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Article

Flux of the Wetted Surface Area on Ships' Hulls in Major Ports of Korea

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Abstract: Biofouling is a significant means for introducing non-indigenous marine species internationally, which can alter habitats and disturb marine ecosystems. This study estimated the flux of ships' wetted surface area (WSA) to Korea in 2020 to assess the risks of biological invasion via biofouling on ships' hulls. The annual total WSA flux entering Korea was estimated to be 418.26 km^2, with short-stay vessels (<3 weeks) contributing to 99.7% of the total WSA flux. Busan and Ulsan ports were identified as the main sources of high-risk flux, with container ships being a major vector in Busan and tankers in Ulsan. Gwangyang port had the third-highest total WSA flux, with nearly half of the flux driven from coastwise voyages, making it particularly vulnerable to the spread of hull fouling organisms. These findings could help enhance the management and inspection of hull fouling organisms in Korea.

Keywords: wetted surface area (WSA); hull fouling; biofouling; marine invasive species; bioinvasion

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1. Introduction

Biofouling is the accumulation of organisms on a ships' surface which can negatively impact its performance and navigation, leading to increased operating expenses such as reduced ship speed and increased fuel consumption. This can be caused by the accumulation of microbes, microalgae, invertebrates, and macroalgae [1–3]. It has been reported that fuel consumption can increase by up to 40% due to biofouling [4]. Biofouling has also long been recognized as a significant pathway for the introduction of non-indigenous marine species internationally [5–8]. Marine invasive species attached and introduced can alter the structure of habitats and disturb the ecosystem and are a significant threat to global biodiversity [9]. Moreover, biofouling occurs continuously over a long period of time because the niche area of the hull and the lower part of the ship act as a hard substrate to which organisms can attach [10]. As a result, all ports where ships stay are at risk of introduction of invasive marine species from other regions. The International Maritime Organization (IMO) has adopted guidelines for the control and management of biofouling on vessels to minimize the transfer of aquatic invasive species. The guidelines aim to maintain submerged surfaces and internal cooling systems of vessels as free of biofouling as is practical. As the need for biofouling management is being recognized globally, it is highly likely that regulations enforcing these guidelines will be put in place [11,12].

The monitoring of fouling organisms on ships' hulls has been conducted to estimate the flux of non-native organisms, which has shown a growing trend in the widespread migration of marine invasive species through vessels [6,13,14]. The results indicate a broad range of organisms attached to the hull, with propagule pressure mostly related to the duration of stay at previous ports-of-call and the diversity related to the number of harbors visited [15]. Furthermore, a survey of hull fouling in Korea found that macrofouling was observed on all surveyed ships, with serious levels of adhesion of macro-organisms in niche areas such as bow thruster, bilge keels, and sea-chest gratings [13].

Direct monitoring of hull fouling organisms would be an ideal approach but obtaining permits to access ships is difficult and acquiring data requires significant effort due to the typically short vessel residence time. As a result, there are only a small number of extensive surveys of ships' hull fouling on international voyages [16–18]. In real-world situations, it would be operationally challenging to inspect all vessel arrivals for biofouling due to limited time and a large area to cover on a vessel. Empirical formulas are used to estimate a ships' wetted surface area (WSA) based on relationships between hull characteristics and known WSA values from ships' records or experimentally tested vessel models. This enables the assessment of the potential for biofouling transfer based on vessel type, source and destination regions, and time. The high correlation between a ships' WSA and net tonnage makes this estimation easier as the gross tonnage on each ship is readily available in shipping information [10,19,20]. In addition, the niche area where most extensive fouling occurs is also available for each type of vessel [10].

Due to Korea's high trade volume conducted through ships, it is likely that a significant number of the invasive species of the previously reported 14 invasive species in the country were caused by ships [21]. It is highly probable that the introduction of fouling organisms such as *Ciona intestinalis* to Korea occurred through vessel hull fouling [21]. To estimate the inflow scale of marine invasive species, it is important to assess the area where organisms can attach. The length of time a vessel remains in port greatly increases the potential for transferring organisms from its hull, and the risk of release is greater with a larger wet surface area and proportional niche area [15,22].

This study estimated the annual total wetted surface area (WSA) in Korea by calculating the WSA flux at major ports from 1 January to 31 December 2020. The annual WSA flux of high-risk vessels for each port was also estimated, considering the niche area and the length of the vessels' stay in ports. The goal of this analysis is to assess the risk of bioinvasion via ships' hull fouling in Korean ports and vessels and provide useful information for monitoring the current and future introduction of marine invasive species into Korea.

2. Materials and Methods

The study obtained data on ship entries into the 12 major Korean ports from 1 January to 31 December 2020, totaling 64,629 vessel arrivals, from Korea's PORT-MIS information (accessed on 15 May 2021, https://new.portmis.go.kr) (Figure 1). It is important to note that the estimated WSA in this study considers repeated entries of the same vessels into Korean ports, providing a total annual exposure of the marine environment to hull fouling estimated by WSA. Therefore, our estimate of the WSA is of total annual exposure of the marine environment to the hull fouling estimated by the WSA.

2.1. Wetted Surface Area (WSA)

Wetted surface area was estimated from the relationship between net tonnage and WSA for each type of vessel [10]. There is a power relationship between the wetted surface area (WSA) of six different commercial ship types and their net registered tonnage (NRT), with the power exponent typically ranging between 0.540 and 0.646 [10]. However, only gross tonnage is provided in Korea's PORT-MIS information. Thus, net tonnage for the vessels was estimated from gross tonnage by multiplying constants which generally ranges between 0.5 and 0.6, except for roll-on/roll-off (RORO), which is about 0.3 [20].

2.2. Niche Area

To estimate niche area, a ship-type-specific multiplier was used, based on research by Moser et al., 2017. Niche areas represent areas on a ship's hull with a higher density of fouling organisms compared to other surfaces in the wetted area [13]. Examples of niche areas include rudders, propellers, propeller shafts, external cooling pipes, bow thrusters, sea-chest grates, and bilge keels, which vary among vessel types (Figure 2). The niche area for each vessel type ranges from 7% to 9%, except for passenger vessels, which have a niche area of 27% [10,19]. The larger proportion of niche area in a passenger vessel is directly linked to the prevalence of hull thruster tunnels and other niche areas on a passenger vessel [19].

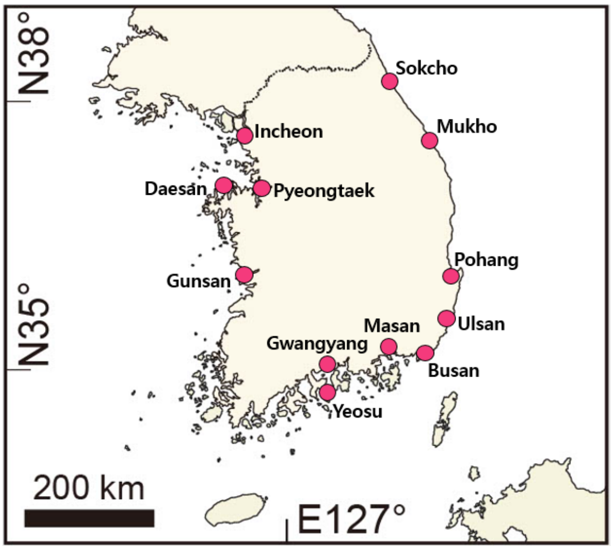


Figure 1. Twelve major ports in Korea with the largest flux of wetted surface area of ships in 2020 in South Korea.

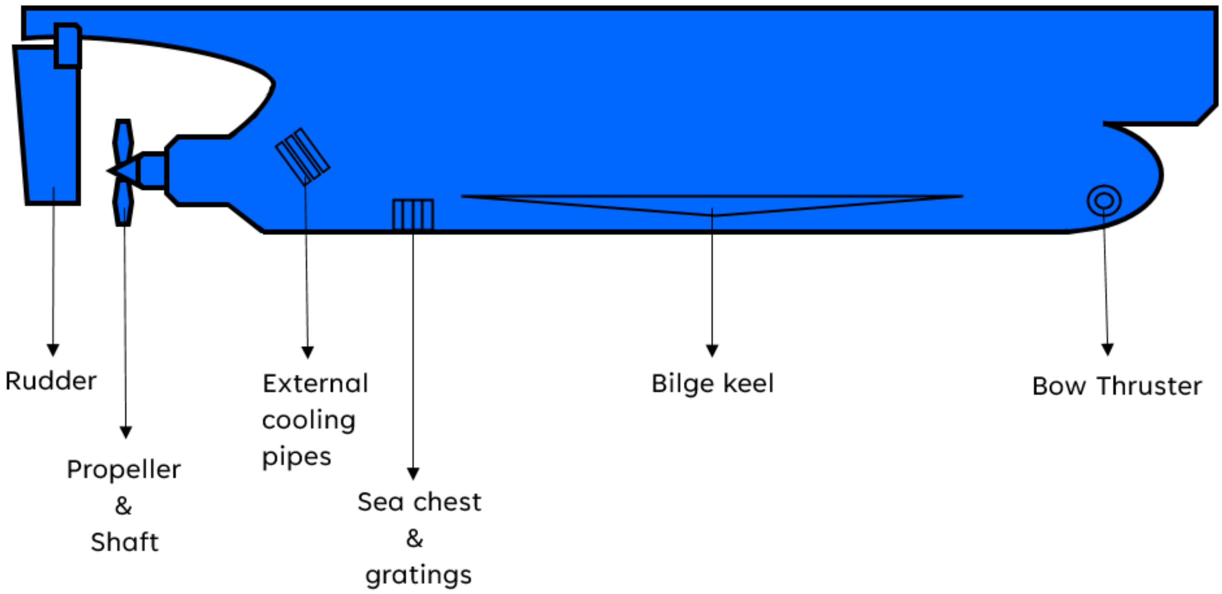


Figure 2. Niche areas of typical vessels, which are hot spots for fouling organisms.

2.3. Classification of Ships According to Stay Period

In this study, vessels were divided into two groups based on their length of stay: those staying for longer periods (>21 days), and those staying for shorter periods (<21 days), with long-stay vessels posing a greater risk of bioinvasion [22]. This is because the majority of species that settle on vessel hulls do not reach sexual maturity within four weeks of settlement [23]. The annual WSA flux of high-risk vessels was estimated for each port based on the percentage of WSA of long-stay vessels, the niche area (area vulnerable to biofouling), and the percentage of vessels with overseas last port-of-call (i.e., consecutive multiplication of each factors).

3. Results

3.1. Total Flux of Wetted Surface Area of Ships' Hulls

The total annual flux of wetted surface area (WSA) in ships' hulls into the 12 major ports in Korea was estimated to be approximately 418.26 km^2. Among the ports, Busan had the highest estimated annual WSA flux at 148.62 km^2, followed by Ulsan (63.20 km^2), Gwangyang (44.76 km^2), Incheon (44.09 km^2), Pyeongtaek (33.43 km^2), and Yeosu (33.36 km^2) ports in descending order. The lowest WSA flux was observed at Sokcho Port, estimated to be 0.003 km^2 (Figure 3).

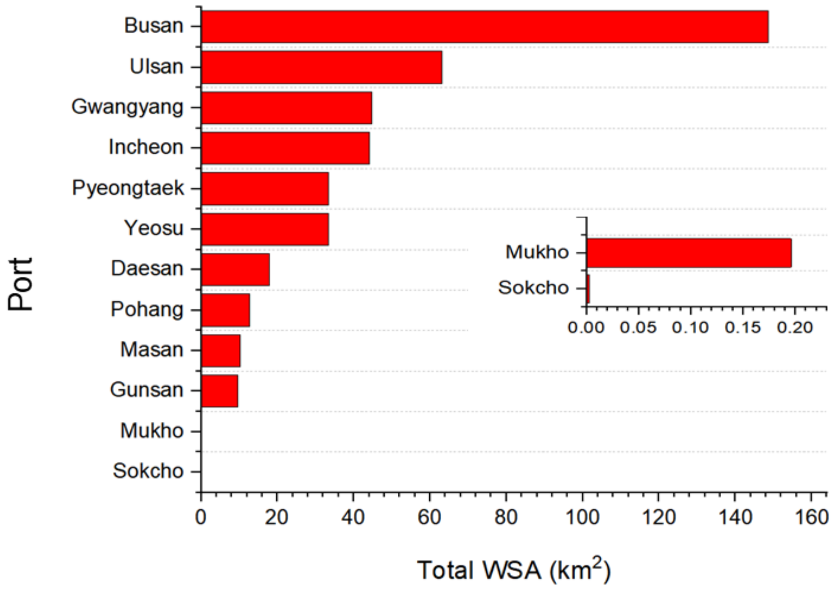


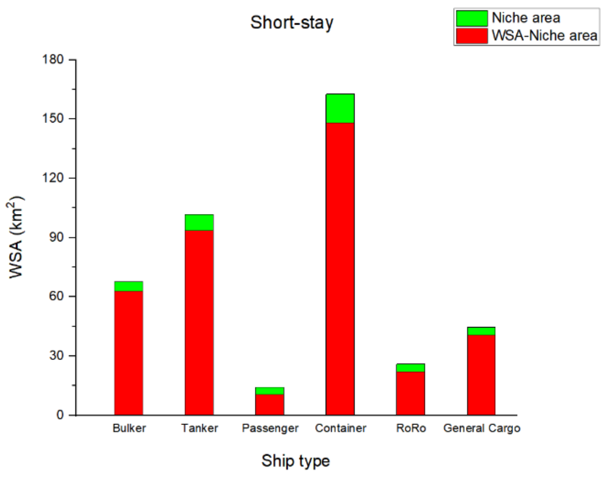
Figure 3. Estimation of total flux of wetted surface area of ships' hulls in 12 major ports in 2020 in South Korea.

3.2. Wetted Surface Area Flux by Vessel Type

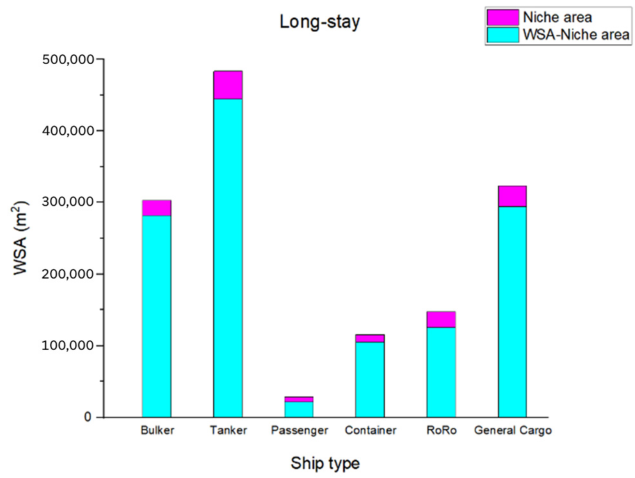
The vast majority of the ships entering Korea were short-stay vessels. The WSA flux of short-stay vessels was about 416.86 km^2, accounting for more than 99% of the total WSA flux. In contrast, the WSA flux of long-stay vessels was about 1.40 km^2, accounting for only about 0.3% of the total WSA flux.

In the case of short-stay, container ships were estimated the highest of WSA flux at 162.61 km^2, followed by tankers (about 101.67 km^2) and bulkers (about 67.68 km^2). Vessels smaller than 50 km^2 were the majority. Long-stay vessels had tankers as the largest at 482,932 m^2, followed by general cargo ships (about 323,141 m^2) and bulkers (about 302,989 m^2) (Figure 4). Short-stay vessels had the highest number of container ships arrivals and departures, with 23,501 entries. Despite general cargo ships having the highest number of reentries (126) among long-stay vessels, tankers still had a higher average WSA per ship at 6833 m^2 compared to 3101 m^2 for general cargo ships. Therefore, tankers have a higher annual WSA flux than general cargo ships among long-stay vessels. Passenger vessels had the lowest WSA flux for both short and long-stay periods, at 14.31 km^2 and 28,878 m^2, respectively (Figure 4).

For short-stay vessels, the niche area flux was the highest in containers at 14.64 km^2, while for long-stay vessels, it was highest in tankers at 38,635 km^2 (Figure 4). Niche area varied from 3.86 to 14.64 km^2 for short-stay vessels and from 7797 to 38,635 m^2 for long-stay vessels. Passenger vessels had the lowest niche area flux for both stay periods, at 3.86 km^2 and 7797 m^2, respectively.



(**a**)



(**b**)

Figure 4. Estimation of annual WSA and niche area by ship type for stay period (**a**) short-stay; (**b**) long-stay.

3.3. Short-Stay WSA at Each Major Port

Short-stay vessels' WSA flux was highest for container ships in Busan (109.04 km^2) accounting for 26% of the total WSA flux (Figure 5). Tankers in Ulsan and container ships in Gwangyang had 42.88 km^2 and 23.72 km^2, respectively. Incheon and Pyeongtaek had more evenly distributed WSA flux among vessel types. In Incheon Port, passenger ships had the highest WSA flux at 6.46 km^2 among all 12 ports. Some ports had specific trade patterns. Tankers dominated the WSA flux in Daesan, while both bulkers and tankers dominated in Yeosu and bulkers and general cargo ships dominated in Pohang. General cargo ships, mostly fishing boats, dominated the WSA flux in Mukho and Sokcho ports, despite having the smallest WSA flux. Masan and Gunsan ports had WSA flux of less than 5 km^2 for each vessel type, and the flux was relatively evenly distributed among ship types.

For short-stay vessels, the niche area flux ranged from 0.0003 to 9.81 km^2 (Figure 5). Busan had the highest niche area at 9.81 km^2, with containers accounting for 72% of the total niche area for short-stay vessels in the port. Tankers were responsible for the niche area in Ulsan, estimated at 3.43 km^2.

3.4. Long-Stay WSA at Each Major Port

Long-stay vessel WSA flux was dominated by Busan and Ulsan ports (Figure 6), which was different from the more evenly distributed pattern seen in short-stay vessels. Busan had the highest long-stay WSA flux at 651,789 m^2, accounting for 47% of the total long-stay vessels' WSA flux, with tankers and general cargo ships accounting for 64% of the flux in Busan. Tankers dominated the WSA flux in Ulsan at 202,240 m^2, accounting for 71% of the port's WSA flux. Incheon and Yeosu had near-equal contributions to the WSA flux, following Busan and Ulsan.

Car carriers (RORO) in Incheon had the highest WSA flux among all ports, at 66,107 m^2, even higher than Busan (Figure 6). In Gwangyang, the WSA flux of long-stay vessels accounted for only 0.07% of the total WSA flux, the lowest percentage among all ports, with an estimated 32,020 m^2. Long-stay vessels were concentrated on only one type of vessel in Pohang, Pyeongtaek, Daesan, and Gunsan ports, with no long-stay vessels found in Mukho and Sokcho ports (Figure 6).

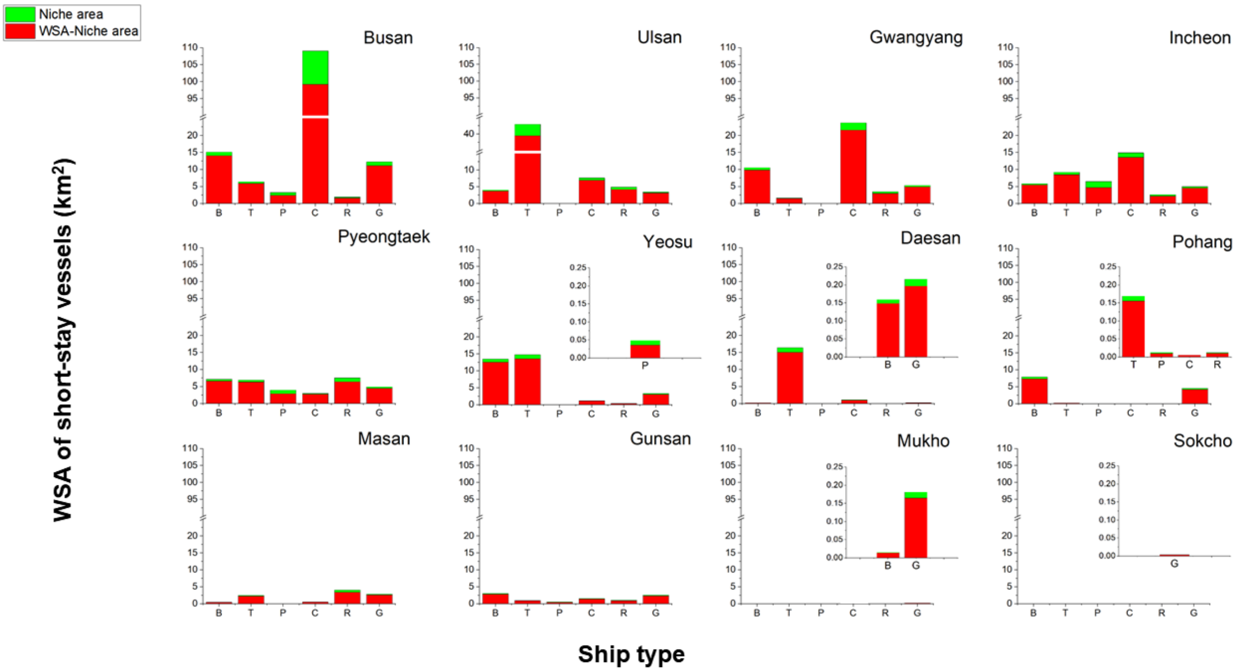


Figure 5. Estimation of WSA and niche area of short-stay vessels by ship type for each major port between 2020 and 2021 B: bulkers, C: container ships, G: general cargo ships, P: passenger ships, R: roll-on and roll-off carriers, T: tankers.

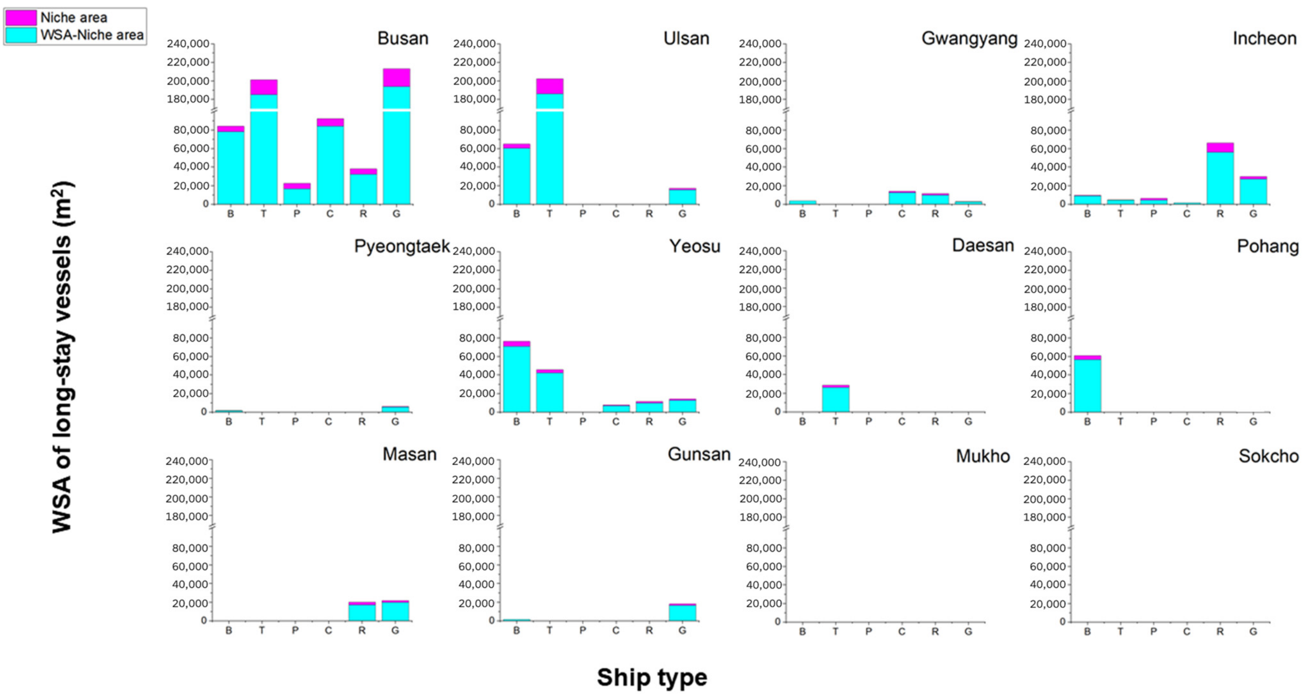


Figure 6. Estimation of WSA and niche area of short-stay vessels by ship type for each major port between 2020 and 2021 B: bulkers, C: container ships, G: general cargo ships, P: passenger ships, R: roll-on and roll-off carriers, T: tankers.

For long-stay vessels, the niche area flux of each ship type ranged from 110 to 19,180 m^2. Busan had the highest niche area flux at 19,180 m^2, with both general cargo ships and tankers contributing the most. In Ulsan, Tankers had the highest contribution to the niche area flux at 16,179 m^2, while in Incheon, RORO had a contribution of 9916 m^2 (Figure 6).

The duration of long-stay vessels in each port exhibits significant variation, as indicated in Table 1. Certain vessels remained anchored for more than a year, with average stays spanning from 24 days in Pohang to 83 days in Gwangyang.

Table 1. Average stay period and minimum/maximum stay period of long-stay vessels in each port.

Port	Average Period (Day)	Min	Max	Number of Entries
Busan	61	21	454	176
Ulsan	27	21	53	26
Gwangyang	83	26	141	4
Incheon	60	21	222	25
Pyeongtaek	55	21	89	2
Yeosu	32	21	74	21
Daesan	27	26	28	2
Pohang	24	22	27	5
Masan	42	22	96	8
Gunsan	45	21	111	7

3.5. Contribution of Overseas Visits to Wetted Surface Area Flux

Overseas visits accounted for 31–91% of the total WSA flux across ports, with an average of 70% (Table 2). Sokcho had the highest contribution from overseas vessels at 91%, while Mukho had the lowest. Gwangyang and Gunsan had less than 60% of their WSA flux contributed by overseas visits, but Yeosu had a high overseas contribution of 81% despite being situated close to Gwangyang Port (Figure 1).

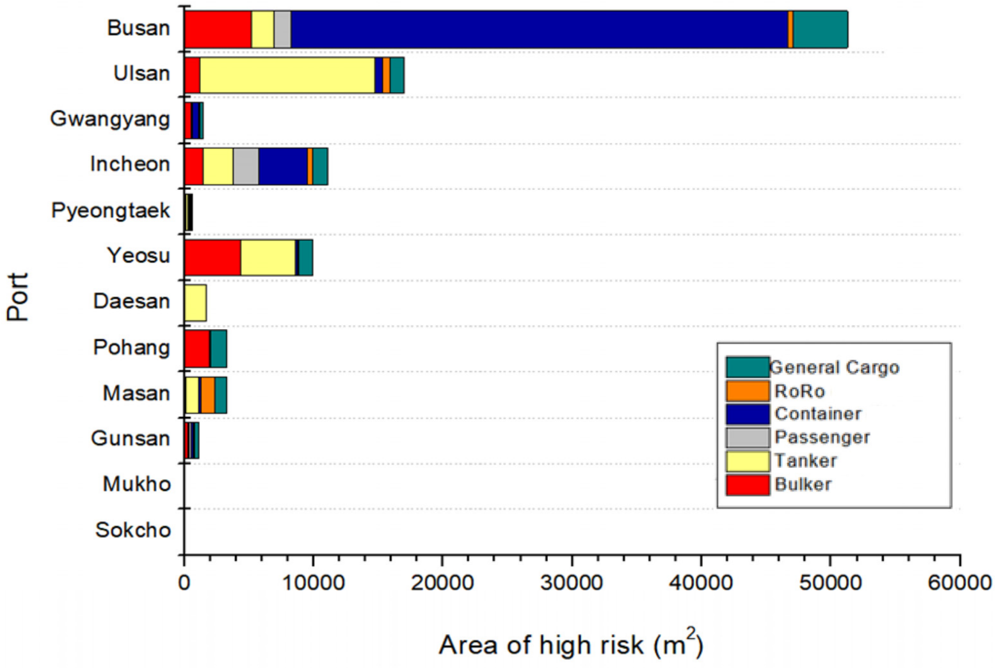
Table 2. Estimation of each rate of long-stay WSA, niche area and overseas WSA in total WSA flux of each port and WSA flux of high risk between 2020 and 2021 in South Korea.

Port	Total WSA Flux (km^2)	Long-Stay WSA (%)	Niche Area (%)	Overseas WSA (%)	WSA Flux of High Risk (m^2)
Busan	148.62	0.44	9.23	84.91	51,250
Ulsan	63.20	0.45	8.66	69.10	17,019
Gwangyang	44.76	0.07	8.96	51.32	1441
Incheon	44.09	0.27	11.53	80.73	11,081
Pyeongtaek	33.43	0.02	11.84	79.44	629
Yeosu	33.36	0.47	7.85	80.72	9935
Daesan	17.90	0.16	8.06	73.64	1700
Pohang	12.72	0.48	7.76	69.18	3278
Masan	10.32	0.41	11.04	70.29	3283
Gunsan	9.66	0.20	9.99	59.80	1154
Mukho	0.20	0	8.85	31.20	0
Sokcho	0.003	0	9.00	90.67	0
Sum	418.26	-	-	-	100,770

3.6. Wetted Surface Area Flux of High Risk

The WSA flux of high risk (FHR) for each port (Figure 7) showed a slightly different picture from the total WSA flux (Figure 3). Busan had the highest annual FHR WSA flux at 51,250 m^2, representing 51% of the total FHR, followed by Ulsan at 17,019 m^2 (17%), Incheon at 11,081 m^2 (11%), and Yeosu at 9935 m^2 (10%). Gwangyang, Pyeongtaek, and Daesan, which had significant contributions to the total WSA flux, accounted for less than 1.7% of the FHR (Figure 7).

Mukho had no FHR estimated, as there were no long-stay vessels in the port. Although Gwangyang had the third-highest total WSA flux among the ports (Figure 3), the FHR was low, estimated to be just 1441 m^2. This is because the percentage of long-stay vessels and overseas vessels in Gwangyang is relatively low (Table 2). Pyeongtaek had the highest percentage of niche WSA flux (11.84%, Table 2), but due to a low percentage of long-stay WSA (0.02%, Table 2), the FHR was only 629 m^2, the lowest except for Mukho and Sokcho ports. In Pohang, although the total WSA flux was low compared to other ports, the percentage of long-stay WSA flux was the highest at 0.48%, and the estimated FHR was 3278 m^2 (Table 2).



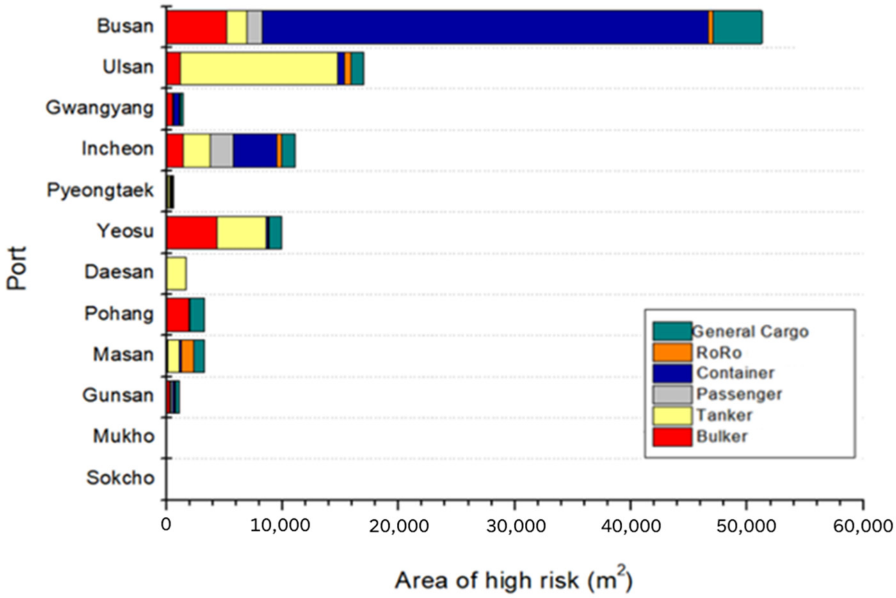


Figure 7. Estimation of wetted surface area flux of high risk for each port and ship type.

For each type of vessel in Busan, Ulsan, Incheon, and Yeosu, where the FHR is high, container ships accounted for the highest percentage among all ship types, at around 75% in Busan. In Ulsan, tankers accounted for the highest percentage at about 79%. In Incheon, container ships accounted for about 33%, and bulker ships accounted for the highest proportion at about 44% in Yeosu (Figure 7).

4. Discussion

4.1. Total Wetted Surface Area Flux

This is the first attempt to assess the WSA flux in Korea in relation to hull fouling for potential bioinvasion. WSA is estimated for various purposes for ships operation and maintenance. It is useful for measuring the drag force on a ship in order to estimate its performance and fuel efficiency. It is an important piece of data when calculating the area, time, and cost of antifouling paint [24]. There are several models available for estimating the hull wetted surface area, but they all require ships dimensions and other ship design parameters, of which information are not easily available. The PORT-MIS information service in Korea provides simple information such as gross tonnage of vessel related to ships capacity. Therefore, the use of a well-established empirical relationship is highly useful and would facilitate the comparison of the analysis of WSA in countries concerned with invasion of biofouling organisms by ships [10].

Currently, there are few estimates reported about the flux of WSA into ports. The mean total WSA flux into US ports was about 510 km^2 per year, of which 65% of total was from overseas (333 km^2) and 35% (177 km^2) was coastwise [10]. The total annual flux of WSA into 12 major domestic ports in Korea was estimated to be about 418.26 km^2 (Figure 3), of which 76% of total was from overseas (317 km^2) and 24% (101 km^2) was inter-ports in Korea (Table 2). The total WSA flux into Korean ports is just about 20% smaller than that into the USA. Such a high rate of WSA flux into Korea indicates that Korean harbors are major receivers of foreign hull fouling organisms, but they also represent a potential major donner of the fouling organisms to other countries.

4.2. Niche Area Flux

Niche area represents the area hot spot for fouling organisms. They are recognized as a dominant vector for the transfer and introduction of marine species [23,25,26]. Fouling organisms tend to concentrate in sheltered areas of the hull, such as sea chest intakes and rudder posts, and develop in areas where anti-fouling coatings have been compromised [27,28]. Sea-chests are particularly vulnerable to heavy fouling [29]. Anti-fouling coatings wear off and are often inadequately applied in some cases, which makes the surfaces susceptible to settlement by fouling organisms [6]. The splash zone, which refers to the section of a ship's hull between the water and air, is susceptible to significant biofouling accumulation in the case of extended stays. This area provides an ideal environment for biological growth due to the favorable conditions it offers. Niche area as a hot spot for fouling may also vary among vessels type. When examining the various types of niche areas, thruster tunnels had the most significant overall extent, constituting a disproportionately large amount (50%) of the total niche area for passenger vessels and tugs when compared to other types of vessels [19]. The niche area flux of the long-stay vessels varied generally little across the ports (Table 2), ranging from 7.85% to 11.84%, with an average of 9.40%. This value is similar to the total niche area estimated for the global commercial vessels which represented approximately 10% of the total WSA available for colonization by biota [19].

In a survey of five international ships entering South Korea, macrofouling was common on all ships surveyed, and particularly the adhesion of macro-organisms in niche areas such as bow thruster, bilge keels and sea-chest gratings appeared to be at a serious level [13]. This suggests that niche areas would be the major spots of invasive species in vessels coming to and departing from Korea. 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 wetted surface of ships [19].

4.3. Microbial and Microalgal Community on the Hull

If microbial and microalgal assemblages are the main concern, managing the entire WSA may be more appropriate. Risk analysis on hull-attached microbes have been conducted overseas [30], and some insidious strains of sulfate reducing bacteria are highly dangerous and would quickly corrode the hull [31]. There are limited studies on this topic in Korea [32,33]. During an in situ antifouling coating experiment, the control plate had a strong association with pathogenic *Vibrio* spp. related to invertebrate growth. In the anti-fouling coted plate, however, the bacteria's chemical antagonism response stimulated the proliferation of specific biofilm bacteria and impacted the interactions and recruitment of other bacterial communities [34].

A recent survey on ships' hulls in Korea identified 11 species of benthic diatoms, including *Achnanthes brevipes* and *Licmophora* sp., as microalgae adhered to the hull [33]. These microalgae are very small, less than 20 μm in size, and are distinguishable from phytoplankton present in water masses [33]. The findings imply that harmful algae have the potential to attach to the hull. The risk analysis of vessel biofouling acknowledges that restricting fouling on vessels entering New Zealand to the level of slime layer (microfouling) or lower can mitigate the biosecurity risk [30].

4.4. Long-Stay vs. Short-Stay

Staying in port for an extended period can affect the degree of biofouling on a ships' hull by increasing the amount of time that the hull is exposed to potential fouling organisms. Morrisey (2013) found that vessels staying in New Zealand for more than three weeks tend to release a higher concentration of hull-fouling organisms than those staying for shorter durations [22]. Increased age of the antifouling paint, as well as long stationary periods and reduced sailing activity increase the risk of macrofouling species attaching to hulls [35]. It had been found that mooring for a long period of time in the San Diego area caused an extensive fouling community [6]. A survey of stay in the Keppel Terminal showed that over 90% of vessels spent less than seven days in port [36]. They concluded that the likelihood of the majority of vessels taking up biofouling is likely to be low [36]. On average, vessels spent up to five days in port and less than five days at sea. However, there was strong variation, with general cargo ships recording up to 13 days in port [37]. A review of maritime transport shows global average times in port of 1.4 days for merchant vessels in 2016 (ranging between 0.9 for container ships and 2.7 days for bulk carriers) [38]. Port stays for recreational vessels, service vessels (e.g., barges and tugs) and fishing vessels were significantly longer than those of merchant vessels, and they would continue to pose a greater risk in this regard [39].

These results indicate that long-stay vessels make up only a small fraction of the total WSA flux globally. In Korea, the WSA flux of long-stay vessels was a small fraction (<0.5%) of total WSA in Korea, with Mukho and Sokcho port having no long-stay vessels (Table 2). In addition, there showed considerable flux from long-stays across all types of vessels except passenger vessels (Figure 4). Long-stays are, however, concentrated on several ports, suggesting that ports are more important than vessel type with respect to risks of hull fouling associated with duration of vessels in ports (Figure 6). The port stay of vessels would likely decrease in the long term given the advance of information technology and port automation [39]. However, at times of economic downturn and reduced shipping activity, commercial vessels may lay idle in ports for protracted periods, increasing fouling risk, as occurred during the global financial crisis in 2008–2009 [40].

Presumably, those vessels became heavily fouled before returning into service when trade rebounded. The COVID-19 outbreak that occurred in the period of this study also could have affected the port stay period. The average anchoring time and berthing time increases by 62% and 11% for cargo ships and by 112% and 63% for tankers in China after the outbreak of COVID-19 compared with that before COVID-19 [41]. The shipping volume has steadily increased over the years from the analysis of shipping data in Korea from 2009 to 2019 [42]. Busan, Gwangyang, Ulsan and Incheon were the top ports in the descending order in terms of shipping volume. In this study, the higher total WSA flux of Ulsan than in Gwangyang would be due to the higher total ship reentries in Ulsan (11,136) than in Gwangyang (6541) (Figure 3). Therefore, these competing factors should be accounted for the prediction of WSA flux in the future.

4.5. Overseas vs. Coastwise Flux

Coastwise voyages have been rarely assessed for their potential to spread introduced organisms, but they may act as vectors [43]. Studies have shown that recreational boating has a high potential for distributing marine species throughout Scotland, with 59% of surveyed yachts found to have macrofouling attached to their hulls [35]. In Prince William Sound, coast voyages accounted for the majority of all vessel types incoming, posing a greater risk associated with vessel fouling and non-indigenous species [43]. Slower vessel speeds on coastwise voyages likely contribute to differences in fouling among ships [16]. In Korea, the spread of *Balanus perforatus*, a relatively new invader, was potentially attributed to coastwise traffic, with the barnacle's habitat extending southward, against the currents flowing northward, since it was first found in an area near Pohang Port in 2006 [21,44].

4.6. WSA Flux of High Risk and Development in Regulation of Hull Fouling in Korea

Most bioinvasive species in Korea seem to be associated with hull fouling, with their first appearance commonly seen at major ports [21]. Among the Korean ports, Gwangyang port is the most vulnerable to coastwise invasion or spread of hull fouling organisms, and Busan container ships and Ulsan tankers could be carriers of the majority of hull fouling organisms because of their high WSA fluxes (Figure 7, Table 2). While the shipping industry has implemented guidelines to manage living fouling on ships [45], marine fouling organisms have not yet been properly managed in Korea, and there are no specific laws for the AFS Convention in Korea [46]. To prevent or minimize harm from invasive species, many countries have adopted regulations and guidelines, including ballast water treatment systems and antifouling coatings. Given the high WSA flux into Korean ports, measures should be taken to regulate the introduction and spread of invasive species via ships' hulls [46,47].

5. Conclusions

The total annual WSA flux in 2020 entering 12 major ports in Korea was 418.26 km^2, of which 76% was from overseas and 24% from coastwise ships. This indicates that Korea's major ports are exposed to the possibility of non-indigenous species invasion and that ships passing through Korea may contribute to the transport of fouling organisms to other countries. Among Korea's 12 major ports, Busan, Ulsan, Incheon, and Yeosu are highly susceptible areas with a high risk of flux. Meanwhile, Gwangyang Port has a high potential to contribute to the spread of non-indigenous species introduced into Korea to other ports in the country. With the distribution of WSA flux across ports and vessel types estimated in this study, these findings could help enhance the management and inspection of hull fouling organisms in Korea. Furthermore, the findings of this study could prove useful for approximating the drag forces exerted on a ship, which can have a significant impact on the ship's efficiency, especially with regard to curbing greenhouse gas emissions.

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