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Relation between the ship's biofouling and the places they come from: Case study of a merchant ship in the Bay of Biscay

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ABSTRACT

Biofouling is the accumulation of aquatic organisms on surfaces immersed into the water such it could be the hull of a ship. What is more, biofouling generates several inconveniences in the development of a ship's operation. The first one arises when they act as a vehicle for the transfer of possible invasive exotic species, which can also travel through ballast water from one region to another and creates what is known as biological contamination. The second is the decrease in speed caused by the friction which affects the performance during transit. Under this problematic situation, a case of study has been done in a merchant ship in the Bay of Biscay to predict which invasive species could have been attached to the hull according to the vessel's voyages and to assess the most affected parts of the hull by biofouling.

1. Introduction.

For millions of years, marine organisms have been separated by geographic barriers, unable to disperse over long distances. However, as transportation has become faster and more accessible, these barriers have been disappearing (Castellanos-Galindo et al., 2020). During 2020 the world merchant fleet increased by 3%, reaching 99,800 vessels and, during the period 2022-2026, maritime trade is expected to have an annual growth of 2.4% (UNCTAD, 2021). This intense maritime traffic has provided opportunities for thousands of species to be transported to new habitats (Williams et al., 2013), via ballast water or attached to the hull of ships in the form of fouling (Sharma, 2006).

On the one hand, ballast water provides stability to the vessel and is essential to maintain safe conditions during the voyage when it is not loaded. The ballast is stored in dedicated tanks or in empty cargo holds at the time of discharge of cargo. Then when the cargo or bunkers are loaded the water is deballasted (International Maritime Organization, 2004). The amount of ballast water carried can be as high as 113,000 tonnes for certain types of ships such as bulkcarriers, 45,000 tonnes for tankers or 6,000 tonnes for general cargo ships. Therefore, ballast water consists of port water, which may contain many viable exotic organisms even after long voyages (Globallast Partnerships, 2017).

On the other hand, the biofouling, marine organisms that attach themselves to the hulls of ships, is considered to be the main reason for unintentional entry and distribution of species according to European regulations (Ashton et al., 2016). The IMO defines biological pollution as *"accumulation of aquatic organisms, such as microorganisms, plants and animals on surfaces or structures submerged in or exposed to the aquatic environment"* (International Maritime Organization, 2022).

Among the European seas, the Mediterranean is the most affected by the introduction of species, mainly due to its worldwide connection through the Suez Canal and the intense maritime traffic (Tsiamis et al., 2020). The Convention on Biological Diversity (CBD) adopted at the Earth Summit in Rio de Janeiro in 1992 considers both ballast water and fouling on the hull of ships as subcategories within the vector of species

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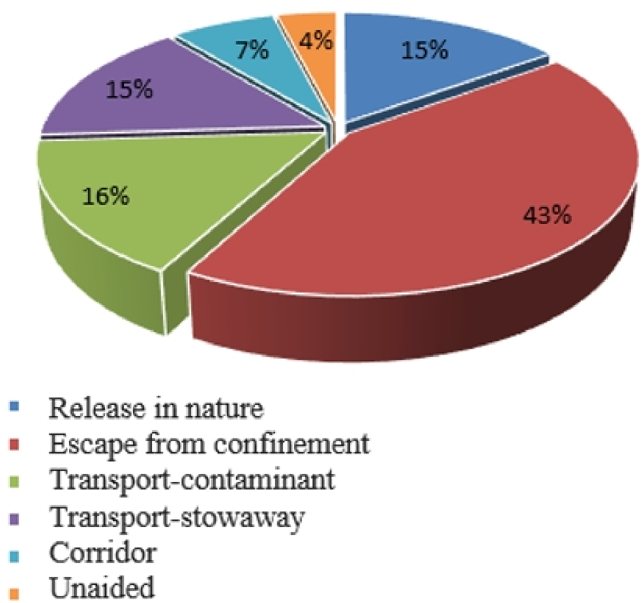
introduction by transport-pollution (CBD, 2023). In Europe, this vector represents the 15% of the introduction pathways by which the species are transferred (Figure 1).

Figure 1: Pathways of introduction that have been used by IAS of concern to the EU.



Source: Adapted figure from (Ministry for the ecological transition and the demographic challenge [MITECO], 2022).

If these organisms are introduced outside their natural geographical range, the species is commonly referred to as alien, exotic, non-native or non-indigenous species (Ojaveer et al., 2017). These are any species outside the natural range either due to international or accidental human-mediated transport, or transport by natural processes (Ministerio para la transición Ecológica y el Reto Demográfico Gobierno de España, 2013). When they are in a new port they may begin to displace native species and disrupt local ecosystem (Cebrian et al., 2013).

Invasive Aquatic Species (IAS) are defined as any species that is introduced or establishes itself in an habitat and is an agent of change and threat to native biological diversity, either by its invasive behavior, or by the risk of genetic contamination (Boletín Oficial del Estado del Gobierno de España, 2007). The introduction of IAS, into new environments by ships has been identified by the International Maritime Organization, henceforth, IMO, as a major threat to the world's oceans and to biodiversity conservation. Multiple marine species that have been transported in ballast water or on the hulls of ships can survive and establish a reproductive population in the host environment, becoming invasive, displacing native species and multiplying to become pests (International Maritime Organization, 2019).

It must be considered that invasive species can have a great impact on the environment, the economy and even threaten human health because of their harmful or poisonous potential (Galil et al., 2015). Most of them have the ability to choose their location influenced by environmental inputs: factors such as light, gravity, hydrostatic pressure, temperature and salinity mainly affect their distribution (Pérez, 2012). When invasive aquatic species are introduced into a habitat that is not their own and manage to adapt, reproduce and colonize the environment, they pose a threat to the marine ecosystem (Kenworthy et al., 2018). They can physically and chemically modify the ground, compete for food and space, and act as predators preventing the development of native species (Iberdrola, 2022).

Fouling and ballast water are the main systems for the movement of invasive species from one region to another, as they have been the vector for the introduction of seven of the 49 IAS of concern in Europe (MITECO, 2022). Once the species becomes established in the new environment it is very difficult to eradicate (Coughlan et al., 2018). In cases where eradication is not possible, pest control is maintained, which can entail very high costs. For example, the economic costs of the zebra mussel plague in the Ebro River have been estimated at 11.6 million euros during the period 2005-2009 and today it has still not been possible to exterminate it from the area (Perez and Chica Moreu, 2006). Agricultural and fishing activity is also economically affected due to the alteration of the marine habitat of local fish and species (Durán, 2011). The IAS can even endanger public health, for humans, one of their most dangerous effects is that they carry diseases.

To control and prevent biological contamination, international organizations are adopting a variety of measures. In the case of fouling, antifouling paints are used to prevent the adhesion of species to the hull (Dafforn et al., 2011). These are coatings, paints, surface treatments, or devices used on board. Even if ships have recently had their hulls cleaned or a new antifouling coating system applied, they will still have some level of biological contamination. For years metallic compounds such as tributyltin or TBT have been used in antifouling systems, which were very effective in preventing hull fouling, but were also harmful to the environment as they were shown to persist in water (Amara et al., 2018). As indicated in the existing regulations of the International Convention on the Control of Harmful Anti-Fouling Systems on Ships (AFS), the time it takes to apply this paint to the hull usually corresponds to the time between dry-dockings (International Maritime Organization, 2001). However, the focus should be put on the prevention of the introduction of invasive species through fouling on ships.

Regarding biofouling, the IMO has published recommendations for implementing certain operational practices on board to prevent the development of biofouling on the hull (International Maritime Organization, 2011). In contrast to the case of Ballast Water Management Convention (BWM) that regulates the introduction of invasive species, which will be fully implemented in September 2024 (International Maritime Organization, 2019).

Studies have shown that the biofouling process begins within the first few hours of a ship's immersion in water (International Maritime Organization, 2011). The biofouling that may be found on a ship is influenced by a range of factor, such as follows:

- Design and construction, particularly the number, location, and design of niche areas (Ulman et al., 2019),

- Specific operating profile, including factors such as operating speeds, ratio of time underway compared with time alongside, moored or at anchor, and where the ship is located when not in use (e.g., open anchorage or estuarine port) (Davidson et al., 2009), and
- Maintenance history, including: the type, age and condition of any anti-fouling coating system, installation and operation of anti-fouling systems and dry-docking/slipping and hull cleaning practices (Davidson et al., 2016).

Fouling also plays an important role in the ship's drag, as it can have such an effect on the hull roughness that it doubles the frictional resistance compared to a clean hull (Montes Coto, 2009). The species remain attached in the areas where they are least affected by the friction of the water against the hull and remain there throughout the voyage until the vessel reaches the port of destination. This applies a greater resistance to the ship's movement and generates a lower performance during navigation (Schultz, 2007).

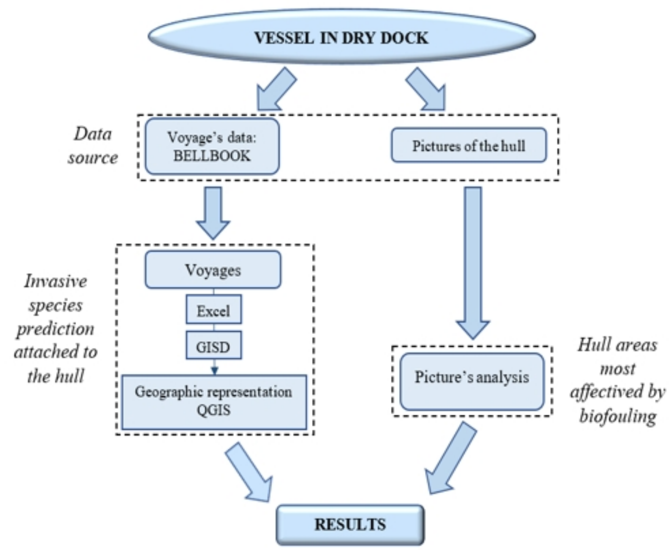
One of the reasons why organisms can be detached is the friction exerted by the water against the hull during navigation. This force does not affect the entire hull equally, allowing certain areas to be more susceptible to the accumulation of fouling. However, the variation in water characteristics between the port of origin and the port of destination, such as salinity or temperature, can help these species to be detached from the hull without causing any damage (Iacarella et al., 2020). This arises when they are not able to survive the conditions of the new habitat by accidentally detaching themselves from the hull of the ship.

This study aims to determine how merchant ships can generate biological pollution from fouling. To this end, a case study of a merchant ship entering dry dock has been carried out, predicting which invasive species have been able to adhere to the hull based on information from the ports it has called at since its last entry into dry dock. In addition, photographic data are taken of the affected hull areas to identify which parts of the hull are most affected by fouling and to be able to relate them to water friction during navigation.

2. Methodology.

In the Figure 2 you can see schematically the methodology of this research; that the following is explained in detail. The phases of this process are explained from the moment the ship enters the shipyard and the data are taken. The study of the prediction of species and the areas of the hull most affected by fouling is carried out to obtain the results of this study. First, to determine the possible introduction of species through biofouling, the data of the voyages are taken from the bellbook or logbook on board the vessel. This is the document that records the vessel's docking and undocking operations in port. Secondly, to determine which areas of the hull are most affected by the fouling, photographs are taken to analyze its condition in relation to the species it presents.

Figure 2: Overview of the methodology used.



Source: Authors.

2.1. Data source.

The information analyzed in this study is collected from a merchant vessel of 99.9 meters in length and 15.6 meters in beam that enters the Avilés Port Shipyard (Aviles Port, 2023) for maintenance work. The port of Avilés is located on an estuary in the Bay of Biscay, in the center of the Spanish Cantabrian coast. It has a storage area of 375,000 m2 and a berthing line of docks of 2 km, suitable to operate any type of merchandise (Figure 3). A total of 15 vessels of different dimensions enters this shipyard every year to carry out any maintenance task.

Figure 3: Location of the port of Aviles.

Source: Image adapted from Google Maps.

2.2. *Invasive species prediction attached to the hull.*

To predict the invasive species embedded in the hull, first, the ship's voyages were analyzed based on the information in the bellbook, where arrivals and departures to ports and anchor operations are recorded chronologically. In this way, the ship's itinerary since its last stop in dry dock was obtained. These data made it possible to identify the ports and anchorages visited by the vessel and information that made it possible to analyse possible invasive species attached to the hull.

To obtain the voyage data, this bellbook tracked and provided the port of call, the date and time of docking and undocking, the coordinates at the anchor position, the date and time the anchor was lowered and raised, and the navigation status. The data were acquired and organized simultaneously using the Microsoft Office Excel application. A table was made in which the collected data were laid out in an organized manner. As many rows were entered as the number of voyages made by the vessel compiling all travel information. The ship's voyages have to be analyzed to check the biological contamination that the ship may have caused taking into account the following situations:

- First, the navigational status that it has had throughout the voyages were considered. It could be found in a navigational state, docked in port or anchored (outside the port). It is important to point out these conditions since during the time the vessel is under navigation, the species have more difficulties to adhere due to the increased friction of the water with the hull. However, while docked or at anchor, the species have been able to attach more easily to the submerged structures of the vessel.

- Secondly, all the ports and anchorages visited by the vessel were presented chronologically, since these are the places where there is the possibility of species adhesion to the hull.

- Thirdly, the geographical areas were introduced, these are the oceans, seas, rivers, or canals where the ports and anchorages are located.

- Fourth and lastly, the characteristics of the water in each port or anchorage that could affect the survival of the species transferred as fouling were identified.

Once the data from the trips were obtained, we proceeded to search for invasive species through the online database Global Invasive Species Database, hereinafter GISD (http://www.iucn-gisd.org/gisd/). This website aims to increase public awareness of invasive species and facilitate effective prevention activities by disseminating the knowledge and expertise of specialists to a wide global audience (GISD, 2022). It focuses on invasive alien species, which are considered much more dangerous than non-invasive species as they threaten native diversity and natural areas by having a high capacity to adapt and survive in different environments. To perform this search, the GISD work option by filters was used, defined below in the Table 1. As many searches were made as ports visited by the vessel during the voyages, modifying the location in each one of them. The location filter corresponds to the ports or geographical regions that the vessel visits since the last departure to the shipyard. They try to be as specific as possible, but sometimes the GISD database does not have the specific port filter, so it is extended to the region.

Table 1: Filter selection on GISD.

Taxonomy	Animalia Plantae
Localización	The location of the port in question will be marked. If we do not have th option, we will mark one or several nearby ports that bring us closer to tl place. We could also mark by seas or rivers as long as the area is not too distant from the port, since species that do not belong to the area we are interested in could appear.
System	Marine Marine / freshwater / brackish
Pathway	Transport-stowaway: ship/boat hull fouling

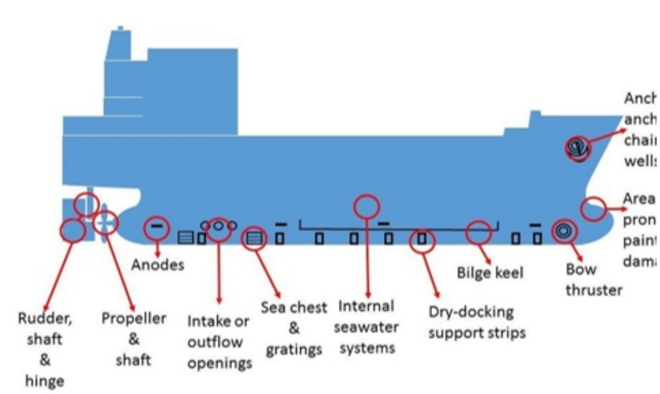
Source: Authors.

Once the search is done, each species found, and the location is recorded in an Excel table and then plotted on a map using the QGIS geographic information system (https://www.qgis-.org/en/site/). QGIS is an open-source Geographic Information System that allows you to create maps to visualize, manage and analyze data in a more simplified way.

2.3. *Hull areas most affected by biofouling.*

While the vessel is in dry dock, photographs of the hull are taken to evaluate its condition in terms of the fouling it shows. All areas of the hull in contact with the water are looked at, including the side, bow, stern, propeller, etc., searching for the parts where the organisms have adhered in greater quantities. In addition, the niche areas of the ship where these organisms are found were identified, knowing that those most susceptible to their accumulation are usually the ones represented in the Figure 4.

Figure 4: Niche areas of the ship susceptible to IAS accumulation.



Source: Georgiades and Kluza, 2020.

3. Results and discussions.

3.1. Invasive species prediction attached to the hull.

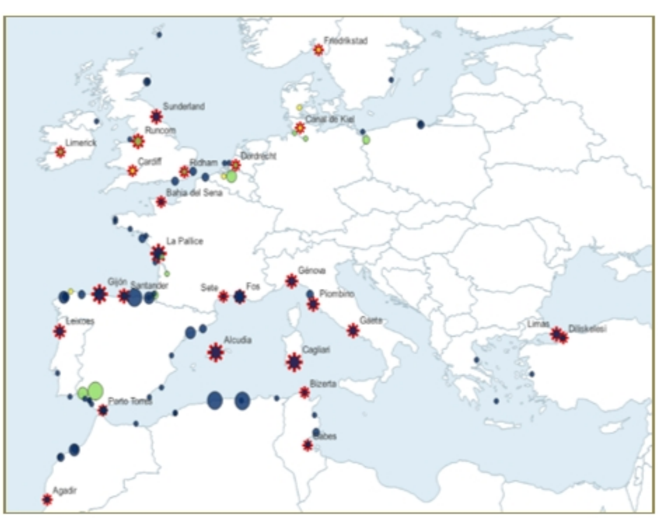
The vessel under study called at 80 ports of which 11 are freshwater, 9 are brackish water and the rest are saltwater. The map in the Figure 5 shows all of them, and these ports are mainly centered in areas of the Mediterranean Sea, North Atlantic, Cantabrian Sea and North Sea, passing through narrow channels such as the Kiel Canal. The passage through this channel is relevant for the research, due to its shallowness, narrowness, number of species detected and intense maritime traffic, which causes long waits for vessels wishing to cross it.

Species do not automatically adhere to the hull while the ship is sailing but need to be kept static for a period, either at berth or at anchor. Therefore, long waits at the entrance of the harbor also make possible the adhesion of the species in the area to the hull structure. In relation to the total time of the study, the vessel spends almost a tenth of the time at anchor and more than a quarter of the time at berth.

Also in the Figure 5 are highlighted in red those ports where some of the invasive species were found after searching through the GISD database.

Although it does not sail around the globe, there are enormous distances between some of the ports visited, so it suffers very different characteristics of temperature, salinity, PH, depth, sea currents and other variables that influence the survival of the fouling. For example, one of the trips has been from the port of Agadir in Morocco to Szcecin in Poland, passing through the Kiel Canal. This is an example of a long voyage in which the vessel has sailed in very particular waters that make up habitats of different characteristics. In the map of the Figure 5 the salinity of each port is differentiated into salty, fresh, and brackish depending on whether they are represented by blue, green, or yellow circles, respectively.

Figure 5: Distribution of the ports visited by the ship. Circles in blue: salty, in green: fresh, in yellow: brackish and with a red star: where IAS were detected.



Source: Authors.

The species from different areas may not survive due to the changing characteristics of the environment, which may not be suitable for their development. These habitats are distinguished by the salt content, depth, or temperature of the particular geographical area.

After searching the GISD database by applying the filters mentioned in the methodology section, 15 invasive species were found that may come from the 80 ports where the ship calls. One third of those ports were identified with invasive species. The Table 2 summarizes all the species found, specifying the area and the port from which they may come.

Table 2: IAS detected by zone and port of origin.

IAS	Zone	Port
Styela clava	North Atlantic	La Pallice
		Leixoes
	Cantabrian Sea	Gijón
		Santander
	Mancha Canal	Sena Bay
	Bristol Canal	Cardiff
	Támesis River	Ridham
	Mersey River	Runcorn
	North Sea	Sunderland
Codium fragile ssp. Tomentosoides	Mediterranean Sea	Alcudia
		Bizerta
		Gabes
		Fos
	Bristol Canal	Cardiff
	Oude Mass River	Dordrecht
	Shannon River	Limerick
	Mersey River	Runcorn
Crassostrea gigas	North Atlantic	Agadir
	Mediterranean Sea	Bizerta
		Gabes
	Bristol Canal	Cardiff
	Mersey River	Runcorn
	North Sea	Sunderland
Alitta succinea	Mediterranean Sea	Cagliari
		Porto Torres
	Kiel Canal	Kiel Canal
Sabella spallanzanii	North Atlantic	Agadir
	Mediterranean Sea	Bizerta
		Gabes
Rapana venosa	Marmara Sea	Diliskelesi
		Limas
	North Sea	Sunderland
Gracilaria vermiculophylla	North Atlantic	Agadir
	North Sea	Sunderland
Mytilusgalloprovincialis	Mediterranean Sea	Bizerta
		Gabes
Caulerpa taxifolia	Mediterranean Sea	Génova
		Piombino
Mya arenaria	North Sea	Sunderland
	Kiel Canal	Kiel Canal
Ascidiella aspersa	Mancha Canal	Sena Bay
Dreissena polymorpha	Kiel Canal	Kiel Canal
Polysiphonia brodiei	North Atlantic	Agadir
Bugura neritina	Mediterranean Sea	Gaeta
Musculista senhousia	Mediterranean Sea	Sete

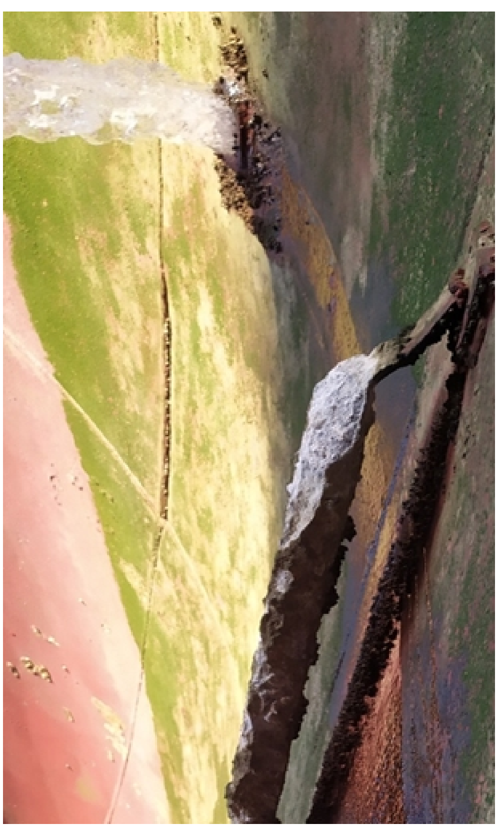
Source: Authors.

3.2. Hull areas most affected by biofouling.

As soon as the vessel arrives in dry dock, photographs are taken to evaluate its condition in relation to the fouling. The effect caused by the friction of the water during navigation on the incrusted species is considered, which causes them to detach from the surface by themselves. The higher the speed of the ship, the greater the frictional force on the hull surface. Actually, the surface of the hull is not completely flat and homogeneous but presents certain uniformities where the friction does not affect with such force as to detach the encrusted organisms, these are the so-called niche areas.

As an example of this, one of the ship's sacrificial anodes can be seen in the image in the Figure 6. This system is used to prevent corrosion in the submerged part of the hull. Due to the low water flow between the anode and the surface of the hull, the species are able to remain adhered in that area, since there is much less friction as the hull is protected by the anode. The same figure also shows the ballast water outlet surrounded by fouling due to the deterioration of the antifouling film by the friction exerted by the water during discharge.

Figure 6: Picture of a sacrificial anode and water intake of the vessel.



Source: Authors.

The hull has a balance keel along both sides, as shown in the image of the Figure 7, in order to reduce the rolling movement during navigation. Only moss and minor algae encrustations can be detected on the outside of the hull. However, in its inner part, since there is not enough friction to remove the species that have adhered, a larger number of incrustations can be detected.

Figure 7: Balance keel of the vessel. The image above is the outer part, and the image below is the inner part of the keel.

Source: Authors.

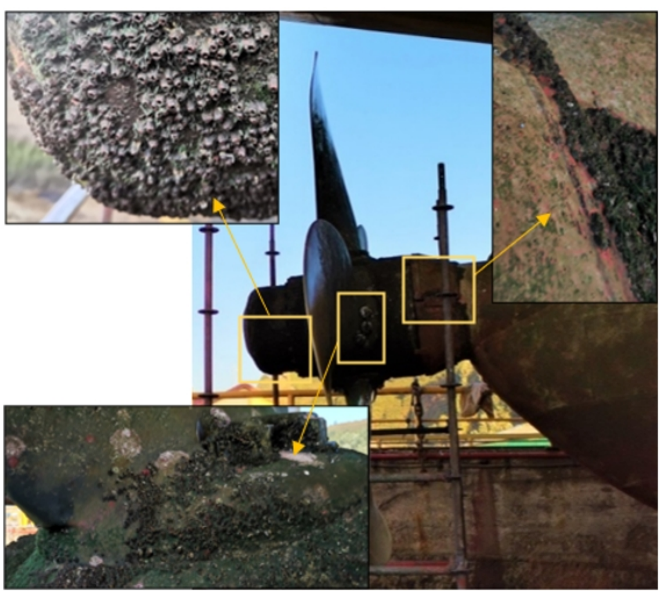
Lastly, the Figure 8 shows the aft area of the hull corresponding to the area most affected by fouling. In particular, the propeller is where the largest size and quantity of fouling is located in the entire hull, since it is easier for the species to remain adhered as it is not so affected by the friction of the water. The figure shows in detail the parts with the greatest accumulation of organisms, such as the piece behind the propeller, called cone, where the larger species accumulate due to the hydrodynamic action of the propeller. In the same way, the core and the roots of the blades also have a large accumulation of species. The propeller is affected by the cavitation phenomenon reflected in the outer edges of the blades. This effect caused by the explosion of tiny air bubbles corrodes this area leaving it completely smooth and free of incrustations.

The upper right of the Figure 8 shows another of the most affected areas both at the stern and along the side. This is the welded joint between the hull plates, which forms a roughness where the species manage to wedge in and remain attached, sheltered from any force that could dislodge them.

Despite all the time the vessel has been in the water, in general terms the hull does not present a large amount of fouling. This is associated with the navigation between different geographical areas and the variation in salinity that may have caused incompatibilities for the life of the species causing their disconnection with the surface of the hull. Even so, as explained from the photographs, the following areas of the hull are defined as the most likely to be affected by biofouling:

- Rudder blade,
- Propeller,
- Propeller shaft,
- Union between the welded parts of the hull,
- Inner part of the stabilizer fin,
- Cathodic protection anodes, and
- Seawater intakes.

Figure 8: Biofouling on the ship's propeller. Upper left image: cone, upper right image: junction of the parts, lower image: core of the blade.



Source: Authors.

Conclusions

In the research, we have predicted the invasive species that have been able to adhere to the ship according to its voyages, in addition to assessing the condition of the hull for fouling once it arrives at the shipyard and the parts of it most affected.

The survival of the species attached to the hull are affected during the operation of the vessel for two reasons; one is due to the itinerary of the vessel and the passage through waters of different characteristics and the other is due to the effect of the friction of the water against the hull during navigation. Although the vessel's voyages are not global in scope and are centered in Europe and North Africa, changes in the characteristics of the water are recognized throughout its voyage, which affects the life of the species, causing them to detach from the hull by themselves. However, after searching for invasive species present in each port of call, some of them are found in both saltwater and freshwater ports. Throughout the voyages, IAS are detected in more than 30% of the ports, where the species have had the opportunity to adhere to the ship's structure to be transferred to new locations. The species that survive long journeys are more likely to survive in the new environment and displace the native species, so special care must be taken with them.

The condition of the ship's hull once it arrives at the shipyard after all its time afloat may be dirty but not particularly affected by fouling. The water friction has affected the hull in such a way that during navigation they are detached by themselves, especially in the bow part. The greatest accumulation of fouling is found in the niche areas and in the aft part of the hull where the propeller is located. These are areas where, due to lack of maintenance or due to the operational design of the hull itself, it may be easier for the antifouling paint to be missing at some point and allow the adhesion of species. The propeller is where the greatest number and size of fouling is detected because it is where the water friction has the least effect.

This accumulation of organisms also leads to lower performance in the ship's propulsion equipment, increasing fuel consumption by requiring more power to reach the required speed, and we consider that further study of this is required. The hulls must be treated by applying antifouling paints and cleaning them from time to time, so that the operation of the ship is not so affected by the loss of speed caused by fouling, in addition to reducing the impact of biological contamination.

It is necessary on the part of international organizations the publication of mandatory regulations for the control of invasive species through fouling. The non-mandatory recommendations already published (International Maritime Organization, 2011) should be implemented as mandatory, just as the BWM Convention (International Maritime Organization, 2017) was done since most of the time the recommendations are not applied by those responsible.

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