



**US Army Corps  
of Engineers®**  
Engineer Research and  
Development Center



*Aquatic Nuisance Species Research Program (ANSRP)*

## **Marine Bioinvasion Risk**

Review of Current Ecological Models

Safra Altman, Krystyna T. Powell, and Marin M. Kress

October 2023



Hull-Fouling Organisms  
in a Recreational Marina



**The US Army Engineer Research and Development Center (ERDC)** solves the nation's toughest engineering and environmental challenges. ERDC develops innovative solutions in civil and military engineering, geospatial sciences, water resources, and environmental sciences for the Army, the Department of Defense, civilian agencies, and our nation's public good. Find out more at [www.erdclibrary.on.worldcat.org/discovery](http://www.erdclibrary.on.worldcat.org/discovery).

To search for other technical reports published by ERDC, visit the ERDC online library at <http://www.erdclibrary.on.worldcat.org/discovery>.

# **Marine Bioinvasion Risk**

## **Review of Current Ecological Models**

Safra Altman and Krystyna T. Powell

*US Army Engineer Research and Development Center (ERDC) Environmental  
Laboratory (EL)  
3909 Halls Ferry Road  
Vicksburg, MS 39180-6199*

Marin M. Kress

*US Army Engineer Research and Development Center (ERDC)  
Coastal and Hydraulics Laboratory (CHL)  
3909 Halls Ferry Road  
Vicksburg, MS 39180-6199*

## **Final Special Report (SR)**

Distribution Statement A. Approved for public release: distribution is unlimited.

Prepared for US Army Engineer Research and Development Center  
Environmental Laboratory  
3909 Halls Ferry Road  
Vicksburg, MS 39180-6199

Under Aquatic Nuisance Species Research Program Project “Modeling Marine Bioinvasion Risk using Automated Information System (AIS)”; Civil Direct—Funding Account Code U4372082, AMSCO Code 008284

## Abstract

This special report describes the first phase of developing an ecological model to inform marine bioinvasion risks in the United States. The project responds to the needs of the US Army Corps of Engineers (USACE) Aquatic Nuisance Species Research Program, or ANSRP, which addresses all problematic invasive aquatic species affecting the nation's waterways, infrastructure, and associated resources, and the needs of the USACE navigation and dredging programs. Multiple port-deepening studies are either in progress or under consideration, and all must address ecological risk. Understanding whether and how increased dredging contributes to increased marine bioinvasion risk allows risk mitigation during early planning phases. Considering the potential impacts of future environmental change, such as changing sea level, ocean temperature, and ocean chemistry, will further strengthen planning for marine bioinvasion risk. Therefore, this special report documents current ecological modeling approaches to marine bioinvasion risk models and identifies models that incorporate shipping as a vector. The special report then presents a conceptual model and identifies historic vessel position data from the Automatic Identification System, or AIS, now available for most commercial and some recreational vessels around the United States, as a key source for future model development and testing.

**DISCLAIMER:** The contents of this report are not to be used for advertising, publication, or promotional purposes. Citation of trade names does not constitute an official endorsement or approval of the use of such commercial products. All product names and trademarks cited are the property of their respective owners. The findings of this report are not to be construed as an official Department of the Army position unless so designated by other authorized documents.

**DESTROY THIS REPORT WHEN NO LONGER NEEDED. DO NOT RETURN IT TO THE ORIGINATOR.**

# Contents

<b>Abstract</b> .....	<b>ii</b>
<b>Figures and Tables</b> .....	<b>iv</b>
<b>Preface</b> .....	<b>v</b>
<b>1 Introduction</b> .....	<b>1</b>
1.1 Background.....	1
1.2 Objective.....	3
1.3 Approach.....	3
<b>2 Methods</b> .....	<b>4</b>
<b>3 Results</b> .....	<b>6</b>
3.1 Results of Literature Review.....	6
3.2 Commercial versus Recreational Vessel Movements in Aquatic Nuisance Species (ANS) Literature.....	12
<b>4 Conceptual Model</b> .....	<b>14</b>
4.1 Conceptual Model Development.....	14
4.2 Future Research and the Automatic Identification System (AIS).....	16
4.3 AIS.....	16
<b>5 Conclusion</b> .....	<b>21</b>
<b>Bibliography</b> .....	<b>22</b>
<b>Report Documentation Page (SF 298)</b> .....	<b>29</b>

# Figures and Tables

## Figures

1. Example of marine hull fouling or biofouling. Sessile and mobile invertebrates grow on hard submerged surfaces such as docks and pilings (*left*). Close-up example of a hull-fouling community in San Francisco Bay, where the majority of the dominant species are aquatic nuisance species (ANS; *right*). (Photo credit: S. Altman.)..... 2
2. Examples of common ANS seen in San Francisco Bay fouling communities, such as solitary and colonial tunicates or sea squirts (*top row*), bryozoans or moss animals (*bottom left and bottom center*), and sea sponges (*bottom right*). (Photo credit: S. Altman.)..... 2
3. Distribution of literature reviewed across study locations according to recipient geography. .... 6
4. Summary of studies identified in reviewed publications that included recreational vessels, commercial vessels, both vessel types, or no shipping factors. .... 13
5. Conceptual model informed by current studies showing four components: Disturbance (*top*), Environment (*left*), Vectors/Propagule Pressure (*right*), and Biofouling Invasion Risk (*bottom*)..... 15
6. Map showing the approximate spatial coverage (reception) of terrestrial Automatic Identification System (AIS) towers around the United States. (Reprinted from Kress et al. 2021, 9. Public domain.)..... 18
7. Example of pleasure craft track lines (created by connecting sequential AIS position reports) for vessels calling at Jacksonville, Florida, and tracked for seven days. .... 19
8. AIS signal-density plot of pleasure-craft vessels identified in the Sarasota, Florida, region (*orange box*) at some point in 2020 and then tracked for one month after departure from Sarasota (*blue*—low signal, *red*—middle signal, *white*—high signal)..... 20

## Tables

1. List of scholarly journals sourced for the literature review. .... 4
2. Model component categories and individual measures. .... 9
3. Studies, model types, and categories of model components. .... 11

## Preface

This study was conducted for the US Army Engineer Research and Development Center–Environmental Laboratory (ERDC-EL) under Aquatic Nuisance Species Research Program Project “Modeling Marine Bioinvasion Risk using Automated Information System (AIS)”;

Civil Direct—Funding Account Code U4372082, AMSCO Code 008284. The technical monitor was Dr. Christine VanZomeren.

The work was performed by the Wetlands and Coastal Ecology Branch (EEW) of the Ecosystem Evaluation and Engineering Division (EE), ERDC-EL, and the Navigation Branch (HNN) of the Navigation Division (HN), US Army Research and Development Center–Coastal and Hydraulics Laboratory (ERDC-CHL). At the time of publication, Ms. Patricia Tolley was chief, EEW; Mr. Mark Farr was division chief, EE; Mr. Benjamin Burnham was chief, HNN; Ms. Ashley Frey was division chief, HN; Mr. Eddie Wiggins was the technical director for Navigation; and Dr. Jennifer Seiter-Moser was the technical director for Civil Works, Environmental Engineering and Sciences. The deputy director of ERDC-EL was Dr. Brandon Lafferty, and the director was Dr. Edmond J. Russo Jr. The deputy director of ERDC-CHL was Mr. Keith Flowers, and the director was Dr. Ty Wamsley.

COL Christian Patterson was commander of ERDC, and Dr. David W. Pittman was the director.

This page intentionally left blank.

# 1 Introduction

## 1.1 Background

Aquatic nuisance species (ANS) can cost millions of dollars in mitigation and management every year (USACE 2022) and have deleterious environmental impacts on species of concern and species of commercial importance. The US Fish and Wildlife Service (USFWS) describes ANS as “nonindigenous species that threaten the diversity or abundance of native species; the ecological stability of infested waters; or commercial, agricultural, aquacultural, or recreational activities dependent on such waters. [ANS] include nonindigenous species that may occur within fresh, estuarine, or marine waters and that presently or potentially threaten ecological processes or natural resources” (USFWS 2023). Non-native species are estimated to cost the public more than \$137 billion per year (Pimentel et al. 2000). Some species, such as the zebra mussel (*Dreissena polymorpha*), cost the public more than \$1 billion per year (USACE 2022).

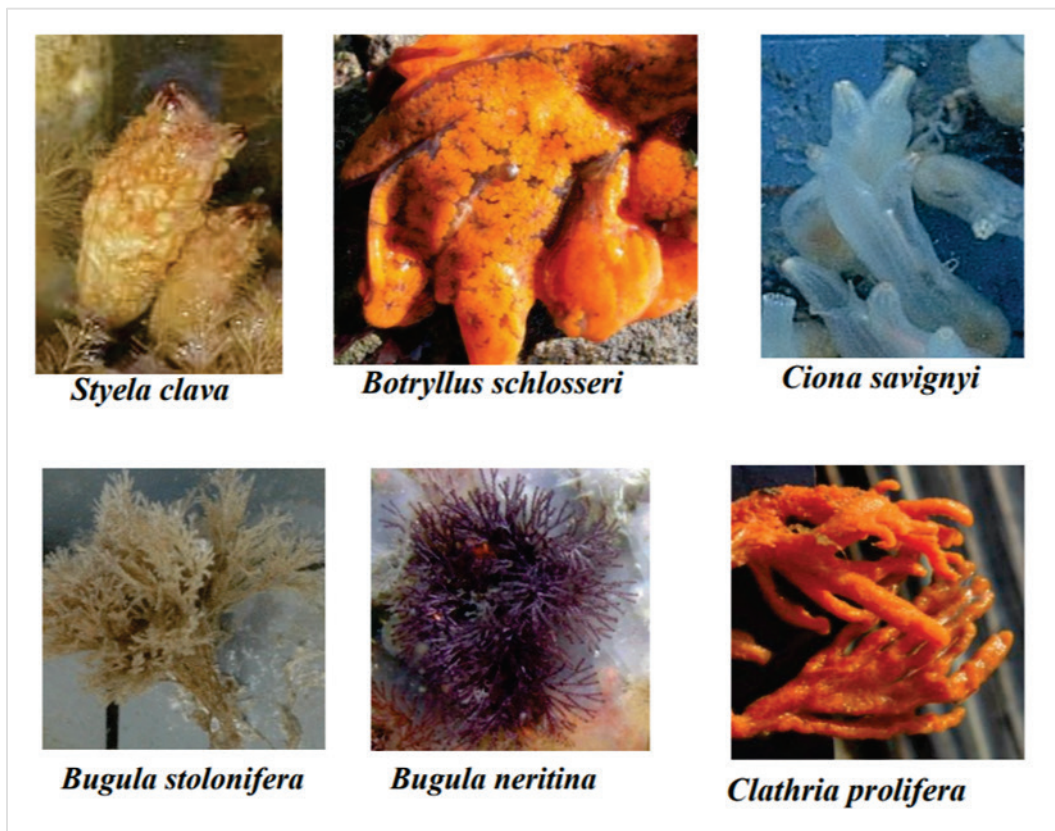
ANS are of concern to the US Army Corps of Engineers (USACE) mission areas of environmental restoration, navigation, and hydropower because of overlapping requirements for infrastructure construction and maintenance in environments where ANS may occur. Multiple vectors for ANS movements exist, including human-controlled vectors (for example, ship hulls, ship ballast water, aquaculture trade, aquarium trade) and natural forces (for example, storms, flotsam, natural range expansion). Examples of some marine ANS that have been transported by commercial and recreational vessels can be seen in Figure 1 and Figure 2.

As a component of the USACE responsibility to operate and manage water resources projects on navigable waters, USACE must also develop and consider effective, inexpensive methods of prevention and control of ANS to reduce impacts on public facilities and natural resources (USACE 2022). Understanding the difference in magnitude of risk of ANS spread due to dredging activities managed by USACE versus the risk of ANS spread due to the regular movement of hundreds or thousands of commercial and recreational vessels can help inform management and mitigation strategies within the purview of USACE or other resource agencies.

Figure 1. Example of marine hull fouling or biofouling. Sessile and mobile invertebrates grow on hard submerged surfaces such as docks and pilings (*left*). Close-up example of a hull-fouling community in San Francisco Bay, where the majority of the dominant species are aquatic nuisance species (ANS; *right*). (Photo credit: S. Altman.)



Figure 2. Examples of common ANS seen in San Francisco Bay fouling communities, such as solitary and colonial tunicates or sea squirts (*top row*), bryozoans or moss animals (*bottom left and bottom center*), and sea sponges (*bottom right*). (Photo credit: S. Altman.)



## 1.2 Objective

This special report seeks to synthesize contemporary ecological modeling approaches that incorporate shipping as a vector for ANS introduction. Previous efforts to model the risk of ANS introduction and spread have varied widely in scale and scope. This project addresses the needs of the USACE Aquatic Nuisance Species Research Program, or ANSRP, and some of the needs of the operations and maintenance, or O&M, dredging program, which consistently receives inquiries from stakeholders about known and unknown environmental effects of dredging. All port-deepening studies, either in progress or under consideration, must address the topic of ecological risk in some way. Understanding whether and how increased dredging would contribute to increased marine bioinvasion risk would allow this issue to be addressed proactively in early planning phases instead of reactively during project execution or monitoring. Understanding the extent to which normal commercial and recreational vessel movements in US waters facilitate ANS is fundamental to an accurate assessment of marine bioinvasion risk.

## 1.3 Approach

This special report covers the first phase of a marine bioinvasion risk modeling effort, consisting of (1) a literature review, (2) the development of a conceptual model, and (3) an initial exploration of the Automatic Identification System (AIS) as a future data source that will help parameterize the vector and propagule pressure components of the conceptual model.

## 2 Methods

We performed literature searches using the Google Scholar website (<https://scholar.google.com>) to identify published literature containing one or more of the following key terms or phrases: *invasive species*, *invasive alien introduction*, *non-native*, *shipping*, *shipping trends*, *Automatic Identification System data*, *vessel AIS*, *marine invasion modeling*, *ship*, *vector*, *recreational vessel*, *model*. Multiple searches were employed, each using the term *invasive species*, *invasive alien introduction*, or *non-native* in combination with the term *model* and each of the other listed terms. The first 100 papers returned for each search on Google Scholar were assessed for relevance concerning development of ecological models of aquatic invasion involving recreational or commercial ships (non-English papers were excluded). If the paper referred to or described an ecological model, it was selected for review. The literature review focused on invasion mechanisms, drivers, and modeling approaches that include shipping vectors associated with ANS. Modeling methodologies were broken down into model components to understand the most common factors. The final number of papers included in this review was 40. We down selected to include papers that described ecological models of marine invasions with a shipping component. The publication dates ranged from 2009 to 2020 and were sourced from 27 scholarly journals, indicating widespread interest in invasive species (Table 1).

**Table 1. List of scholarly journals sourced for the literature review.**

<b>Journal Title</b>
<i>Aquatic Ecosystem Health &amp; Management</i>
<i>Biologia Marina Mediterranea</i>
<i>Biological Conservation</i>
<i>Biological Invasions</i>
<i>Bioscience</i>
<i>Bulletin of Marine Science</i>
<i>Canadian Journal of Fisheries and Aquatic Sciences</i>
<i>Diversity and Distributions</i>
<i>Ecological Modelling</i>
<i>Ecology and Evolution</i>
<i>Ecology Letters</i>
<i>Frontiers in Ecology and the Environment</i>
<i>Global Ecology and Biogeography</i>

**Table 1 (cont.). List of scholarly journals sourced for the literature review.**

<b>Journal Title</b>
<i>Hydrobiologia</i>
<i>ICES Journal of Marine Science</i>
<i>Journal of Applied Ecology</i>
<i>Journal of Environmental Management</i>
<i>Journal of the Royal Society Interface</i>
<i>Management of Biological Invasions</i>
<i>Marine Biology</i>
<i>Marine Pollution Bulletin</i>
<i>Molecular Ecology</i>
<i>Nature Communications</i>
<i>Nature Sustainability</i>
<i>PLOS ONE</i>
<i>Proceedings of the National Academy of Sciences</i>
<i>Scientific Reports</i>

## 3 Results

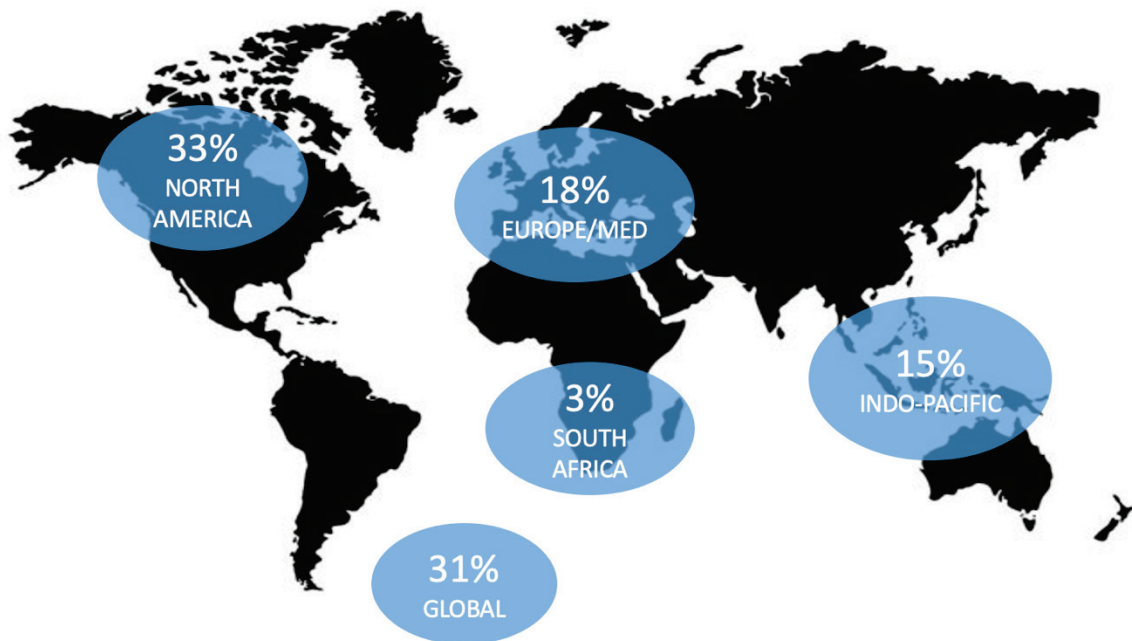
### 3.1 Results of Literature Review

Of the 40 papers identified in the literature review, 39 were identified as containing studies or models that met our inclusion criteria and pertained to ANS and shipping. These models covered a range of invasive species and geographic regions. Geographic regions along with number of papers per region included

- Africa (1),
- Indo-Pacific (6),
- Europe (7),
- North America (13), and
- Global studies (12).

The studies and models described had a global distribution. Of the 39 papers, 33% (13 of 39) of the studies focused on recipient geography (that is, where the non-native species was invading) within the coastal United States, followed by 18% (7 of 39) in Europe and Mediterranean regions and 15% (6 of 39) in the Indo-Pacific (Figure 3).

Figure 3. Distribution of literature reviewed across study locations according to recipient geography.



Of the 39 papers reviewed, 23 (59%) highlighted specific taxonomic groups or invertebrate clades of interest whose non-native range has or may spread via shipping vectors. Non-native species modeled within the literature reviewed include terrestrial and aquatic plants, algae (Chlorophyta, Phaeophyceae, and Rhodophyta species), invertebrates (that is, tunicates, crustaceans, bivalves, etc.), vertebrates (fish, reptiles, and amphibians), and invertebrate clades such as zooplankton or hull-fouling benthic invertebrates.

A detailed analysis of the model components incorporated across studies revealed six standard categories: *Invasiveness*, *Habitat Suitability*, *Environmental Metrics*, *Shipping Frequency or Connectivity*, *Shipping Volume*, and *Socioeconomic Factors* (Table 2). The Invasiveness category focuses on the spreading potential of ANS, concentrating on metrics such as the number of introduction events, propagule or colonization pressure, and the number of sampled species (that is, concerning species occurrences, richness, abundance), among several other available metrics. Habitat Suitability describes a species' ability to survive and persist through factors such as dispersal pathways, gene flow, amount of available habitat, and ecological impacts. Related to Habitat Suitability, Environmental Metrics focus on aspects that can determine a species' ability to survive in a given environment (that is, salinity, temperature, nutrient levels, etc.).

The Shipping Frequency or Connectivity category, which assesses ships as vectors of ANS spread, had the most data-collection metrics (18) of all the categories, exhibiting the highest degree of variance in assessment methods across studies. The Shipping Volume category displayed less variety in data collection metrics (6), focusing on ballast water and cargo. Shipping Volume is an essential aspect in the characterization of invasion risk because of stowaways found inside or on the surface of the container or vessel. In all, 33% (13 of 39) of studies used metrics of shipping volume in their models. Finally, Socioeconomic factors (for example, population growth, gross domestic product, the value of imported goods) were used to capture how societal elements (such as treaties, trade practices, legal borders) are connected to the physical risk of ANS spread.

In Table 2, each column represents a component category containing an unordered list, where each cell is individually considered a measurement metric. Modeling component categories varied in the types and number of representative data sets used across the literature reviewed—suggesting

that there may be greater flexibility in representing specific model components. This greater flexibility proved especially true for the Shipping Frequency or Connectivity category, defined by 18 metrics, while the Shipping Volume category only included 6 unique metrics.

When examining how each category of metrics was incorporated into individual studies, we found that 87% (33 of 39) of models considered Invasiveness, and 92% (35 of 39) considered Shipping Frequency or Connectivity (Table 3). Out of 39 models, one (2%) study incorporated all six categories (Hulme 2009), 2 (5%) studies contained five categories (Seebens et al. 2013; Seebens et al. 2016), and the rest used four or fewer categories in their models (Table 3). Only 6 (15%) studies included Socioeconomic factors in their models (Hulme 2009, Azmi et al. 2015; Early et al. 2016; Tidbury et al. 2016; Turbelin et al. 2017; Sardain et al. 2019). The relative brevity of individual measures listed in the Environmental Metrics category (Table 2) is likely due to the wide recognition of sea surface temperature (mean, maximum, and minimum) and salinity metrics as significant biological determinants (or limiting factors) of ANS spread in the reviewed models (Keller et al. 2011; Ware et al. 2014; Seebens 2016, Goldsmit et al. 2017). That is, temperature and salinity influence the likelihood of organism survival in a new area so strongly that other factors are simply not measured. Model types included regression analysis, fuzzy logic models, species-distribution models, ecological-niche models, gravity models, and spatial models.

Table 2. Model component categories and individual measures.

Invasiveness	Habitat Suitability	Environmental Metrics	Shipping Frequency or Connectivity	Shipping Volume	Socioeconomic Factors
Threat scoring system	Ecological impact	Sea surface temperature (mean, max, and min)	Types of transport nodes (ports, harbors, marinas)	Ballast-water volume	Income growth
Invasive potential	Geographic extent or distance	Salinity	Number of ports	Ballast-water release protocols	Gross domestic product
Propagule pressure	Estimate environmental suitability of the region to specific aliens	Source-sink environmental matching	Number of voyages connected to foreign ports to unique connections	Shipping-cargo volume	Human population size
Colonization pressure	Assign dispersal costs to distinct landscape features	Total land area of a country (km <sup>2</sup> )*	Number of voyages connected to foreign ports to total voyages	Volume of goods shipped	Distance between two countries (ports)
Patterns of recorded species invasions	Biogeography dissimilarity (community mismatch)	Environmental conditions for each port	Frequency of port visits by international arrivals	Magnitude of ballast water exchanged in ports	Common colonial history
Number of introduction events	Potential donor regions and dispersal pathways of future invaders	Forecasted environmental conditions based on IPCC <sup>a</sup> scenarios	Vectors traffic derived from geo-referenced monitoring data	Water and sediment retention	Common land border
Sampled number of species	Biological characteristics of selected potential invaders	Mean nutrient levels (calcite, nitrate, phosphate, silicate)	Transport efficiency (sailing speed)	—	Existence of regional trade agreement

<sup>a</sup> Intergovernmental Panel on Climate Change

\* For a full list of the spelled-out forms of the units of measure used in this document, please refer to *US Government Publishing Office Style Manual*, 31st ed. (Washington, DC: US Government Publishing Office, 2016), 248–52, <https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf>.

Table 2 (cont.). Model component categories and individual measures.

Invasiveness	Habitat Suitability	Environmental Metrics	Shipping Frequency or Connectivity	Shipping Volume	Socioeconomic Factors
Asymmetry level between number of invasive species in country and number of native species invasive elsewhere	Gene flow via migration	Chlorophyll minimum and maximum	Geographic extent of vectors	—	Management difficulty (measure of effort to reverse threat, remove or manage species)
Occurrence data of native and invaded ranges	Total amount of habitat available	Sea-ice concentration	Capacity of transport vectors	—	Number of international treaties subscribed to
Invasion history	Latitude and longitude	Bathymetry	Arrival and departure dates of single shipments	—	Quantity of international trade
Species richness	—	Mean photosynthetically available radiation	Ship physical characteristics (size, length, type)	—	Human population density used as a proxy for spatial-introduction pressure
Transmission rate	—	Geography layers such as distance to land (in km) and maximum depth (in m)	Port dwell time (total and average)	—	Mean annual USD value of all goods imported by country
Macrophyte fouling score or fouling rank	—	—	Recreational cruising routes, total number of cruise ports per spatial area	—	USD value of imported live plants and animals not intended for food
Likelihood of invasion (that is, present status, rate of introduction, survival, establishment, and spread)	—	—	Vessel type (container ships, bulk carriers, tankers)	—	Import USD value per m <sup>2</sup> (product of per capita import values and population density)
Species percent cover	—	—	Time since last dry-docking, time since last painting	—	Number of live aquaculture and shellfish imports per spatial unit

Note: USD—US dollars.

Table 3. Studies, model types, and categories of model components.

Model type	Study	Invasiveness	Habitat Suitability	Environmental Metrics	Shipping Frequency or Connectivity	Shipping Volume	Socioeconomic Factors
Asymmetry index	Turbelin et al. (2017)	X	–	X	–	X	X
Demographic	Hulme (2009)	X	X	X	X	X	X
Dynamic spatial	Sieracki, Bossenbroek, and Chadderton (2014)	X	X	–	X	X	–
	Sieracki, Bossenbroek, and Faisal (2014)	X	X	–	X	X	–
Fault tree analysis	Acosta and Forrest (2009)	X	–	–	X	X	–
First-order Markov chain	Paini and Yemshanov (2012)	X	–	–	X	–	–
Fuzzy logic systems	Acosta et al. (2010)	X	X	–	X	–	–
	Ferrario et al. (2016)	X	–	–	X	–	–
Gravity	Kaluza et al. (2010)	X	–	–	X	–	–
	Sardain et al. (2019)	X	–	X	X	–	X
Heat map	Tidbury et al. (2016)	X	–	X	X	–	X
Hub-and-spoke network	Azmi et al. (2015)	–	–	–	X	–	X
Hypothetical dispersal network	Darling et al. (2012)	–	X	–	X	–	–
Invasion threat risk map with binned risk levels	Early et al. (2016)	X	–	X	X	–	X
Multivariate comparisons	Mineur et al. (2007)	X	–	X	X	–	–
Regression (linear, GLM, <sup>a</sup> GAM <sup>b</sup> )	Chan et al. (2018)	X	–	–	X	–	–
	Iacarella et al. (2020)	X	–	–	X	–	–
	Keller et al. (2011)	–	–	X	X	–	–
	Kelly et al. (2013)	X	–	–	X	X	–
	Martínez-Laiz et al. (2019)	X	–	–	X	–	–
	Lacoursière-Roussel et al. (2016)	X	–	–	X	X	–

<sup>a</sup> GLM—generalized linear model

<sup>b</sup> GAM—generalized additive model

Table 3 (cont.). Studies, model types, and categories of model components.

Model Type	Study	Invasiveness	Habitat Suitability	Environmental Metrics	Shipping Frequency or Connectivity	Shipping volume	Socioeconomic Factors
Regression (linear, GLM, <sup>a</sup> GAM <sup>b</sup> )	Molnar et al. (2008)	X	X	–	X	X	–
	Montes et al. (2018)	–	–	X	X	–	–
	Peters et al. (2019)	X	–	–	X	–	–
	Sylvester et al. (2011)	X	–	X	X	–	–
	Ulman et al. (2019)	X	–	–	X	–	–
	Ware et al. (2014)	X	–	X	X	X	–
Spatially explicit	Floerl et al. (2009)	X	X	–	X	–	–
	Mellin et al. (2016)	X	X	X	–	–	–
Species distribution	Crafton (2015)	X	–	X	X	–	–
	Goldsmid et al. (2017)	X	X	X	X	–	–
	Herborg et al. (2009)	X	–	X	X	–	–
	Hertzog et al. (2014)	X	X	X	–	–	–
	Leidenberger et al. (2015)	X	X	X	X	–	–
	Moore et al. (2018)	X	–	X	X	–	–
Species-flow networks	Saebi et al. (2020)	–	X	X	X	X	–
Vector based	Seebens et al. (2013)	X	X	X	X	X	–
	Seebens et al. (2016)	X	X	X	X	X	–
	Williams et al. (2013)	X	–	–	X	X	–

<sup>a</sup> GLM—generalized linear model

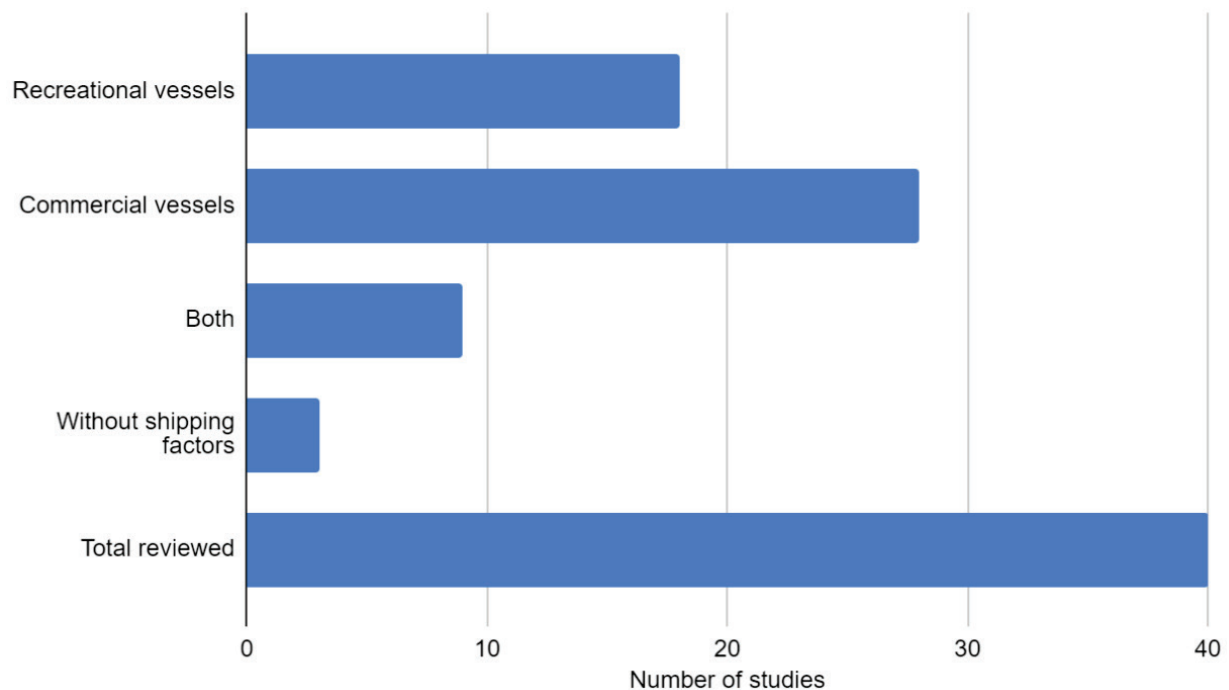
<sup>b</sup> GAM—generalized additive model

### 3.2 Commercial versus Recreational Vessel Movements in Aquatic Nuisance Species (ANS) Literature

Commercial vessels may include large oceangoing ships with extensive hull surface and ballast-water storage. In contrast, recreational vessels (that is, pleasure crafts) tend to be smaller (in dimension), travel at slower speeds, dwell for extended periods in one location, and have limited off-shore range. Distinguishing between commercial vessel movements and

recreational vessel movements is essential because of these vessels' different usage and activity patterns. Of the articles included in this literature review, only a few (Hulme 2009; Seebens et al. 2013; Williams et al. 2013; Tidbury et al. 2016) used historic vessel-movement information in their model. Of the 39 papers, 18 (46%) included recreational-vessel movements as model components, while 28 (72%) included commercial vessels (Figure 4). Only 9 (23%) studies included both commercial and recreational vessels in their analysis (Figure 4). Finally, 2 (5%) studies did not have shipping components in their models: Mellin et al. (2016) focused on biotic interactions and demographics influencing marine invasions, while Hertzog et al. (2014) focused on a terrestrial species.

**Figure 4. Summary of studies identified in reviewed publications that included recreational vessels, commercial vessels, both vessel types, or no shipping factors.**

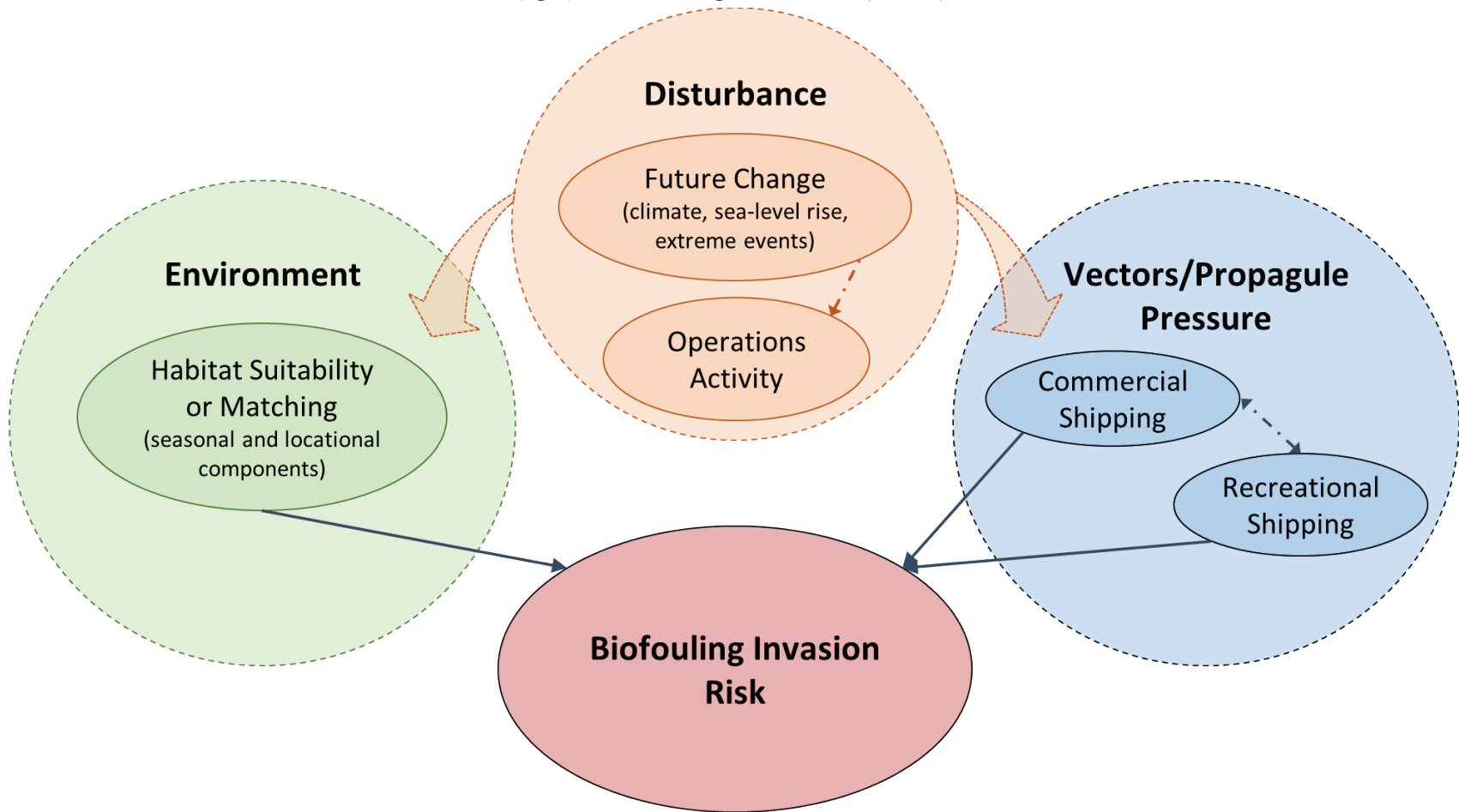


## 4 Conceptual Model

### 4.1 Conceptual Model Development

Our literature review highlighted standard components incorporated within ecological models that describe or predict species spread via vessel movement. Using the review findings as a guide, we developed a conceptual model to determine biofouling invasion risk due to environmental constraints, vector and propagule pressure, and disturbance regime (Figure 5). Conceptually, ecological conditions are modeled through habitat suitability (also known as *habitat matching*) of nonindigenous species (or suite of species) with the new location under assessment. Vector and propagule pressure can be separated into commercial- and recreational-vessel patterns, which are related but may have different impacts on a species or taxonomic group of interest because of distinctly different traffic patterns. Disturbance regime, which influences both habitat compatibility and propagule success, could incorporate ongoing and future environmental disturbances, such as climate variability, sea-level rise, and extreme weather events (for example, hurricanes, flooding). An additional disturbance component is an operational activity such as harbor deepening or channel maintenance (that is, dredging), which can alter the habitat suitability, especially within the benthic footprint of the channel. The three components in our conceptual model—*Environment*, *Disturbance*, and *Vector/Propagule Pressure*—contribute to invasion risk.

Figure 5. Conceptual model informed by current studies showing four components: Disturbance (*top*), Environment (*left*), Vectors/Propagule Pressure (*right*), and Biofouling Invasion Risk (*bottom*).



## 4.2 Future Research and the Automatic Identification System (AIS)

Additional research is underway to examine the level of vessel movement in domestic waters that may contribute to the spread of ANS within the United States. This information would benefit USACE’s navigation mission; other federal and state agencies would benefit from estimates of the relative magnitude of potential ANS transfer risk caused by different categories of vessels (that is, pleasure craft, commercial freight vessels, and working vessels such as dredges). Future research will use historic vessel-position reports from the US Coast Guard (USCG) Nationwide Automatic Identification System (NAIS), described in Section 4.3.

## 4.3 AIS

The Automatic Identification System (AIS) is a ship-to-ship, ship-to-shore, and shore-to-ship communication system based on radio-frequency transmissions and approved by the International Maritime Organization, or IMO as a global communication standard (USCG [2018?]). Extensive information on AIS specifications can be found through international associations that set technical standards (IALA 2008; IEC 2018; ITU 2014; PIANC 2019, as cited by Kress et al. 2021, 2). AIS transponders have been standard equipment on oceangoing commercial ships for over a decade, but widespread usage installation on inland vessels is more recent. As Kress et al. (2021) explain, since 2016, AIS carriage requirements set by the USCG “have included most commercial self-propelled vessels on US navigable waters” (2). Specifically, any vessel over 65 ft\* (19.8 m) in length, vessel towing vessels over 26 ft (7.9 m) in length with an engine greater than 600 hp (608 metric hp), vessel certified to carry 150 or more passengers, dredge in or near a commercial channel, or vessel moving specific dangerous cargo must adhere to USCG AIS carriage requirements (USCG [2023?]); 33 C.F.R. § 164.46<sup>†</sup>, as cited by Kress et al. 2021, 2). AIS transponders are now carried on most commercial vessels in the United States, including those that remain within domestic waters, such as tugs and towboats (USCG [2023?]).

---

\* For a full list of the spelled-out forms of the units of measure used in this document, please refer to *US Government Publishing Office Style Manual*, 31st ed. (Washington, DC: US Government Publishing Office, 2016), 248–52, <https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf>.

<sup>†</sup> Automatic Identification System. 33 C.F.R. § 164.46. <https://www.govinfo.gov/content/pkg/CFR-2021-title33-vol2/pdf/CFR-2021-title33-vol2-sec164-46.pdf>.

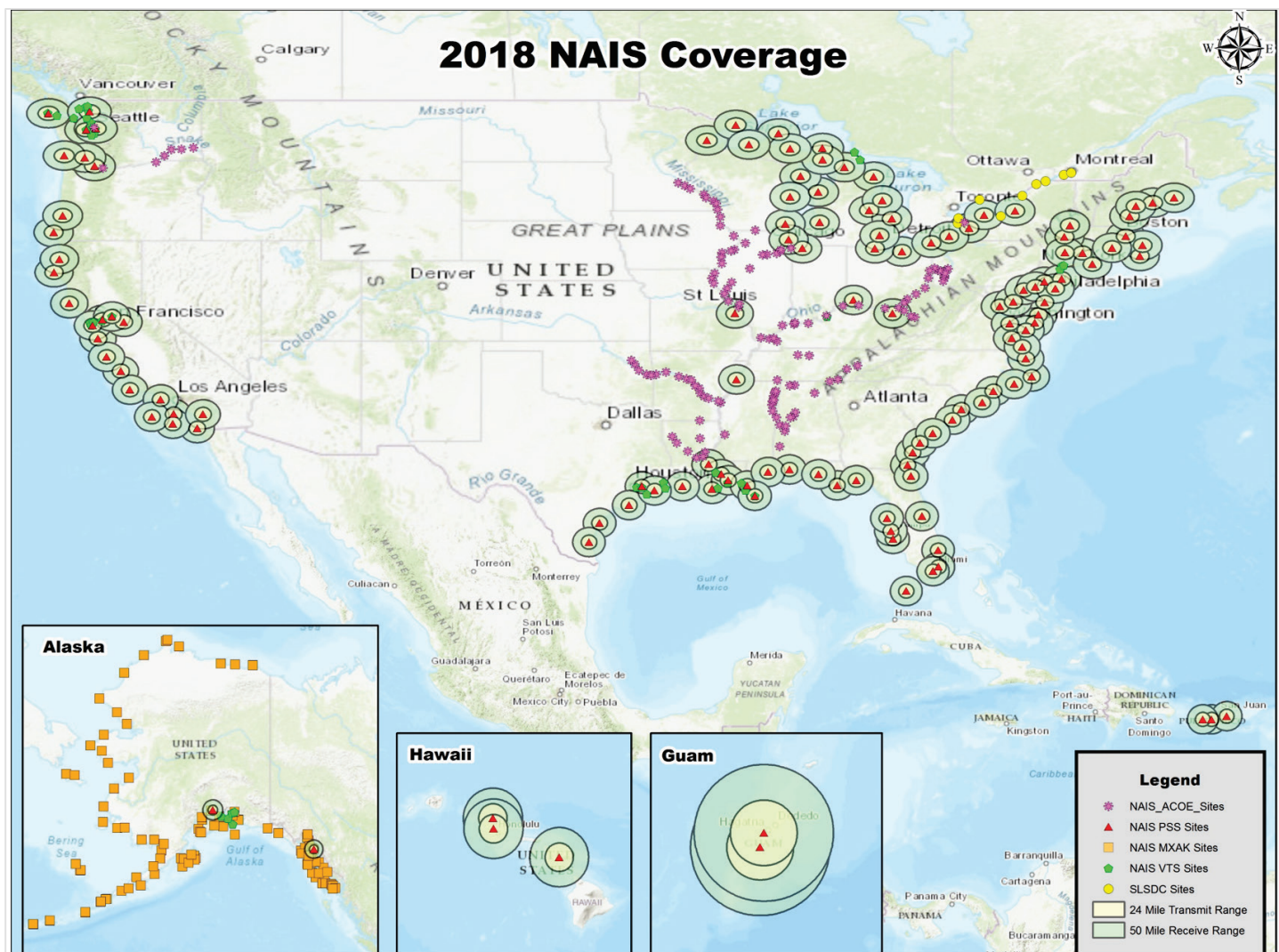
Noncommercial private vessels (recreational vessels, pleasure crafts) can also use AIS transponders the same way as commercial vessels.

The USCG NAIS program archives AIS records from coastal and inland areas received by shoreside towers (USCG [2023?]). AIS messages are time-stamped and geospatially referenced and include user-input fields such as vessel name and Maritime Mobile Service Identity, or MMSI, number. The geospatial reference information (latitude and longitude) inside an AIS message is derived from a connection to an onboard GPS device (USCG [2023?]). Archived AIS records can be accessed from the USCG through requests to the agency, via web services (such as those used by the AIS Analysis Package, or AISAP, software), or through collaborative efforts for large-scale releases of AIS data such as the Marine Cadastre website at [MarineCadastre.gov](https://www.marinecadastre.gov) (NOAA 2023). Researchers can use archived AIS records to investigate a wide variety of topics related to vessel movements, including port connectivity (Kress et al. 2021), waterway use by commercial vessels (Kress et al. 2020; Mitchell and Scully 2014; Tabbert et al. 2021; Young and Scully 2018), travel time along inland river systems (DiJoseph et al. 2019), and maritime resilience (Farhadi et al. 2016; Scully and Chambers 2019; Touzinsky et al. 2018).

Reception of AIS transmissions goes through a network of shoreside (terrestrial) towers, with higher-powered AIS transmissions received by satellites. The USCG maintains an archive of these terrestrial AIS signals through their NAIS program (USCG [2023?]). While there are gaps in AIS reception coverage along coastal and inland waterways, the US Atlantic and Gulf coasts generally have excellent AIS coverage in nearshore areas. A map of AIS towers and generalized reception zones as of 2018 are shown below in Figure 6.

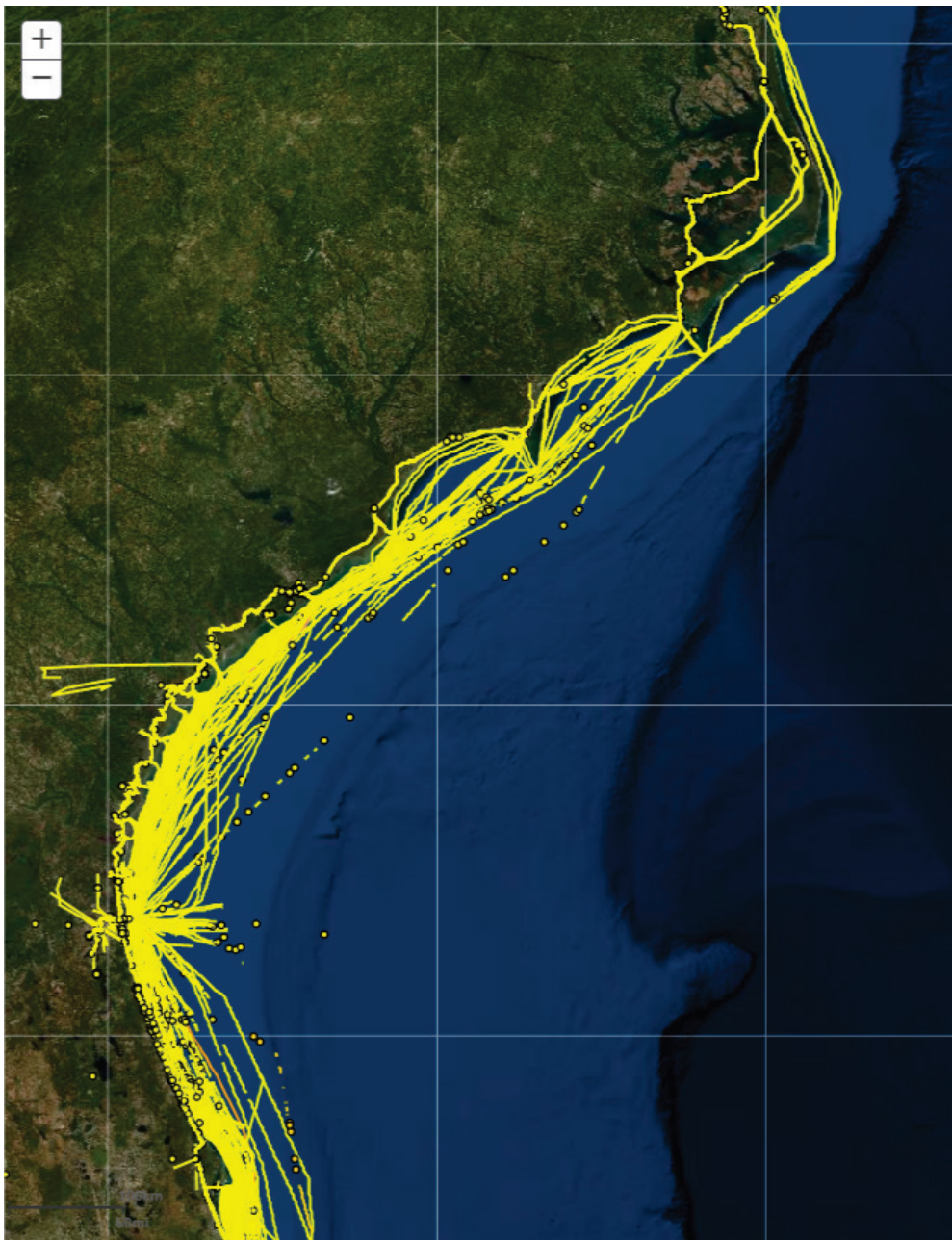
This project carried out a preliminary examination of the existence of AIS data to describe and quantify the movement of recreational vessels (that is, pleasure craft) in and out of the state of Florida during the years 2019 and 2020. Initial results suggest that AIS data for vessels that self-identify as pleasure craft are available in sufficient quantity to compare the magnitude of pleasure-craft movements to those of commercial ships. An example of plotted historical position reports from pleasure craft is shown in Figure 7, depicting track lines of vessels that called at Jacksonville, Florida, and their track line for seven days. Although not all pleasure crafts carry AIS transponders, thousands do.

Figure 6. Map showing the approximate spatial coverage (reception) of terrestrial Automatic Identification System (AIS) towers around the United States. (Reprinted from Kress et al. 2021, 9. Public domain.)



Note: NAIS—Nationwide Automatic Identification System; ACOE—Army Corps of Engineers; PSS—primary shoreside (US Coast Guard); MXAK—Marine Exchange of Alaska; VTS—Vessel Traffic Service; SLSDC—St. Lawrence Seaway Development Corporation)

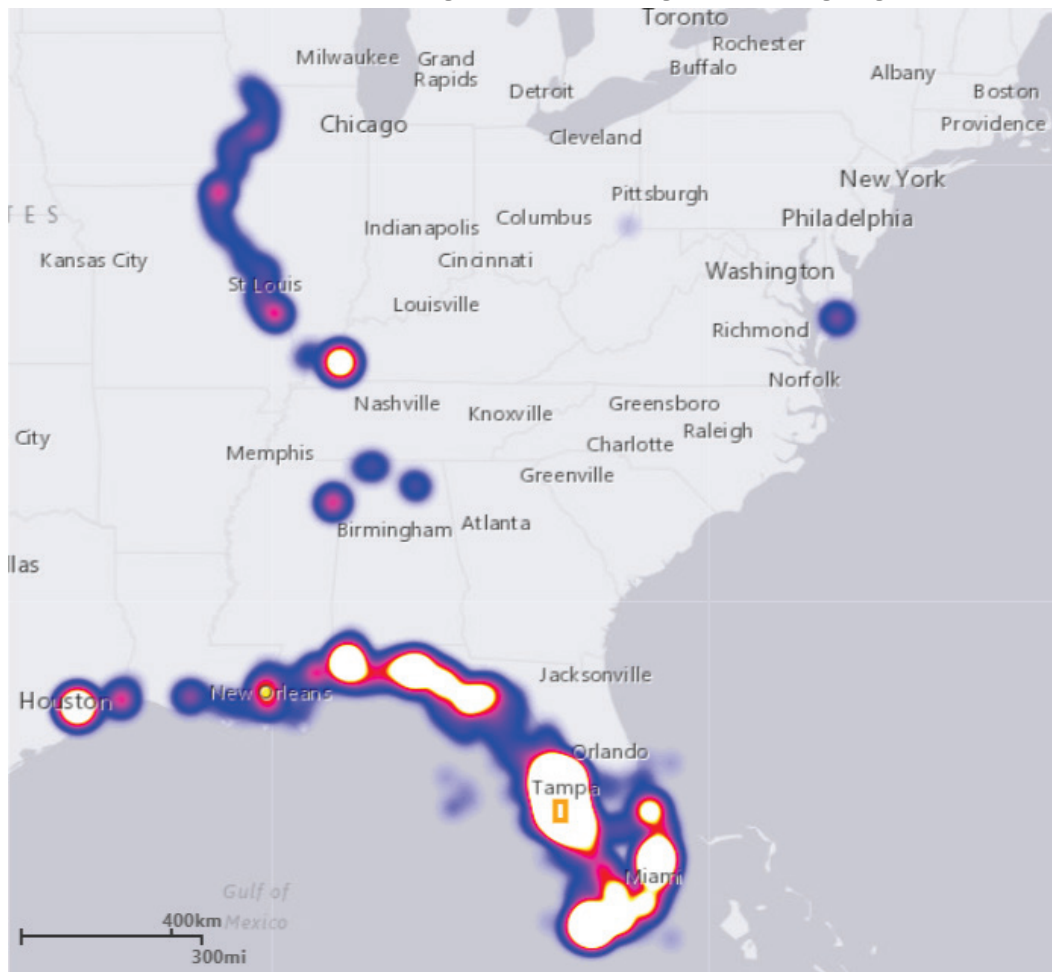
Figure 7. Example of pleasure craft track lines (created by connecting sequential AIS position reports) for vessels calling at Jacksonville, Florida, and tracked for seven days.



In Figure 8, vessel hot spots are shown around the Sarasota-Tampa, Florida, area on the Gulf Coast; around the Florida Keys; along the southern Atlantic coast of Florida; in two areas along the Florida panhandle; one area near Houston, Texas; one area on the New Jersey Atlantic Coast; and in a few places along the Mississippi River from Tennessee to as far north as Iowa. These hot spots represent vessels identified as present in the Sarasota, Florida, area during the year 2020 and then tracked for one month

after their departure from Sarasota. The geographical extent of the hot spots demonstrates that vessels cover significant distances around the United States. This mapping of the hot spots supports the idea that private pleasure crafts can travel long distances and cross ecoregions in a relatively short amount of time (for example, from subtropical saltwater to midlatitude freshwater) and thus serve as vectors for the movement of ANS. Because private pleasure crafts travel at slower speeds and to different destinations (regions, ports, marinas) they likely present a different vector risk than commercial vessels.

Figure 8. AIS signal-density plot of pleasure-craft vessels identified in the Sarasota, Florida, region (*orange box*) at some point in 2020 and then tracked for one month after departure from Sarasota (*blue*—low signal, *red*—middle signal, *white*—high signal)



## 5 Conclusion

This special report presented a review of existing literature relevant to models that predict the spread of ANS. This review provided an overview of multiple approaches, parameters, and data sources that researchers have previously used to develop models. Understanding and ideally preventing the introduction and spread of ANS is of interest to the US government because of the known mitigation costs associated with existing ANS and the unknown potential costs of future ANS mitigation. In addition to the literature review, we describe a novel conceptual model combining environmental features, disturbance features, and vector features to develop a biofouling invasion risk prediction. The next step in this research project will be to identify and use quantitative data from a real-world case study to test the conceptual model. Preliminary research suggests that recreational boating in the state of Florida could serve as a real-world test case.

## Bibliography

- Acosta, Hernando, and Barrie M. Forrest. 2009. "The Spread of Marine Non-indigenous Species via Recreational Boating: A Conceptual Model for Risk Assessment Based on Fault Tree Analysis." *Ecological Modelling* 220 (13–14): 1586–98. <https://doi.org/10.1016/j.ecolmodel.2009.03.026>.
- Acosta, Hernando, Dongrui Wu, and Barrie M. Forrest. 2010. "Fuzzy Experts on Recreational Vessels, a Risk Modelling Approach for Marine Invasions." *Ecological Modelling* 221 (5): 850–63. <https://doi.org/10.1016/j.ecolmodel.2009.11.025>.
- Automatic Identification System. 2021. 33 C.F.R. § 164.46. <https://www.govinfo.gov/content/pkg/CFR-2021-title33-vol2/pdf/CFR-2021-title33-vol2-sec164-46.pdf>.
- Azmi, Fauziah, Chad L. Hewitt, and Marnie L. Campbell. 2014. "A Hub and Spoke Network Model to Analyse the Secondary Dispersal of Introduced Marine Species in Indonesia." *ICES Journal of Marine Science* 72 (3): 1069–77. <https://doi.org/10.1093/icesjms/fsu150>.
- Chan, Farrah T., Hugh J. MacIsaac, and Sarah A. Bailey. 2015. "Relative Importance of Vessel Hull Fouling and Ballast Water as Transport Vectors of Nonindigenous Species to the Canadian Arctic." Edited by Martin Krkošek. *Canadian Journal of Fisheries and Aquatic Sciences* 72 (8): 1230–42. <https://doi.org/10.1139/cjfas-2014-0473>.
- Crafton, R. Eliot. 2014. "Modeling Invasion Risk for Coastal Marine Species Utilizing Environmental and Transport Vector Data." *Hydrobiologia* 746 (1): 349–62. <https://doi.org/10.1007/s10750-014-2027-x>.
- Darling, John A., Leif-Matthias Herborg, and Ian C. Davidson. 2012. "Intracoastal Shipping Drives Patterns of Regional Population Expansion by an Invasive Marine Invertebrate." *Ecology and Evolution* 2 (10): 2557–66. <https://doi.org/10.1002/ece3.362>.
- Dijoseph, P.K., K.N. Mitchell, B.J. Tetreault, and J. Marshall, 2019. Dijoseph 2019 *Inland Marine Transportation System Travel Time Atlas via Automatic Identification System (AIS) Data: Ohio River, Upper Mississippi River, and Illinois River*. ERDC/CHL TR-19-15. Vicksburg, MS: US Army Engineer Research and Development Center. <https://doi.org/10.21079/11681/34083>.
- Early, Regan, Bethany A. Bradley, Jeffrey S. Dukes, Joshua J. Lawler, Julian D. Olden, Dana M. Blumenthal, Patrick Gonzalez, et al. 2016. "Global Threats from Invasive Alien Species in the Twenty-First Century and National Response Capacities." *Nature Communications* 7 (1). <https://doi.org/10.1038/ncomms12485>.

- Epps, Clinton W., John D. Wehausen, Vernon C. Bleich, Steven G. Torres, and Justin S. Brashares. 2007. "Optimizing Dispersal and Corridor Models Using Landscape Genetics." *Journal of Applied Ecology* 44 (4): 714–24. <https://doi.org/10.1111/j.1365-2664.2007.01325.x>.
- Farhadi, Nafiseh, Scott A. Parr, Kenneth N. Mitchell, and Brian Wolshon. 2016. "Use of Nationwide Automatic Identification System Data to Quantify Resiliency of Marine Transportation Systems." *Transportation Research Record: Journal of the Transportation Research Board* 2549 (1): 9–18. <https://doi.org/10.3141/2549-02>.
- Ferrario, Jasmine, Agnese Marchini, Paola Borrelli, Francesca Gigli Berzolari, and Anna Occhipinti-Ambrogi. 2016. "A Fuzzy 'Boater' Model to Detect Fouling and Spreading Risk of Non-indigenous Species by Recreational Boats." *Journal of Environmental Management* 182 (November): 198–207. <https://doi.org/10.1016/j.jenvman.2016.07.029>.
- Floerl, O., G. J. Inglis, K. Dey, and A. Smith. 2009. "The Importance of Transport Hubs in Stepping-Stone Invasions." *Journal of Applied Ecology* 46 (1): 37–45. <https://doi.org/10.1111/j.1365-2664.2008.01540.x>.
- Goldsmid, Jesica, Philippe Archambault, Guillem Chust, Ernesto Villarino, George Liu, Jennifer V. Lukovich, David G. Barber, and Kimberly L. Howland. 2017. "Projecting Present and Future Habitat Suitability of Ship-Mediated Aquatic Invasive Species in the Canadian Arctic." *Biological Invasions* 20 (2): 501–17. <https://doi.org/10.1007/s10530-017-1553-7>.
- Herborg, Leif-Matthias, Patrick O'Hara, and Thomas W. Therriault. 2009. "Forecasting the Potential Distribution of the Invasive Tunicate *Didemnum vexillum*." *Journal of Applied Ecology* 46 (1): 64–72. <https://doi.org/10.1111/j.1365-2664.2008.01568.x>.
- Hertzog, Lionel R., Aurélien Besnard, and Pierre Jay-Robert. 2014. "Field Validation Shows Bias-Corrected Pseudo-Absence Selection Is the Best Method for Predictive Species-Distribution Modelling." Edited by David M. Richardson. *Diversity and Distributions* 20 (12): 1403–13. <https://doi.org/10.1111/ddi.12249>.
- Hulme, Philip E. 2009. "Trade, Transport and Trouble: Managing Invasive Species Pathways in an Era of Globalization." *Journal of Applied Ecology* 46 (1): 10–18. <https://doi.org/10.1111/j.1365-2664.2008.01600.x>.
- Iacarella, Josephine C., Lily Burke, Ian C. Davidson, Claudio DiBacco, Thomas W. Therriault, and Anya Dunham. 2020. "Unwanted Networks: Vessel Traffic Heightens the Risk of Invasions in Marine Protected Areas." *Biological Conservation* 245 (May): 108553. <https://doi.org/10.1016/j.biocon.2020.108553>.
- IALA (International Association of Marine Aids to Navigation and Lighthouse Authorities). 2008. *The Establishment of Ais as an Aid to Navigation*. G1062. Version 1.1, July 2022. Saint Germain en Laye, France: International Association of Marine Aids to Navigation and Lighthouse Authorities. <https://www.iala-aism.org/product/establishment-of-ais-as-an-aid-to-navigation-1062/>.

- IEC (International Electrotechnical Commission). 2018. *Maritime Navigation and Radiocommunication Equipment and Systems - Automatic Identification Systems (AIS) - Part 2: Class A Shipborne Equipment of the Automatic Identification System (AIS) - Operational and Performance Requirements, Methods of Test and Required Test Results*. IEC 61993-2:2018. 3rd ed. Geneva, Switzerland: International Electrotechnical Commission. <https://webstore.iec.ch/publication/34277>.
- ITU (International Telecommunications Union). 2014. *Technical Characteristics for an Automatic Identification System Using Time Division Multiple Access in the VHF Maritime Mobile Frequency Band*. Recommendation M.1371. 18 February 2014. Geneva, Switzerland: International Telecommunications Union. <https://www.itu.int/rec/R-REC-M.1371/en>.
- Kaluza, Pablo, Andrea Kölzsch, Michael T. Gastner, and Bernd Blasius. 2010. "The Complex Network of Global Cargo Ship Movements." *Journal of The Royal Society Interface* 7 (48): 1093–1103. <https://doi.org/10.1098/rsif.2009.0495>.
- Keller, Reuben P., John M. Drake, Mark B. Drew, and David M. Lodge. 2010. "Linking Environmental Conditions and Ship Movements to Estimate Invasive Species Transport across the Global Shipping Network." *Diversity and Distributions* 17 (1): 93–102. <https://doi.org/10.1111/j.1472-4642.2010.00696.x>.
- Kelly, Noreen E., Kristina Wantola, Erika Weisz, and Norman D. Yan. 2012. "Recreational Boats as a Vector of Secondary Spread for Aquatic Invasive Species and Native Crustacean Zooplankton." *Biological Invasions* 15 (3): 509–19. <https://doi.org/10.1007/s10530-012-0303-0>.
- Kress, Marin, Brian Tetreault, Kenneth Mitchell, Matthew Balazik, and Michael Booton. 2020. *AIS Data Real-Time Operation Support, Incident Investigations, and Waterway Use Analysis*. ERDC/CHL CHETN-IX-53. Vicksburg, MS: US Army Engineer Research and Development Center–Coastal and Hydraulics Laboratory. <https://doi.org/10.21079/11681/36395>.
- Kress, Marin M., David L. Young, Katherine F. Chambers, and Brandan M. Scully. 2021. *AIS Data Case Study: Quantifying Connectivity for Six Great Lakes Port Areas from 2015 through 2018*. ERDC/CHL CHETN-IX-56. Vicksburg, MS: US Army Engineer Research and Development Center–Coastal and Hydraulics Laboratory. <https://dx.doi.org/10.21079/11681/40720>.
- Lacoursière-Roussel, Anaïs, Dan G. Bock, Melania E. Cristescu, Frédéric Guichard, and Christopher W. McKindsey. 2016. "Effect of Shipping Traffic on Biofouling Invasion Success at Population and Community Levels." *Biological Invasions* 18 (12): 3681–95. <https://doi.org/10.1007/s10530-016-1258-3>.
- Leidenberger, Sonja, Matthias Obst, Robert Kulawik, Kerstin Stelzer, Karin Heyer, Alex Hardisty, and Sarah J. Bourlat. 2015. "Evaluating the Potential of Ecological Niche Modelling as a Component in Marine Non-indigenous Species Risk Assessments." *Marine Pollution Bulletin* 97 (1–2): 470–87. <https://doi.org/10.1016/j.marpolbul.2015.04.033>.

- Martínez-Laiz, G., A. Ulman, M. Ros, and A. Marchini. 2019. "Is Recreational Boating a Potential Vector for Non-indigenous Peracarid Crustaceans in the Mediterranean Sea? A Combined Biological and Social Approach." *Marine Pollution Bulletin* 140 (March): 403–15. <https://doi.org/10.1016/j.marpolbul.2019.01.050>.
- Mellin, C., M. Lurgi, S. Matthews, M.A. MacNeil, M.J. Caley, N. Bax, R. Przeslawski, and D.A. Fordham. 2016. "Forecasting Marine Invasions under Climate Change: Biotic Interactions and Demographic Processes Matter." *Biological Conservation* 204 (December): 459–67. <https://doi.org/10.1016/j.biocon.2016.11.008>.
- Mineur, Frédéric, Mark P. Johnson, Christine A. Maggs, and Herre Stegenga. 2006. "Hull Fouling on Commercial Ships as a Vector of Macroalgal Introduction." *Marine Biology* 151 (4): 1299–1307. <https://doi.org/10.1007/s00227-006-0567-y>.
- Mitchell, Kenneth N., and Brandan Scully. 2014. "Waterway Performance Monitoring with Automatic Identification System Data." *Transportation Research Record: Journal of the Transportation Research Board* 2426 (1): 20–26. <https://doi.org/10.3141/2426-03>.
- Molnar, Jennifer L, Rebecca L Gamboa, Carmen Revenga, and Mark D Spalding. 2008. "Assessing the Global Threat of Invasive Species to Marine Biodiversity." *Frontiers in Ecology and the Environment* 6 (9): 485–92. <https://doi.org/10.1890/070064>.
- Montes, Nancy, Robert Swett, and Robert Ahrens. 2018. "Modeling the Spatial and Seasonal Distribution of Offshore Recreational Vessels in the Southeast United States." Edited by Athanassios C. Tsikliras. *PLOS ONE* 13 (11): e0208126. <https://doi.org/10.1371/journal.pone.0208126>.
- Moore, Andrea, Ben Lowen, and Claudio DiBacco. 2018. "Assessing Invasion Risk of *Didemnum vexillum* to Atlantic Canada." *Management of Biological Invasions* 9 (1): 11–25. <https://doi.org/10.3391/mbi.2018.9.1.02>.
- NOAA (National Oceanic and Atmospheric Administration). 2023. "About: MarineCadastre.gov." <https://marinecadastre.gov/about/>.
- Paini, Dean R., and Denys Yemshanov. 2012. "Modelling the Arrival of Invasive Organisms via the International Marine Shipping Network: A Khapra Beetle Study." Edited by Carlos Garcia de Leaniz. *PLOS ONE* 7 (9): e44589. <https://doi.org/10.1371/journal.pone.0044589>.
- Peters, Koebraa, Kerry J. Sink, and Tamara B. Robinson. 2019. "Sampling Methods and Approaches to Inform Standardized Detection of Marine Alien Fouling Species on Recreational Vessels." *Journal of Environmental Management* 230 (January): 159–67. <https://doi.org/10.1016/j.jenvman.2018.09.063>.
- PIANC (The World Association for Waterborne Transport Infrastructure). 2019. *Guidelines and Recommendations for River Information Services*. InCom PWG 125/I-2019. Brussels, Belgium: PIANC General Secretariat. <https://www.pianc.org/publication/guidelines-and-recommendations-for-river-information-services/>.

- Pimentel, David, Lori Lach, Rodolfo Zuniga, and Doug Morrison. 2000. "Environmental and Economic Costs of Nonindigenous Species in the United States." *BioScience* 50 (1): 53. [https://doi.org/10.1641/0006-3568\(2000\)050\[0053:eaecon\]2.3.co;2](https://doi.org/10.1641/0006-3568(2000)050[0053:eaecon]2.3.co;2).
- Robards, MD, GK Silber, JD Adams, J Arroyo, D Lorenzini, K Schwehr, and J Amos. 2016. "Conservation Science and Policy Applications of the Marine Vessel Automatic Identification System (AIS)—A Review." *Bulletin of Marine Science* 92 (1): 75–103. <https://doi.org/10.5343/bms.2015.1034>.
- Saebi, Mandana, Jian Xu, Erin K. Grey, David M. Lodge, and Nitesh Chawla. 2019. "Higher-Order Patterns of Aquatic Species Spread through the Global Shipping Network," July. <https://doi.org/10.1101/704684>.
- Sardain, Anthony, Erik Sardain, and Brian Leung. 2019. "Global Forecasts of Shipping Traffic and Biological Invasions to 2050." *Nature Sustainability* 2 (4): 274–82. <https://doi.org/10.1038/s41893-019-0245-y>.
- Scully, B.M., and K.F. Chambers, 2019. "Measuring Port Disruptions with Automatic Identification System Data." In *Ports 2019: Port Planning and Development*. Reston, VA: American Society of Civil Engineers. <https://doi.org/10.1061/9780784482629.030>.
- Seebens, H., M. T. Gastner, and B. Blasius. 2013. "The Risk of Marine Bioinvasion Caused by Global Shipping." Edited by Franck Courchamp. *Ecology Letters* 16 (6): 782–90. <https://doi.org/10.1111/ele.12111>.
- Seebens, Hanno, Nicole Schwartz, Peter J. Schupp, and Bernd Blasius. 2016. "Predicting the Spread of Marine Species Introduced by Global Shipping." *Proceedings of the National Academy of Sciences* 113 (20): 5646–51. <https://doi.org/10.1073/pnas.1524427113>.
- Sieracki, Jennifer L., Jonathan M. Bossenbroek, and W. Lindsay Chadderton. 2014. "A Spatial Modeling Approach to Predicting the Secondary Spread of Invasive Species Due to Ballast Water Discharge." Edited by Christopher W. McKindsey. *PLOS ONE* 9 (12): e114217. <https://doi.org/10.1371/journal.pone.0114217>.
- Sieracki, Jennifer L., Jonathan M. Bossenbroek, and Mohamed Faisal. 2013. "Modeling the Secondary Spread of Viral Hemorrhagic Septicemia Virus (VHSV) by Commercial Shipping in the Laurentian Great Lakes." *Biological Invasions* 16 (5): 1043–53. <https://doi.org/10.1007/s10530-013-0556-2>.
- Sylvester, Francisco, Odion Kalaci, Brian Leung, Anaïs Lacoursière-Roussel, Cathryn Clarke Murray, Francis M. Choi, Monica A. Bravo, Thomas W. Therriault, and Hugh J. MacIsaac. 2011. "Hull Fouling as an Invasion Vector: Can Simple Models Explain a Complex Problem?" *Journal of Applied Ecology* 48 (2): 415–23. <https://doi.org/10.1111/j.1365-2664.2011.01957.x>.

- Tabbert, Cory R., John C. Vest, and Marin M. Kress. 2021. "Waterway Engineering Applications of Automatic Identification System Data along the Mississippi River and at Lock Structures." *Journal of Waterway, Port, Coastal, and Ocean Engineering* 147 (5). [https://doi.org/10.1061/\(asce\)ww.1943-5460.0000658](https://doi.org/10.1061/(asce)ww.1943-5460.0000658).
- Tidbury, Hannah J., Nick G. H. Taylor, Gordon H. Copp, Eva Garnacho, and Paul D. Stebbing. 2016. "Predicting and Mapping the Risk of Introduction of Marine Non-indigenous Species into Great Britain and Ireland." *Biological Invasions* 18 (11): 3277–92. <https://doi.org/10.1007/s10530-016-1219-x>.
- Touzinsky, Katherine F., Brandon M. Scully, Kenneth N. Mitchell, and Marin M. Kress. 2018. "Using Empirical Data to Quantify Port Resilience: Hurricane Matthew and the Southeastern Seaboard." *Journal of Waterway, Port, Coastal, and Ocean Engineering* 144 (4). [https://doi.org/10.1061/\(asce\)ww.1943-5460.0000446](https://doi.org/10.1061/(asce)ww.1943-5460.0000446).
- Turbelin, Anna J., Bruce D. Malamud, and Robert A. Francis. 2016. "Mapping the Global State of Invasive Alien Species: Patterns of Invasion and Policy Responses." *Global Ecology and Biogeography* 26 (1): 78–92. <https://doi.org/10.1111/geb.12517>.
- Ulman, Aylin, Jasmine Ferrario, Aitor Forcada, Hanno Seebens, Christos Arvanitidis, Anna Occhipinti-Ambrogi, and Agnese Marchini. 2019. "Alien Species Spreading via Biofouling on Recreational Vessels in the Mediterranean Sea." Edited by Nessa O'Connor. *Journal of Applied Ecology* 56 (12): 2620–29. <https://doi.org/10.1111/1365-2664.13502>.
- USACE (US Army Corps of Engineers). 2022. "Aquatic Nuisance Species Research Program – ANSRP." <https://www.erd.c.usace.army.mil/Missions/Civil-Works/Aquatic-Nuisance-Species-Research-Program/>.
- USCG (US Coast Guard). [2018?]. "Acquisition Directorate: Nationwide Automatic Identification System." <https://www.dcms.uscg.mil/Our-Organization/Assistant-Commandant-for-Acquisitions-CG-9/Programs/C4ISR-Programs/NAIS/>.
- USCG (US Coast Guard). [2023?]. "Navigation Center." <https://www.navcen.uscg.gov/?pageName=AISmain>.
- USFWS (US Fish and Wildlife Service). 2023. "Aquatic Nuisance Species Task Force News and Announcements." <https://www.fws.gov/library/collections/aquatic-nuisance-species-task-force-news-and-announcements>.
- Ware, Chris, Jørgen Berge, Jan H. Sundet, Jamie B. Kirkpatrick, Ashley D. M. Coutts, Anders Jelmert, Steffen M. Olsen, Oliver Floerl, Mary S. Wisz, and Inger G. Alsos. 2013. "Climate Change, Non-indigenous Species and Shipping: Assessing the Risk of Species Introduction to a High-Arctic Archipelago." Edited by Hugh MacIsaac. *Diversity and Distributions* 20 (1): 10–19. <https://doi.org/10.1111/ddi.12117>.

- Williams, S.L., I.C. Davidson, J.R. Pasari, G.V. Ashton, J.T. Carlton, R.E. Crafton, R.E. Fontana, E.D. Grosholz, A.W. Miller, G.M. Ruiz, and C.J. Zabin. 2013. "Managing Multiple Vectors for Marine Invasions in an Increasingly Connected World." 2013. *BioScience* 63 (12): 952–66. <https://doi.org/10.1525/bio.2013.63.12.8>.
- Young, David L., and Brandan M. Scully. 2018. "Assessing Structure Sheltering via Statistical Analysis of AIS Data." *Journal of Waterway, Port, Coastal, and Ocean Engineering* 144 (3). [https://doi.org/10.1061/\(asce\)ww.1943-5460.0000445](https://doi.org/10.1061/(asce)ww.1943-5460.0000445).

## REPORT DOCUMENTATION PAGE

<b>1. REPORT DATE</b> October 2023		<b>2. REPORT TYPE</b> Final Special Report (SR)		<b>3. DATES COVERED</b>	
				<b>START DATE</b> FY19	<b>END DATE</b> FY22
<b>4. TITLE AND SUBTITLE</b> Marine Bioinvasion Risk: Review of Current Ecological Models					
<b>5a. CONTRACT NUMBER</b>		<b>5b. GRANT NUMBER</b>		<b>5c. PROGRAM ELEMENT</b>	
<b>5d. PROJECT NUMBER</b>		<b>5e. TASK NUMBER</b>		<b>5f. WORK UNIT NUMBER</b>	
<b>6. AUTHOR(S)</b> Safra Altman, Krystyna T. Powell, and Marin M. Kress					
<b>7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)</b> See reverse.				<b>8. PERFORMING ORGANIZATION REPORT NUMBER</b> ERDC SR-23-10	
<b>9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)</b> US Army Engineer Research and Development Center Environmental Laboratory 3909 Halls Ferry Road Vicksburg, MS 39180-6199				<b>10. SPONSOR/MONITOR'S ACRONYM(S)</b>	<b>11. SPONSOR/MONITOR'S REPORT NUMBER(S)</b>
<b>12. DISTRIBUTION/AVAILABILITY STATEMENT</b> Distribution Statement A. Approved for public release: distribution is unlimited.					
<b>13. SUPPLEMENTARY NOTES</b> Aquatic Nuisance Species Research Program Project "Modeling Marine Bioinvasion Risk using Automated Information System (AIS)"; Civil Direct—Funding Account Code U4372082, AMSCO Code 008284.					
<b>14. ABSTRACT</b> This special report describes the first phase of developing an ecological model to inform marine bioinvasion risks in the United States. The project responds to the needs of the US Army Corps of Engineers (USACE) Aquatic Nuisance Species Research Program, or ANSRP, which addresses all problematic invasive aquatic species affecting the nation's waterways, infrastructure, and associated resources, and the needs of the USACE navigation and dredging programs. Multiple port-deepening studies are either in progress or under consideration, and all must address ecological risk. Understanding whether and how increased dredging contributes to increased marine bioinvasion risk allows risk mitigation during early planning phases. Considering the potential impacts of future environmental change, such as changing sea level, ocean temperature, and ocean chemistry, will further strengthen planning for marine bioinvasion risk. Therefore, this special report documents current ecological modeling approaches to marine bioinvasion risk models and identifies models that incorporate shipping as a vector. The special report then presents a conceptual model and identifies historic vessel position data from the Automatic Identification System, or AIS, now available for most commercial and some recreational vessels around the United States, as a key source for future model development and testing.					
<b>15. SUBJECT TERMS</b> Dredging--Environmental aspects; Harbors; Introduced aquatic organisms; Marine biological invasions--Risk assessment; Ships--Automatic identification systems; Waterways					
<b>16. SECURITY CLASSIFICATION OF:</b>				<b>17. LIMITATION OF ABSTRACT</b> SAR	<b>18. NUMBER OF PAGES</b> 38
<b>a. REPORT</b> Unclassified	<b>b. ABSTRACT</b> Unclassified	<b>c. THIS PAGE</b> Unclassified			
<b>19a. NAME OF RESPONSIBLE PERSON</b> Safra Altman				<b>19b. TELEPHONE NUMBER (include area code)</b> (601) 634-3435	

**7. PERFORMING ORGANIZATION NAMES AND ADDRESSES (concluded)**

US Army Engineer Research and Development Center (ERDC)  
Environmental Laboratory (EL)  
3909 Halls Ferry Road  
Vicksburg, MS 39180-6199

US Army Engineer Research and Development Center (ERDC)  
Coastal and Hydraulics Laboratory (CHL)  
3909 Halls Ferry Road  
Vicksburg, MS 39180-6199