

Quantifying the extent of niche areas in the global fleet of commercial ships: the potential for “super-hot spots” of biofouling

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Abstract Niche areas of ships, such as lateral thruster tunnels, sea chests, and propellers, are often hot spots for the accumulation of biofouling organisms, a potential source of aquatic invasive species. Yet, the relative importance of different niche areas is poorly resolved, in terms of both total surface area and the associated biota (i.e., the species of organisms and their abundances). To address this information gap, a method was developed to estimate the extent of various niche areas in the global fleet of 120,252 commercial ships active between 1999 and 2013. The total niche area for these vessels was estimated to be $32,996 \times 10^3 \text{ m}^2$, representing approximately 10% of the total wetted surface area (WSA) available for colonization by biota. Considering the

portion of niche areas relative to the total WSA, it was highest for passenger vessels (27%), followed by tugs (25%), and fishing vessels (21%), with niche areas representing a small portion of the WSA for bulk carriers and tankers (7–8%). Examining the different types of niche areas, thruster tunnels had the greatest total extent ($10,189 \times 10^3 \text{ m}^2$), representing a disproportionately large contribution (>50%) of the total niche area for passenger vessels and tugs compared to other vessel types. This result, combined with the use and cleaning of thrusters, may render them “super-hot spots” of biofouling. The uneven distribution and extent of niche areas across vessels has implications for transfers of organisms and management strategies to reduce invasions associated with the surfaces of ships.

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Introduction

Biofouling can accumulate quickly when a surface is submerged in natural waters, allowing bacteria to establish microbial biofilms (e.g., Zobell 1943; Baier et al. 1983; Decho 2000), thereby providing a biological substrate for additional microfouling and macrofouling. Macrofouling in particular, which includes a range of visible organisms such as barnacles, mussels, tunicates, and bryozoans, accumulates on ships' surfaces (e.g., Visscher 1928; Carlton 1987; Gollasch 2002), and macrofouling communities can carry potentially invasive species among bodies of water (e.g., Hewitt 2002; Davidson et al. 2008). Upon establishment, the invasive species can displace native species (e.g., Simberloff and Von Holle 1999) and cause ecological and economic damage to local natural resources and infrastructure (e.g., Pimentel et al. 2005; Lovell and Drake 2009).

To date, efforts to reduce the transfer of aquatic nuisance species (ANS) by ships have focused primarily on the management of organisms in *ballast water*. At the global level, management strategies for ballast water have been advancing for decades at the International Maritime Organization (IMO), which has adopted the Convention for the Control and Management of Ships' Ballast Water and Sediments (IMO 2004). This Convention, which will enter into force in September 2017, sets standards establishing stringent limits on the discharge of living organisms in ships' ballast water. In contrast, the IMO has only adopted guidelines—not a standard—to minimize the transfer of species via *biofouling* on ships (IMO 2011) and recreational craft (IMO 2012). These guidelines advocate the use of best management practices to reduce the likelihood and degree of species transfers. Among all nations, only New Zealand has issued a biofouling standard. It will enter into force in May 2018 and requires vessels arriving to the country to have “clean hulls,” which will be assessed based on factors including coating type, application history, vessel transit locations, hull maintenance records, and in some cases, hull inspections (MPI 2014). Australia is currently considering a similar regulatory tool (Australian Department of Agriculture 2015), although it should be noted that the Northern Territory government has been inspecting all vessels entering their locked marinas in Darwin since the introduction of the black striped mussel in 1999 (NT 2016). At the

regional level, other actions have been taken: Ecuador has implemented a hull inspection program in the Galapagos Islands (Campbell et al. 2015). Hawaii requires a hull inspection for biofouling organisms prior to entering the Papahānaumokuākea Marine National Monument Northern of the US northern Hawaiian islands (Papahānaumokuākea Marine National Monument 2008). California has proposed performance standards for biofouling management, but to date, they have not entered into law.

Despite the limited and nascent focus on reducing species transfers via ships' hulls, it is evident that hull biofouling is a potent vector (e.g., Williams et al. 2013; Ruiz et al. 2015), and in some areas, it may surpass ballast water as a potential source of coastal marine invasions (Hewitt 2002; Drake and Lodge 2007). Moreover, a recent study estimated that the total *hull wetted surface area* (WSA; also referred to as the “naked wetted surface area”) of the global fleet of commercial ships was approximately 325 km², which, for perspective, is roughly equal to double the area of Washington D.C. (Moser et al. 2015). This previous analysis underscores the extent of hull surface area available for colonization and transfer of biofouling organisms that are associated with the commercial ships moving among ports throughout the world.

Measures to manage biofouling on ships include undertaking regular cleaning (both in-water cleaning and at dry dock) and applying anti-fouling coating systems. However, the hulls of vessels are complex surfaces, having many different “niche areas” that affect the performance of various management strategies. Some areas can be difficult or unsafe to access for cleaning while the ship is in the water. Hull protrusions, cavities, and appendages alter the hydrodynamic flow around the ship's hull and cause heavy turbulence that can abrade coating systems in local areas faster than under normal flow conditions (Carlton 2007). Further, coating systems are susceptible to failure around the angular edges of ship penetrations, appendages, or gratings, where access for coating application is limited, surface tension can cause cracking in the coating, and there is a reduced dry film thickness of the coating system (Parente et al. 1996). Thus, with respect to biofouling, coatings systems in these areas may be subject to erosion, facilitating colonization by organisms. In contrast,

ablative coatings, which are designed to gradually wear away to liberate or expose new antifouling or biocidal agents to reveal new coatings, lose effectiveness in areas where water is stagnant or there is little agitation to wear away old layers depleted of biocidal agents (Lanier 2014). Therefore, the efficacy of these coating systems decreases in low-flow regimes. In addition, on certain surfaces, the coating may be physically damaged or completely lacking (e.g., propellers and sacrificial anodes). Regardless of the mechanism for management strategies' loss of effectiveness, when and where it occurs, biofouling accumulates at an accelerated rate.

Historically, efforts to prevent biofouling on niche areas have been much less than that for the overall flat surface of the hull, since the primary goal of hull cleaning is to reduce hydrodynamic drag and, in turn, fuel consumption (e.g., Schultz et al. 2011). The favorable conditions that some niche areas provide, however, can result in “hot spots” of biofouling (Sylvester and MacIsaac 2010). This phenomenon has been recognized in a limited number of studies focusing on the extent and type of fouling in particular niche areas (e.g., Coutts and Taylor 2004; Davidson et al. 2009) such as sea chests (Coutts et al. 2003, Coutts and Dodgshun 2007). As a result, some niche areas are more likely to harbor biofouling organisms, although a full analysis of the likelihood of ANS invasions by organisms associated with these special areas is lacking. A next step is to quantify the extent of the niche areas. In doing so, the extent of niche areas can be quantified according to niche area function for various ship types, and the opportunity for biofouling in each sub-area examined. With this knowledge, resources for the management of biofouling can focus on the high-risk areas.

The goals of this study were to (1) develop a method to estimate the extent of niche areas for a diversity of vessel types using publicly available ships' measurements, and (2) apply this method to generate an initial, contemporary measurement of the extent of niche areas for the global fleet of commercial ships. The method was developed from a data set of ~191,000 commercial ships and applied to a subset of these data comprising ~120,000 ships known to be active between 1999 and 2013. The results were categorized by ship type (e.g., bulk carriers, tankers, etc.) and niche area.

Materials and methods

Data collection

The scope of the study, the data collected, and the data sources were similar to the study estimating the total hull wetted area of the global fleet of commercial ships (Moser et al. 2015). Briefly, the study was limited to ships with assigned IMO numbers. Data for 191,440 ships were collected from the Smithsonian Environmental Research Center (SERC), the National Ballast Information Clearinghouse (NBIC), American Bureau of Shipping (ABS), Bureau Veritas (BV), Det Norske Veritas (DNV; now DNV GL), Russian Maritime register of Shipping (RU), and Maritime-connector.com databases. Overall statistics (e.g., total gross tonnage [GT], number of ships, etc.) describing the global commercial shipping fleet were obtained from Equasis through the European Maritime Safety Agency (EMSA 2012). Using Equasis statistics as a guide, ships were categorized according to operational profiles into the following nine functional types: bulk carriers, tankers, containerships, general cargo ships, liquefied natural gas and liquefied petroleum gas carriers (LNG and LPG carriers), passenger ships, fishing vessels, tugs and supply vessels, and “other” ships (i.e., ships that did not fit into one of the previous functional types [EMSA 2012]). Categorizing ships in this manner allowed assumptions specific to a given hull form to be applied to that ship type rather than generalizing across the entire fleet.

In addition, similar to the previous study, not all ships from the databases could be included in the global estimate, since some of the vessels for which data were extracted were inactive or removed from service. Records of active ships provided by SERC from the NBIC found 120,252 vessels were active between 1999 and 2013 in the U.S. (NBIC 2013). While these data were obtained from ships arriving to the U.S. during 1999–2013, they likely represent a major portion of the global fleet, since a large fraction of their records were present in databases from organizations around the world. Note that all ships in the database (191,440 ships, potentially including inactive ships) were used to develop the *method* of calculating the extent of the niche area since their design parameters were relevant. That is, ship design standards are fairly rigid over time—the same design

standards applied over 50 years ago are still in use today (e.g., Saunders 1957).

An additional data set was obtained via published records of ships' specifications: *Significant Ships*, a yearly periodical that is commercially available. Each issue contained records—sets of fields that contain a single item of information on a ship such as the number of lateral thrusters or the propeller diameters—and approximately 50 ships were described each year. The entire set of data included records for 984 ships described over 19 years (1993–2012). The journal also contained general arrangement drawings for each ship that were important for visually confirming various features of the ships. General dimensions published in *Significant Ships* (e.g., length overall of the ship, breadth overall, depth, etc.) were linked to the database of ships compiled from publicly available sources and to compensate for incomplete data.

Estimating the extent of niche areas

To estimate the total WSA of the global fleet of commercial ships, multiple statistical models were developed so commonly available ships' parameters could be used to estimate the WSA for a given set of fleet data. This was done for the hull only, i.e., the surface area of features or appendages external to the hull were not included (Moser et al. 2015). The methods used to estimate the total WSA were closely followed to estimate extent of niche areas for a given set of fleet data.

Generalizing any aspect of ship design can be problematic, as many features and characteristics of an individual ship are based on specific requirements of the ship's mission profile and the individual preferences of the ship-owner and naval architect to meet those requirements. Optimal performance in areas such as maneuverability, speed, safety, and fuel consumption are achieved by considering a range of operating conditions that are specific to the ship's purpose and geographic location. This includes, but is not limited to, wave heights, sea surface roughness, currents, water temperatures, navigation restrictions of ports and canals, travel distances, depth and clearance thresholds, cargos, as well as port authority laws and regulations. Data for many of these conditions were not present in any of the sources surveyed. Without

knowledge of these particulars, many niche areas on a ship could not be included in this study (e.g., rudder horns, bulbous bows, anchor chains, propulsor shafts, rope guards, internal piping, etc.). Moreover, the scarcity of detailed data does not permit the use of traditional approaches to the design of any ship features. However, in the initial design phases of a ship, architects use standards and guidelines based on general empirical data from similar ships to derive preliminary dimensional estimates for several critical features of the ship. These standards were adapted and applied to the available data in this study to approximate the extent of the following niche areas: bilge keels, dry dock support strips (DDSS), propellers, rudders, sea chests, sea chest gratings, lateral thrusters, thruster gratings, and thruster tunnels. Because of this inconsistent availability of data, the niche area estimates in this study are likely underestimates, but they serve as a standardized baseline from which to conduct future work.

Although the data needed to calculate the extent of the niche areas (Table 1) were available for some ships, most ship records were incomplete (e.g., many records are missing the length between perpendiculars, L_{BP}). To complete the analysis, it was necessary to model the relationships of some parameters in terms of those that were more frequently included in the data. For example, 55% of the ship records for active ships contained only the L_{BP} , so it was modeled in terms of the dead weight tonnage (DWT), which was contained in 78% of the records. In fact, the DWT was the most frequently listed parameter in all databases, and it showed a strong correlation with many of the primary dimensions of the ship; therefore, it was used as the "base parameter" in all but two of the models (Table 2; discussed below).

Using data from ~191,000 ships, both active and inactive, relationships between the modeled parameter (e.g., L_{BP} as in previous example) and the base parameter (e.g., DWT) were modeled using a non-linear regression performed using SigmaPlot (V11, Systat, San Jose, CA). The relationship between the modeled parameter and base parameter best conformed to the power equation: $y = ax^b$, where y = modeled parameter, x = base parameter, and a and b are the coefficient and the exponent of the base parameter, respectively. The curve-fitting algorithm optimized values of a and b to maximize the

Table 1 List of acronyms of ship design parameters and their descriptions

Acronym or symbol	Parameter	Description
Δ	Displacement tonnage	The weight of the water that a vessel displaces at maximum summer draft
∇	Volumetric displacement	Volume of water that a vessel displaces at maximum summer draft; calculated using the displacement tonnage and an assumed seawater density of 1025 kg m^{-3}
B_{OA}	Breadth overall	The extreme breadth of a vessel
C_b	Block coefficient	Ratio of a vessel's volume displacement over the block volume of its submerged hull
D	Depth	The vertical distance between the keel and the uppermost continuous deck of a vessel
D_P	Propeller diameter	Diameter of the a vessel's primary propeller(s)
D_T	Thruster diameter	Diameter of a vessel's thruster propellers
DWT	Dead weight tonnage	The maximum summer weight a vessel can carry (e.g., cargo, fuel, passengers, etc.)
GT	Gross tonnage	Represents the molded volume of all enclosed spaces of a vessel
K	Rudder proportional constant	Proportion of the side profile of a vessel's rudder to its submerged lateral area; dependent on ship type
L_{BP}	Length between perpendiculars	The length between perpendiculars of a vessel (main bow perpendicular member to the after surface of the sternpost)
L_{BPT}	Submerged lateral area	Value obtained by multiplying a vessel's length between perpendiculars by its draft
L_{OA}	Length overall	The length overall of a vessel
S	Speed	The service speed of a vessel at maximum continuous rating of the engines at loaded draft
ST	Speed draft factor	Value obtained by multiplying a vessel's speed by its draft
T	Draft	The vertical distance measuring the depth to which a vessel is immersed in water at maximum summer draft (service draft for container vessels)
V	Speed	Vessel's service speed

Table 2 Models of the relationships between parameters used to compute the extent of niche areas

Niche area	Model used	Modeled parameter	Base parameter	Average R^2	Minimum R^2	Maximum R^2
Bilge keels	Power	L_{BP}	DWT	0.92	0.78	0.99
Dry dock support strips	Linear	Δ	DWT	0.95	0.80	>0.99
Propellers	Power	D_P	ST	0.87	0.73	0.94
	Power	ST ($S \cdot T$)	DWT	0.81	0.54	0.97
Rudders	Power	L_{BPT} ($L_{BP} \cdot T$)	DWT	0.92	0.80	>0.99
Sea chests, sea chest gratings	None	N/A	N/A	N/A	N/A	N/A
Lateral thruster propellers, tunnels, and gratings	Power	D_T	P_T	0.98	0.98	0.98

The models were developed for each of the nine ship types. For linear models, the y-intercept was set to zero, and in all cases, the relationships were significant ($p < 0.001$)

L_{BP} length between perpendiculars, L_{BPT} submerged lateral area, DWT dead weight tonnage, Δ displacement tonnage, D_P propeller diameter, S speed, ST speed draft factor, T draft, D_T thruster diameter, P_T thruster power

coefficient of determination (R^2). This method was used to model all relationships except for the displacement tonnage (Δ) vs. DWT (Table 2), where a

linear regression model provided the best fit. The methods pertinent to each niche area are unique, but in general, estimates were derived by (1) applying the

naval architecture standards and guidelines directly to ships using available data, (2) applying the naval architecture standards and guidelines directly to ships using regression analyses to provide missing data, and (3) assuming the average area for the ship type (Fig. 1).

Bilge keels

Bilge keels provide hydrodynamic stability to protect the vessel against roll (Saunders 1957). They are typically paired symmetrically about the keel line at the turn of the bilge and run approximately half the length of the ship. The length and depth of most common bilge keels can be calculated using the following formulas (Watson 1998):

$$\text{Length of Keel} = 0.6 \times C_b \times L_{BP} \tag{1}$$

$$\text{Depth of Keel} = \frac{0.18}{(C_b - 0.2)} \tag{2}$$

The block coefficient C_b is calculated by dividing the vessel’s volume displacement over the block volume of its submerged hull,

$$C_b = \frac{\nabla}{L_{WL} \times B \times T} \tag{3}$$

where ∇ = Volume displacement at maximum summer draft, calculated using the weight of the vessel, or the displacement tonnage (Δ), and an assumed seawater density of 1025 kg m^{-3} , L_{WL} = Length at the waterline, calculated from L_{BP} using the conversion factor $L_{BP} = 0.97 L_{WL}$ (MAN Diesel and Turbo

2011), B = Breadth, substituted using breadth overall (B_{OA}), and T = Draft.

The following formula can be used to approximate the block coefficient where a vessel’s B , T , or Δ is unknown (Watson 1998):

$$C_b = 0.70 + \frac{1}{8} \tan^{-1} \left(\frac{23 - 100F_n}{4} \right) \text{radians} \tag{4}$$

where F_n is the Froude number expressed as (Watson 1998),

$$F_n = \frac{V}{\sqrt{g \times L_{WL}}} \tag{5}$$

where V = Speed and g = Force due to gravity.

The L_{BP} is required to calculate the length and depth of the bilge keel using the above equations, therefore, a regression model was developed for the relationship between the L_{BP} and DWT. Where it was missing, the L_{BP} was estimated using the model for ship records as described above. Next, C_b was calculated using Eq. 3, while Eq. 4 was used to calculate C_b where B_{OA} , T , or Δ data was missing from ship records. For ships with no data, the average C_b for the ship type was assumed. For example, if a containership did not include data for B_{OA} , T , or Δ , then the average C_b for all containerships was applied to this record. Using L_{BP} and C_b , the length and depth of the bilge keel were calculated using Eqs. 1 and 2, respectively. The bilge keel shape was assumed to be rectangular, with a constant depth from the hull (Eq. 1) multiplied by the length of the keel (Eq. 2), to obtain the area of one side of the bilge keel. The area was quadrupled to total all sides of two bilge keels. The thickness of the keels was not taken into consideration. Since there were no data to verify the presence or absence of bilge keels in the ship records, it was assumed that all ships have bilge keels.

Dry dock support strips (DDSS)

When a ship is placed into a dry dock, it is supported using blocks placed along the hull of the ship. The ship is floated onto the blocks and after the water is drained from the dry dock, the area in contact between the ship’s hull and support blocks is inaccessible, so coatings are often not applied to these areas (Piola and Conwell 2010). Areas where coating systems exist can also be worn by abrasion against the blocks. The dry dock support blocks must have sufficient load bearing

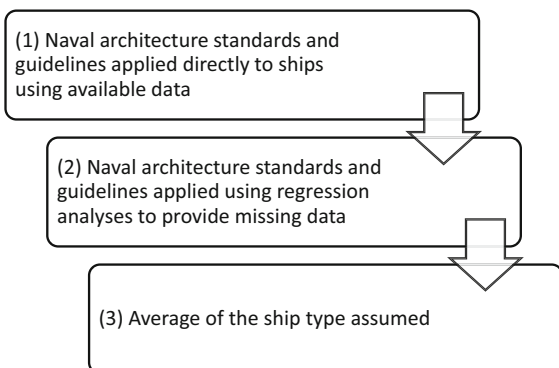


Fig. 1 Flow chart illustrating the general decision process used to calculate the area for each niche area

area in contact with the ship's hull to prevent damage to the internal structure. The U.S. Navy requires that the average hull bearing stress be less than 20 long tons ft⁻² (219 tonne m⁻²) (Heger 2005). Applying this standard to commercial vessels, the total area of DDSS for a single ship was calculated by dividing its displacement tonnage by the maximum hull bearing stress. The resulting area is assumed equivalent to the minimum support surface area in contact with the hull during dry docking. Then the area of DDSS can be expressed as,

$$\text{Total Area, DDSS} = \frac{\Delta}{\sigma_{\max}} \quad (6)$$

where Δ = Displacement tonnage at maximum summer draft and σ_{\max} = Maximum hull bearing stress. For those vessels without displacement data, a linear regression was used to model Δ based on DWT.

Propellers

Ship propulsion devices come in many forms, but fixed-pitch propellers—also referred to as screw propellers—are by far the most common type used on modern commercial ships. Hence, only fixed-pitch propellers were considered in this study. Distinguished by their helical shaped blades, these propellers usually have between three and six blades on a single hub (MAN Diesel and Turbo 2011). Propeller designs can be highly sophisticated, depending on a ship's required performance, hydrodynamic conditions, available power, and construction costs, but, in general, a ship's draft and required speed greatly influence the propeller design (e.g., Carlton 2007).

The surface area for a propeller was determined by considering the area of the circle that the propeller inscribes, assuming a ratio for the area of the blades of 0.55 (MAN Diesel and Turbo 2011) and doubling to account for both sides,

$$\text{Total Area, Propeller} = 1.1\pi \frac{(D_P)^2}{4} \quad (7)$$

where D_P = Propeller diameter. Since the diameter of the propeller was not a parameter included in the database, data from *Significant Ships* journals were used to develop a regression model to estimate the diameter of the propeller in terms of a ship's speed and

draft (ST). For those vessels lacking speed or draft data, the ST was modeled based on DWT.

Only about 57% of ship records contained data for the number of propellers, and of those, many ships had multiple propellers, and sometimes—although rarely—as many as eight. Analyzing the relationships between the number of propellers and common ship parameters revealed no apparent correlations. For ship records without propeller data, the number of propellers for each ship type was assumed the same percentage as those in the available data. For example, of the 10,299 bulk carriers with data for the number of propellers, 98.1% had one and 1.9% had two. Then, it was assumed for the 251 bulk carriers without data for the number of propellers that 246 (98%), had one, and the remainder (2%), had two. The number of propellers was *not* assumed to affect the size of the propellers since ship designers normally prefer the largest possible diameter to maximize efficiency (Saunders 1957).

Rudders

For merchant ships, rudders are typically stern-mounted and centered about the outflow jet, abaft (behind) the propeller. The ship's rudder must provide a sufficient control surface to provide an acceptable range of maneuverability (IMO 1993). This area can generally be approximated as a proportion of the submerged lateral area, based on the ship type (Saunders 1957),

$$\text{Side Profile Area, Rudder} = KL_{BP}T \quad (8)$$

where K = Proportional constant, dependent on ship type. For example, the proportional constant K for containerships is 0.018 (no units), so the area of the side profile of the rudder would be approximately 1.8% of the ships' submerged lateral area, $L_{BP} \cdot T$. For comparison, the proportional constant for tug and supply ships is 0.035. This method was used for all ship records containing L_{BP} and T data. To complete the analysis, the relationship between the lateral area and DWT was modeled and used for ship records without L_{BP} and T data. For ship records without L_{BP} and T , or DWT data, the average rudder area of the ship type was assumed. It was also assumed that the same rudder surface area from Eq. 8 applies, even when there are multiple rudders.

The top profile of modern rudders is generally a symmetrical foil, similar to a teardrop viewed in cross section, to streamline flow around the leading and trailing edges (Molland and Turnock 2007). For simplicity in this study, the contours of this shape were approximated by assuming a triangle with the base adjoining a half-circle, or “snow cone” geometry. Here, the ratio of the half-circle diameter to the chord, or the total length of the rudder, is equivalent to the relative maximum thickness (RMT) of the rudder. The RMT, a parameter used in rudder design, was assumed 0.15, a value frequently used by designers (Thieme 1965). The aspect ratio of the rudder i.e., the ratio of the rudder’s span to its chord was assumed to be 1.75 (Barrass 2004). Given these assumptions, the area of the top profile of the rudder can be estimated as 4.47% of the side profile area. The total area of the rudder was calculated by doubling the area of the side profile and top profile of the rudder and summing those values for each ship, which ultimately reduces to,

$$\text{Total Area, Rudder} = 2.0894KL_{BP}T \quad (9)$$

The areas of the structures attaching the rudder to the ship (e.g., post or the horn coupling) were not considered in the calculation of the rudder area.

Sea chests and sea chest gratings

While sea chests are primarily used for ballasting, cooling, and fire prevention purposes, they also prevent suction or discharge flows from disrupting laminar flow over the ship’s hull (Taylor and Rigby 2001), as these deep penetrations into hulls are designed to optimize flow into seawater intake pipes. The size of sea chests varies depending on flow requirements, and larger ships normally have multiple upper and lower sea chests. Sea chests have slotted, perforated, or flush-mounted gratings to prevent large debris from entering the system, and the open area of the gratings are sized to allow for proper suction from the pumps.

Typical ballasting rates are listed by ship type and size class in the American Bureau of Shipping Ballast Water Advisory (ABS 2014). Assuming these rates represent the design flow of the seawater intake, and using guidance from the United States Code of Federal Regulations that cooling water structures should have through-screen intake velocity of no more than

0.5 ft s⁻¹ (CFR 2003), the total open area, or the area through which water flows into the sea chest, was calculated as

$$\text{Open Area, Sea Chest Gratings} = \frac{Q_B}{V_{g,max}} \quad (10)$$

where Q_B = Volumetric flow rate of the seawater intake and $V_{g,max}$ = Maximum flow velocity through the grating. As a general practice, the open area of the grating should be 80% of the total area of the entrance of the sea chest (WorleyParsons Ltd. 2006). Thus, the total area of the exterior of the sea chests was assumed to be 125% of the open area at the gratings. The area of the gratings, inside and out, which are prone to biofouling was assumed to be 40% of the exterior. The areas of the interior regions of the sea chests were estimated by assuming they were in the shape of a cube, with each wall having an area equal to the exterior of the sea chest. It follows that the total area of the interior region of the sea chest was assumed to be 500% of the total area of the sea chest exterior. Note that these estimates are the same, regardless of the number of sea chests.

Lateral thruster propellers, tunnels, and gratings

Lateral thrusters provide thrust to a ship for increased side-to-side maneuverability, especially at low speeds where the effectiveness of a conventional rudder is greatly reduced (PIANC 1992). Numerous thrusters (typically one or two, but as many as six) are mounted in tunnels that run athwart the ship (perpendicular to the main axis), and they can be installed on the bow or stern, though the bow is much more common (Carlton 2007). Thrusters are primarily designed to achieve a required thrust or power that is typically calculated from a ship’s resistance against anticipated wind speeds or water currents (Carlton 2007).

Descriptions of thrusters were contained in 22% of ship records, and the data included number, power, and location on the bow or stern. To derive a relationship between thruster power and propeller diameter, data from multiple vendors were compiled, and a power regression analysis revealed a clear positive trend between the two. With the diameter of the thruster propeller, the area of the blades was estimated using Eq. 7 above and substituting the diameter of the thruster propeller (D_T) for D_P . Each

thruster tunnel presumably contained two propellers (port and starboard), so the total blade area of the single thruster propeller was doubled. The thruster tunnel area was estimated by assuming the same diameter as the propeller and multiplying the circumference by the ship's breadth overall (i.e., the length of the thruster tunnel),

$$\text{Total Area, Thruster Tunnel} = \pi \frac{(D_T)^2}{4} B_{OA} \quad (11)$$

where D_T = Diameter of the thruster propeller. The area of the grating was estimated to be 20% of the area of the tunnel opening (assuming 80% open area as above); this value was then quadrupled to account for the front and back of the gratings and the two openings (port and starboard).

For the 78% of ships without thruster data, it could be assumed that thrusters were not installed, however, that does not seem likely given the amount of missing information in the data set. Rather, it was assumed the data were incomplete, and a method was developed to estimate the number of thrusters for each. Through inspection of the general arrangement drawings that were available for each ship, it was verified that the data in the *Significant Ships* journals contained complete information on thrusters for each ship in their records. It was assumed that if ship records in the *Significant Ships* journals did not contain thruster data and did not have any clear indication that a thruster existed in the general arrangement drawings, then they did not have thrusters installed. Then it was assumed, for each ship type, that the percentage of ships in the *Significant Ships* dataset installed with thrusters and the number of thrusters could be extrapolated to all ships of a similar ship type. This statistical approach was used to estimate the number of ships with thrusters and the number of thrusters per ship in the database when that data was not available. For example, of the passenger ships in *Significant Ships* journals, 14% were installed with single bow thrusters, 56% were installed with double bow thrusters, 22% were installed with triple bow thrusters, and 8% did not have thrusters. These percentages were applied to the 5293 passenger ships in the database without thruster data to assume that 745 (single); 2941 (double); 1176 (triple); and 431 (none) ships were installed with single, double, triple, and no thrusters, respectively. For these, the average diameter using the former method was assumed. In addition, the percentages of

“other” ships were used for tugs and supply vessels and fishing vessels, since *Significant Ships* journals did not contain data on these ship types.

Results and discussion

Statistical strength of the models

Regression analyses between the modeled and base parameters showed strong, significant relationships (Table 2). The minimum R^2 value (0.54) was observed for the relationship between the speed draft factor (ST) and DWT for tugs and supply vessels, likely because power requirements for tugs are greatly based on towing load and conditions, rather than on the weight characteristics of the vessel itself (Watson 1998). Nonetheless, the average R^2 for the lines of best fit relating the ST to DWT for all ship types was 0.81. Among the other models, the lowest R^2 was 0.69. For all models, the equation parameters—both coefficients and exponents—showed a high level of significance ($p < 0.001$ in all cases), and the lines-of-best fit were all highly significant ($p < 0.001$).

Total extent of niche areas of the global commercial shipping fleet

The estimated total extent of *niche* areas in the global fleet of 120,252 active commercial ships was $32,996 \times 10^3 \text{ m}^2$ (Table 3), which was approximately 10% of the total *hull wetted surface area* of the global fleet ($324,846 \times 10^3 \text{ m}^2$, as determined by Moser et al. [2015]). Three niche areas in this study far exceeded the others in surface area: (1) thruster tunnels ($10,189 \times 10^3 \text{ m}^2$), (2) DDSS ($9803 \times 10^3 \text{ m}^2$), and (3) bilge keels ($6032 \times 10^3 \text{ m}^2$) (Fig. 2). These three areas comprised over three-quarters (79%) of the total niche areas in the study. Conversely, the surface areas of sea chest gratings and thruster gratings were almost negligible compared to other areas (52 and $141 \times 10^3 \text{ m}^2$ respectively, both $< 0.1\%$ of total niche area of the global fleet). Notably, all niche areas except the DDSS that coincide with the hull surface provide surface area not accounted for in the WSA estimate of Moser et al.

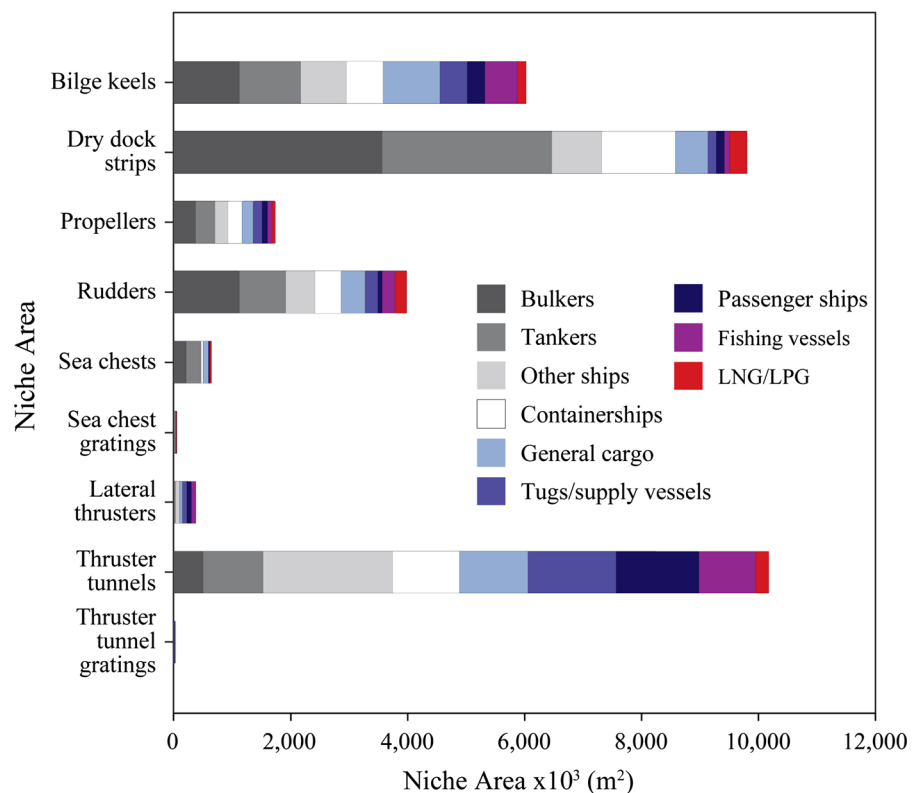
Considering the extent of the niche areas by ship type, the results largely aligned with the results from the total hull wetted surface area analysis (Moser et al.

Table 3 Estimated total surface area of each niche area in the global fleet of commercial ships

Niche area	Area ($\text{m}^2 \times 10^3$)	Area as % of total hull WSA ^a
Bilge keels	6032	1.9
Dry dock support strips	9803	3.0
Propellers	1747	0.5
Rudders	3994	1.2
Sea chests	651	0.2
Sea chest gratings	52	<0.1
Lateral thruster propellers	388	0.1
Thruster tunnels	10,189	3.1
Thruster tunnel gratings	141	<0.1
Total	32,996	10.2

WSA wetted surface area

^a Hull WSA is $324,846 \times 10^3 \text{ m}^2$ (from 120,252 active ships; Moser et al. 2015)

Fig. 2 Stacked bars showing the extent of each niche area and contributions from each ship type. LNG/LPG liquid natural gas/liquefied petroleum gas

2015). That is, bulk carriers ($6978 \times 10^3 \text{ m}^2$) and tankers ($6404 \times 10^3 \text{ m}^2$) were the largest contributors to the total area (Table 4; Fig. 3). In contrast to the WSA analysis, “other” ships ($4648 \times 10^3 \text{ m}^2$) represented the third largest niche surface area. The smallest extent of niche areas among ship types was LNG and LPG carriers ($938 \times 10^3 \text{ m}^2$), which differed from the hull WSA analysis, where passenger ships had the smallest hull WSA.

The extent of niche areas on passenger ships was 27% of the total hull WSA, which was a larger percentage than all other ship types (Table 4; Fig. 3). This result is mainly attributable to the numerous thrusters installed on passenger ships. The tugs and supply vessels and fishing vessels also had many thrusters, which boosted the area of niche areas to 25 and 22% of their total WSAs, respectively. Bulk carriers, tankers, and containerships had relatively few

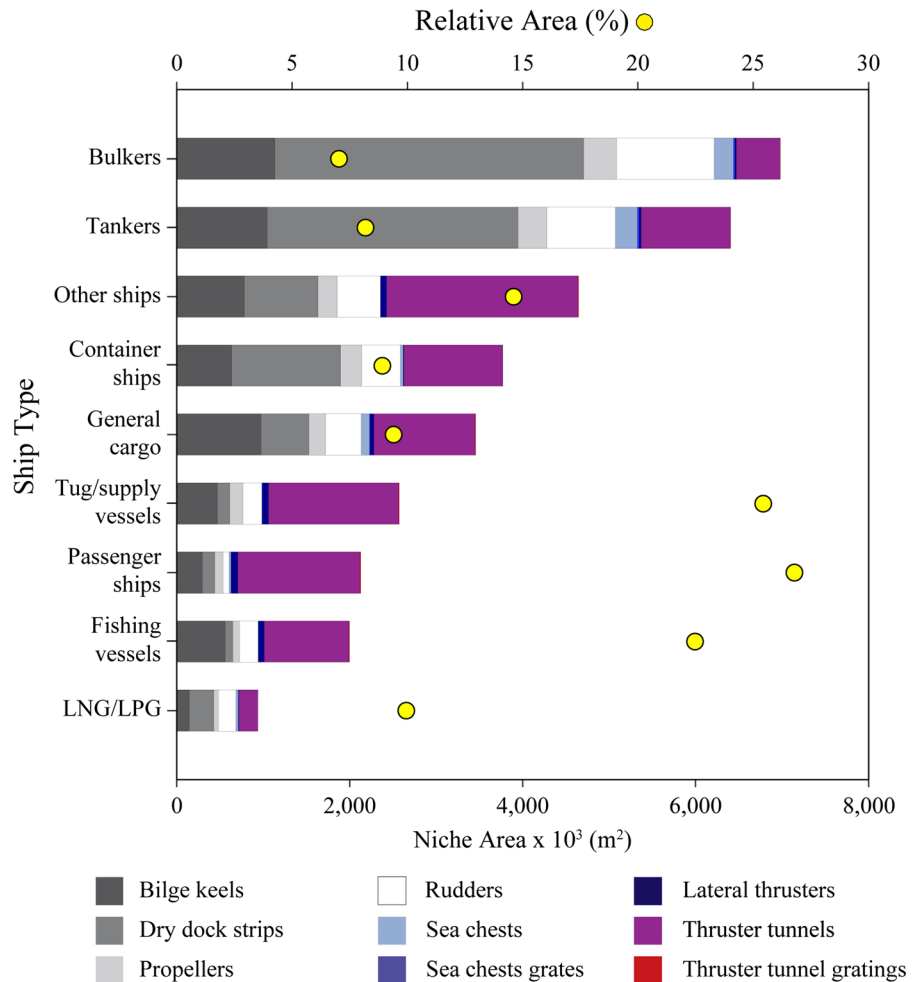
Table 4 Estimated extent of niche areas of the global fleet of commercial ships by ship type

Ship type	Total extent of niche areas (m ² × 10 ³)	Hull WSA (m ² × 10 ³)	Niche areas of the hull WSA (%)	No. ships	Extent of niche area per ship Type (m ²)
Bulkers	6978	99,238	7	10,550	661
Tankers	6404	78,272	8	14,194	451
Other ships	4648	31,829	15	17,017	273
Containerships	3771	42,323	9	5109	738
General cargo	3457	36,800	9	20,792	166
Tugs/supply ships	2575	10,124	25	20,658	125
Passenger ships	2127	7941	27	6922	307
Fishing vessels	1997	8888	22	23,358	85
LNG/LPG carriers	938	9431	10	1652	568
Total	32,996	324,846,268	100^a	120,252	375

No. number, LNG/LPG liquid natural gas/liquefied petroleum gas, WSA wetted surface area

^a The average percentage the niche areas in a given ship type represented in the global fleet was 10%

Fig. 3 Stacked bars showing the extent of niche areas for each ship type and the extent of the niche areas relative to the total hull wetted surface area of the ship type (yellow circles). LNG/LPG liquefied natural gas and liquefied petroleum gas carriers



thrusters and consequently, the lowest proportion of area of niche area to WSA at 7, 8, and 9%, respectively.

The estimated total niche area for *all* of the ships in the database, both active and inactive, was approximately $54,843 \times 10^3 \text{ m}^2$ ($n = 191,440$). Because the status of many of the ships could not be confirmed as active, this number should be considered an upper bound on the total niche area of the global fleet with assigned IMO numbers. Ships with records obtained from sources other than NBIC (e.g., from ABS, DNV, etc.) may have been active, but there was no feasible method of sorting active from inactive ships from those records.

Analysis of the extent of niche areas of the global commercial shipping fleet

From the data, thruster tunnels, DDSS, and bilge keels comprised a large majority of the niche areas in the global fleet of commercial ships. The DDSS and bilge keels run along much of the length of the ship and the thruster tunnels transect the width, which likely accounts for the larger areas than the more singular features such as rudders and propellers. While the area of DDSS and bilge keels was consistently high across ship types, the area of thruster tunnels was highly variable by ship type, having potentially important implications for the likelihood of species transfers associated with various types of vessels.

In the context of biofouling growth and likelihood for invasion, thrusters present a case that deserves special attention, not just for the sheer extent of their surface area, but also for the ways in which they are operated and maintained. For most ships, thrusters are installed to avoid the costs of towing into port (Watson 1998), i.e., they are only used periodically when it is necessary to maneuver a vessel in constricted settings. Otherwise, the thruster tunnels are isolated from the shear forces produced as the hull moves through the water, and they are a prime location for the development of extensive biofouling communities (Davidson et al. 2009). However, when thrusters are operated, likely in ports and coastal settings where tight maneuvering is required, they have the strong potential to expel organisms during each use. In addition, after long dormant periods, the flow through the thruster tubes could trigger a reproductive response from marine organisms living within (Davidson et al.

2013). Biofouling management strategies involving waterborne underwater cleaning in and around thruster tunnels may also not be as effective as other areas on the hull since access to the thruster tunnels is restricted by the gratings, and they endanger to divers if they are inadvertently activated. Additionally, biofouling in these areas does not increase drag and subsequent fuel costs, which make them a lower priority for cleaning. For these reasons, thrusters may warrant designation as a “super-hot spot” among niche areas for invasion likelihood, but these topics need further research.

Clearly, the extent of niche areas alone does not adequately inform the opportunity for biofouling colonization and transfers. To demonstrate this point further, the estimated area of DDSS—approximately 3% of the total WSA (Table 3)—far exceeds that of most the other niche areas (we note that the value derived here is a minimum estimate, based on hull loading restrictions of the U.S Navy). Further, other studies have shown that the area of DDSS can be as great as 20% of the area of the WSA of a ship (Coutts 1999). However, DDSS lay along the exterior hull and are, especially on faster moving vessels, exposed to hydrodynamic stress while underway (Coutts and Dodgshun 2007) as opposed to thruster tunnels and sea chests where organisms living in the recesses may experience favorable conditions for growth and persistence. In fact, it has been observed that many of the niche areas *themselves* contain “sub-niche areas” or “nooks-and-crannies” where conditions are substantially favorable for biofouling growth compared to the flat surfaces surrounding them (Davidson et al. 2009, 2014). It seems likely that DDSS would be less densely populated with biofouling than areas with complex surfaces or those that are more protected from turbulent flows (although see Coutts and Taylor 2004). The differences between the niche areas—in terms of attracting, harboring, and shedding biofouling organisms—will cue managers and inspectors on the optimal locations to focus their efforts.

The analysis presented here narrows the focus from the much broader total hull WSA to particular habitat types or areas where biofouling can be more likely to occur. Quantifying the relative risks of biological invasions among each niche area will require a deeper understanding of the community composition, species abundance, life-history stage, and condition of biota associated with these surfaces. Of course, the likelihood of a successful biological invasion is

complicated by a number of interconnected, external factors as well: percent cover of coating systems, age and type of coating systems, ships' maximum and average speeds, movement of ships between regions, port residence times, and environmental conditions in the receiving waters. These additional elements represent the next phase in a stepwise analysis—now underway—that aims to quantify the niche areas in the global commercial fleet and the associated biota on hulls and niche areas of vessels arriving to the United States.

Once the full analysis is completed, models can be developed to characterize ships' wetted surfaces, including the niche areas that are scalable and can support further risk assessments of bioinvasions via ships. Already, models have been developed to predict or simulate the spread of ANS based on colonization of vessel hulls, voyage routes, and propagule pressure (e.g., Leung et al. 2004; Floerl et al. 2009; Muirhead and MacIsaac 2011). Models like these would benefit from refined estimates for the potential magnitude of flux for biofouling organisms by applying the methods described in this paper to estimate the extent of niche areas of local fleets. Until these models can be parameterized by the complete suite of biological information, the extent of niche areas may be able to serve as a more precise proxy for ANS exposure than the total WSA.

Conclusions

The extent of niche areas in the global fleet of commercial ships was estimated using available ships' records. Where data were unavailable to calculate the niche area directly, an indirect approach was developed using regression analyses to model the relationship between niche area and other accessible parameters. Thruster tunnels had the greatest extent among niche areas, followed by DDSS, and bilge keels. By ship type, bulk carriers and tankers contained the greatest extent of niche areas. The total extent of niche areas of the global fleet of commercial ships was estimated to be approximately $32,996 \times 10^3 \text{ m}^2$, representing approximately 10% of the total hull wetted surface area.

The analysis and reckoning of the quantity and distribution of ships' niche areas can inform risk assessments and guide policymaking to mitigate

aquatic invasions. Combining this analysis with the (1) density of organisms in the biofouling communities within niche areas, (2) invasion-relevant parameters within the communities, e.g., the prevalence of organisms with planktotrophic vs. lecithotrophic larvae, and (3) presence, age, and condition of coating systems will lead to a clearer understanding of the risk of ANS invasions from biofouling on and within ships.

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