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Costs and benefits to European shipping of ballast-water and hull-fouling treatment: Impacts of native and non-indigenous species

Jose A. Fernandes [a,*], Lionel Santos [a], Thomas Vance [b], Tim Fileman [b], David Smith [a], John D.D. Bishop [c], Frédérique Viard [d,e], Ana M. Queirós [a], Gorka Merino [f], Erik Buisman [g], Melanie C. Austen [a]

[a] Plymouth Marine Laboratory, PL1 3DH Plymouth, UK
[b] PML Applications, PL1 3DH, Plymouth, UK
[c] Marine Biological Association of the United Kingdom, Citadel Hill, PL1 2PB Plymouth, UK
[d] Sorbonne Universités, UPMC Univ Paris 06, UMR 7144, Station Biologique de Roscoff, 29680 Roscoff, France
[e] CNRS, UMR 7144, Divco Team, Station Biologique de Roscoff, 29680 Roscoff, France
[f] AZTI-Tecnalia, Herrera Kaia, Portualdea, z/g, Pasaia, Gipuzkoa 20110, Spain
[g] LEI-Wageningen UR, Alexanderveld 5, 2585DB, 'S Gravenhage, Netherlands

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ABSTRACT

Maritime transport and shipping are impacted negatively by biofouling, which can result in increased fuel consumption. Thus, costs for fouling reduction can be considered an investment to reduce fuel consumption. Anti-fouling measures also reduce the rate of introduction of non-indigenous species (NIS). Further mitigation measures to reduce the transport of NIS within ballast water and sediments impose additional costs. The estimated operational cost of NIS mitigation measures may represent between 1.6% and 4% of the annual operational cost for a ship operating on European seas, with the higher proportional costs in small ships. However, fouling by NIS may affect fuel consumption more than fouling by native species due to differences in species' life-history traits and their resistance to antifouling coatings and pollution. Therefore, it is possible that the cost of NIS mitigation measures could be smaller than the cost from higher fuel consumption arising from fouling by NIS.

1. Introduction

Fouling on hulls and ballast water in ships are two of the most important vectors for the introduction of non-indigenous species (NIS) into aquatic ecosystems [32,37,4,47]. As many as 990 different living taxa have been observed in ballasts in Europe [18], including microbes harmful to human health such as *Vibrio cholerae* [28] and *Escherichia coli* [54]. These routes can act as vectors for human-mediated introduction of species to new regions and the expansion of species' native ranges, depending on other factors such as climate change [20,43,56,64]. Current projections estimate that climate change alone may increase the rate of NIS introductions into European waters by 15 to 30% by mid-century [14,39,8]. Potential synergies between shipping vectors and other human-driven effects like climate change can thus lead to substantial changes in the distribution and productivity of both native species and NIS. These can cause important changes to the structure and functioning of marine ecosystems, with social and economic consequences [40,41,48,65].

These impacts have been recognized by the International Maritime Organization (IMO) and local agencies, which have introduced management guidelines for biofouling [21,49,55,61]. The IMO also strives to implement legislation in the Ballast Water Management Convention; Section D of the Convention Regulation considers the installation of IMO- type-approved onboard ballast water treatment systems (BWTS) to meet the D-2 discharge standard – a quality standard insuring against the presence of living organisms in discharged waters. The recently introduced US Coast Guard and US EPA regulations establish similar standards [61,63]. As of 17 October 2014, after 14 years of negotiations, 43 states had ratified the convention, representing 32.5% of world merchant shipping tonnage (IMO; http://www.imo.org/About/Conventions/StatusOfConventions), still below the tonnage

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[*] Corresponding author.
E-mail address: jfs@pml.ac.uk (J.A. Fernandes).

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required to enable the convention to enter into force (35%). However, it is approaching the threshold for enforcement [27]. The cost of these mitigating strategies to the shipping industry is largely unquantified. This study aimed to bridge this gap.

Anti-fouling and new ballast regulations are seen as costs by the shipping industry. However NIS, which have the potential to become invasive, could also negatively affect the industry through biofouling of hulls, increasing fuel consumption. Organism assemblages attached to the underwater surfaces of ships (biofouling) significantly reduce propulsion efficiency through increased drag, leading to increased fuel consumption and emissions [42]. A significant portion of this fuel is used to overcome the frictional resistance between the ship's hull and the water [59], and this can be as high as 40–80% of the total fuel consumption of a given ship. Antifouling paints and coatings that help to control biofouling of ships hulls have thus been in use for many decades [46]. In parallel, most of the world's shipping fleets have decreased their average speeds by up to 56% to reduce fuel consumption [58], driven by the onset of the Western financial crisis and a decrease in global trade in recent years [3]. Regardless, the potential financial gain associated with a reduction of biofouling and of the associated fuel expenditure in shipping remains unquantified. It is therefore unclear whether mitigation measures aimed at reducing transport of organisms could generate long-term financial benefits to the shipping industry by reduction of drag and hence of fuel consumption.

In this work, the cost of NIS mitigation measures and potential savings from those measures due to the additional cost of hull fouling caused by NIS relative to native species in terms of fuel consumption is examined. This difference is due to differences in their respective biological traits. Antifouling is directed at both native and non-indigenous species and costs are offset by fuel savings. But antifouling will also reduce the spread of NIS. Ballast water treatment is primarily directed at reducing/preventing the spread of NIS, with no immediate compensatory fuel saving. However, reducing the spread of NIS may lead to a reduction in future fuel costs imposed by biofouling, if fouling NIS that have been spread in ballast (e.g. as larvae) subsequently exert heavier fouling costs than native species. Therefore the increased cost of fuel consumption between NIS and native species is estimated. But, the potential savings if NIS species have a higher impact on hull bio-fouling is also calculated and, therefore, fuel consumption considering that ballast water treatment systems will reduce NIS spread.

2. Materials and methods

A list of species was collated that have been observed to be the most problematic for the shipping industry in European waters in terms of their prevalence on ships hulls, even when anti-fouling measures are in place. Then, possible ecological differences between the native species and NIS in these communities are investigated, which may have a bearing on fuel consumption. The effect of those factors is then contrasted with the cost to the shipping industry of NIS mitigation measures (anti-fouling and ballast waters) under current maritime regulation trends. These costs are break down in relation to the different types of ship to investigate impacts on the consumer, because different types of ship are associated with the transport of different types of goods.

2.1. Calculation of impact on fuel consumption of native and non-indigenous species (NIS)

A list of algal and animal species found in external ship fouling and in ballast waters in Europe was compiled based on publications that comprehensively studied these communities [18,26,29,30,32,37,38,47,53], together with a selection of species from the AquaNIS database on aquatic NIS (http://www.corpi.ku.lt/databases/index.php/aquanis/). This list of 302 species was reviewed by a biofouling expert (T.V.) who selected a subset of 59 species considered to be most problematic for increasing the fuel consumption of ships through biofouling due to their prevalence on hulls, resistance to anti-fouling measures, frictional resistance and growth (henceforth, “the most problematic”; Appendix 1). The species list was then revised by an external, independent expert in another European country. The final list included barnacles (15), tunicates (14), bryozoans (13), tube worms (4), molluscs (4), sponges (3), algae (3) and cnidarians (3). Once this list was established, four categories of ecological traits were considered based on the reasons for their impact on fuel consumption: (1) fast growth or high reproduction rate; (2) known resistance to pollutants or anti-fouling measures; (3) morphological shape or size that produces frictional resistance; or 4) high abundance/biomass or prevalence. Information regarding these traits, for the species list, was sought from public datasets, specifically: SeaLifeBase (http://www.sealifebase.org); BIOTIC (http://www.marlin.ac.uk/biotic); WoRMS (http://www.marinespecies.org); MarBEF (http://www.marbef.org/data/aphia.php?p=match) and Natural England database (http://www.naturalengland.org.uk/ourwork/conservation/biodiversity/threats/nonnativeaudit.aspx). These databases were further used to determine which of the species listed are present in each of the three specific European regional seas of interest to this study (Western Mediterranean, Baltic and North Sea) and whether each species is considered native or NIS in each area. Given data availability, a set of factors associated with these traits were selected covering all the trait categories.

The factors considered were: the von Bertalanffy growth parameters (Linf, theoretical maximum size of an organism; K, growth rate; and, Ø, mean size; from public and private databases) because rapid growth leads to greater fouling potential; length-weight relationship parameters (referred to as a and b; from public databases) for the same reasons; resistance to contamination (from literature) indicating greater ability to withstand anti-fouling measures [10,23]; bending capacity (from public databases) indicating greater ability to persist when underway instead of breaking and falling off; salinity range, enabling resistance to possible hydrological changes during transport; growth pattern (from biological databases and J.B. expert knowledge), considering colonial growth patterns leading to greater fouling potential than solitary patterns; hydrodynamic resistance (T.V. expert knowledge), proportional to impact on drag; and ability to colonize artificial substrates (presence on settlement panels from unpublished data sets), also associated with greater fouling potential. In the case of hydrological resistance, the species were ranked between 1 and 3, where thin and flexible morphological forms such as filamentous algae would be considered to have a resistance of 1 and an organism with a large, architecturally complex and inflexible form such as oysters were classified as having a resistance of 3. As an exception, the trait value for “Growth pattern”, representing whether the species multiplies vegetatively into a group of associated modular units (e.g. zooids or polyps in animal taxa) following settlement (=colonial), or grows as a single organism from the settling propagule (=non-colonial), could be specified in all instances, because expert knowledge was used when published data were not available (J.B.). For the qualitative growth pattern, a value was assigned to each category since a colonial pattern can lead to more successful lateral spreading [15]: two for colonial; and one for non-colonial (as defined in the BIOTIC database).

Direct species-by-species comparison was not possible since no species had data for all the traits and the percentage of species