ERDC/CHL SR-23-1

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US Port Connectivity and Ramifications for Maintenance of South Atlantic Division Ports

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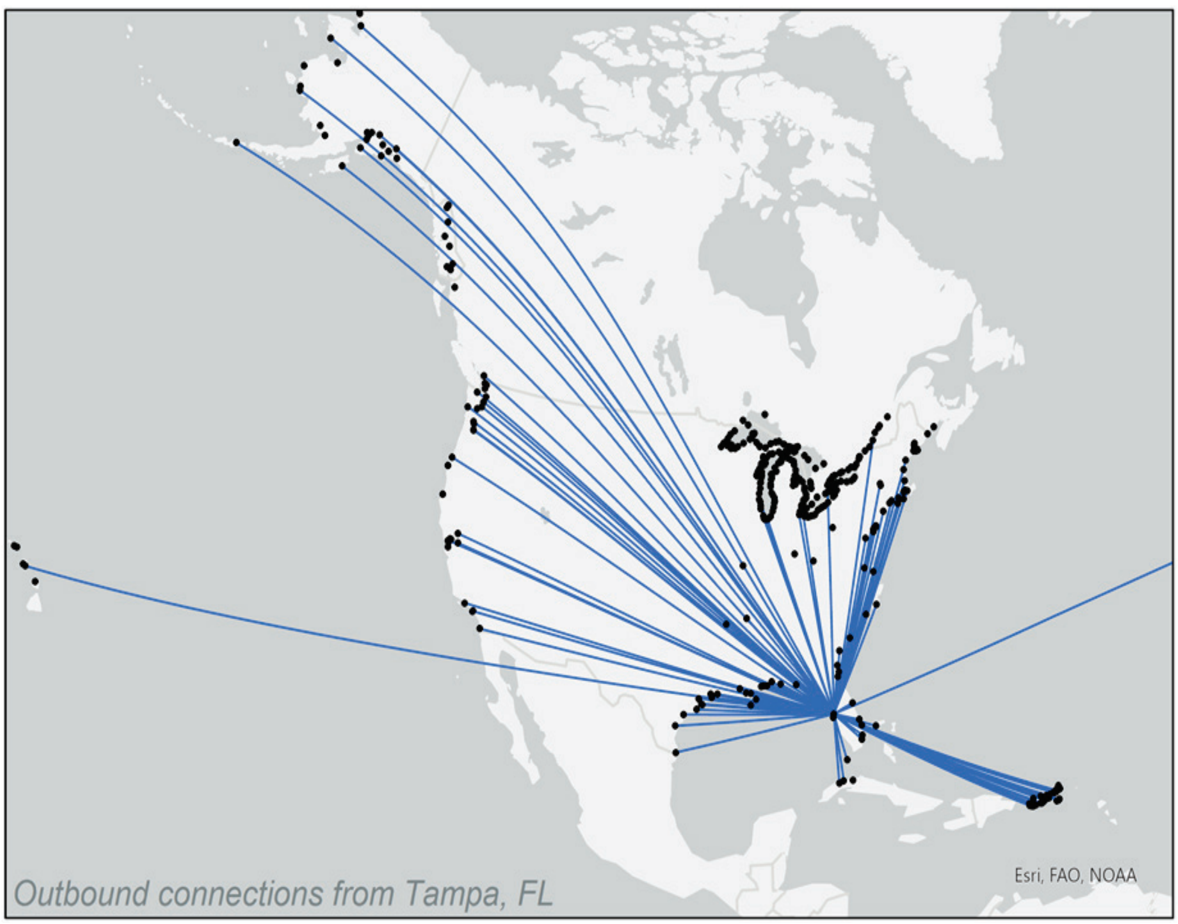
January 2023



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Special Report (SR)

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Under Scope of Work, “Port Connectivity and Underkeel Clearance for South Atlantic Division Ports,” funded via Labor Charge Code.

Abstract

This study utilized automatic identification system (AIS) data to quantify vessel traffic patterns within a predominantly US port network from 1 January 2009 to 31 December 2020, with the methods validated using independent data sets collected between 1 January 2015 and 31 December 2019. The analysis focused on South Atlantic Division (SAD) ports. AIS-derived data characterized individual ports' traffic and port-to-port connectivity for the network. With foreign vessel entrances and clearances (E&C) data, the AIS-reported vessel characteristics enabled calculation of ships' physical volume, which was a reasonable proxy for tonnage at many SAD ports. The PageRank algorithm was then applied to port-to-port traffic, revealing how individual ports participate in cargo movement through the network. PageRank scores also provided insight into the maritime supply chain beyond traditional traffic metrics. For example, many East Coast SAD ports ranked higher by PageRank than by raw tonnage. Because of the supply chain implications of shared vessel traffic, PageRank scores can augment tonnage metrics when prioritizing channel and infrastructure maintenance. Vessel volume, port-to-port connectivity, and PageRank scores reveal maritime supply chain resilience by identifying alternative destinations for cargo bound for disrupted ports, robustness across supply chains, and the effects of seasonality and disruptions.

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Preface

This study was conducted for the USACE Jacksonville District (CESAJ) under the scope of work for “Port Connectivity Underkeel Clearance for South Atlantic Division,” funded via Labor Charge Code. The technical monitor was Mr. Matthew P. Davies.

The work was performed by the Coastal Observation and Analysis Branch of the Flood and Storm Protection Division and the Coastal Engineering and Navigation Branches of the Navigation Division, US Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory (ERDC-CHL). At the time of publication of this ERDC-CHL special report, Ms. Erin Diurba was chief, Coastal Analysis and Observation Branch; Ms. Lauren Dunkin was chief, Coastal Engineering Branch; Mr. Benjamin Burnham was chief, Navigation Branch; Dr. Cary Talbot was chief, Flood and Storm Protection Division; Ms. Ashley Frey was chief, Navigation Division; Mr. Charles E. Wiggins, CHL Technical Programs Office, was the ERDC technical director for Navigation. The deputy director of ERDC-CHL was Mr. Keith Flowers, and the director was Dr. Ty V. Wamsley.

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

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1 Introduction

1.1 Background

The US maritime transportation system (MTS) is an integral part of the national supply chain. The MTS is responsible for over 90% of US imports and exports and supports more than $4.6 trillion in economic activity every year (USCG 2018). Because of its importance, the owners, operators, and regulators of the MTS are tasked with ensuring that it is reliable and efficient. The US Army Corps of Engineers (USACE) spends approximately $1 billion annually, primarily on dredging, to maintain constructed waterways that connect open oceans to marine terminals with design depths greater than 15 feet. The MTS is vulnerable to a range of environmental and nonenvironmental disruptions. These vulnerabilities are expected to be exacerbated as climate extremes worsen, demand grows, and technology advances (PIANC 2020). In tandem with the increasing vulnerability of the MTS, the need to maintain navigation channels and infrastructure continues to grow. As ports and connecting waterways have gotten deeper and wider to accommodate larger vessels, associated maintenance costs have increased (IWR 2017).

In an environment of constrained maintenance funding, it is critical to ensure good stewardship of USACE dredging dollars. Historically, USACE prioritized the selection of maintenance projects, including their timing and dredging depth, based on the total tonnage of the port(s) served by each waterway using a risk-based approach described in annual budget guidance (USACE 2020). Modern data sources allow for a thorough examination of the contribution of each channel reach to nationwide commerce, the degree to which transiting vessels are most exposed to risk from minimal clearance or keel strikes, and the reaches in which vessels are taking full advantage of the depth provided by USACE dredging (i.e., measurements of observed channel usage).

The maturation of the vessel automatic identification system (AIS) has resulted in a spatiotemporal record of vessels transiting US waterways. AIS data enable mapping of the shipping routes used by AIS-carrying vessels while in US waters, thus describing the port network transited by US vessel traffic. USACE researchers have demonstrated that this data source is useful for monitoring waterway activity (Scully and Mitchell 2017; Young and Scully 2018; Scully et al. 2020) and can be combined with vessel draft information (IWR n.d.) to generate other useful metrics, such as the volume of arriving vessels. The AIS-based spatiotemporal record of vessel sizes and transits can augment traditional tonnage metrics by identifying the criticality of a given port to regional or nationwide commerce. Understanding the connectivity of the port network based on observed traffic patterns is key to grasping how its structure affects overall resilience and to determining the criticality of individual ports to network-wide traffic flow (Scully and Chambers 2019).

Metrics describing how central ports are to traffic flow across a network are referred to as *centrality* metrics; one of the more advanced centrality metrics is the PageRank algorithm (Page et al. 1999). In the context of port maintenance, PageRank may be used along with tonnage to identify ports that are not only commercially critical but, due to their position in the network, would have an outsized impact on regional or nationwide commerce if they were to be disrupted (Young et al. 2022). The present study proposes that the PageRank score could augment the traditional cargo tonnage utilized for dredge maintenance prioritization of USACE navigation channels in the approach to these critical ports. Using the PageRank score as a supplement to traditional port metrics may be particularly relevant to prioritizing funding at similar-sized ports.

The full description of nationwide commercial vessel traffic provided by this data set has additional benefits for understanding waterborne commerce and improving supply chain resilience. A prior characterization of the US MTS (Young et al. 2022) weighted the network connections based on the raw count of vessels transiting that route, but this method may inflate the importance of routes transited by a large quantity of small vessels. The physical volume of vessels arriving at individual ports is a possible proxy for tonnage at most US ports, and it may provide a useful alternative network weighting that is less likely to under-weight high tonnage routes transited by large commercial vessels.

Calculation of a port’s total vessel volume may also provide insight into vessel transit patterns at higher temporal resolution than traditional tonnage metrics. Because AIS data are sampled at high frequency (i.e., 1-minute intervals for the data in this study), the data set readily lends itself to describing port and port-network activity at monthly, weekly, or daily timescales, whereas tonnage data are available only on yearly timescales. In addition, AIS data are available earlier than the release schedule of official tonnage statistics. This facilitates the calculation of vessel dwell-time (i.e., the time a vessel remains at a port) statistics and can describe the immediate impacts of disruptive events, such as the COVID-19 pandemic, the Notpetya Cyber Attack, and Hurricanes Harvey, Irma, Maria, and Florence, on an individual port or regional traffic flow (Scully and Chambers 2019). Identifying shared vessel traffic among ports also identifies ports that are likely to have the capability, if not necessarily the capacity, to serve as alternative destinations for vessels during potential disruptions at specific ports. For example, such an analysis could have identified possible container port destinations for vessels originally bound for the Los Angeles–Long Beach port area during the 2021 supply chain delays amid the COVID-19 pandemic.

1.2 Objectives

The project described in this report had four primary objectives. The first was to generate an expanded characterization of the US MTS by utilizing AIS data from a much larger set of ports than was analyzed in earlier studies. The second objective was to test the hypothesis that the summed physical volume of ships (i.e., vessel length × draft × beam) visiting a port is a suitable tonnage proxy. Third, the study proposed to develop an algorithm for identifying vessel transits to international ports that lack AIS coverage, thereby improving the overall accuracy of the representation of the MTS network. Finally, the study explored how the PageRank scores of South Atlantic Division (SAD) ports compared to their tonnage rankings, with vessel volume and international transits taken into consideration. The implications of the tonnage versus PageRank-score comparison are discussed in the context of port maintenance decision-making.

1.3 Approach

The study proceeded as follows. First, vessel AIS data sampled at 1-minute intervals were obtained from Marine Cadastre (BOEM and NOAA n.d.) for the period between 1 January 2009 and 31 December 2020. These data were processed to identify vessel arrival and departure times at 385 North American ports, which were primarily in the United States but also included some locations in Canada, the Bahamas, Cuba, and the British Virgin Islands. The arrival and departure times were then used to generate a time series of each AIS-equipped vessel's path through the port network over the 12-year period of record. Sections 3.1 through 3.3 provide a detailed description of this procedure.

Static vessel dimensions (i.e., length L and beam B) were compiled from the transmitted AIS data or the Authoritative Vessel Identification System (AVIS) database (Winkler 2012). The time-varying vessel draft, $D(t)$, was determined from US Customs and Border Protection's entrances and clearances (E&C; IWR n.d.) reports, with the vessel's AIS- or AVIS-reported design draft substituted if E&C draft data were unavailable. Time-varying volume for individual vessels was then calculated as $V(t) = L \times B \times D(t)$, and the cumulative vessel volume for a given port was determined as the summed volumes of all arriving vessels during the period of record. Cumulative volume was then evaluated as a potential proxy for port tonnage by comparing the calculated port volume with reported tonnage values from the USACE Institute for Water Resources (BTS n.d.). This procedure is detailed in Sections 3.5 and 4.1.

An algorithm for identifying vessel transits to international ports lacking AIS coverage was developed for this study. For each pair of consecutive port visits in a vessel's route through the network, the actual transit time was compared to an estimate of the minimum time duration required to transit between those two ports with an intervening stop at an unknown international location. If the AIS-based travel time exceeded this threshold value, then a visit to an abstract *international* node was inserted into the ship's route. The algorithm was validated by comparing the calculated number of foreign arrivals to the known number of foreign arrivals from the E&C reports for 2015 through 2019. For further information, see Sections 3.6 and 4.3.

Finally, the importance of each port to the overall traffic flow across the network was quantified with the PageRank score (Page et al. 1999) for the largest 182 ports in the network. The original 385 ports were filtered to avoid biasing the results by overrepresenting vessel traffic in the Great Lakes. For the PageRank calculations, the links between ports were weighted by the cumulative physical volume of vessels transiting that route. In this manner, routes that were frequently transited by large commercial vessels carried more weight in the network representation than routes primarily used by small, noncommercial vessels. The PageRank results are discussed in the context of various SAD ports; this provides meaningful insight into how the PageRank scores should be interpreted. Details on the PageRank methodology appear in Section 3.7, and the description and interpretation of the results are in Section 4.2.

1.4 Definitions

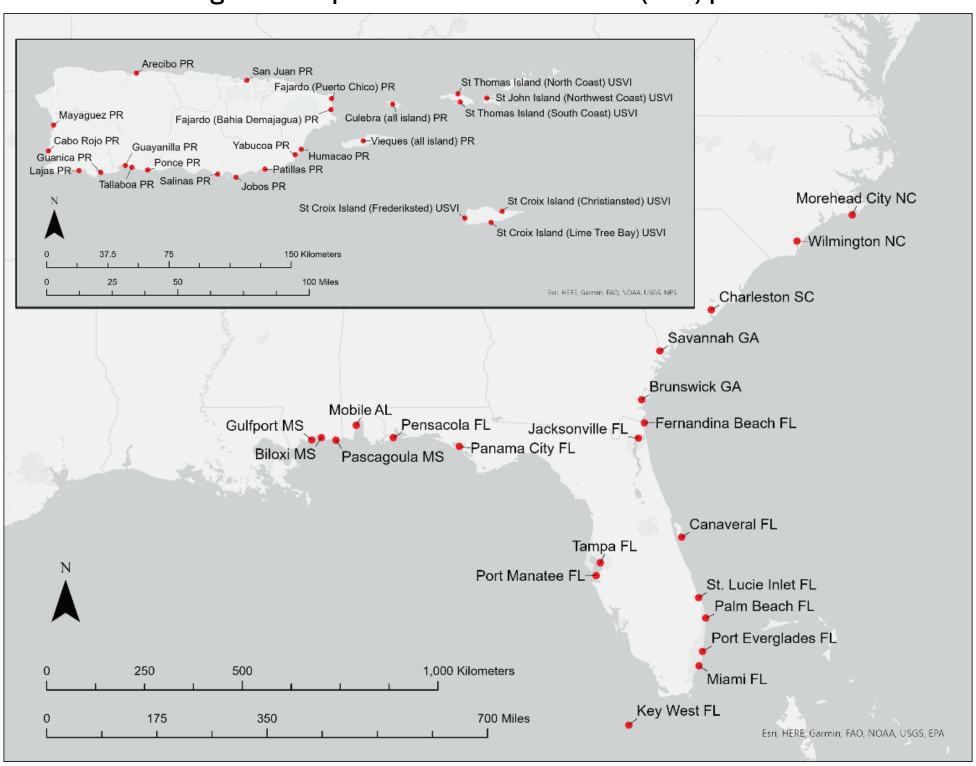
In this work, the following related but distinct terms are used:

- *Port-to-port connectivity/interconnectivity*: the observed quantity of vessel traffic (i.e., schedule and volume of vessels) moving between all ports in the network. This information is derived from AIS data and is used to calculate the PageRank score.
- *PageRank score*: metric describing how important each port is to the overall flow of vessel traffic across the entire country. The metric uses port-to-port connectivity data as an input to quantify the traffic between ports.

2 South Atlantic Division (SAD) High Tonnage Ports

USACE SAD comprises over 150 navigation projects (including ports, channels, and rivers) across coastal and inland areas. However, only 10 are categorized as *high tonnage projects*, meaning they handle 10 million or more short tons of cargo every year. A total of 17 are categorized as *moderate tonnage projects*, meaning they handle 1 to 10 million tons of cargo, and the remainder are classified as *low use projects*. Of the 10 high tonnage projects in SAD, 8 are coastal ports. Figure 1 shows a map of 45 SAD ports of varying size, and a brief description of the eight high tonnage coastal ports is provided in the subsections that follow. These descriptions reflect the traditional metrics for classifying port importance. As demonstrated in Sections 3 and 4, network criticality metrics such as the PageRank score may provide insight into a given port's importance that is not apparent from the tonnage or the type of cargo.

Figure 1. Map of South Atlantic Division (SAD) ports.*

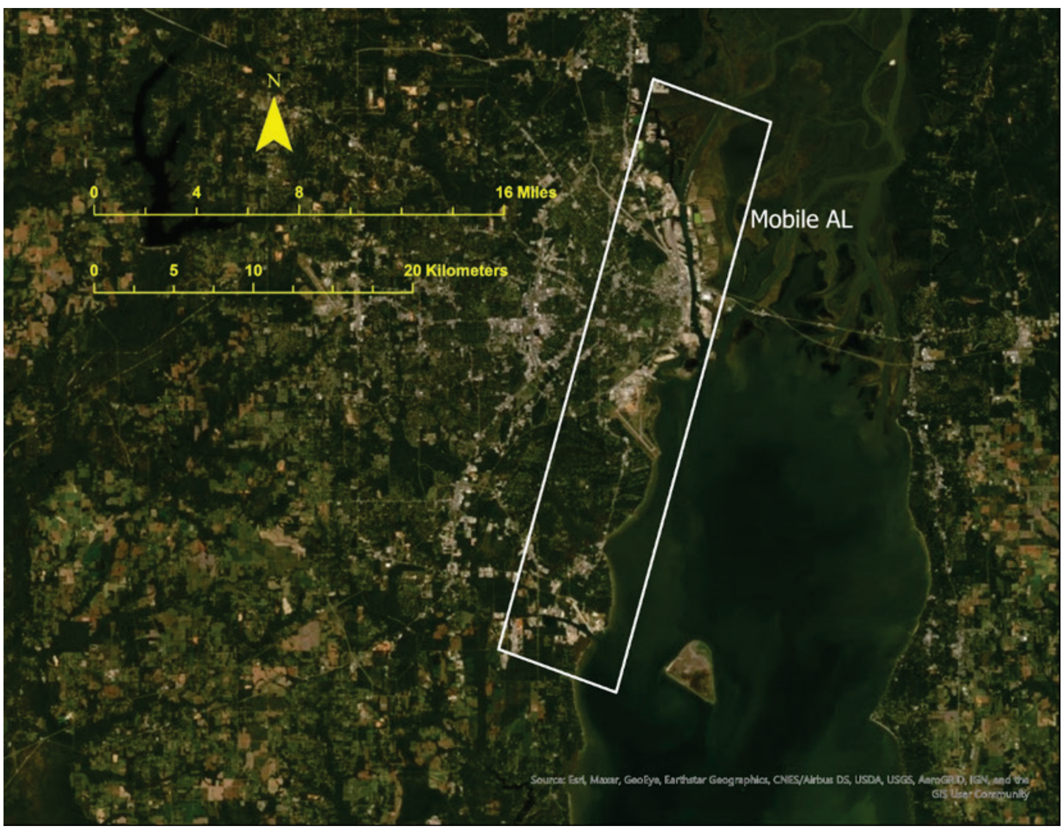


* Maps throughout this report were created using ArcGIS® software by Esri. ArcGIS® and ArcMap™ are the intellectual property of Esri and are used herein under license. For more information about Esri® software, please visit www.esri.com.

2.1 Mobile Harbor, Alabama

The Mobile Harbor navigation project includes the 40-mile-long approach channel across Mobile Bay into the harbor area. In the 2020 fiscal year (FY20), this project handled over 55 million tons of cargo from both deep-draft and shallow-draft vessels. Vessels drafting 45 feet handled over 10 million tons, and vessels drafting 12 feet or less (predominantly liquid barges and dry cargo barges) handled over 19.4 million tons of the cargo that moved into or through Mobile Harbor. In FY20, the largest single commodity type handled was coal (over 15 million tons); this was followed by iron and steel products (over 11 million tons) and crude petroleum (over 9 million tons; WCSC n.d.). Figure 2 shows, outlined in white, the geofenced area of Mobile Harbor included in this AIS-based study.

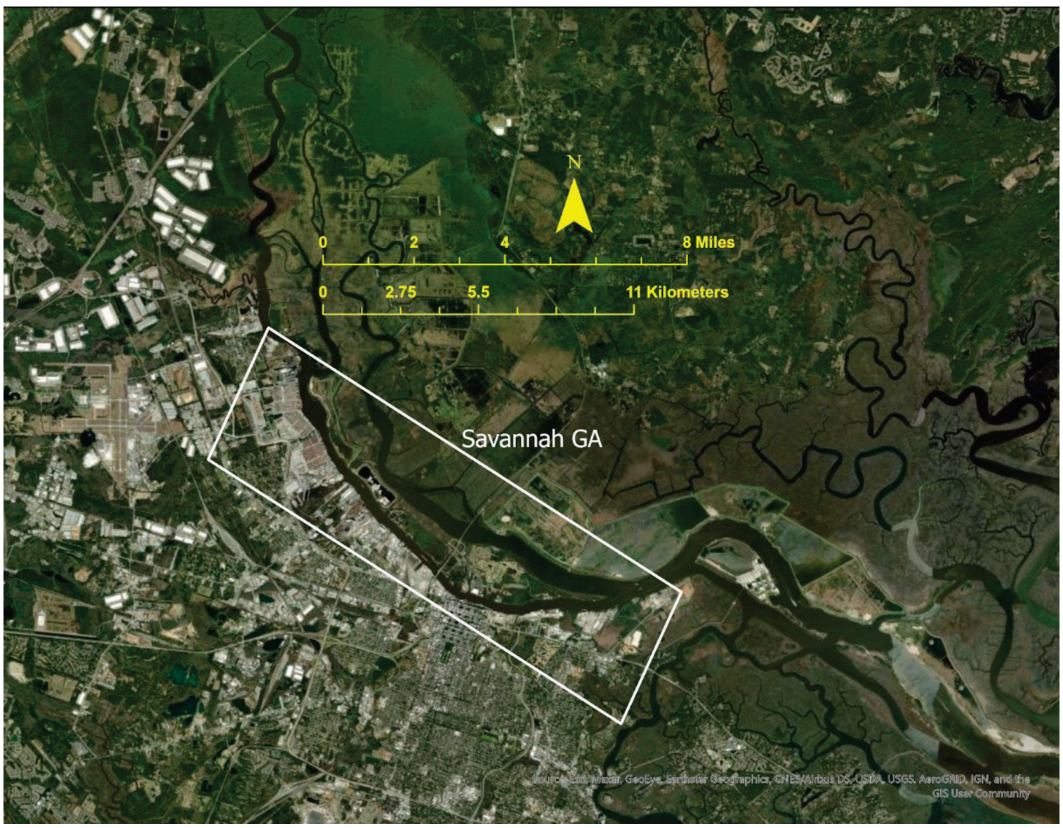
Figure 2. Satellite imagery of Mobile Harbor with boundaries for automatic identification system (AIS)-based port visits outlined in *white*.



2.2 Savannah Harbor, Georgia

Savannah Harbor handles a significant amount of containerized tonnage (over 33 million tons in FY20) and bulk commodities such as chemicals and forest products. Of the more than 42 million tons handled by the port during FY20, the largest single commodity group was manufactured equipment and machinery (over 12 million tons); this was followed by agricultural products (over 4.6 million tons) and chemicals (over 3 million tons; WCSC n.d.). Savannah primarily serves deep-draft oceangoing vessels. The two most frequent types of traffic were related to overseas imports (over 23 million tons) and overseas exports (over 17 million tons), with over 2,000 trips recorded in each category during FY20 (WCSC n.d.). Figure 3 shows the bounding polygon used for identifying ship visits to Savannah Harbor using AIS data.

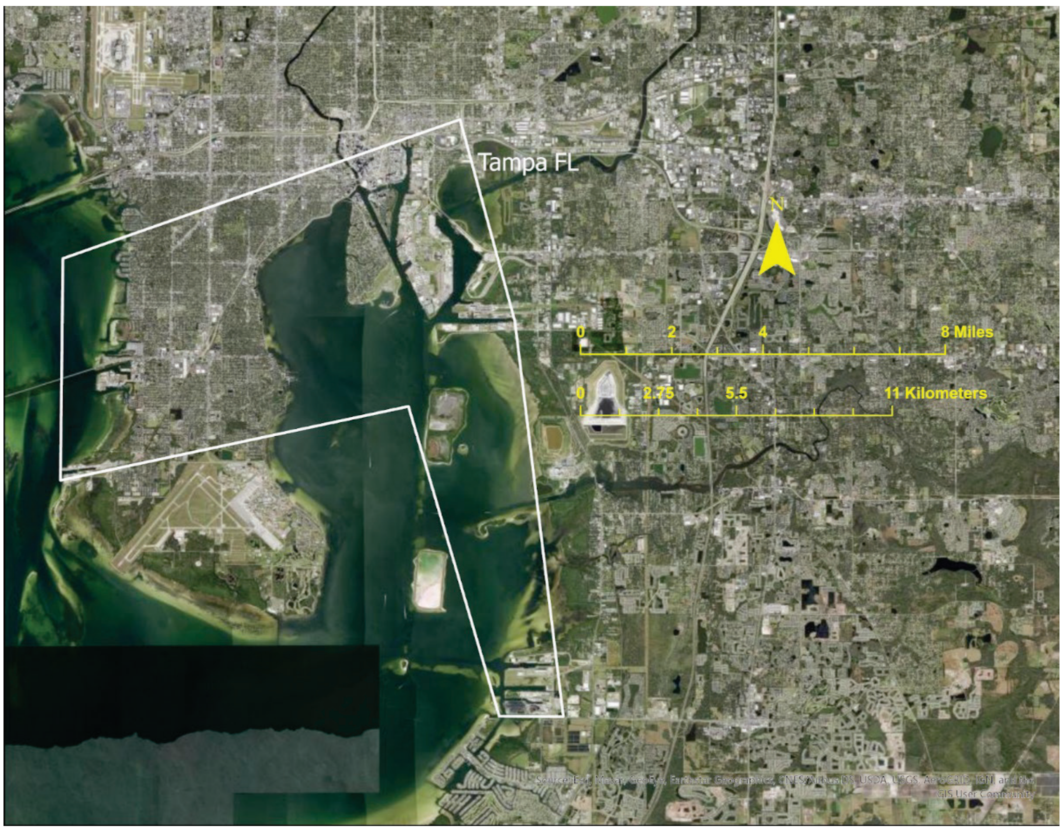
Figure 3. Satellite imagery of Savannah Harbor with boundaries for AIS-based port visits outlined in *white*.



2.3 Tampa Harbor, Florida

Tampa Harbor is a key hub for the receipt of liquid bulk products. In FY20, the harbor handled over 33 million tons of commodities. The largest-tonnage commodity was gasoline (over 11 million tons); this was followed by sand, gravel, stone (over 4.8 million tons) and fertilizers (over 4.4 million tons). Of the commodities that moved through Tampa in FY20, the majority (over 17 million tons) were part of domestic shipments with an origin and destination in the United States, although imports and exports to both overseas and Canadian locations totaled over 15 million tons (WCSC n.d.). Almost 90% of the commercial tonnage that moved through Tampa in FY20 involved vessels drafting over 25 feet. Figure 4 shows the bounding polygon used for Tampa Harbor.

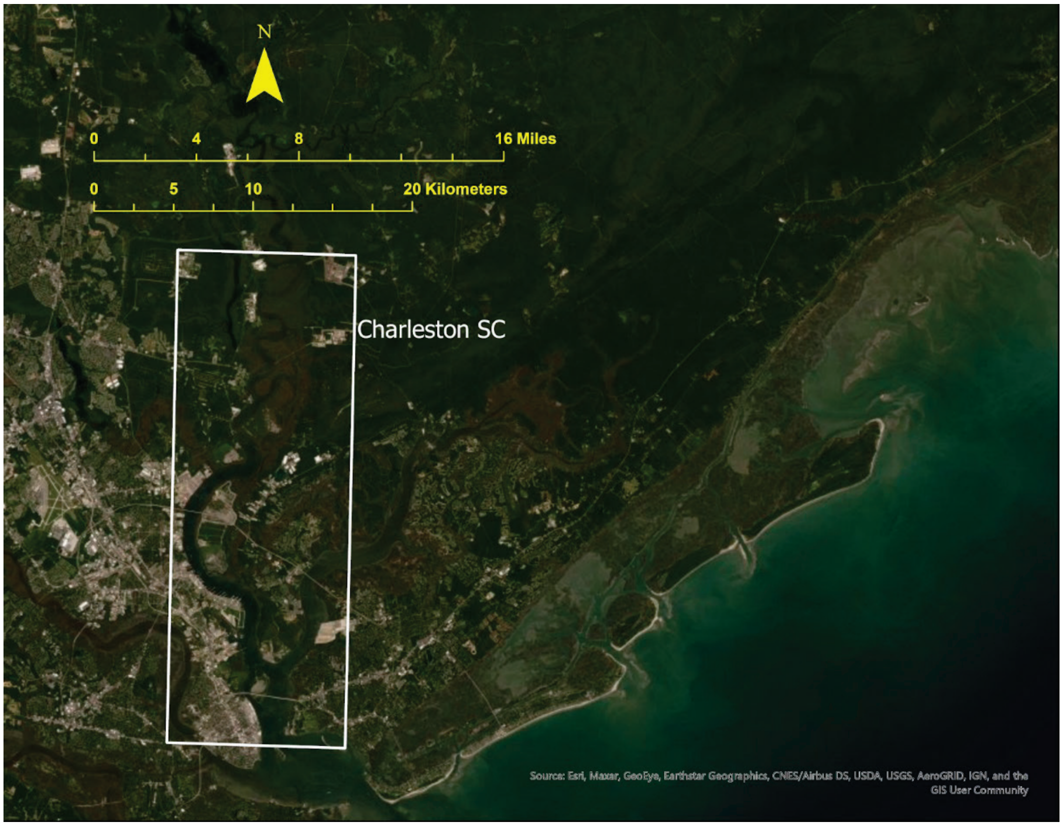
Figure 4. Satellite imagery of Tampa, Florida, with the boundary for AIS-based port visits outlined in *white*.



2.4 Charleston Harbor, South Carolina

Charleston Harbor handled over 24 million tons of commodities in FY20. Of that amount, over 16.7 million tons were in the form of containerized tonnage. The top three commodity types handled by the project were manufactured equipment (over 6.8 million tons), chemicals (over 4.2 million tons), and iron and steel products (over 2.2 million tons). Most of the vessels that moved through Charleston were involved in overseas import or export shipments (over 21 million tons), with a much smaller amount of tonnage resulting from domestic shipments that started and ended within the US (over 1.6 million tons; WCSC n.d.). Figure 5 shows the bounding polygon for Charleston Harbor.

Figure 5. Satellite imagery of Charleston, South Carolina, with the boundary for AIS-based port visits outlined in *white*.



2.5 Pascagoula Harbor, Mississippi

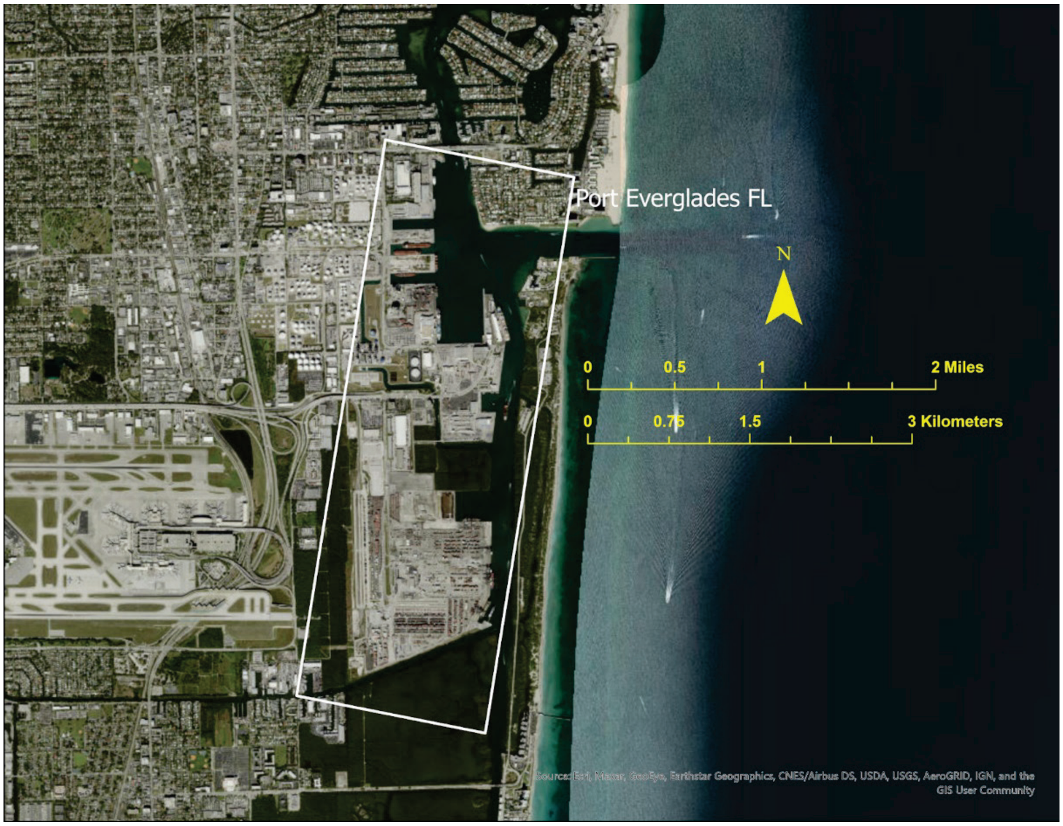
Pascagoula Harbor handled over 23.5 million tons of cargo in FY20, mostly in the form of liquid bulk commodities. The largest three commodity groups handled at Pascagoula were distillates and fuel oils (over 8.5 million tons), gasoline (over 5.9 million tons), and crude petroleum (over 4.4 million tons). Approximately 63% of the tonnage that moved through Pascagoula was from overseas imports and exports (over 14 million tons), with approximately 35% (over 8 million tons) moving along domestic routes. Over 5 million tons of cargo in Pascagoula moved on vessels identified as the liquid barge type. Very little containerized cargo (less than 500,000 tons) was recorded in Pascagoula in FY20 (WCSC n.d.). Figure 6 shows the bounding polygon for Pascagoula Harbor.

Figure 6. Satellite imagery of Pascagoula, Mississippi, with the boundary for AIS-based port visits outlined in *white*.

2.6 Port Everglades Harbor, Florida

Port Everglades handled commodities comparable to those handled in Pascagoula in FY20. Of the 20.7 million tons handled in total, approximately 10 million tons were gasoline, more than 2.8 million tons were distillates and fuel oils, and more than 1.9 million tons were manufactured equipment. The traffic that moved through Port Everglades included numerous trips related to overseas imports and exports, but the largest single traffic category was domestic traffic (over 11 million tons). Almost one-third of the vessel trips in Port Everglades were made by vessels drafting in the 2- to 15-foot range. Of the tonnage that moved through Port Everglades in FY20, over 5.8 million tons were in the form of containerized cargo (WCSC n.d.). Figure 7 shows the bounding polygon used for identifying ship visits to Port Everglades Harbor using AIS data.

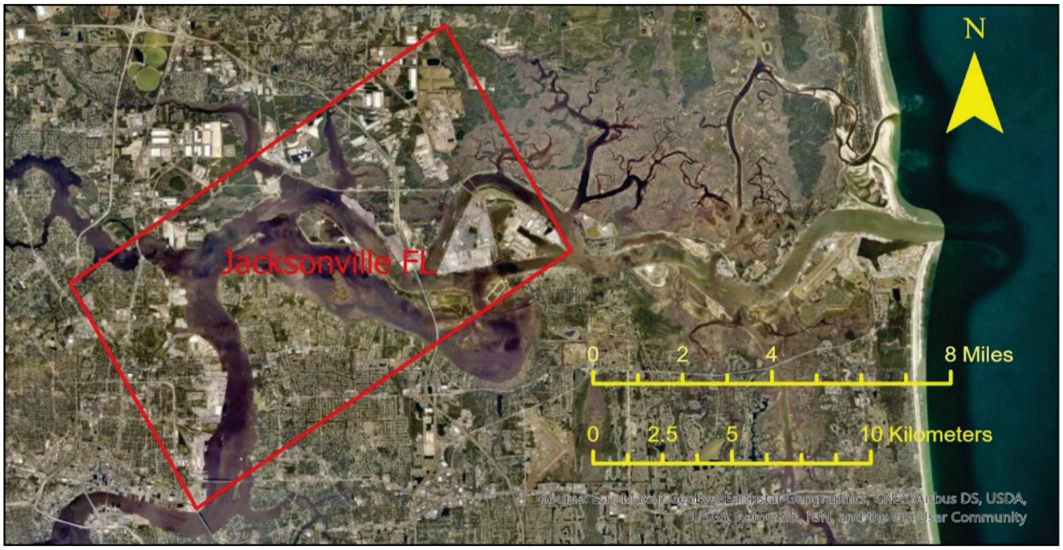
Figure 7. Satellite imagery of Port Everglades, Florida, with the boundary for AIS analysis shown in *white*.



2.7 Jacksonville Harbor, Florida

Jacksonville Harbor handled over 16 million tons of cargo in FY20, with the largest share (7.7 million tons) in the form of coastwise traffic that connected to other US ports; this was followed closely by overseas imports (6.8 million tons). The largest single commodity type was manufactured equipment (over 4 million tons); this was followed by gasoline (2.9 million tons) and sand, gravel, and stone (2.1 million tons). A significant portion of the commodities that moved through Jacksonville were containerized, with over 6.1 million tons of containerized cargo handled in FY20 (WCSC n.d.). Jacksonville is an important mainland supply hub for the port of San Juan, Puerto Rico; the two ports exchanged over 3.6 million tons in FY20 (WCSC n.d.). Figure 8 shows the bounding polygon used for Jacksonville Harbor, Florida.

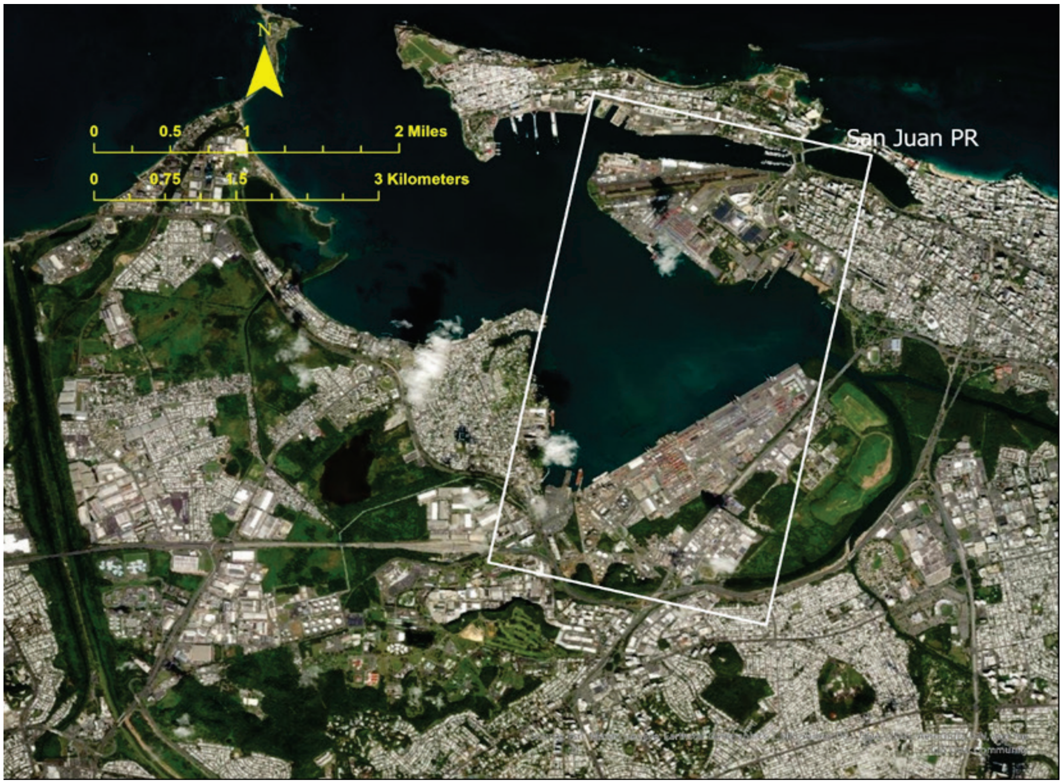
Figure 8. Satellite imagery of Jacksonville, Florida, with the boundary for AIS-based port visits outlined in *red*.



2.8 San Juan Harbor, Puerto Rico

San Juan Harbor handled over 10.9 million tons of cargo in FY20, with the largest commodity type being manufactured equipment (over 2.7 million tons); this was followed by agricultural products (2.1 million tons). The largest share of total tonnage was supplied by overseas imports (5.2 million tons); this was followed closely by coastwise traffic from other US ports (4.5 million tons). Although San Juan can handle ships drafting 40 feet, the most frequent vessel draft was 12 feet. Vessels drafting 12 feet handled 2.3 million tons of coastwise traffic in FY20. Of the total tonnage that moved through San Juan in FY20, over 5.2 million tons were in the form of containerized cargo. Jacksonville Harbor, Florida, is the largest mainland US port partner for shipments to San Juan (WCSC n.d.). Figure 9 shows the bounding polygon used for San Juan Harbor.

Figure 9. Satellite imagery of San Juan, Puerto Rico, with the boundary for AIS-based port visits shown in *white*.



3 Methodology

Tonnage is a traditional and widely used metric for ranking or comparing ports. However, when considering how a port fits into the local or regional supply chain or the role that a port plays in local resilience, newer measures like port-to-port connectivity and PageRank score may be more appropriate. With the widespread availability of multiple years of AIS data, these measures can be calculated in a consistent and meaningful way.

3.1 Automatic identification system (AIS) data

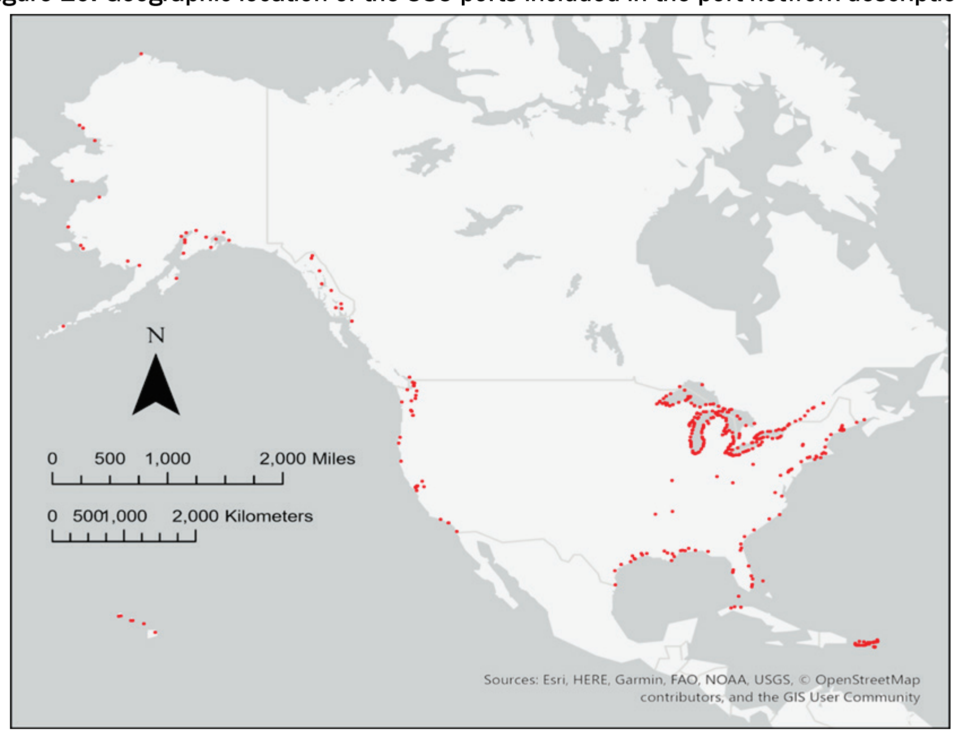
The present study represents an effort to expand upon the port network description supplied by Young et al. (2022); the current methodology follows that work closely. Like Young et al.'s study, this study used AIS data to quantify the vessels' transits between ports. AIS was originally developed as an aid to maritime domain awareness and to help vessels avoid collisions. It has matured to a sufficient extent that the data have been successfully interrogated for a wide range of maritime interests and waterway maintenance concerns (Robards et al. 2016; Young and Scully 2018; Varlamis et al. 2019, 2021; Kress et al. 2020; Scully et al. 2020). AIS data include dynamic, time-stamped information on vessel operating conditions, such as vessel position, course, heading, and speed over ground. AIS also includes static information for vessel identification, such as name, Maritime Mobility Service Identity (MMSI) number, dimensions, and type (ITU 2014). Robards et al. (2016) described the vessel populations that are required or often elect to carry AIS transceivers; the most significant gap in AIS data coverage comes from small personal craft. AIS carriage requirements in US waters are specified by 33 CFR § 164.46, signed in 2019. The overwhelming majority of commercial vessels are mandated to carry AIS, justifying its use in monitoring MTS traffic. Note that AIS operates on the very high frequency (VHF) maritime band and is therefore limited by distance and line of sight (USCG n.d.).

AIS data are available from several sources, both public and proprietary. This study used Marine Cadastre data (BOEM and NOAA n.d.), which is a publicly available aggregation of AIS data provided by the Nationwide AIS (NAIS) system (USCG n.d.), subsampled at 1-minute intervals. Several characteristics of Marine Cadastre data are uniquely suited for analyzing the movement of vessels between ports in the United States. These include its no-cost availability, extensive North American coverage, multiyear span of data coverage, and relatively high-frequency sampling rate. The Marine Cadastre data set from 1 January 2009 through 31 December 2020 was analyzed for the present study. However, this report emphasizes results from 1 January 2015 through 31 December 2019, corresponding to the availability of independent validation data sets.

3.2 Port areas

The Marine Cadastre data indicate when vessels enter and leave the port areas of 385 North American (primarily US) ports and account for approximately 98% of US total tonnage. Figure 10 shows the geographic locations of these ports; a list of all port coordinates is available in Appendix A. Although some very small ports were not included in the analysis, these 385 ports were more than sufficient for describing the migration of cargo-bearing vessels within US waters and drawing meaningful conclusions. They were also exhaustive enough to partially account for international transits by exclusion. The areas that define each port (i.e., port areas) were manually identified by ensuring that the terminals of each port were fully enclosed in a polygon drawn with ArcGIS ArcMap (ESRI software). Figures 2 through 9 provided several examples of the port area polygons for major SAD ports. Although the port network spans the entire United States, the analysis and results of this report focus on ports within the SAD (Figure 1).

Figure 10. Geographic location of the 385 ports included in the port network description.



3.3 Determining arrivals and departures

To determine vessel transits between ports, the Marine Cadastre vessel position points within each port area polygon were identified. These data were sorted into single files for each unique MMSI number and then arranged by time. This described both the motion of the vessel within each port area and the order in which the vessel visited the ports. *Port visits* made by these vessels were defined either as instances of the vessel leaving one port area and arriving in another port area or leaving a port area and returning to the same area after a time delay ≥24 hours. Once the port visits were determined, the data were downsampled to include only the first and last appearances of each vessel in a given port area for each port visit. This final step reduced the data set to a manageable size while retaining the information necessary for analysis. The resulting data product was a time-stamped list of arrivals and departures for every AIS-equipped vessel transiting the network of ports.

3.4 Data filtering

The vessel MMSI numbers from the time-stamped list of arrivals and departures were cross-referenced with a list of vessel identities obtained from the USCG and validated using the AVIS (Winkler 2012). Table 1 provides a nonexhaustive categorization of vessels by their AIS ship and cargo type code. Unmatched vessels were assigned a type code of zero to indicate that the vessel type was unknown. The list of arrivals and departures was further filtered to require that vessels spent a sufficient duration within each port area (i.e., dwell time) for that record to be retained. Vessels were required to remain within the port area for one hour or for the number of hours required for a vessel traveling at 5 knots to transit the long axis of the port area polygon, whichever was larger.

Table 1. Vessel types that were retained during the PageRank calculations. (Reprinted from Young et al. 2022, with permission.)

AIS ship and cargo type code	Description
30	Commercial fishing
31, 32	Towing of barges (ahead or alongside, astern)
6X[a,b]	Passenger ships
7X[b]	Cargo (freight) ships or integrated tug barge (ITB) vessels
8X[b]	Tankers or integrated tug tank barge vessels

[a] Older versions of the AIS encoding guide only specify passenger vessels exceeding 100 gross tons.

[b] Where X indicates 0–9, representing all vessels of this class.

3.5 Vessel volume estimates

Vessel volume was explored as a proxy for estimating tonnage based on AIS records. The advantages of an AIS-derived proxy for tonnage are twofold. First, AIS data are available at 1-minute temporal resolution. Thus, the AIS-derived tonnage proxy allows for estimating tonnage on daily, weekly, or monthly timescales, whereas port tonnage metrics are traditionally reported on the yearly timescale (BTS n.d.). Second, the AIS-derived tonnage proxy allows for estimation of vessel tonnage for ports that are frequently omitted from lists of tonnage at the top US ports (BTS n.d.). Specifically, the AIS-derived proxy can be calculated for any port within range of an NAIS receiver. Descriptions of vessel net registered tonnage (NRT) and gross tonnage (GT) are not broadcast within AIS transmissions, although these values may be available from other sources. However, NRT and GT are static values that do not vary through time. Consequently, vessel volume estimates that incorporate the effects of varying vessel draft on estimated cargo throughput have the potential to represent actual time-varying tonnage values more accurately.

For a vessel of length L, beam B, and time-varying draft $D(t)$, the vessel volume during the ith port visit was estimated as $V(t_i) = L \times B \times D(t_i)$. The static vessel dimensions (L and B) may be extracted from the AIS data; alternatively, these values are included in the cross-referenced AVIS database (Winkler 2012). If a vessel did not report its dimensions via AIS and was not included in the AVIS database, but the vessel class was known, then L and B were assigned as the average length and beam of all same-class vessels in the AVIS database. For vessels of unknown dimension and class that did not appear in the AVIS database, placeholder values of $L = 5$ meters and $B = 1$ meter were assigned. This followed from the assumption that any vessels that were omitted from the AVIS database and did not report their vessel dimensions via AIS were likely to be small watercraft with a limited contribution to overall port tonnage.

Vessel draft varies as a function of time, but AIS-broadcast draft values are normally static design draft values that do not vary with vessel operating conditions (Scully and Young 2021). Consequently, to estimate draft during any particular port visit, draft data from the US Customs and Border Protection's foreign vessel E&C reports (IWR n.d.) were substituted for the AIS-reported draft whenever possible. For each ship appearing in the E&C reports, a vessel draft time series, $D(t)$, was constructed using all available

E&C data between 2009 and 2019. Then, the time series was interpolated to estimate the vessel draft at time t_i. If a vessel did not appear in the E&C reports but broadcast its draft via AIS, then $D(t_i)$ was assumed to equal the AIS-broadcast draft. If a vessel did not appear in the E&C reports and did not broadcast its draft via AIS, but the vessel class was known, then $D(t_i)$ was assigned as the average draft for all same-class vessels in the E&C data. Vessels of unknown class with no E&C or AIS draft data were assigned a placeholder value of $D(t_i) = 1$ meter under the assumption that these vessels were likely small watercraft with limited contribution to commercial tonnage.

3.6 International visits

Although some international ports (specifically other North American ports in Canada, the British Virgin Islands, the Bahamas, and Cuba) are represented in the Marine Cadastre AIS data, transits between the United States and most international ports are not explicitly captured. For example, a ship that transits from Charleston (South Carolina) to Hamburg (Germany) and then to Jacksonville (Florida) will appear in the Marine Cadastre AIS record as a port visit in Charleston followed by a multiple-week period in which the ship disappears before finally reappearing in Jacksonville. In a previous iteration of the US MTS description (Young et al. 2022), this would have been treated as a direct trip from Charleston to Jacksonville, potentially inflating the importance of the Charleston–Jacksonville linkage within the overall network. The present study implemented a new methodology for inserting visits to unidentified international ports into the AIS data set prior to calculating network connectivity metrics.

For each state or region represented by AIS, the present study estimated the minimum time required for a one-way journey to either Mexico or Panama at 18 knots. These two countries were considered representative of international locations that can be reached relatively quickly from the United States but are not covered by US terrestrial AIS records. Then, for each combination of states, the minimum international travel time, T_{min}^{int}, was defined as the minimum time required to make a trip between those states with an intervening visit to the closest of the two representative international ports. In most cases, T_{min}^{int} was the sum of the one-way travel times between the two states and the international port plus one additional day for offloading at the international location. However, for trips between the US Pacific Coast and the US Gulf Coast, T_{min}^{int} was set to 40 days, whereas for trips between the US Pacific Coast and the US Atlantic Coast, T_{min}^{int} was set to 60 days. This allowed for a possible increase in travel time if the ship was delayed while transiting the Panama Canal or the Suez Canal. Although the values of T_{min}^{int} for Panama Canal and Suez Canal transits are poorly constrained by available data, a round-trip travel time between 40 and 60 days is consistent with travel times published by the US EIA (2016). A summary of T_{min}^{int} for all pairs of states, provinces, and countries with AIS coverage appears in Appendix B.

Finally, the analysis examined the time series of port visits for all passenger ships (vessel class 7X), cargo ships (class 8X), and tankers (class 9X; see Table 1). The actual travel time, $T_i = t_{i+1} - t_i$, for each pair of consecutive port visits in the AIS data set was compared to the value of T_{min}^{int} for the departure and arrival states. If $T_i > T_{min}^{int}$, then it was assumed that the vessel transited to some unknown international location between times t_i and t_{i+1}, and a visit to an abstract international node was inserted into the AIS data set. For example, a transit from South Carolina to Panama was estimated to require four days at 18 knots, while the return transit from Panama to Florida was estimated to require three days. Adding one day for offloading generated a value of $T_{min}^{int} = 8$ days as the minimum time required for a trip from South Carolina to Florida with a stop at an unknown international port. If AIS data recorded a vessel departing Charleston, South Carolina, and then arriving in Jacksonville, Florida, nine days later, the current methodology assumed that the vessel visited an unknown international port, and the direct link between Charleston and Jacksonville was eliminated from the network. However, a ship that transited from Charleston to Jacksonville in three days was assumed to have made a direct trip, and the network connection between Charleston and Jacksonville was retained. This method for determining international transits was possible because of the large number of domestic ports included in the current version of the port network, which provided confidence that the vessel did not transit to another domestic port during the time when the international transit was determined to occur. However, international transits may have been erroneously added to the data set if a vessel anchored offshore for a multiday period during a domestic transit. Potential consequences for the analysis are further discussed in Section 4.3.

3.7 PageRank

PageRank is a method for evaluating the importance of a node to an interconnected network, and it was applied herein to port traffic to rank how critical individual ports are to facilitating countrywide commercial vessel traffic. It was originally developed to quantitatively estimate the importance of Web pages for Internet search engines; higher scoring pages were pushed to the top of a prospective search for the most critical website by analyzing the structure of the Internet network in which the pages existed (Page et al. 1999). The PageRank algorithm assigned Web page importance based on three conditions: (1) the number of connections the Web page had, (2) the weights of those connections (i.e., if a Web page had 100 connections but sent 90% of its traffic to 1 connected Web page, that connection was deemed more important than the other 99), and (3) the importance of those connected Web pages themselves. The iterative PageRank algorithm explicitly propagated the importance score of each Web page out to its neighbors based on their weighted connections until a stable score for each page was reached.

To apply PageRank to a port network, the port areas were conceptualized as websites, and the vessel traffic between ports was treated as an analog for links between websites (Scully and Chambers 2019; Young et al. 2022). As an improvement over the previous network description from Young et al. (2022), the vessel traffic in the present study was quantified by the physical volume of the vessels transiting between ports, rather than the number of vessels transiting between ports. Cumulative volume was assumed to be more closely correlated with the degree of commerce between ports than the raw count of vessels.

To improve the representation of the commercial exchange between ports, the only vessel volumes used in the PageRank analysis were those with known vessel types engaged in commercial activities. (See a list of retained vessel types in Table 1.) Furthermore, the list of ports that were included in the port network for PageRank analysis was filtered to retain only those ports with a total volume greater than or equal to the total volume of the 30th largest port on the Great Lakes (in Sandusky, Ohio). This cutoff was arbitrary but was applied uniformly across the entire list of ports, leaving 182 total ports. The volume cutoff was necessary because PageRank can be sensitive to the concentration of nodes in particular regions. There is a floor to the PageRank score for a node (i.e., port) if it receives any traffic at all; consequently, high concentrations of extremely small ports in a region can inflate the score of that region's hubs. The AIS data set used to generate this port network was also used to update the study presented by Kress et al. (2021), which generated a regional description of vessel traffic for the Great Lakes. As a result, there was an unusually high degree of coverage of all possible vessel destinations on the Great Lakes that was not replicated in any other geographic region (202 of 385 total port areas were in the Great Lakes). Filtering out ports below a certain size ensured the high spatial concentration of ports on the Great Lakes did not bias the PageRank results.

4 Results and Discussion

4.1 Suitability of ship volume as a proxy for tonnage

Whereas the study by Young et al. (2022) calculated each port's PageRank score based on the raw count of vessels, the present study calculated PageRank after weighting each port by its summed vessel volume. This considered the size of the vessels transiting between ports; large container ship traffic between ports was weighted more heavily than barge traffic on a per-vessel basis, for example. This weighting was predicated on the assumption that vessel volume (i.e., length × beam × draft) was a reasonable proxy for vessel tonnage. If so, the link weights would be better predictors of total cargo movement between ports, and the PageRank scores would reflect this improvement in accuracy. To evaluate the validity of this assumption, Figure 11 displays the relationship between summed vessel volume and tonnage for all Atlantic, Pacific, and Gulf Coast ports with reported tonnage data from 2015 to 2019. Volume and tonnage were found to be positively correlated, with the R^2 value for a linear trendline ranging between 0.62 and 0.70, depending on the year. This suggests that vessel volume is a reasonable order-of-magnitude predictor of tonnage.

The general trend of positively correlated volume and tonnage remained valid when limited to SAD ports (Figure 12; note that certain SAD ports were omitted from the tonnage reports and are not displayed). Linear trends for the SAD data have R^2 values ranging between 0.36 and 0.42, depending on the year. However, three SAD ports (Mobile, Alabama; Tampa, Florida; Pascagoula, Mississippi) deviated considerably from the overall trend during all years, with reported tonnage persistently exceeding the tonnage predicted by the trendline. Of these, the largest outlier was Mobile, Alabama, where the measured tonnage of about 60 million short tons was approximately three times larger than the tonnage predicted based on volume.

Figure 11. Comparison of calculated ship volume and reported tonnage for all Atlantic, Pacific, and Gulf Coast ports in the years 2015 to 2019.

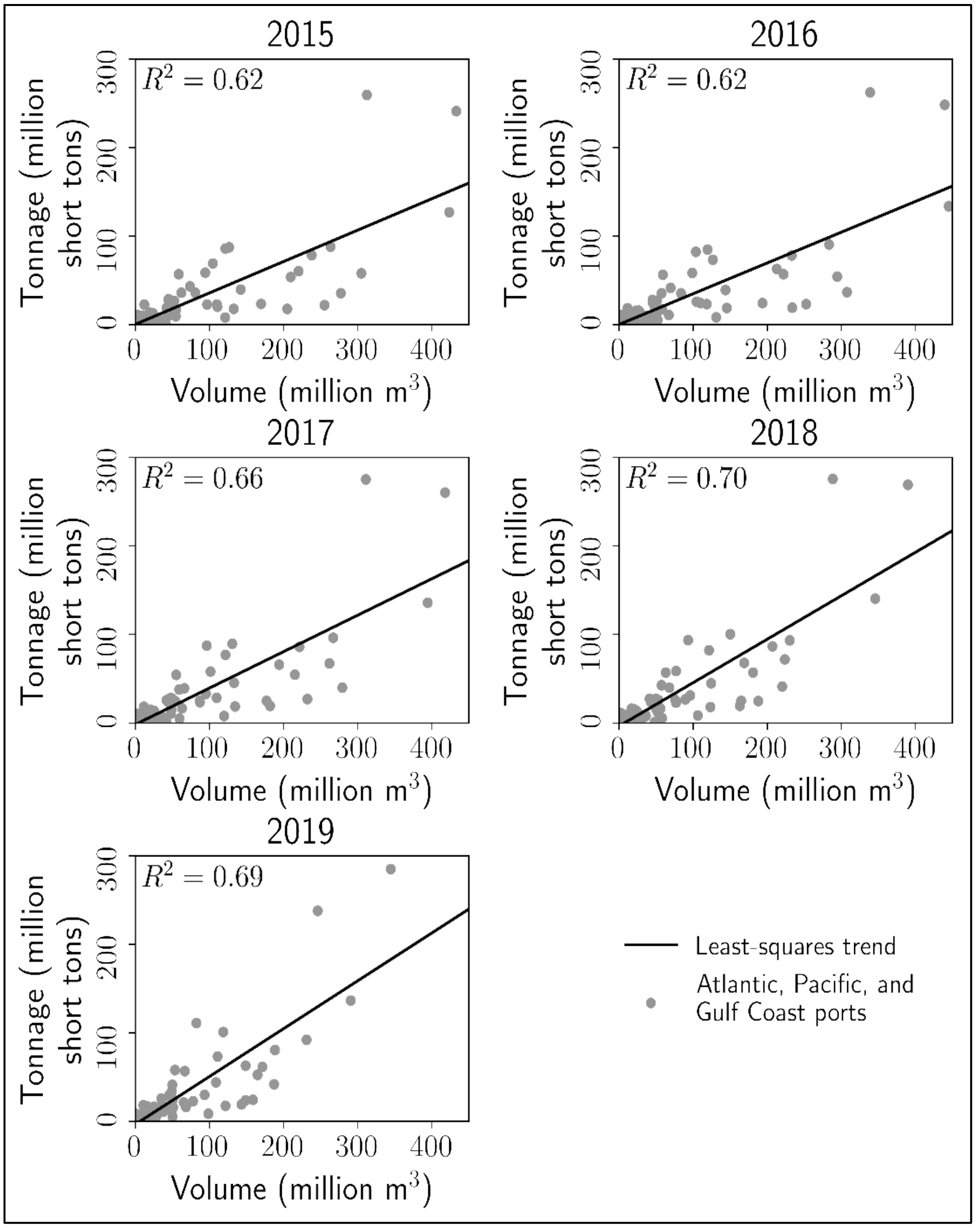
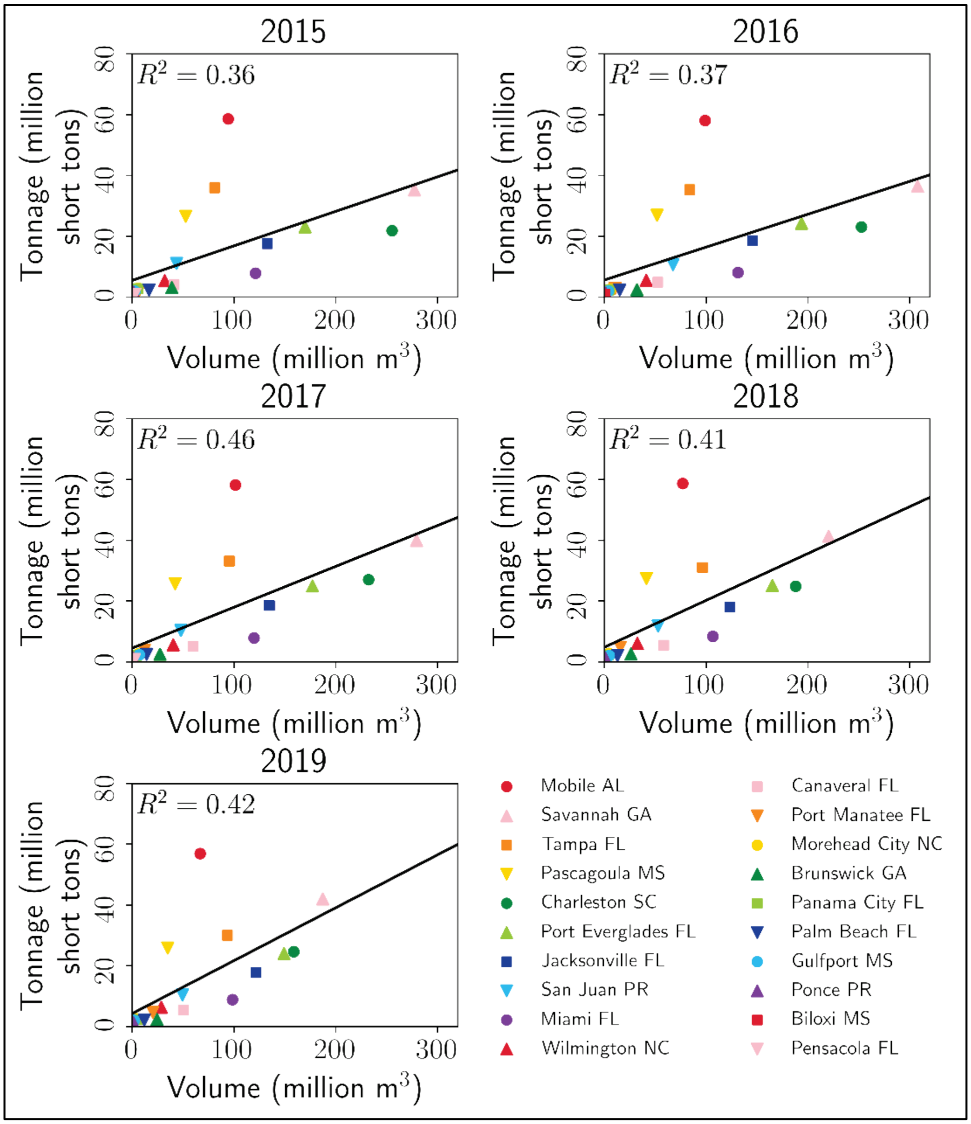


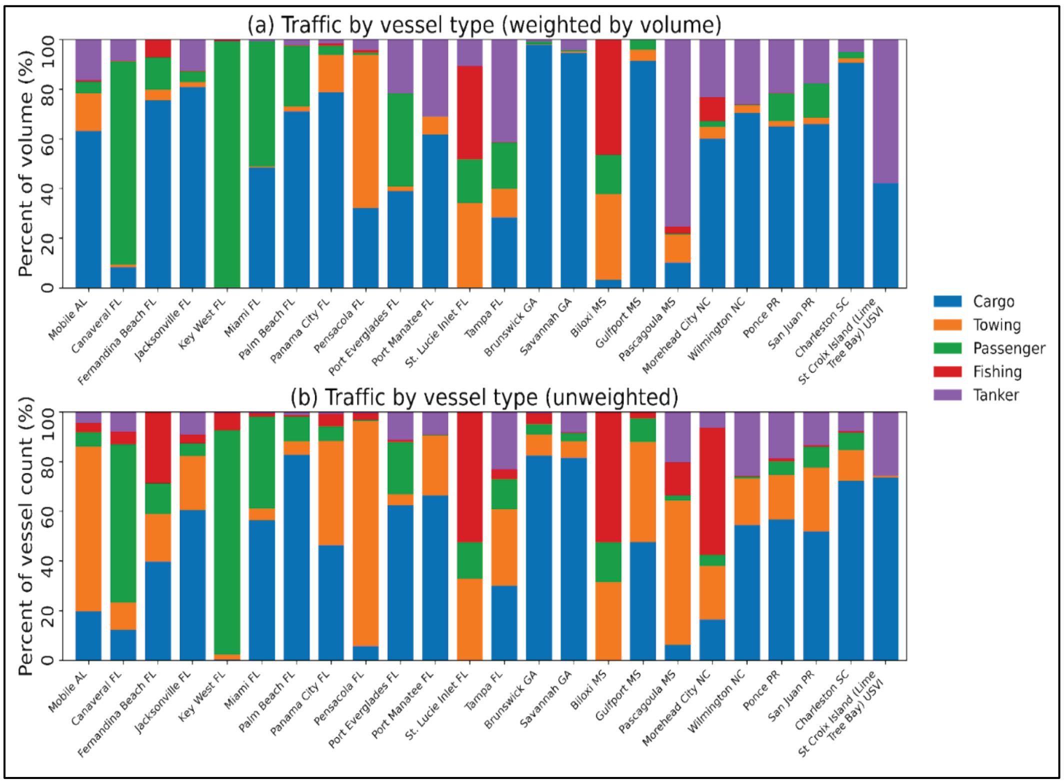
Figure 12. Comparison of calculated ship volume and reported tonnage for SAD ports. Note that two ports with a high percentage of tow traffic (Mobile and Pascagoula) deviate from the broader trend. The reason for Tampa's deviation from the trend remains undetermined.



The systematic deviation between volume and tonnage at Mobile and Pascagoula may have resulted from the type of vessels frequenting these ports. Young et al. (2022) previously noted that despite these ports' geographic positions along the Gulf Coast, they are classified as members of a "Mississippi River/East Gulf" community based on a label propagation algorithm. The defining characteristic of the Mississippi River/East Gulf community (and all other riverine communities) is a high proportion of overall transits made by tug and tow vessels moving barge traffic. In other words, ports along the eastern Gulf Coast receive a large proportion of tow traffic from the Mississippi River. The volume calculation methodology described in

Section 3.5 accounts for the volume of the tug or tow vessel, but the additional volume of the barges was not included in AIS and was therefore omitted from these calculations. This is illustrated in Figure 13, which displays the relative proportions of vessel types at various SAD ports using the volume-weighted versus unweighted algorithms. At Mobile, the volume-weighted algorithm indicated that tow traffic was 15% of total volume, whereas tow traffic accounted for 66% of Mobile's traffic based on raw vessel count. Similarly, the tow percentages for Pascagoula were 11% of total volume but 58% of the raw vessel count.

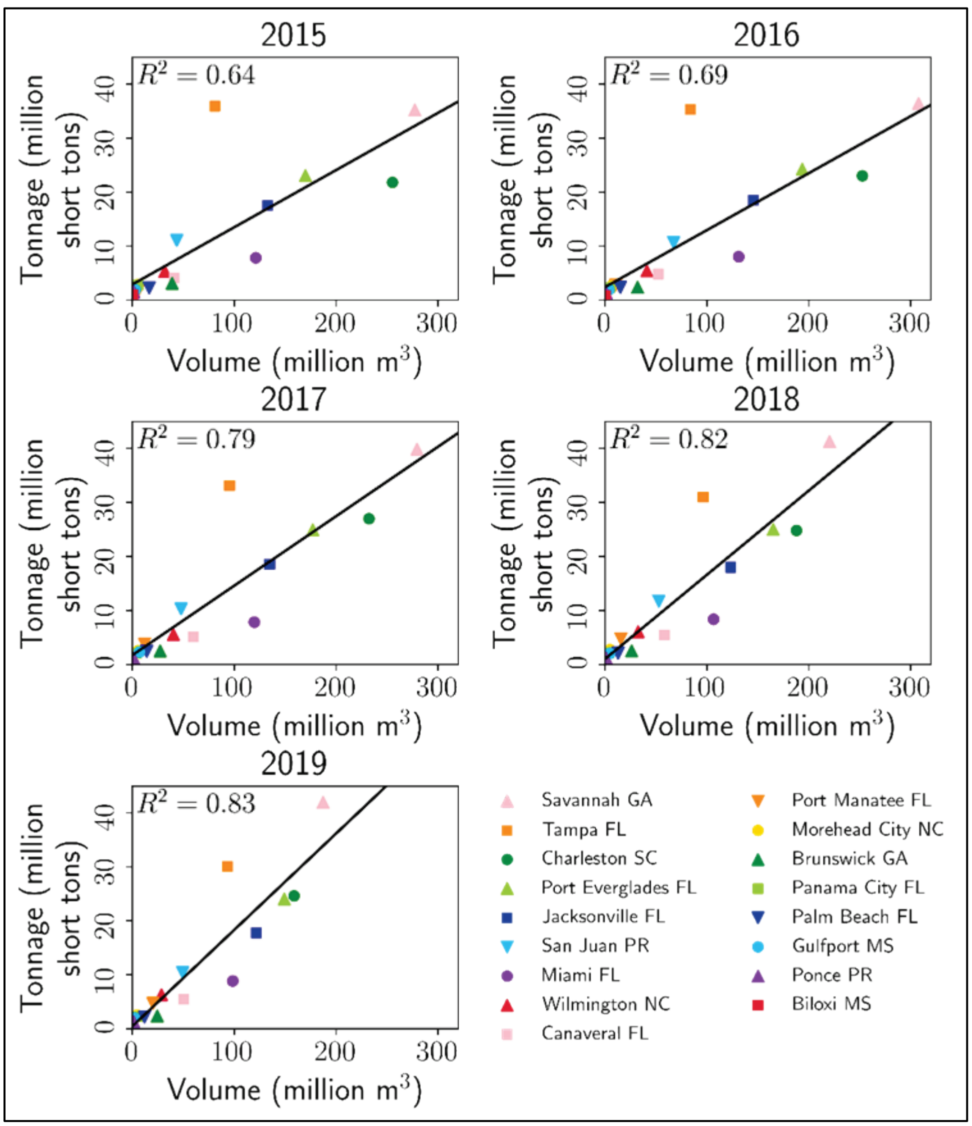
Figure 13. Vessel type distribution as (*a*) the percentage of the total volume of vessels visiting selected SAD ports and (*b*) the percentage of the unweighted count of vessels visiting each port. The proportion of tows varies considerably between the upper and lower plots.



It is likely that the volume–tonnage relationships in Figures 11 and 12 would improve if the volume of the barges were included in the ports' total volume. However, this approach would require an additional source of data on the size of the barge flotillas to augment the AIS-derived connections. Alternatively, limiting the volume–tonnage relationship to ports dominated by larger vessels (e.g., container ships) would also generate a stronger correlation. To test this idea, Figure 14 displays the relationship between volume and tonnage after removing the three ports with >50%

tow traffic by raw vessel count (Mobile, Alabama; Pascagoula, Mississippi; and Pensacola, Florida; see Figure 13*b*). When these tow-dominated ports were discarded from the analysis, the R^2 value for a linear relationship between volume and tonnage was as high as 0.83 in 2019, with Tampa, Florida, being the only notable outlier. The reason for Tampa's deviation from the overall trend remains unclear, and further study would be required to determine why the volume–tonnage relationship performs poorly at this location. However, despite the presence of one outlier, the analysis broadly supported the conclusion that a port's cumulative volume is a reasonable proxy for tonnage in deep-draft-vessel dominated ports.

Figure 14. Comparison of calculated ship volume and reported tonnage for SAD ports, excluding ports with >50% tow traffic by raw vessel count (Mobile, Alabama; Pascagoula, Mississippi; and Pensacola, Florida; see Fig. 13*b*).



4.2 Ranking of SAD ports within the US maritime transportation network

A primary goal of this study was to quantify the relative criticality of SAD ports within the full US maritime transportation system. This was achieved by considering the ports' PageRank scores and evaluating why the PageRank algorithm identified certain ports as more or less important than the raw tonnage suggests. To provide context for the results, it should be noted that the PageRank algorithm assigns port importance based on a combination of three conditions: (1) how many trading partners a port has; (2) how much traffic moves between those ports (i.e., if a port has 10 trading partners but sends 90% of its traffic to 1 port, the connection between those 2 ports is deemed more important than the other 9 connections); and (3) how important the connecting ports themselves are. Consequently, extremely large ports like Houston and New York–New Jersey receive high PageRank scores as a simple consequence of their frequent visits by large commercial vessels arriving from many other ports. Other ports' PageRank scores may also be elevated if they receive substantial traffic directly from one of these extremely large ports. Some ports may achieve higher PageRank scores if they serve as a hub for an unusually large number of smaller ports. For example, Duluth-Superior serves as a hub for a significant amount of Great Lakes traffic from smaller ports; this causes Duluth-Superior to have the fourth-highest PageRank score in North America, despite having smaller tonnage than major Atlantic, Pacific, and Gulf Coast hub ports. For further details on interpreting the PageRank algorithm, see Young et al. (2022).

Table 2 contains a comparison of rankings by tonnage and PageRank score for selected SAD ports. The highest-ranking SAD port by total tonnage was Mobile, Alabama, which ranked 11th in the United States based on aggregate tonnage data from 2015 through 2019. Meanwhile, the highest-ranking SAD port based on PageRank was Savannah, Georgia, which ranked 6th in the United States. The results for all SAD ports are available in Appendix C.

Table 2. Ranking of selected SAD ports by tonnage and by PageRank based on data from 2015 through 2019.

Port	National rank by tonnage	National rank by PageRank score
Mobile, AL	11	32
Savannah, GA	17	6
Tampa, FL	22	26
Pascagoula, MS	25	52
Charleston, SC	26	9
Port Everglades, FL	27	15
Jacksonville, FL	36	18
Miami, FL	58	29

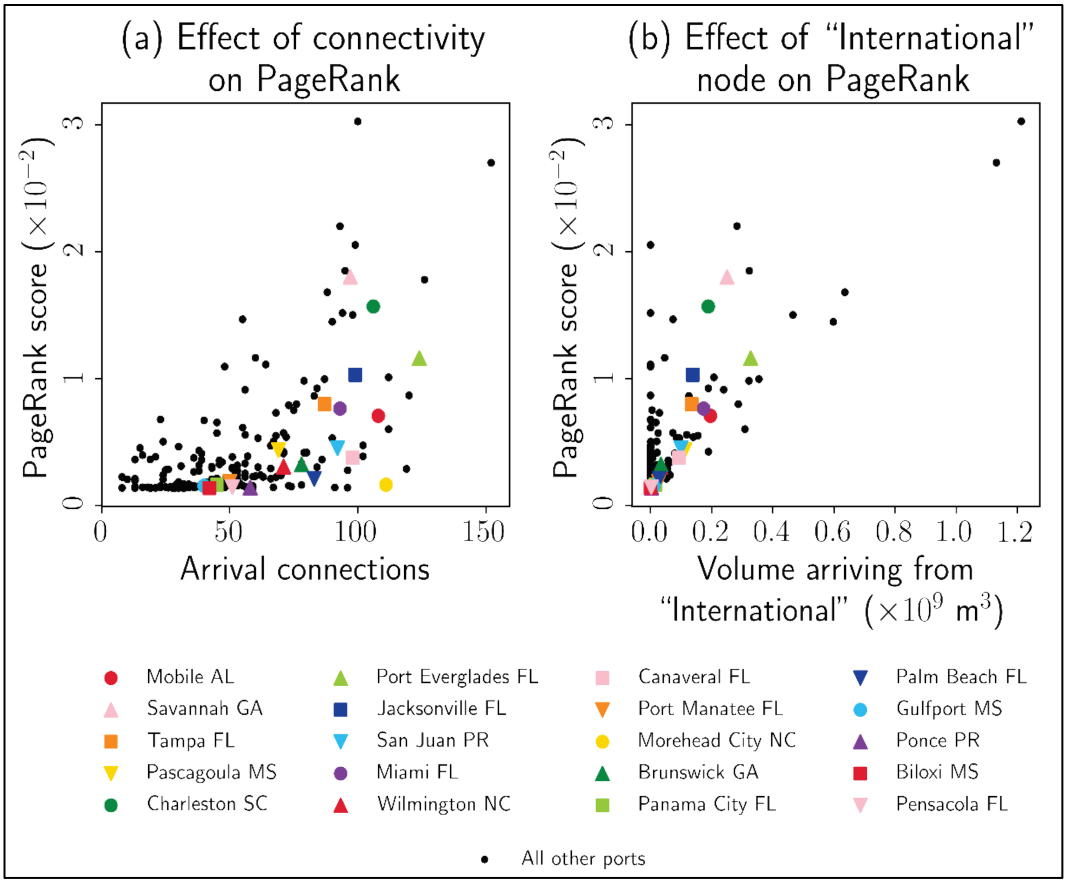
As seen in Table 2, discrepancies between a port's tonnage ranking and its PageRank position were frequent. For example, several of the ports ranked substantially higher by tonnage than by PageRank, including Mobile (11th by tonnage versus 32nd by PageRank) and Pascagoula (25th by tonnage versus 52nd by PageRank). The comparatively low PageRank scores at these ports partly reflect the structure of the Gulf Coast network. Young et al. (2022) previously noted that there is a high concentration of "medium to large" ports along the Gulf Coast. The interconnected configuration of the Gulf transit network implies that many large- and medium-sized ports handle similar levels of traffic, lowering their individual PageRank scores relative to their tonnage rankings. Additionally, these Gulf ports are proximal to the extremely high-tonnage (i.e., >80 million short tons) and high-traffic ports of Houston, New Orleans, and South Louisiana. PageRank results are sensitive to the proximity, size, and number of neighboring ports, and they do not allow for ties in the ranking. In simpler terms, PageRank highlights the distinction between a "big fish in a little pond" and a "big fish in the ocean."

The discrepancy between tonnage and PageRank at Mobile and Pascagoula may also relate to the volume weighting in the PageRank algorithm. As discussed previously, both Mobile and Pascagoula receive a large proportion of tow traffic, which causes the calculated volume to be a poor predictor of tonnage at these locations. The error in calculated volume could propagate into the volume-weighted PageRank algorithm, leading to a PageRank score that is lower than expected. However, the weighting by total number of arrivals in Young et al. (2022), which should preferentially bias toward tow-heavy ports, also indicated a similar result for the Pascagoula and Mobile PageRank scores, suggesting that the network structure explanation is more plausible.

In other instances, the ranking by PageRank score was substantially higher than the ranking by tonnage. Examples include Savannah (17th by tonnage versus 6th by PageRank), Charleston (26th by tonnage versus 9th by PageRank), Port Everglades (27th by tonnage versus 15th by PageRank), Jacksonville (36th by tonnage versus 18th by PageRank), and Miami (58th by tonnage versus 29th by PageRank). This suggests that these ports are more important to the overall flow of vessel traffic across the port network than implied by tonnage alone. Explanations for the discrepancy include port connectivity, the effect of the abstract international node, the role of certain ports as a hub for other relatively isolated portions of the network, and the presence of vessel traffic that is not represented in the reported tonnage. Each of these possibilities will be further explored in the paragraphs that follow.

For relatively large East Coast container ports like Savannah and Charleston, the elevated PageRank scores may have resulted from a combination of their size and a high degree of connectivity with other ports in the network. However, neither of these factors is individually sufficient to guarantee a high PageRank score. For example, Charleston and Jacksonville had comparable tonnages (121 million short tons for Charleston versus 90 million short tons for Jacksonville, summed across the years 2015–2019), and tonnage was accurately predicted by vessel volume at these two locations (Figure 14). Nevertheless, Charleston's PageRank score was notably higher than Jacksonville's PageRank score. A large number of connections is likewise insufficient to guarantee a high PageRank score (although a high PageRank score cannot be achieved without a large number of connections; Figure 15*a*). For example, Canaveral had 98 arriving connections, which was comparable to both Savannah (97 arriving connections) and Charleston (106 arriving connections), yet Canaveral received a much lower PageRank score. Rather, it appears that the combination of large overall size and a large number of connections contributes to the high PageRank scores at Savannah and Charleston.

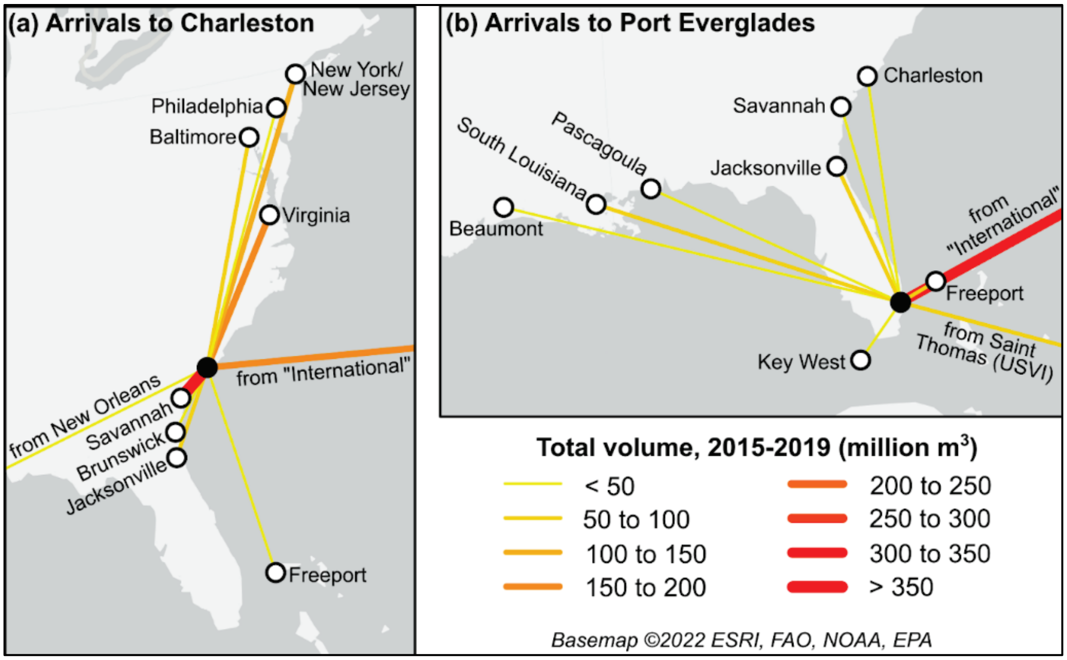
Figure 15. Relationship between (*a*) connectivity and PageRank and (*b*) international volume and PageRank. The number of arrival connections in subplot *a* is the total number of ports that send vessels to the port of interest. The international volume in subplot *b* is the volume arriving at a given port from the abstract international node summed over the years 2015 through 2019.



The introduction of an abstract international node, which collectively represents transits to and from all unknown international ports, also may have enhanced certain ports' PageRank scores. A total of 184 US ports were determined to send vessel traffic to the international node. For comparison, the port with the next-largest number of inbound connections was New York–New Jersey, with 152 ports sending traffic to this location. The calculated volume traveling to the international node (i.e., 11 billion cubic meters from all other nodes to international summed over 2015–2019) was also an order of magnitude larger than the volume for Houston, Texas, which was the next-largest port by volume (with 2.8 billion cubic meters from all other nodes to Houston, summed over 2015–2019). The combination of a large number of arriving connections and a large total volume caused the PageRank score at the international node to be an order of magnitude larger than the PageRank scores for Houston and New York–New Jersey. Due to the iterative nature of the PageRank algorithm, ports that received relatively high percentages of vessel traffic from the international node also achieved an elevated PageRank score. This was apparent in the correlation between international volume and PageRank that appears in Figure 15*b*.

Although ports that received a large volume of vessels from the international node tended to have higher PageRank scores (Figure 15*b*), connectivity to other important ports in the network also influenced the PageRank results. For example, Port Everglades and Charleston are comparable ports based on tonnage (Table 2) and have similar vessel type distributions (Figure 13). The international volume arriving at Port Everglades is also larger than the international volume arriving at Charleston (i.e., 330 million versus 190 million cubic meters, summed over 2015–2019). Nevertheless, Charleston ranked higher than Port Everglades by PageRank. This may be a result of Charleston's stronger connection to other important ports in the network. As shown in Figure 16*a*, Charleston's top 10 trading partners by arrival volume include New York–New Jersey, New Orleans, and Savannah, which are all high-scoring ports by PageRank. In contrast, Port Everglades has fewer high-ranking ports among its top 10 connections (Figure 16*b*). This example demonstrates that although connectivity to the international node contributes to a high PageRank score, connections to other major ports also influence the study results.

Figure 16. Map of top 10 ports sending traffic to Charleston and Port Everglades based on summed arrival volume from 2015 through 2019. Although Port Everglades received more volume from the abstract international node, Charleston had more connections to major US ports, including Savannah, Virginia, New York–New Jersey, and New Orleans. Receiving a large volume of ships from these important ports caused Charleston to have a higher PageRank score than Port Everglades.



The port of Jacksonville may rank higher by PageRank than by tonnage because it is a hub for Puerto Rican shipping traffic. The Jacksonville Port Authority (n.d.) reports that over 85% of goods traveling to and from Puerto Rico are shipped through Jacksonville. The present analysis suggested that 28% of cargo volume imported to Puerto Rico comes from Jacksonville. Although this value was lower than expected, the discrepancy may be due to the addition of transits to and from the generalized international node, from which 49% of inbound Puerto Rican traffic originated. During the analysis, an international transit was added if a ship took more than seven days to travel from Puerto Rico to Jacksonville (or vice versa; Appendix B). If transit delays resulted in a >7 day travel time between these two locations, an international stop was erroneously added to the data set, reducing the apparent volume shipped directly between Jacksonville and Puerto Rico. Regardless of these potential errors, it is important to note that Puerto Rico's next-largest trading partner by volume was determined to be St. Thomas Island (US Virgin Islands), which contributes approximately 4% of Puerto Rico's total import volume. Because a large percentage of Puerto Rican traffic is concentrated along the Jacksonville route, the PageRank algorithm identified Jacksonville as an important node in the structure of the transportation network.

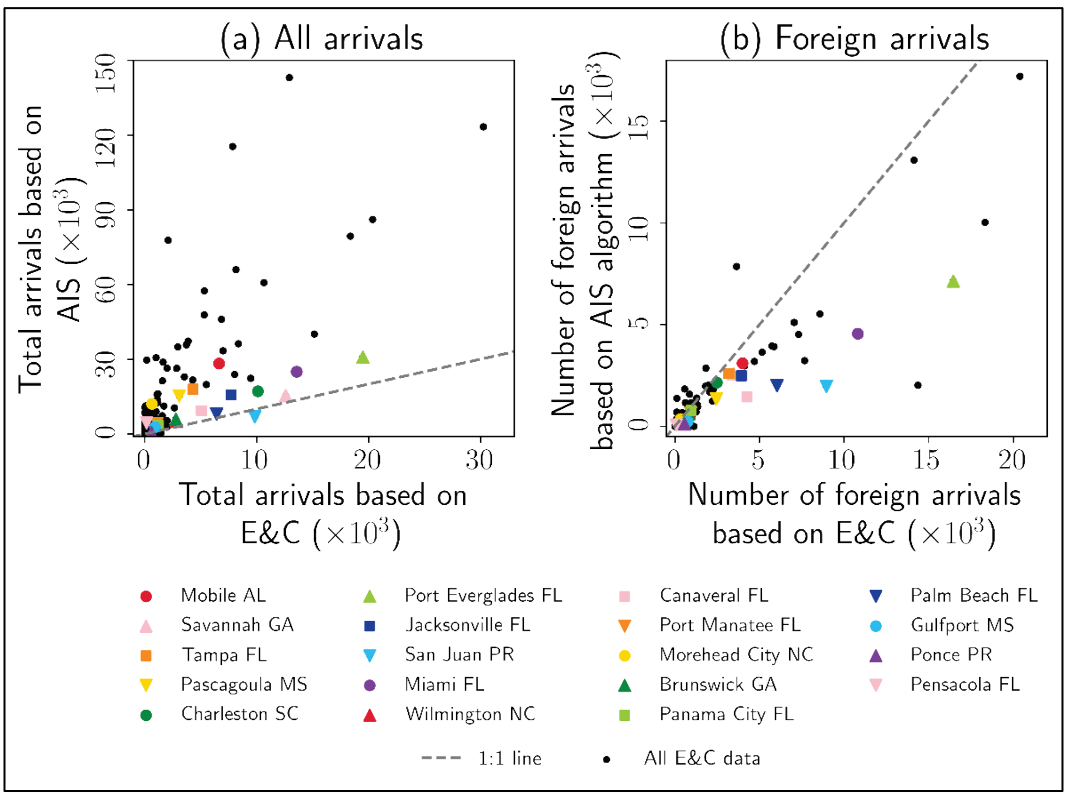
The high proportion of passenger cruise traffic at Miami may have contributed to its comparatively high PageRank score, relative to tonnage. The tonnage statistics from BTS (n.d.) do not include passenger vessels, yet the dimensions and draft of large cruise ships are comparable to cargo ships (Kizielewicz 2020), and large passenger vessels are equally important to port safety considerations. Because the volume weighting within the PageRank algorithm accounts for all vessel types in Table 1, PageRank may identify certain ports with significant passenger traffic as more important nodes than their commercial tonnage suggests. However, having significant passenger traffic alone does not guarantee a major elevation in the relative PageRank score. For example, Canaveral, Florida, ranked 68th by tonnage and 65th by PageRank (Appendix C) despite the high proportion of passenger vessels at this location (Figure 13). As described previously, this may relate to the overall structure of the network. If Canaveral's inbound passenger vessel traffic originates at small ports, then a large number of arriving passenger ships will not generate a large relative increase in PageRank. The fact that Miami also gets an appreciable volume of traffic from commercial vessels may account for this discrepancy.

4.3 Accuracy of transits to the international node

Given the influence of the abstract international node on the PageRank score, it was worthwhile to evaluate the accuracy of the AIS-based travel time algorithm for predicting international transits. The method for algorithm validation involved comparing vessel counts based on the E&C data set to counts based on AIS. As shown in Figure 17*a*, the number of AIS-based arrivals almost always exceeds the number of arrivals included in the E&C reports. This behavior is consistent with US Customs requirements. Because US-flagged ships arriving from domestic ports are not required to report to customs upon arrival, a subset of the ships arriving at any given port will not be listed in the E&C data set, yet their arrival can still be identified via AIS.

Furthermore, the number of foreign arrivals contained in the E&C reports is positively correlated with the sum of AIS-based arrivals from Canada, Cuba, the Bahamas, the British Virgin Islands, and the abstract international node (Figure 17*b*). These results suggest that the AIS-based travel time algorithm developed for this study has reasonable predictive ability for identifying transits to foreign ports that lack AIS coverage. However, the AIS-based algorithm tends to underpredict the known number of foreign arrivals based on the E&C reports. This may be a partial consequence of adding international transits only for passenger ships (class 7X), cargo ships (class 8X), and tankers (class 9X; Table 1). Future studies may observe an improvement in accuracy if additional vessel types are assumed to be capable of international transits.

Figure 17. (*a*) Count of total number of arrivals based on the entrances and clearances (E&C) reports versus based on AIS data. The displayed data are for 2015 through 2019. (*b*) Comparison of foreign arrival count based on E&C versus the AIS-based travel time algorithm developed for this study. On the vertical axis, the foreign arrivals are defined as any ship arriving at a US port from Canada, the Bahamas, Cuba, the British Virgin Islands, or the abstract international node.



For the present study, the AIS-based travel time algorithm was run using a fixed set of values for T_{min}^{int} (Appendix B). Future implementation of the algorithm could obtain improvements in performance if the values in Appendix B were iteratively modified to improve the overall fit in Figure 17*b*. In almost all cases, the value of T_{min}^{int} between two states would need to be reduced relative to the value used in the present study, thereby increasing the number of transits to the international node that are added to the AIS data set. Defining T_{min}^{int} for pairs of ports (rather than for pairs of states) could also improve the accuracy of the algorithm, particularly for states with above average coastline lengths (e.g., California, Alaska, and Florida).

For the present study, the value of $T_{min}^{int}$was set to 40 days for transits between the US Pacific and Gulf Coasts and to 60 days for transits between the US Pacific and Atlantic Coasts. These values of T_{min}^{int} are broadly consistent with reported transit times via the Suez and Panama Canals (US EIA 2016). Additional improvements in the performance of the travel time algorithm could likely be obtained if an additional source of data quantifying transoceanic transit times were used to further refine these values.

An additional limitation of the algorithm for identifying international transits is its inability to account for multiple-day anchorages during domestic transits. For example, if a ship transiting between two domestic ports anchored offshore from its destination for an extended duration, the apparent transit time between those two ports may have exceeded T_{min}^{int}, leading to the erroneous addition of an international transit. Extended anchorages were broadly reported by the popular media during pandemic-related supply chain delays in 2020 and 2021. Because the validation analyses for this study (i.e., Figures 11 through 17) only consider data through the end of 2019, such supply chain issues were assumed to have minimal influence on the validation results. However, additional data quantifying the frequency of extended anchorages under nonpandemic shipping conditions would be valuable for further verifying the validity of the travel time algorithm.

5 Summary

This study utilized AIS data to characterize the US maritime transportation network by quantifying the port-to-port connectivity for all ports in the network, with a particular focus on the SAD. The AIS data were used to identify all vessel arrivals and departures at 385 North American ports, which were primarily concentrated in the United States (including Puerto Rico and the US Virgin Islands) but also included major ports in Canada, Cuba, the Bahamas, and the British Virgin Islands. Visits to international ports that fell outside of US terrestrial AIS data coverage were identified and added to the analysis based on the exceedance of a predefined travel time between individual departure and arrival points. The linkages between pairs of ports were then weighted by the summed volume (defined as vessel length × beam × draft) of all vessels transiting the route. Using this volume-weighted representation of the network, PageRank scores for each port were calculated to provide insight into the relative importance of individual ports for facilitating commercial vessel traffic flow across the country.

The total volume of vessels arriving at a port was proposed as a possible proxy for the port's tonnage because total volume allows for an analysis of port cargo trends at a finer temporal resolution than is achievable from annual tonnage reports. AIS-derived volume was also proposed because it permits an estimate of tonnage at ports where tonnage metrics are unavailable. To test this idea, calculated volume and reported tonnage were compared for all years between 2015 and 2019. For all US ports with reported tonnage, the R^2 value for a linear fit between volume and tonnage ranged between 0.62 and 0.70. Limiting the analysis to just SAD ports reduced the R^2 value to a maximum of 0.46. This was largely attributed to the high proportion of tow traffic at Mobile and Pascagoula; because the barge flotilla is not included in the volume calculations, the actual tonnage at tow-dominated ports is substantially underpredicted by AIS-based volume. Removing ports with >50% tow traffic by vessel count improves the fit, with a maximum R^2 of 0.83. The use of volume as a proxy for tonnage is therefore recommended for ports dominated by traffic from larger vessels, but it has less applicability at tow-dominated ports. Alternatively, an additional data source that reports registered GT for individual vessels could be introduced in future studies.

The PageRank algorithm is sensitive to the concentration of network nodes within a particular geographic region. Because of the large quantity of Great Lakes ports included in the analysis, it was necessary to filter the data set such that only the 30 largest Great Lakes ports were included in the national PageRank analysis. Omitting this step would have resulted in biased PageRank results that assigned unrealistically high importance to the Great Lakes region. Future studies may build on this analysis via a more systematic quantification of the algorithm's sensitivity to geographic node concentration. Alternatively, increasing the density of port polygons along the Atlantic, Gulf, and Pacific Coasts to mimic the existing Great Lakes coverage would also reduce the necessity of filtering the data set.

Differences in tonnage ranking and PageRank scores revealed information about the relative role of various SAD ports within the US maritime transportation network. Ports along the Gulf Coast tended to score higher by tonnage than by PageRank due to the highly interconnected character of the Gulf ports, the high concentration of relatively large ports along the Gulf, and their proximity to several extremely large ports, including Houston, New Orleans, and South Louisiana. Meanwhile, several SAD ports along the Atlantic Coast scored higher by PageRank than by tonnage. This was due to a variety of factors, including a combination of large size and relatively large number of connections (e.g., Savannah and Charleston), serving as a hub for more isolated regions of the network (e.g., Jacksonville), or a high concentration of passenger vessels that are not included in the tonnage reports (e.g., Miami). Ports that received a high volume of traffic from the abstract international node also tended to have an elevated PageRank score due to the iterative nature of the PageRank algorithm, although by itself a strong international connection was insufficient to guarantee a high PageRank score.

Within the context of waterway management decision-making, we propose port ranking by PageRank as a means of supporting traditional tonnage metrics when considering which ports to prioritize for funding. For sufficiently large ports (e.g., within top 10 by tonnage), this additional metric may be unnecessary; they are already likely to receive the funding required to maintain them. However, for smaller ports that rank very closely by tonnage and are competing for the remaining funds, PageRank highlights other factors that decision-makers may wish to consider, such as (1) receiving a much higher portion of traffic from overseas (e.g., Savannah), (2) serving as a critical hub for otherwise isolated areas of the country (e.g., Jacksonville and Puerto Rico), and (3) having commercial tonnage and also supporting large volumes of commercial passenger vessel traffic (e.g., Miami).

The procedure for identifying transits to unknown international ports using AIS data was also evaluated for accuracy by comparing the number of arriving vessels based on US Customs foreign vessel E&C reports to the count obtained based on travel time exceedance. The measured and calculated values were found to be positively correlated, although the AIS-based algorithm tended to underpredict the total number of international transits. Future studies could improve on these results by adjusting the travel time threshold between pairs of ports until more accurate output is obtained.

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Appendix A: Location of All Ports Represented in the Maritime Transportation Network

Table A-1 displays the geographic coordinates of the 385 ports included in the network analysis. Ports that were not included in the PageRank calculations (Section 3.7) are shaded gray.

Table A-1. Geographic coordinates of the 385 ports represented by AIS data. Ports that are shaded gray were discarded prior to the PageRank calculations.

Ports (alphabetical by state/province)	Latitude (˚N)	Longitude (˚W)
Anchorage, AK	61.25	−149.91
Chefornak, AK	60.18	−164.37
Chenega Bay, AK	60.06	−148.04
Cohoe, AK	60.38	−151.3
Cordova, AK	60.55	−145.76
Dillingham, AK	59.05	−158.47
Haines Borough (Port Chilkoot), AK	59.23	−135.43
Homer, AK	59.62	−151.47
Hooper Bay, AK	61.48	−165.95
Juneau, AK	58.3	−134.43
Kenai Peninsula Borough, AK	60.82	−151.78
Ketchikan, AK	55.35	−131.67
Kipnuk, AK	59.96	−164.06
Kivalina, AK	67.72	−164.54
Kodiak, AK	57.74	−152.41
Kotzebue (Red Dog Mine Dock), AK	67.57	−164.06
Kotzebue, AK	66.87	−162.61
Naked Island, AK	60.63	−147.39
Naknek, AK	58.73	−156.99
Nikishka-Kenai, AK	60.62	−151.32
Nome, AK	64.49	−165.44
Petersburg, AK	56.8	−132.97
Pybus Bay, AK	57.31	−134.15
Revillagigedo Island, AK	55.73	−131.69
Skagway, AK	59.45	−135.33

Table A-1 (cont.). Geographic coordinates of the 385 ports represented by AIS data. Ports that are shaded gray were discarded prior to the PageRank calculations.

Ports (alphabetical by state/province)	Latitude (˚N)	Longitude (˚W)
Skowl Arm Bay, AK	55.41	−132.36
St. Michael, AK	63.47	−162.04
Tyonek, AK	61.07	−151.14
Unalaska, AK	53.89	−166.58
Utqiagvik, AK	71.31	−156.79
Valdez, AK	61.1	−146.43
Whittier, AK	60.78	−148.68
Mobile, AL	30.64	−88.07
Little Rock, AR	34.76	−92.27
Freeport, BAHAMAS	26.52	−78.77
Prince Rupert, BC CANADA	54.3	−130.34
Vancouver, BC CANADA	49.3	−123.14
Anegada Island (South Coast), BVI	18.72	−64.39
Jost Van Dyke Island (South Coast), BVI	18.44	−64.74
Tortola Island (Pockwood Pond), BVI	18.39	−64.65
Tortola Island (Road Town), BVI	18.42	−64.61
Tortola Island (West Coast), BVI	18.42	−64.68
Trellis Bay, BVI	18.45	−64.53
Virgin Gorda Island (North Coast), BVI	18.49	−64.37
Virgin Gorda Island (West Coast), BVI	18.45	−64.44
Benicia, CA	38.04	−122.13
Humboldt Bay–Eureka, CA	40.77	−124.22
Long Beach, CA	33.76	−118.21
Los Angeles, CA	33.75	−118.26
Martinez, CA	38.03	−122.13
Oakland, CA	37.81	−122.31
Oleum-Crockett, CA	38.06	−122.24
Port Hueneme, CA	34.15	−119.21
Redwood City, CA	37.51	−122.21
Richmond, CA	37.92	−122.39
Sacramento, CA	38.56	−121.55
San Diego, CA	32.71	−117.21
Stockton, CA	37.95	−121.33
Bridgeport, CT	41.16	−73.17
Fishers Island, CT	41.26	−72.03

Table A-1 (cont.). Geographic coordinates of the 385 ports represented by AIS data. Ports that are shaded gray were discarded prior to the PageRank calculations.

Ports (alphabetical by state/province)	Latitude (˚N)	Longitude (˚W)
New Haven, CT	41.27	−72.91
New London, CT	41.35	−72.09
Havana, CUBA	23.13	−82.35
Mariel, CUBA	23	−82.76
Matanzas, CUBA	23.06	−81.52
Delaware City, DE	39.58	−75.59
Wilmington, DE	39.72	−75.53
Canaveral, FL	28.41	−80.6
Fernandina Beach, FL	30.69	−81.46
Jacksonville, FL	30.39	−81.59
Key West, FL	24.55	−81.81
Miami, FL	25.78	−80.2
Palm Beach, FL	26.77	−80.05
Panama City, FL	30.22	−85.7
Pensacola, FL	30.4	−87.22
Port Everglades, FL	26.08	−80.12
Port Manatee, FL	27.63	−82.56
St. Lucie Inlet, FL	27.18	−80.21
Tampa, FL	27.89	−82.47
Brunswick, GA	31.15	−81.52
Savannah, GA	32.1	−81.1
Guam	13.45	144.77
Barbers Point, HI	21.32	−158.12
Hanapepe Bay, Kauai, HI	21.9	−159.59
Hilo, HI	19.73	−155.07
Honolulu, HI	21.31	−157.89
Kahului, Maui, HI	20.9	−156.47
Nawiliwili, Kauai, HI	21.95	−159.36
Calumet Harbor, IL	41.71	−87.56
Chicago River, IL	41.89	−87.6
Waukegan, IL	42.37	−87.81
Burns Harbor, IN	41.64	−87.15
Gary, IN	41.62	−87.32
Indiana Harbor, IN	41.65	−87.44
Michigan City, IN	41.73	−86.91

Table A-1 (cont.). Geographic coordinates of the 385 ports represented by AIS data. Ports that are shaded gray were discarded prior to the PageRank calculations.

Ports (alphabetical by state/province)	Latitude (˚N)	Longitude (˚W)
Baton Rouge, LA	30.3	−91.12
Lake Charles, LA	30.02	−93.32
New Orleans, LA	29.95	−90.11
Plaquemines, LA	29.6	−89.8
Port Fourchon, LA	29.12	−90.21
Port of South Louisiana, LA	30.02	−90.62
Commonwealth Northern Mariana Islands	15.1	145.71
Boston, MA	42.33	−70.99
Fall River, MA	41.71	−71.17
New Bedford, MA	41.63	−70.91
Baltimore, MD	39.24	−76.55
Bucksport, ME	44.57	−68.8
Cradle Cove, ME	44.26	−68.94
Eastport, ME	44.9	−67
Isle au Haut, ME	44.07	−68.64
Portland, ME	43.65	−70.26
Rockland, ME	44.1	−69.1
Searsport, ME	44.44	−68.9
Stonington, ME	44.15	−68.67
Vinalhaven, ME	44.04	−68.84
Alpena, MI	45.06	−83.42
Arcadia, MI	44.48	−86.25
Au Sable, MI	44.41	−83.32
Bay Port, MI	43.86	−83.37
Big Bay Harbor, MI	46.83	−87.73
Black River (Upper Peninsula), MI	46.67	−90.05
Bois Blanc Island, MI	45.73	−84.45
Bolles, MI	41.86	−83.38
Brevort, MI	46.03	−85.1
Caseville, MI	43.95	−83.28
Cedarville and Port Dolomite, MI	45.99	−84.32
Charlevoix, MI	45.32	−85.26
Cheboygan, MI	45.63	−84.47
Copper Harbor, MI	47.48	−87.88
De Tour, MI	45.99	−83.9

Table A-1 (cont.). Geographic coordinates of the 385 ports represented by AIS data. Ports that are shaded gray were discarded prior to the PageRank calculations.

Ports (alphabetical by state/province)	Latitude (˚N)	Longitude (˚W)
Detroit Harbor, MI	42.29	−83.12
Drummond Island (West End), MI	45.99	−83.88
Eagle Harbor, MI	47.46	−88.16
East China Township, MI	42.76	−82.47
Escanaba, MI	45.76	−87.07
Fairbanks Township, MI	45.74	−86.65
Frankfort, MI	44.63	−86.25
Gladstone, MI	45.85	−87.01
Grand Haven, MI	43.05	−86.17
Grand Marais, MI	46.68	−85.97
Grand Traverse Bay Harbor, MI	47.19	−88.24
Grosse Point, MI	42.44	−82.88
Hammond Bay, MI	45.59	−84.16
Harbor Beach, MI	43.84	−82.64
Harbor Springs, MI	45.43	−84.98
Harrisville, MI	44.66	−83.28
Holland, MI	42.78	−86.18
Houghton Hancock Keweenaw Waterway, MI	47.1	−88.5
Isle Royal, MI	48.07	−88.57
Lac La Belle Harbor, MI	47.38	−87.99
Leland, MI	45.02	−85.77
Lexington, MI	43.27	−82.52
Little Lake Harbor (Upper Peninsula), MI	46.72	−85.37
Ludington, MI	43.95	−86.47
Mackinac Island, MI	45.87	−84.63
Mackinaw City, MI	45.78	−84.72
Manistee, MI	44.25	−86.32
Manistique, MI	45.94	−86.25
Marine City, MI	42.7	−82.5
Marquette, MI	46.54	−87.38
Monroe, MI	41.89	−83.32
Mt Clemens (Clinton River), MI	42.59	−82.82
Munising, MI	46.41	−86.65
Muskegon, MI	43.23	−86.31

Table A-1 (cont.). Geographic coordinates of the 385 ports represented by AIS data. Ports that are shaded gray were discarded prior to the PageRank calculations.

Ports (alphabetical by state/province)	Latitude (˚N)	Longitude (˚W)
New Buffalo, MI	41.8	−86.75
Onekama (Portage Lake), MI	44.36	−86.25
Ontonagan, MI	46.88	−89.33
Pentwater, MI	43.78	−86.44
Petoskey, MI	45.38	−84.96
Point Lookout Harbor, MI	44.02	−83.68
Port Austin, MI	44.06	−83
Port Inland, MI	45.97	−85.88
Port Sanilac, MI	43.43	−82.54
Port Washington, MI	43.39	−87.87
Presque Isle, MI	46.57	−87.38
Resort Township, MI	45.36	−85.03
Rogers City and Port Calcite, MI	45.41	−83.79
Saginaw, MI	43.6	−83.86
Saugatuck, MI	42.67	−86.22
Sault Ste Marie, MI, USA	46.5	−84.33
Sebewaing, MI	43.74	−83.48
Sheboygan, MI	43.75	−87.71
South Haven, MI	42.4	−86.3
St Ignace (Upper Peninsula), MI	45.87	−84.72
St Joseph, MI	42.11	−86.5
Stoneport (Presque Isle Township), MI	45.29	−83.42
Tawas Bay, MI	44.28	−83.5
Traverse City, MI	44.78	−85.62
White Lake, MI	43.37	−86.42
Whitefish Point, MI	46.76	−84.96
Wyandotte, MI	42.2	−83.15
Grand Marais, MN	47.75	−90.34
Knife River, MN	46.94	−91.78
Silver Bay, MN	47.27	−91.27
Taconite Harbor (DNR), MN	47.52	−90.92
Two Harbors, MN	47.02	−91.68
St Louis, MO	38.66	−90.2
Biloxi, MS	30.4	−88.87
Gulfport, MS	30.35	−89.09
Pascagoula, MS	30.35	−88.53

Table A-1 (cont.). Geographic coordinates of the 385 ports represented by AIS data. Ports that are shaded gray were discarded prior to the PageRank calculations.

Ports (alphabetical by state/province)	Latitude (˚N)	Longitude (˚W)
Saint John, NB, CANADA	45.15	−66.06
Morehead City, NC	34.71	−76.69
Wilmington, NC	34.21	−77.95
Portsmouth, NH	43.09	−70.78
Paulsboro, NJ	39.84	−75.25
Albany, NY	42.62	−73.76
Buffalo, NY	42.85	−78.86
Cape Vincent, NY	44.13	−76.33
Clayton (Bluff Island), NY	44.27	−76.07
Clayton (Main Harbor), NY	44.24	−76.09
Clayton (Murray Island), NY	44.29	−76.05
Clayton (Round Island), NY	44.25	−76.06
Clayton (Upper Town Landing), NY	44.26	−76.11
Coeymans, NY	42.48	−73.79
Dunkirk, NY	42.49	−79.34
Fair Haven (Little Sodus Bay), NY	43.35	−76.71
Irving (Cattaraugus Creek), NY	42.57	−79.13
New York–New Jersey	40.73	−73.97
Oak Orchard Harbor, NY	43.37	−78.19
Ogdensburg, NY	44.71	−75.49
Olcott, NY	43.34	−78.72
Oswego, NY	43.47	−76.52
Rochester, NY	43.23	−77.57
Sag Harbor, NY	41	−72.29
Sodus Point, NY	43.28	−76.97
Wilson, NY	43.32	−78.84
Youngstown, NY	43.23	−79.05
Ashtabula, OH	41.91	−80.79
Catawba Island Township, OH	41.59	−82.84
Cincinnati, OH	39.1	−84.52
Cleveland, OH	41.51	−81.69
Conneaut, OH	41.97	−80.55
Cooley Canal Harbor, OH	41.67	−83.28
Fairport Harbor, OH	41.76	−81.28
Geneva-on-the-Lake, OH	41.86	−80.97
Huron, OH	41.41	−82.54

Table A-1 (cont). Geographic coordinates of the 385 ports represented by AIS data. Ports that are shaded gray were discarded prior to the PageRank calculations.

Ports (alphabetical by state/province)	Latitude (˚N)	Longitude (˚W)
Lorain, OH	41.47	−82.18
Marblehead, OH	41.55	−82.73
Port Clinton, OH	41.52	−82.94
Put-in-Bay, OH	41.65	−82.82
Rocky River, OH	41.49	−81.84
Sandusky, OH	41.48	−82.7
Toledo, OH	41.67	−83.49
Toussaint Harbor, OH	41.59	−83.06
Vermilion, OH	41.43	−82.36
Amherstburg, ON	42.1	−83.11
Bath, ON	44.17	−76.78
Bayfield, ON	43.57	−81.71
Blind River, ON	46.17	−82.96
Brockville, ON	44.59	−75.68
Bruce Mines, ON	46.29	−83.77
Clarkson, ON	43.49	−79.61
Cobourg, ON	43.95	−78.17
Cornwall, ON	45.01	−74.71
Cramahe (Point Quarry), ON	43.97	−77.88
Elmbrook, ON	44.05	−77.12
Erieau, ON	42.25	−81.91
Froomfield, ON	42.91	−82.46
Goederich, ON	43.74	−81.73
Grand Bend, ON	43.31	−81.77
Grimsby, ON	43.2	−79.55
Hamilton, ON	43.28	−79.83
Johnstown, ON	44.73	−75.47
Kingsville, ON	42.03	−82.73
Leamington, ON	42.02	−82.6
Manitoulin (West End), ON	45.91	−83.22
Marathon, ON	48.62	−86.38
Meldrum Bay (Manitoulin Island), ON	45.93	−83.11
Midland, ON	44.78	−79.86
Mississauga, ON	43.58	−79.52
Nanticoke, ON	42.79	−80.07
Oakville, ON	43.37	−79.71

Table A-1 (cont.). Geographic coordinates of the 385 ports represented by AIS data. Ports that are shaded gray were discarded prior to the PageRank calculations.

Ports (alphabetical by state/province)	Latitude (˚N)	Longitude (˚W)
Oshawa, ON	43.87	−78.82
Owen Sound, ON	44.58	−80.94
Pickering, ON	43.81	−79.09
Port Dover, ON	42.78	−80.2
Port Maitland (Dunnville) ON	42.86	−79.58
Port Stanley, ON	42.66	−81.21
Prescott, ON	44.71	−75.52
Sarnia, ON	42.97	−82.42
Sault Ste Marie (Steelworks), ON, CANADA	46.51	−84.39
Sault Ste Marie, ON, CANADA	46.51	−84.33
South Baymouth, ON	45.55	−82.02
Spragge, ON	46.2	−82.7
St Catherines, ON	43.21	−79.26
Stoney Creek, ON	43.23	−79.62
Thessalon, ON	46.25	−83.55
Thunder Bay, ON	48.42	−89.22
Tobermory, ON	45.26	−81.67
Toronto, ON	43.63	−79.37
Whitby, ON	43.85	−78.93
Windsor, ON	42.28	−83.1
Coos Bay, OR	43.37	−124.32
Port Orford, OR	42.74	−124.5
Portland, OR	45.59	−122.73
Chester, PA	39.85	−75.34
Erie, PA	42.15	−80.07
Marcus Hook, PA	39.81	−75.41
Philadelphia, PA	39.93	−75.15
Pittsburgh, PA	40.44	−79.98
Arecibo, PR	18.48	−66.71
Cabo Rojo, PR	18.07	−67.19
Culebra (all island), PR	18.32	−65.3
Fajardo (Bahia Demajagua), PR	18.29	−65.63
Fajardo (Puerto Chico), PR	18.34	−65.63
Guanica, PR	17.96	−66.9
Guayanilla, PR	17.99	−66.77
Humacao, PR	18.08	−65.8

Table A-1 (cont.). Geographic coordinates of the 385 ports represented by AIS data. Ports that are shaded gray were discarded prior to the PageRank calculations.

Ports (alphabetical by state/province)	Latitude (˚N)	Longitude (˚W)
Jobos, PR	17.93	−66.16
Lajas, PR	17.97	−67.02
Mayaguez, PR	18.21	−67.16
Patillas, PR	17.98	−66
Ponce, PR	17.97	−66.64
Salinas, PR	17.95	−66.26
San Juan, PR	18.44	−66.1
Tallaboa, PR	17.99	−66.73
Vieques (all island), PR	18.12	−65.46
Yabucoa, PR	18.05	−65.83
Becancour, QC	46.4	−72.38
Montreal, QC	45.57	−73.52
Quebec City, QC	46.83	−71.2
Salaberry-de-Valleyfield, QC	45.22	−74.09
Sorel, QC	46.05	−73.12
Trois-Rivieres, QC	46.33	−72.55
Block Island, RI	41.17	−71.56
Providence, RI	41.62	−71.38
American Samoa	-14.3	−170.69
Charleston, SC	32.9	−79.92
Memphis, TN	35.1	−90.13
Beaumont, TX	30.02	−94
Corpus Christi, TX (Excluding Harbor Island)	27.84	−97.36
Freeport, TX	28.98	−95.37
Galveston, TX	29.31	−94.8
Harlingen (Port Isabel), TX	26	−97.29
Houston, TX	29.72	−95.13
Port Arthur, TX	29.79	−93.92
Port Lavaca - Point Comfort, TX	28.63	−96.59
Texas City, TX	29.37	−94.9
St Croix Island (Christiansted), USVI	17.76	−64.69
St Croix Island (Frederiksted), USVI	17.72	−64.9
St Croix Island (Lime Tree Bay), USVI	17.7	−64.75
St John Island (Northwest Coast), USVI	18.35	−64.78
St Thomas Island (North Coast), USVI	18.37	−64.94
St Thomas Island (South Coast), USVI	18.33	−64.92

Table A-1 (cont.). Geographic coordinates of the 385 ports represented by AIS data. Ports that are shaded gray were discarded prior to the PageRank calculations.

Ports (alphabetical by state/province)	Latitude (˚N)	Longitude (˚W)
Hopewell, VA	37.31	−77.26
Virginia, VA	36.9	−76.38
Anacortes, WA	48.52	−122.61
Bellingham, WA	48.75	−122.51
Everett, WA	47.99	−122.23
Ferndale, WA	48.84	−122.75
Grays Harbor-Aberdeen, WA	46.95	−124.07
Kalama, WA	46	−122.84
Longview, WA	46.11	−122.95
March Point, WA	48.51	−122.58
Olympia, WA	47.06	−122.91
Port Angeles, WA	48.12	−123.43
Seattle, WA	47.59	−122.36
Tacoma, WA	47.27	−122.4
Vancouver, WA	45.63	−122.68
Algoma, WI	44.61	−87.43
Ashland, WI	46.61	−90.9
Bayfield, WI	46.81	−90.81
Cedar River, WI	45.41	−87.35
Cornucopia, WI	46.86	−91.1
Duluth, MN–Superior, WI	46.74	−92.09
Green Bay, WI	44.55	−87.99
Kenosha, WI	42.59	−87.81
Kewaunee, WI	44.46	−87.5
La Pointe, WI	46.78	−90.79
Manitowoc, WI	44.09	−87.66
Menominee, MI/Marinette, WI	45.1	−87.6
Milwaukee, WI	43.02	−87.9
Northport (Ellison Bay), WI	45.29	−86.98
Oak Creek, WI	42.85	−87.83
Oconto, WI	44.9	−87.82
Pensaukee, WI	44.82	−87.89
Port Wing, WI	46.79	−91.39
Saxon Harbor, WI	46.56	−90.44
Sturgeon Bay, WI	44.83	−87.37

Table A-1 (cont.). Geographic coordinates of the 385 ports represented by AIS data. Ports that are shaded gray were discarded prior to the PageRank calculations.

Ports (alphabetical by state/province)	Latitude (˚N)	Longitude (˚W)
Suamico, WI	44.63	−88.01
Two Rivers WI	44.14	−87.56
Washburn, WI	46.67	−90.89
Washington Island (Detroit Harbor), WI	45.34	−86.94
Washington Island (Jackson Harbor), WI	45.4	−86.85
Huntington, WV	38.42	−82.54

Appendix B: Assumed Minimum International Travel Time for all Pairs of States, Provinces, or Countries with AIS Coverage

Table B-1 through Table B-4 display the values of T_{min}^{int} that were used to identify possible vessel transits to unknown international ports (Section 3.6). For each pair of states, provinces, or territories with AIS coverage, T_{min}^{int} was estimated as the minimum travel time, at 18 knots, required for a transit between two AIS-equipped ports with an intervening stop in either Mexico or Panama, plus one day for offloading at the international location. Note that the direction of travel was not assumed to affect the travel time; for example, T_{min}^{int} for a transit from Louisiana to South Carolina is equal to T_{min}^{int} for a transit from South Carolina to Louisiana. Consequently, the departure locations (rows) and arrival locations (columns) are fully interchangeable.

Table B-1. Minimum international travel time for alphabetical departures (*rows*) AK–ME and alphabetical arrivals (*columns*) AK–MS. All numbers are in days. Abbreviations: BAH = Bahamas, BC = British Columbia, BVI = British Virgin Islands. All other locations are noted by their standard US postal abbreviations.

	AK	AL	BAH	BC	BVI	CA	CT	CUBA	DE	FL	GA	HI	LA	MA	MD	ME	MS
AK	19	40	40	16	40	14	60	40	60	60	60	18	40	60	60	60	40
AL	40	9	7	40	7	40	10	6	10	8	9	40	9	10	10	11	9
BAH	40	7	6	41	6	40	9	5	9	7	8	40	7	9	8	9	7
BC	16	40	40	13	40	11	60	40	60	40	60	15	40	60	60	60	40
BVI	40	7	6	41	6	40	9	5	9	7	8	40	7	9	8	9	7
CA	14	40	40	11	40	9	60	40	60	60	60	13	40	60	60	60	40
CT	60	10	8	60	8	60	11	7	11	9	10	60	10	11	11	12	10
CUBA	40	6	5	40	5	40	8	5	8	6	7	40	6	8	7	8	6
DE	60	10	9	61	9	60	11	8	11	9	10	60	10	11	11	12	10
FL	60	8	7	40	7	60	9	6	9	7	8	60	8	9	9	10	8
GA	60	9	8	60	8	60	10	7	10	8	9	60	9	10	10	11	9
HI	18	40	40	15	40	13	60	40	60	60	60	17	40	60	60	60	40
LA	40	9	7	40	7	40	10	6	10	8	9	40	9	10	10	11	9
MA	60	10	8	60	8	60	11	7	11	9	10	60	10	11	11	12	10
MD	60	10	8	61	8	60	11	7	11	9	10	60	10	11	11	12	10
ME	60	11	8	60	8	60	12	7	12	10	11	60	11	12	12	13	11

Table B-2. Minimum international travel time for alphabetical departures (*rows*) MS–WA and alphabetical arrivals (*columns*) AK–MS. All numbers are in days. Abbreviations: BAH = Bahamas, BC = British Columbia, BVI = British Virgin Islands, NB = New Brunswick, ON = Ontario, QC = Quebec, and USVI = US Virgin Islands. All other locations are noted by their standard US postal abbreviations.

	AK	AL	BAH	BC	BVI	CA	CT	CUBA	DE	FL	GA	HI	LA	MA	MD	ME	MS
MS	40	9	7	40	7	40	10	6	10	8	9	40	9	10	10	11	9
NB	60	10	10	60	10	60	12	9	12	10	11	60	10	12	11	12	10
NC	60	9	8	60	8	60	10	7	10	8	9	60	9	10	10	11	9
NH	60	11	8	60	8	60	12	7	12	10	11	60	11	12	12	13	11
NJ	60	10	8	60	8	60	11	7	11	9	10	60	10	11	11	12	10
NY	60	10	8	60	8	60	11	7	11	9	10	60	10	11	11	12	10
ON	60	13	13	61	13	60	15	12	15	13	14	60	13	15	14	15	13
OR	16	40	40	13	40	11	60	40	60	60	60	15	40	60	60	60	40
PA	60	10	9	61	9	60	11	8	11	9	10	60	10	11	11	12	10
PR	40	8	6	40	6	40	9	5	9	7	8	40	8	9	9	10	8
QC	60	11	11	61	11	60	13	10	13	11	12	60	11	13	12	13	11
RI	60	10	8	60	8	60	11	7	11	9	10	60	10	11	11	12	10
SC	60	9	8	60	8	60	10	7	10	8	9	60	9	10	10	11	9
TX	40	9	7	40	7	40	10	6	10	8	9	40	9	10	10	11	9
USVI	40	7	6	41	6	40	9	5	9	7	8	40	7	9	8	9	7
VA	60	10	8	60	8	60	11	7	11	9	10	60	10	11	11	12	10
WA	16	40	40	13	40	11	60	40	60	60	60	15	40	60	60	60	40

Table B-3. Minimum international travel time for alphabetical departures (*rows*) AK–ME and alphabetical arrivals (*columns*) NB–WA. All numbers are in days. Abbreviations: BAH = Bahamas, BC = British Columbia, BVI = British Virgin Islands, NB = New Brunswick, ON = Ontario, QC = Quebec, and USVI = US Virgin Islands. All other locations are noted by their standard US postal abbreviations.

	NB	NC	NH	NJ	NY	ON	OR	PA	PR	QC	RI	SC	TX	USVI	VA	WA
AK	60	60	60	60	60	60	16	60	40	60	60	60	40	40	60	16
AL	10	9	11	10	10	13	40	10	8	11	10	9	9	7	10	40
BAH	10	8	9	9	9	13	40	9	6	11	9	8	7	6	8	40
BC	60	60	60	60	60	60	13	60	40	60	60	60	40	40	60	13
BVI	10	8	9	9	9	13	40	9	6	11	9	8	7	6	8	40
CA	60	60	60	60	60	60	11	60	40	60	60	60	40	40	60	11
CT	11	10	12	11	11	14	60	11	9	12	11	10	10	8	11	60
CUBA	9	7	8	8	8	12	40	8	5	10	8	7	6	5	7	40
DE	12	10	12	11	11	15	60	11	9	13	11	10	10	9	11	60
FL	10	8	10	9	9	13	60	9	7	11	9	8	8	7	9	60
GA	11	9	11	10	10	14	60	10	8	12	10	9	9	8	10	60
HI	60	60	60	60	60	60	15	60	40	60	60	60	40	40	60	15
LA	10	9	11	10	10	13	40	10	8	11	10	9	9	7	10	40
MA	11	10	12	11	11	14	60	11	9	12	11	10	10	8	11	60
MD	11	10	12	11	11	14	60	11	9	12	11	10	10	8	11	60
ME	11	11	13	12	12	14	60	12	10	12	12	11	11	8	12	60

Table B-4. Minimum international travel time for alphabetical departures (*rows*) MS–WA and alphabetical arrivals (*columns*) NB–WA. All numbers are in days. Abbreviations: NB = New Brunswick, ON = Ontario, QC = Quebec, and USVI = US Virgin Islands. All other locations are noted by their standard US postal abbreviations.

	NB	NC	NH	NJ	NY	ON	OR	PA	PR	QC	RI	SC	TX	USVI	VA	WA
MS	10	9	11	10	10	13	40	10	8	11	10	9	9	7	10	40
NB	13	11	12	12	12	15	60	12	9	14	12	11	10	10	11	60
NC	11	9	11	10	10	14	60	10	8	12	10	9	9	8	10	60
NH	11	11	13	12	12	14	60	12	10	12	12	11	11	8	12	60
NJ	11	10	12	11	11	14	60	11	9	12	11	10	10	8	11	60
NY	11	10	12	11	11	14	60	11	9	12	11	10	10	8	11	60
ON	15	14	15	15	15	18	60	15	12	17	15	14	13	13	14	60
OR	60	60	60	60	60	60	13	60	40	60	60	60	40	40	60	13
PA	12	10	12	11	11	15	60	11	9	13	11	10	10	9	11	60
PR	9	8	10	9	9	12	40	9	7	10	9	8	8	6	9	40
QC	14	12	13	13	13	17	60	13	10	14	13	12	11	11	12	60
RI	11	10	12	11	11	14	60	11	9	12	11	10	10	8	11	60
SC	11	9	11	10	10	14	60	10	8	12	10	9	9	8	10	60
TX	10	9	11	10	10	13	40	10	8	11	10	9	9	7	10	40
USVI	10	8	9	9	9	13	40	9	6	11	9	8	7	6	8	40
VA	11	10	12	11	11	14	60	11	9	12	11	10	10	8	11	60
WA	60	60	60	60	60	60	13	60	40	60	60	60	40	40	60	13

Appendix C: Results for All Retained SAD Ports

Table C-1. Tonnage and PageRank results for all retained SAD ports based on data from 2015 through 2019. The first number in each column is the raw value, and the number in parentheses is the ranking among all US ports considered in this study.

Port	Tonnage in millions of short tons and (national rank)	PageRank score (x10^{-3}) and (national rank)
Mobile, AL	290.31 (11)	7.06 (32)
Savannah, GA	194.73 (17)	18.02 (6)
Tampa, FL	165.40 (22)	7.97 (26)
Pascagoula, MS	132.32 (25)	4.35 (52)
Charleston, SC	121.23 (26)	15.68 (9)
Port Everglades, FL	121.20 (27)	11.61 (15)
Jacksonville, FL	90.35 (36)	10.29 (18)
San Juan, PR	54.20 (48)	4.51 (51)
Miami, FL	40.86 (58)	7.62 (29)
Wilmington, NC	28.55 (65)	3.05 (81)
Canaveral, FL	24.86 (68)	3.75 (65)
Port Manatee, FL	18.16 (75)	1.84 (122)
Morehead City, NC	13.32 (79)	1.62 (134)
Brunswick, GA	12.80 (83)	3.21 (76)
Panama City, FL	11.48 (90)	1.62 (132)
Palm Beach, FL	11.44 (91)	2.09 (112)
Gulfport, MS	10.15 (97)	1.55 (140)
Ponce, PR	6.15 (108)	1.39 (166)
Biloxi, MS	1.89 (120)	1.36 (176)
Pensacola, FL	1.68 (121)	1.43 (156)

Table C-1 (cont). Tonnage and PageRank results for all retained SAD ports based on data from 2015 through 2019. The first number in each column is the raw value, and the number in parentheses is the ranking among all US ports considered in this study.

Port	Tonnage in millions of short tons and (national rank)	PageRank score (x10^{-3}) and (national rank)
Key West, FL	No data	3.02 (82)
Guayanilla, PR	No data	1.61 (135)
Jobos, PR	No data	1.47 (150)
Salinas, PR	No data	1.42 (158)
Fernandina Beach, FL	No data	1.40 (162)
Tallaboa, PR	No data	1.37 (174)

Abbreviations

AIS	Automatic Identification System
AVIS	Authoritative Vessel Identification System
E&C	Entrances and clearances
GT	Gross tonnage
ITB	Integrated tug barge
MMSI	Maritime Mobility Service Identity
MTS	Maritime transportation system
NAIS	Nationwide Automatic Identification System
NRT	Net registered tonnage
SAD	South Atlantic Division
USACE	US Army Corps of Engineers
VHF	Very high frequency

REPORT DOCUMENTATION PAGE			*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE (DD-MM-YYYY)	**2. REPORT TYPE**	**3. DATES COVERED (From - To)**
January 2023	Final	FY22

4. TITLE AND SUBTITLE
US Port Connectivity and Ramifications for Maintenance of South Atlantic Division Ports

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT

6. AUTHOR(S)
Rachel L. Bain, David L. Young, Marin M. Kress, Katherine F. Chambers, and Brandan M. Scully

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
US Army Engineer Research and Development Center (ERDC)
Coastal and Hydraulics Laboratory (CHL)
3909 Halls Ferry Road,
Vicksburg, MS 39180-6199

8. PERFORMING ORGANIZATION REPORT NUMBER
ERDC/CHL SR-23-1

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
US Army Corps of Engineers (USACE)
Jacksonville District
701 San Marco Blvd.
Jacksonville, FL 32207

10. SPONSOR/MONITOR'S ACRONYM(S)
CESAJ

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
DISTRIBUTION STATEMENT A. Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES
Funding via labor charge code

14. ABSTRACT
This study utilized automatic identification system (AIS) data to quantify vessel traffic patterns within a predominantly US port network from 1 January 2009 to 31 December 2020, with the methods validated using independent data sets collected between 1 January 2015 and 31 December 2019. The analysis focused on South Atlantic Division (SAD) ports. AIS-derived data characterized individual ports' traffic and port-to-port connectivity for the network. With foreign vessel entrances and clearances (E&C) data, the AIS-reported vessel characteristics enabled calculation of ships' physical volume, which was a reasonable proxy for tonnage at many SAD ports. The PageRank algorithm was then applied to port-to-port traffic, revealing how individual ports participate in cargo movement through the network. PageRank scores also provided insight into the maritime supply chain beyond traditional traffic metrics. For example, many East Coast SAD ports ranked higher by PageRank than by raw tonnage. Because of the supply chain implications of shared vessel traffic, PageRank scores can augment tonnage metrics when prioritizing channel and infrastructure maintenance. Vessel volume, port-to-port connectivity, and PageRank scores reveal maritime supply chain resilience by identifying alternative destinations for cargo bound for disrupted ports, robustness across supply chains, and the effects of seasonality and disruptions.

15. SUBJECT TERMS
Harbors–Atlantic Coast (South Atlantic States); Navigation—Performance; Shipment of goods; Ships–Automatic identification systems

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			**19b. TELEPHONE NUMBER (include area code)**
Unclassified	Unclassified	Unclassified	SAR	72	