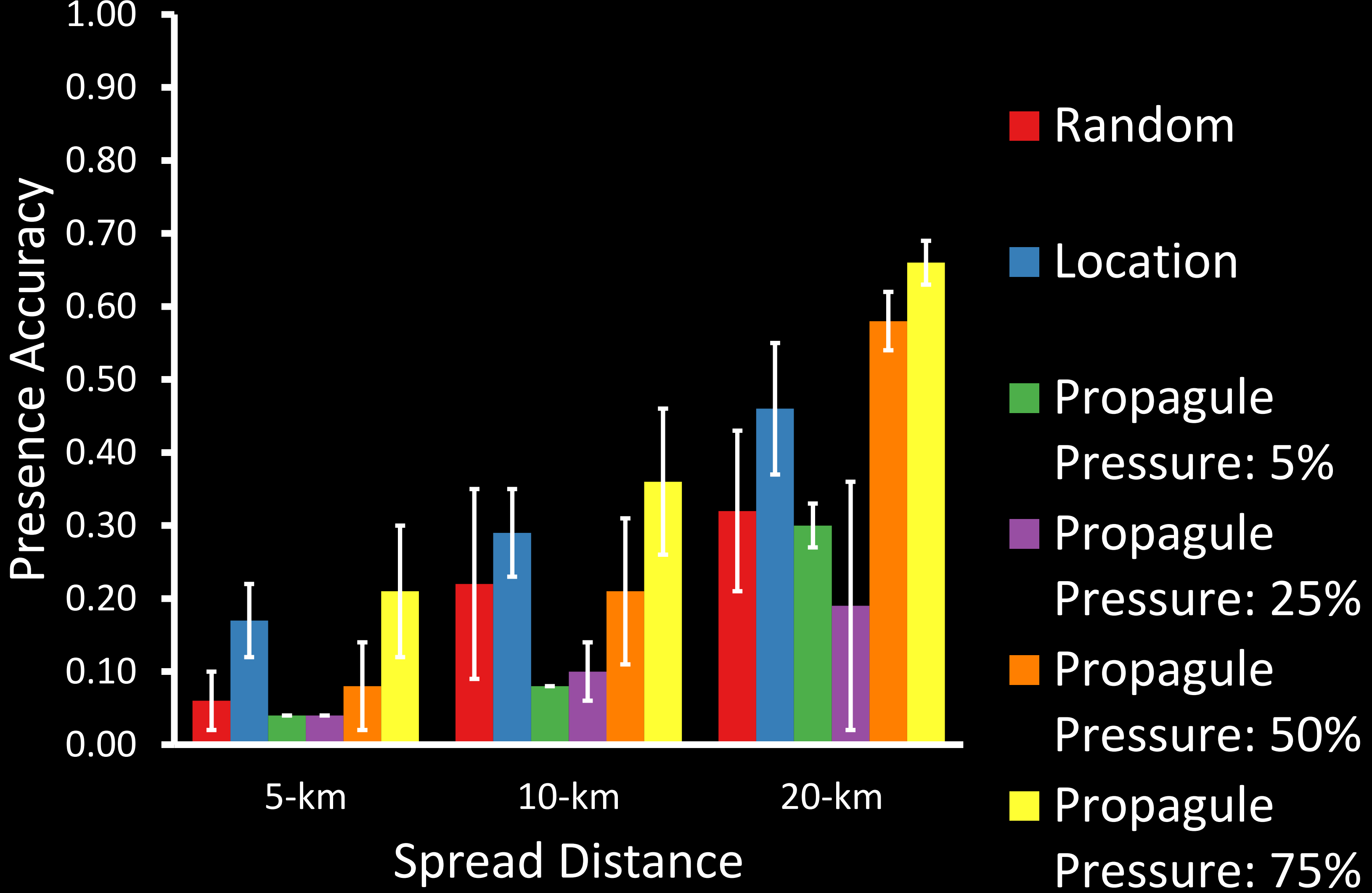
Photo Credit: GerardM, Wikipedia.org



Error Bars = ± 1 St Dev

Zebra Mussel Backcasting Conclusions

- Overall, all 3 models performed similarly…



Presence Accuracy
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
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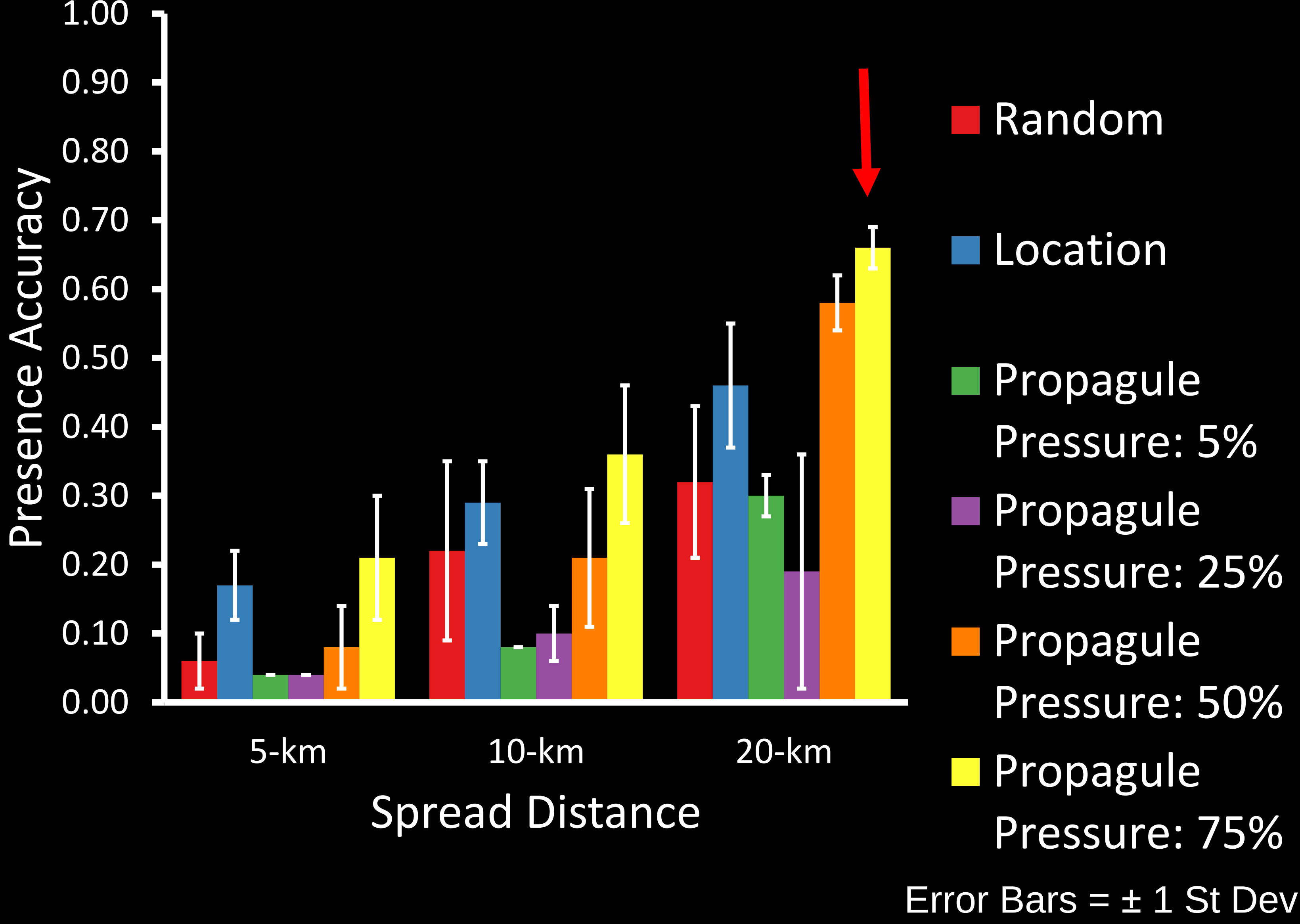
5-km
10-km
20-km
Spread Distance
Random
Location
Propagule Pressure: 5%
Propagule Pressure: 25%
Propagule Pressure: 50%
Propagule Pressure: 75%

Zebra Mussel Backcasting Conclusions

- Overall, all 3 models performed similarly…
- …but the 20-km, 75% propagule pressure model was better at predicting presences…



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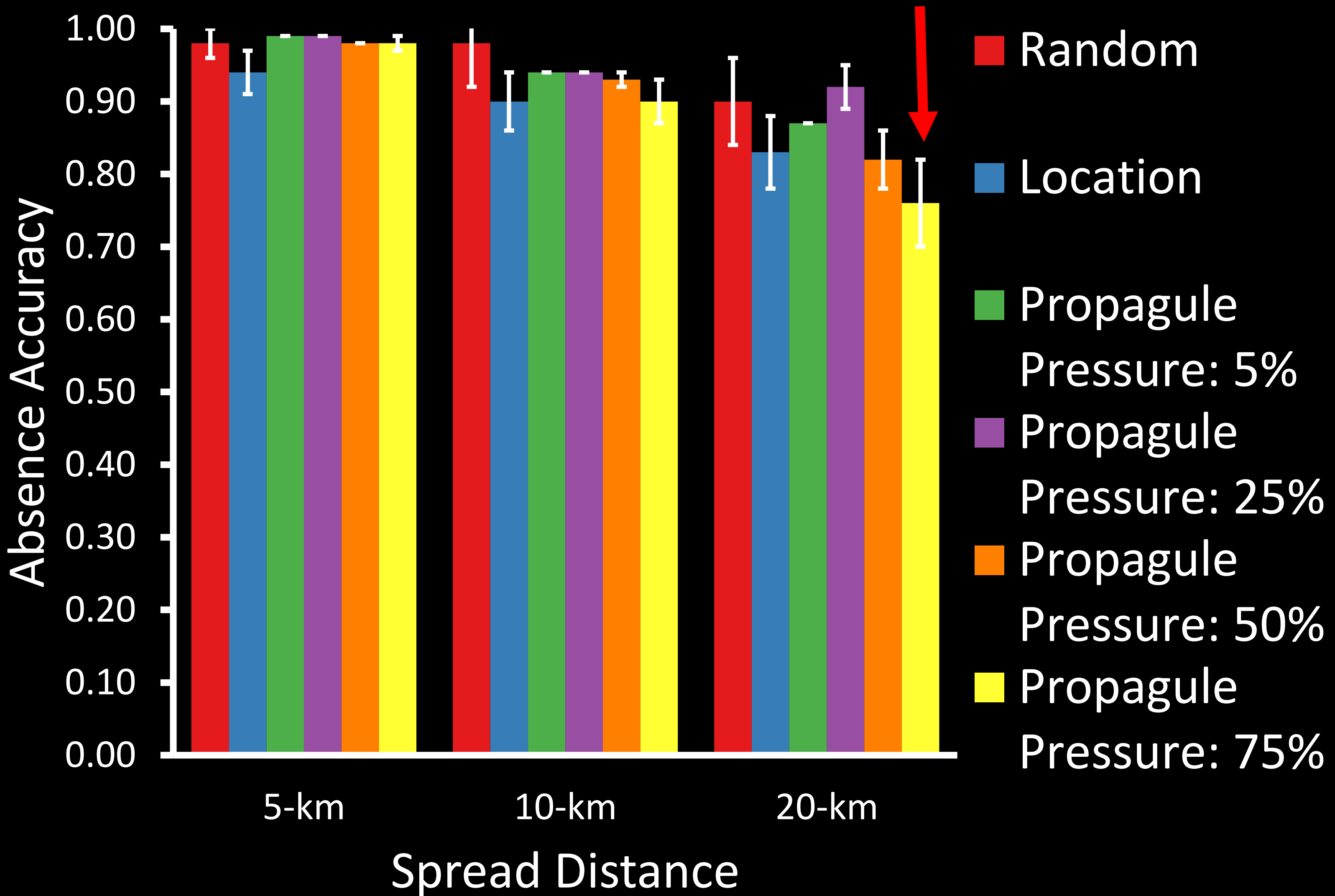
0.00
Presence Accuracy
5-km
10-km
20-km
Spread Distance
Random
Location
Propagule Pressure: 5%
Propagule Pressure: 25%
Propagule Pressure: 50%
Propagule Pressure: 75%
Error Bars = ± 1 St Dev

Zebra Mussel Backcasting Conclusions

- Overall, all 3 models performed similarly…
- …but the 75% propagule pressure model was better at predicting presences…
- …while still predicting absences just over ¾ of the time.



Absence Accuracy
1.00
0.90
0.80
0.70
0.60
0.50
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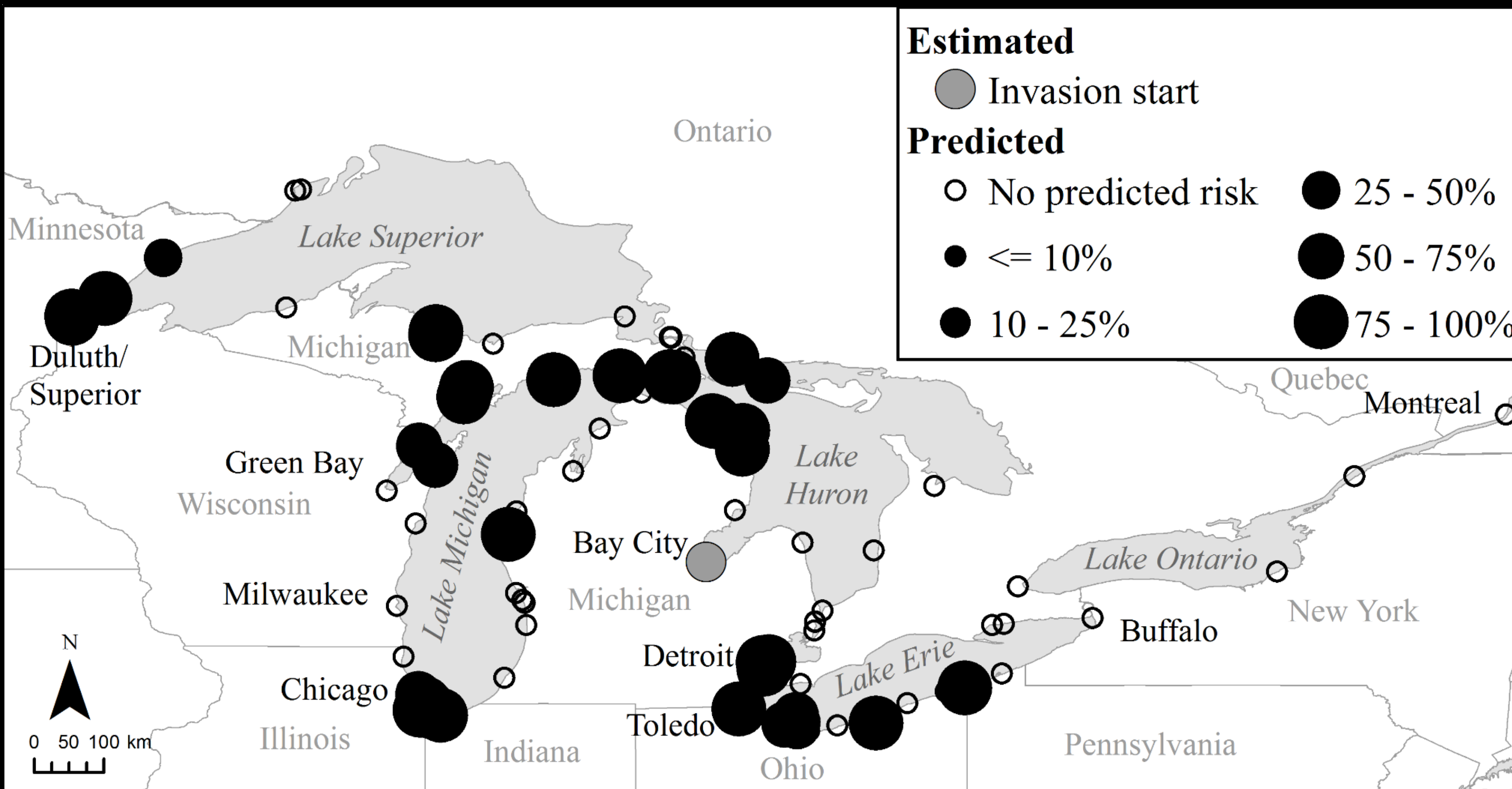
0.30
0.20
0.10
0.00
5-km
10-km
20-km
Spread Distance
Random
Location
Propagule Pressure: 5%
Propagule Pressure: 25%
Propagule Pressure: 50%
Propagule Pressure: 75%

Golden Mussel Predictions

- Introduction site: Bay City and Duluth
- Spread distance: 20-km
- Probability of infestation: 0.75
- Models were run 100 times

http://www.way.com.ar/~invasion/English/Mejillon.htm

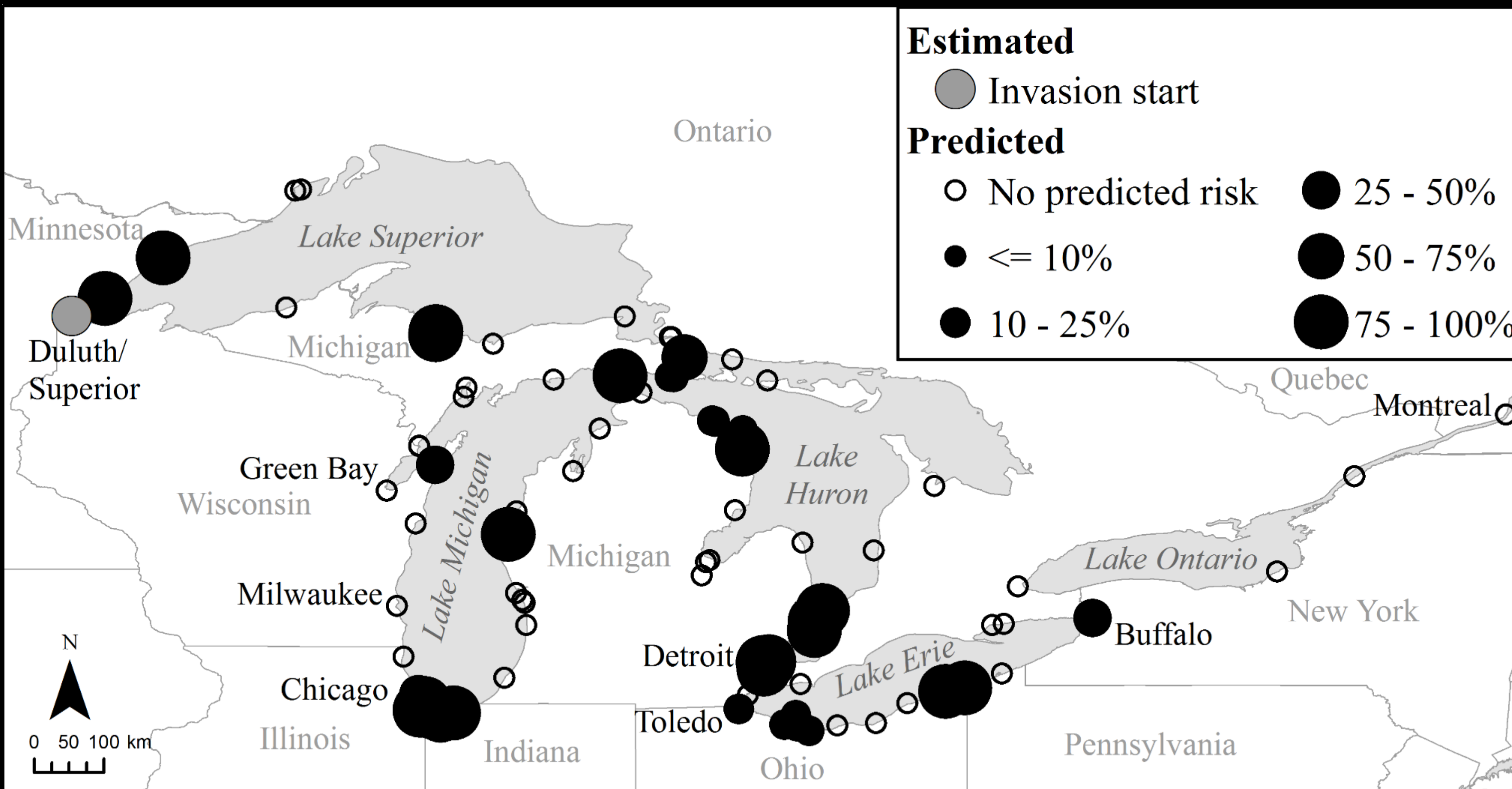
Golden Mussel: Bay City



Golden Mussel Conclusions

- Golden mussel invaded four Great Lakes directly from Bay City all 100 runs

Golden Mussel: Duluth



Golden Mussel Conclusions

- Golden mussel invaded four Great Lakes directly from Bay City all 100 runs
- Golden mussel invaded four Great Lakes directly from Duluth all 100 runs

Golden Mussel Conclusions

- Golden mussel invaded four Great Lakes directly from Bay City all 100 runs
- Golden mussel invaded four Great Lakes directly from Duluth all 100 runs
- Ports were invaded at a lower rate from Duluth

Golden Mussel Conclusions

- Golden mussel invaded four Great Lakes directly from Bay City all 100 runs
- Golden mussel invaded four Great Lakes directly from Duluth all 100 runs
- Ports were invaded at a lower rate from Duluth
- Golden mussel would be expected to become widespread very rapidly so long as it can survive where it is discharged

Killer Shrimp Predictions

- Invasion location:

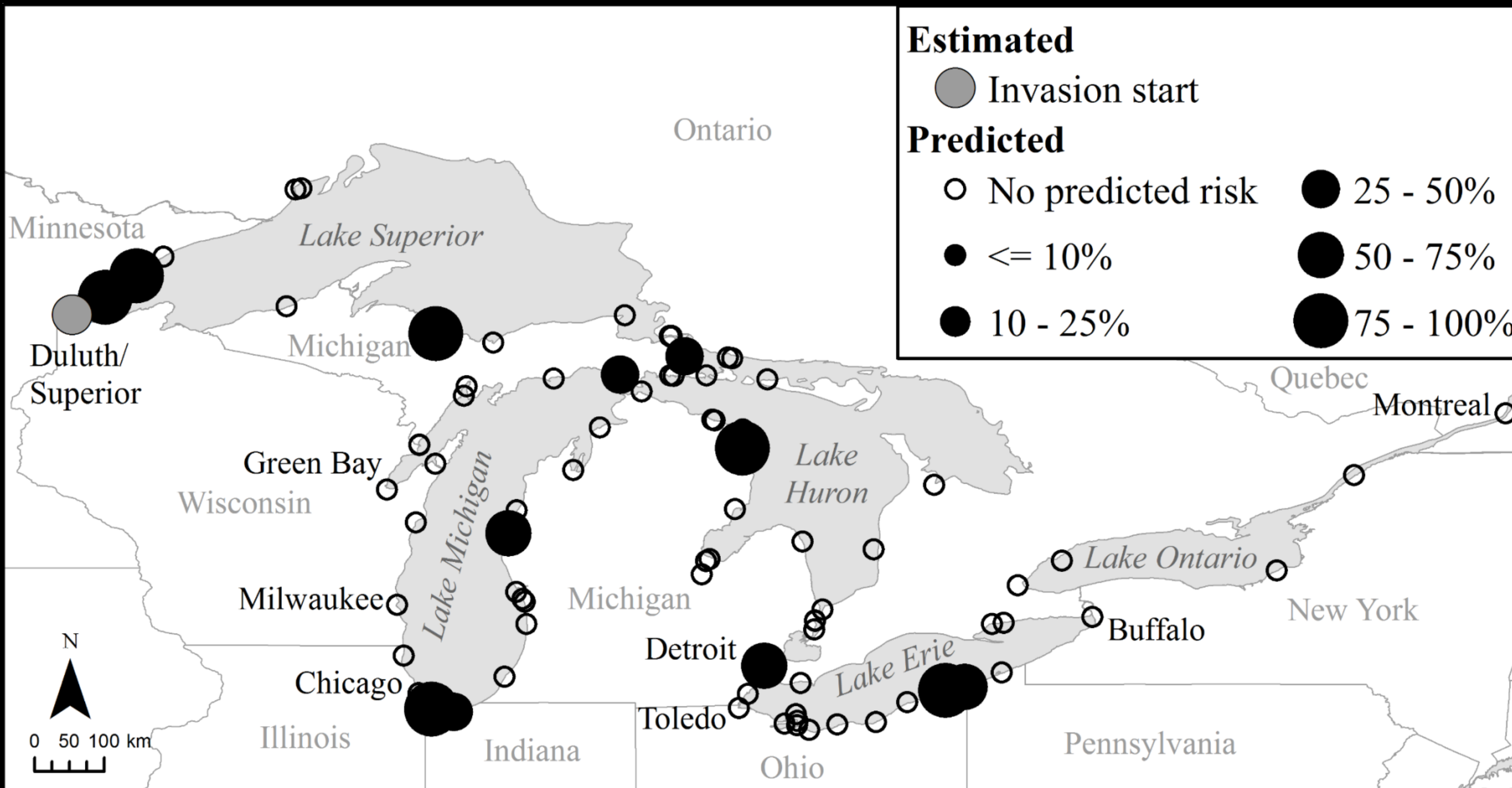
	# Ship Visits
Killer Shrimp	
Duluth, Minnesota	147
Toledo, Ohio	47
Superior, Wisconsin	17
Ogdensburg, New York	8
Green Bay, Wisconsin	7
Goderich, Ontario	4
Detroit, Michigan	1

Killer Shrimp Predictions

- Spread distance: 0-km
- Probability of infestation: 0.75
- Models were run 100 times

Photo Credit: Simon Devin,
Université de Metz, France

Killer Shrimp: Duluth



Killer Shrimp Conclusions

- From all starting points, killer shrimp became widespread throughout four of Great Lakes within the first time period
  - All five Great Lakes if the invasion started from Detroit
- Early detection of killer shrimp could allow for control opportunities depending on where it first invades

Overall Conclusions

- Prediction models can be used to inform detection and monitoring efforts
  - May allow for early detection when coupled with eDNA methods
- Prediction models can identify those species that would become widespread rapidly
- Lake Ontario was least predicted to become invaded

Future Directions

- Modify model for ease-of-use and distribution
- Input circulation model results into ballast model to identify mid-lake ballast water exchange locations

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