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POLICIES AND SUPPORT IN RELATION TO LCA

Environmental impacts of alternative antifouling methods and use patterns of leisure boat owners

Kristina Bergman[1] · Friederike Ziegler[1]

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Abstract

Purpose Leisure boaters in the Baltic Sea apply more copper as antifoulant than needed and permitted. Initiatives have been started to identify efficient means making boat owners comply with regulations through changed consumer behavior. We compare the environmental impacts of conventional and alternative antifouling methods, using Life Cycle Assessment methodology.

Methods Two non-toxic methods were compared with biocide paint. To study the influence of boat owner use patterns, paint and brush washer scenarios (e.g., different paints, amounts, and maintenance) were created based on current use and recommendations. The functional unit was an average Swedish leisure boat kept fouling free for 1 year and impact categories studied were freshwater eco-toxicity and greenhouse gas emissions. Production of paints, fuel, electricity, and material used in the non-toxic methods was included. Sensitivity analysis was performed regarding the characterization method for toxicity, the fuel consumption data, and the copper release data.

Results and discussion The non-toxic methods, hull cover and brush washer, performed best, but a trade-off was identified when the brush washer was located further away from the home port, when additional transportation increased greenhouse gas emissions. The resources needed for the non-toxic methods (production of materials and electricity used) cause considerably lower toxic emissions than paint. In the paint scenarios, using less paint and cleaning the boat over a washing pad with water treatment reduces aquatic emissions significantly. Fuel-related emissions were consistently lower than paint-related emissions. In the best-performing paint scenario, fuel- and paint-related emissions represented 26 and 67% of total emissions, respectively.

Conclusions The non-toxic methods hull cover and brush washers lead to lower emissions, especially when brush washers were located close to the home port. Lacking such infrastructure, "painting less" is a way to reduce emissions, by using lower amounts of paint and painting less frequently. More widespread use of these antifouling strategies would considerably reduce copper emissions from leisure boating to the Baltic Sea. We suggest that support to marinas for investments in brush washers and washing pads should be further developed to enable boat owners to choose more sustainable antifouling methods and that information campaigns on the combined economic, health, and ecosystem impacts of antifouling are especially designed for boaters, marinas, market actors, and policy makers for a change to take place towards more sustainable practices.

Keywords Antifouling · Baltic Sea · Boating · Copper · Environmental impacts · LCA · Leisure boats · Zinc

1 Introduction

The use of conventional antifouling paints to prevent fouling on boat hulls causes intentional emissions of toxic substances to marine ecosystems (Karlsson et al. 2010; Schiff et al. 2004). Copper is the most frequently used active substance in antifouling paints globally (Jones and Bolam 2007; Srinivasan and Swain 2007) ever since the application of tributyltin (TBT) on vessels was banned in 2003 as a response to the severe negative effects that TBT has on other marine organisms (Dafforn et al. 2011; Gibbs and Bryan 1986). However, also copper is associated with negative effects on non-target organisms (Karlsson et al. 2010; Amara et al. 2017). In a number of algal species, copper can have major negative effects on growth and reproduction (Cid et al. 1995; Eklund and Kautsky 2003; Karlsson et al. 2010). Exposure to

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✉ Friederike Ziegler
friederike.ziegler@ri.se

[1] RISE Agrifood and Bioscience, PO Box 5401, 40229 Gothenburg, Sweden

copper-based paint caused failure of osmoregulation in the crustacean *Artemia* (Katranitsas et al. 2003) and negative larval development effects and mortality in another crustacean, *Nitocra spinipes* (Karlsson et al. 2010).

The Baltic Sea ecosystem is particularly vulnerable to pollution. It is an enclosed sea basin surrounded by Sweden, Denmark, Finland, the Baltic countries, Russia, Poland, and Germany and connected to the North East Atlantic only through the shallow Danish Sounds. Due to the limited connection with the Atlantic, the water exchange is slow, and since there is high inflow of freshwater from rivers, the salinity is very low (on average 7.7 psu) (Strandmark et al. 2015) as is the number of species able to survive under these conditions. As the salinity falls from the North East Atlantic to the northern Baltic, many species reach their tolerance limit and fail to survive in the Baltic Sea (Bonsdorff 2006). Several species have a lower tolerance to heavy metal exposure in brackish water compared to marine (Tedengren et al. 1988) and organisms living in the Baltic Sea are exposed to additional stress through widespread eutrophication and hypoxia (Diaz and Rosenberg 2008).

As the number of leisure boats only in Sweden and Finland is 1.5 million (Eklund et al. 2013; Swedish Transport Agency 2016), leisure boats could be an important source of emissions of toxic metals to the coastal areas of the Baltic Sea (Andersson and Kautsky 1996). The toxic compounds spread through antifouling use are reaching not only the water basin but also the soil where boats are kept during the winter. Around 2500 marinas are situated only on the Swedish coast and the soil there has been shown to contain high concentrations of copper, zinc, and TBT (Eklund and Eklund 2014; Lagerström et al. 2016) A considerable part of the coast is therefore likely polluted by antifouling substances from leisure boats. Sweden which has coasts bordering the Baltic Sea on its east side and the more saline and species rich Kattegat and Skagerrak on the west side (Bonsdorff 2006), implying a higher fouling pressure, has different legislation for antifouling paints depending on which of those areas the boat will be used in. A clear majority of Swedish boat owners use biocide paint as the method to prevent fouling on the boat (Swedish Transport Agency 2016). Many boaters use more paint and more toxic paints than actually needed, so-called west-coast paints are used on the east coast, and paints for use in shipping are used on leisure boats on the west coast (Dahlström et al. 2014). Although biocide paint is the dominating method, very few Swedish marinas for leisure boats were in 2015 equipped with cleaning facilities such as washing pads with water treatment (Swedish Transport Agency 2016) to deal with the problem of paint residues contaminating the ground.

Not preventing fouling at all leads to trade-offs, since growth of barnacles, algae, and other fouling organisms on the boat hull results in reduced maneuverability and more drag which increases fuel consumption. Data on this trade-off is, however, very sparse and only available for shipping, not for leisure boats. For ships, literature values on the increased fuel consumption range between 0.3 and 88% (Champ 2000; SIDA 1986). Voulvoulis (2006) stated that after 6 months of fouling, a ship expends 40% more fuel. This trade-off between energy use and toxicity is generally accepted, but there is little scientific data to support it, especially quantifying the relative contribution of various activities to these impacts.

Research on new antifouling methods is mainly focused on new types of paints, but so called booster biocides as zinc oxide that increases the toxicity of copper (Watermann et al. 2005) as well as paints marketed as biocide free have been shown to be highly toxic also to non-target organisms (Karlsson and Eklund 2004; Karlsson et al. 2010; Amara et al. 2017). Consequently, there is a great need for alternative, non-toxic, methods to remove or prevent fouling. For leisure boats, there are several non-coating antifouling methods available designed to reduce (or avoid) toxic emissions. Examples of two such methods are brush washers that clean the hull mechanically similar to an automatic car wash and hull covers that cover the boat hull while in the marina, thereby preventing biofouling by limiting oxygen and light supply. Swedish authorities recommend leisure boat owners to use biocide free, mechanical cleaning methods of this type instead of painting (Swedish Transport Agency 2018). Still, only a few percent of Swedish leisure boat owners part of a Swedish national survey (Swedish Transport Agency 2016) kept their boats clean by visiting brush washers, and none used hull covers as their antifouling method. A majority did not know about any good alternatives to biocide paint.

The environmental impacts of these alternative antifouling methods have, to our knowledge, not been compared with conventional antifouling treatments including all input materials and energy used by each method. An integrated analysis of various antifouling methods, taking into account potential environmental trade-offs (e.g., related to fuel consumption), could inform boat owners, marinas, and policymakers. Life Cycle Assessment (LCA), standardized by ISO (ISO 2006a, b), is a suitable method for this purpose; it is a recognized and widely used method for environmental assessment of products and processes. It could be used to evaluate whether the non-toxic methods are actually preferable in relation to conventional antifouling paints from an overall environmental perspective—and to identify improvement options for each method. One of the main strengths of such an approach is that toxic emissions of upstream activities such as the production of fuel and paint are included, not only emissions from the final product or service. Taking into account the effects of different use patterns for different consumers of that same final product or service, it is possible to provide a more relevant basis for guidelines for future policy-making on various levels (from information campaigns targeting boat owners to legislation). Therefore, our aim was to compare the environmental impacts of alternative and conventional antifouling methods using LCA. We also wanted to study the effect of different boat owner choices concerning how to apply these methods, and potential trade-offs between different types of impacts.

2 Materials and methods

2.1 Goal and scope

The goal of this study was to quantify and compare the environmental impacts of conventional and alternative methods to prevent fouling on leisure boats, including two biocide free, mechanical antifouling methods. In addition, we wanted to investigate what effects different ways of using the same method had in order to illustrate the magnitude of mitigating actions such as performing maintenance on a painted hull at a washing area where paint residues are taken care of. The functional unit (FU) was defined as *an average Swedish leisure boat kept free from fouling during 1 year*. The FU was related to a timespan without fouling to enable comparisons of the very different antifouling methods. Various functional units were considered before deciding on the one used, which is based on our view that the function of owning a boat is to have the freedom of being able to go out to sea whenever you want during the season.

The average boat as well as a number of scenarios for leisure boat and antifouling method use patterns is based on data from national studies on leisure boat life in Sweden from the Swedish Transport Agency (2010, 2016) and a pilot study on boating habits in Sweden (Dahlström et al. 2014). The average leisure boat is a 5-m-long motor boat with a two stroke outboard engine. The national study assumes that the boat is launched in the spring and retrieved in the autumn, on average 152 days later. However, the boat is generally used no more than 18 days, and consuming 0–75 l of petrol during that period of time. For all scenarios, the boating season, i.e., the time spent in water, was therefore set to 152 days and the hull surface calculated to approximately 12 m^2. Emissions from production and combustion of 37.5 l (mean of the range 0 and 75) of petrol in a two stroke engine was also included. Building of boat and engine was not included as it would not influence the evaluation of antifouling treatments differently.

We studied paints containing copper and zinc, brush washer, and hull cover as antifouling methods and designed the treatments to be compared to fulfill the function of preventing fouling based on information from companies and researchers (e.g., that brush washing is needed three times during a season). To study the influence of different boat owner use patterns, different scenarios for usage of copper-based paint and for brush washer were created (Table 1). These scenarios are based on current use patterns (Dahlström et al. 2014; Swedish Transport Agency 2016) and recommendations from Swedish authorities (Swedish Transport Agency 2018). The specific inputs for each scenario in addition to the ones mentioned above are described in Fig. 1.

The four paint scenarios differ regarding the type of paint used, whether a so-called washing pad with water treatment was used during hull maintenance or not and how much paint was used. The two paints were Biltema antifouling 30630 (copper content of 13%) and Biltema antifouling Baltic Sea 30630 (copper content of 7.5%). The paint with higher copper concentration is not allowed on boats with main mooring in the Baltic but as many as 7% of boat owners admitted in the survey by the Swedish Transport Agency (2016) that they used illegal paint. The amount of paint used per year was set to 1.24 based on a Swedish study on leisure boating by Dahlström et al. (2014). We determined how much of the biocides were emitted to water during a year and how much remained on the hull using the release rates of copper and zinc in the paints. There are several methods for measuring and calculating release rates; in our study we have used the same release rates as the Swedish Chemicals Agency uses to approve paints (see Lagerström et al. 2018). The biocides remaining on the hull after the boating season based on the paint specific release rates were assumed to be emitted to soil during maintenance (Lagerström et al. 2016) if a washing pad with water treatment was not used. The washing pad is a designated washing area on land in the marina with a drainage that catches paint residues that fall off during cleaning, e.g., with pressure hosing. The paint residues are then treated as hazardous waste, instead of ending up on bare land. For the scenario with less paint used we assume that only 65% of the average amount of paint was used as a result of one or more of the following actions: painting only every second year, diluting the paint, and painting only parts of the hull most prone to fouling.

The brush washer scenarios are based on the type of brush washers used in Sweden. They work by cleaning the boat hull with rotating brushes in seawater and any fall off from the hull is caught in a container surrounding the washing area, and then treated as hazardous waste. Three visits per season, building of the brush washer, its lifetime, and operation, were included in the scenarios (Klofsten, personal communication). The two scenarios differ by the brush washer's distance to the boat, 30 min being the maximum distance that boat owners have claimed to be willing to travel to clean their boat (Dahlström et al. 2014). The extra fuel needed to get to a brush washer in the scenario where it was located 30-min driving distance away was set to 20.8 l/h based on the consumption of a boat with similar size and engine power as an average Swedish leisure boat (Yamaha 2002). The fuel consumption in that scenario is thereby more than twice that of the others. A 30-min trip corresponds to a distance of about 5 km (assuming

Table 1 Assumptions made in the seven antifouling strategy scenarios analyzed

Scenarios	Assumptions
Paint scenario: paint with high copper concentration, no ground protection used during maintenance, average amount of paint used	Commercial paint with 13% copper content and Cu release rate of 2.37 μg/cm^2/day. Paint residues end up on bare land. 1.24 l of paint used per year.
Paint scenario: paint with low copper concentration, no ground protection used during maintenance, average amount of paint used	Commercial paint with 7.5% copper content and Cu release rate of 0.41 μg/cm^2/day. Paint residues end up on bare land. 1.24 l of paint used per year.
Paint scenario: paint with low copper concentration, washing pad used during maintenance, average amount of paint used	Commercial paint with 7.5% copper content and Cu release rate of 0.41 μg/cm^2/day. Paint residues collected and treated as hazardous waste (through use of washing pad). 1.24 l of paint used per year.
"Paint less" scenario: paint with low copper concentration, washing pad used during maintenance, less paint used	Commercial paint with 7.5% copper content and release rate of 0.41 μg/cm^2/day. Paint residues collected and treated as hazardous waste (through use of washing pad). 0.81 l of paint used per year (65% less than average).
Brush wash scenario: 30-min distance	Epoxy paint used, three visits at brush washer per season, maximum acceptable driving distance (10 l of additional petrol each way) for boat owners assumed.
Brush wash scenario: 0-min distance	Epoxy paint used, three visits per season, brush wash situated at home marina.
Hull cover scenario	Epoxy paint used, lifetime of 5 years.

a speed of five knots). Both in the two brush washer scenarios and the hull cover scenario, we assumed that epoxy paint (biocide free paint) was used. The hull cover prevents fouling when the boat is docked by enclosing the hull and in this way limits oxygen and light supply. Since most leisure boats spend around 90% of the time docked (Swedish Transport Agency 2016), it should be a solution as good as the other alternatives for the average boat owner.

We limited our analysis to two impact categories: freshwater eco-toxicity and greenhouse gas emissions. These impact

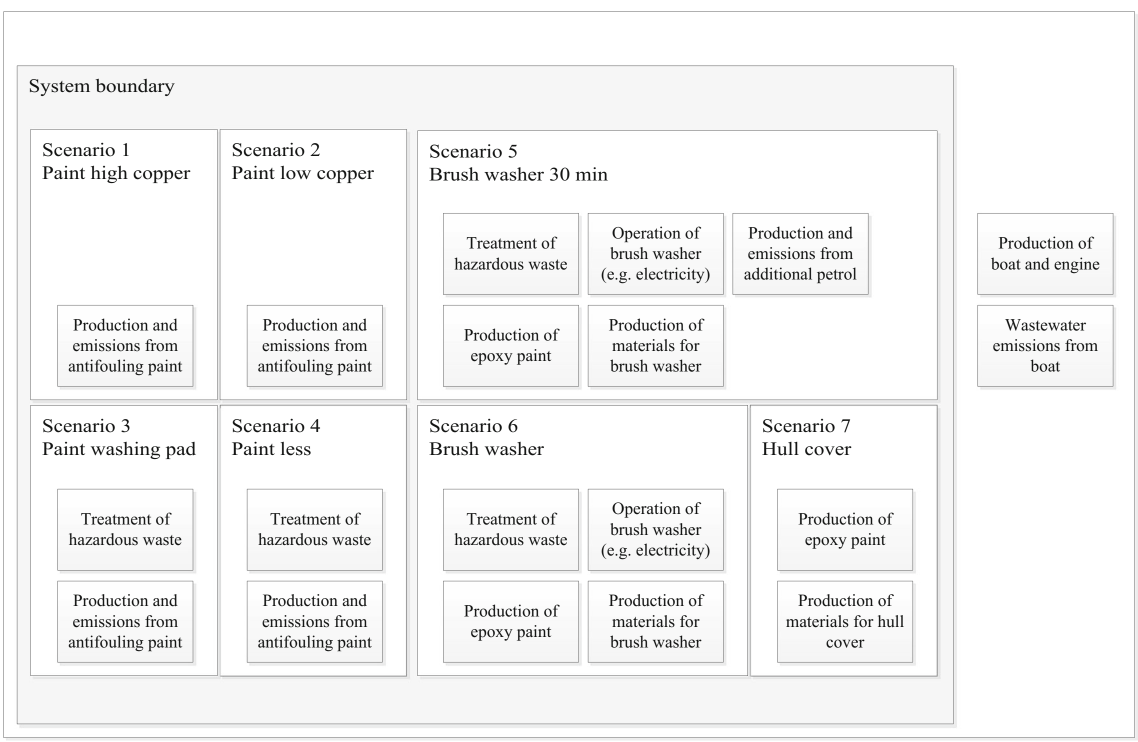

Fig. 1 Activities included in and excluded from the comparison of antifouling treatments

categories were selected to analyze if a trade-off between toxic emissions and energy use or greenhouse gas emissions, as has been described in shipping (Voulvoulis 2006), exists also for leisure boats.

2.2 Life cycle impact assessment

The USEtox (recommended + interim) version 1.04 (Rosenbaum et al. 2008) impact category freshwater ecotoxicity was chosen to analyze the effects of leisure boating activities in the Baltic Sea, although it is a brackish ecosystem and not freshwater. Other LCIA methods exist that include impact categories for aquatic and marine eco-toxicity (ReCiPe, IMPACT 2002+); however, they are aged and have been improved and incorporated in the USEtox model which is the recommended method for LCIA of the impact categories human toxicity and freshwater eco-toxicity by the ILCD handbook (European Commission 2010). USEtox also has characterization factors (CFs) for more substances emitted in our scenarios than other methods for eco-toxicity.

Dong et al. (2015) calculated eco-toxicity characterization factors for copper and zinc in marine and brackish coastal waters including the Baltic Sea using a new method that includes USEtox methodology. This method was not used as; to our knowledge, CFs for other substances than metals have not yet been calculated, which makes it unsuitable in this case where we want to compare the emissions of antifouling paints to those of other activities such as petrol combustion and material production with non-metal toxic emissions.

The method used to model climate change was IPCC (2013), and all analyses were performed using SimaPro software (v.8.3) with background data primarily from the Ecoinvent v.3 database (Wernet et al. 2016).

2.3 Sensitivity analysis

The seven antifouling scenarios were in addition to USEtox analyzed using three other LCIA methods (ReCiPe, IMPACT 2002+, and EDIP 2003) to investigate effect of method on the eco-toxicity of the scenarios in relation to each other.

The effect of higher fuel consumption per season was also analyzed, as we expected that it might change the relative contribution to freshwater eco-toxicity of petrol compared to paint emissions. The fuel consumption was increased from 37.5 to 162.5 liters per year, which was in the upper range of fuel consumption in the national study on leisure boat life in Sweden (Swedish Transport Agency 2010).

A new method of measuring release rates for antifouling biocides, X-ray fluorescence spectrometer (XRF), has been suggested as the commonly used methods underestimate release rates (Lagerström et al. 2018). In the sensitivity analysis, we investigated the impact on results of using different release rate data.

3 Results

Copper and zinc emissions to water and soil from antifouling paints are the dominant toxic emissions from leisure boating, overshadowing, e.g., the combustion of fuel or production of paint and fuel (Fig. 2). Moreover, when biocide paints were used, toxic emissions were much higher than non-toxic treatments irrespective of the toxic content as well as the way boat owners used it, i.e., whether or not a washing pad was used when the hull was cleaned in fall or how much paint was applied (Fig. 2). Maintenance of a painted boat at a washing pad greatly reduced total emissions by more than two thirds by eliminating the emissions of both copper and zinc to soil, which eventually leak to water and cause aquatic toxicity. The difference between using paints with high and low copper contents was smaller than expected (Fig. 2), given the large importance of copper emissions and this is because zinc is in the low-copper paints used as a “booster biocide” and the toxicity of zinc is ranked in the same range as that of copper in the method used here (USEtox). As mentioned, the non-toxic methods boat washer and hull cover lead to even lower toxic emissions than best-performing paint scenario, which was using a low-copper paint sparsely and cleaning the boat over a washing pad in the fall. For boats kept fouling free by visiting boat washers, emissions mainly originate from fuel combustion for transportation to a boat washer and secondly from production of materials and energy for operating the boat washer. Using a hull cover was the best-performing method analyzed here and emissions originate from production of the hull cover.

Changing the perspective from aquatic toxicity to greenhouse gas emissions, the picture changes and the different treatments are more similar, since the basic fuel use is assumed to be the same between the different treatments (Fig. 3). The main contributing processes are now, for all treatments, fuel production and combustion. For the boat washer and the hull cover, production of the epoxy paint used on the hull also contributes. Due to the importance of fuel use, the need for additional transportation becomes very important and the worst case here is visiting a brush washer that is located 30 min away, approximately corresponding to a distance of 5 km. The increase in emissions of toxic substances from combustion of petrol in that scenario resulted in a slightly higher contribution to aquatic toxicity than the other brush washer scenario (Fig. 2), but not enough to reach the paint scenarios. The production of materials and energy for operating the brush washer gave rise to negligible emissions in both impact categories.

We first analyzed the sensitivity of our results on the choice of the method for characterization of toxic emissions. We compared results of USEtox with the methods EDIP, ReCiPe, and IMPACT. All methods showed decrease in toxicity from high-copper paint to the hull cover and ranked the treatments in the

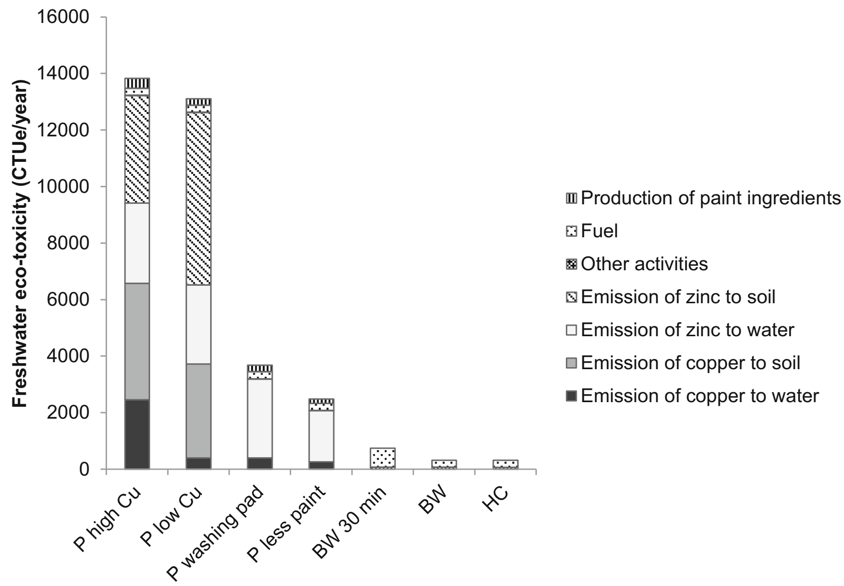

Fig. 2 Freshwater eco-toxicity of different antifouling treatments per year (P high Cu = paint, average amount, with high copper concentration and no washing pad, P low Cu = paint, average amount, with low copper concentration and no washing pad, P washing pad = paint, average amount, with low copper concentration and washing pad used, P less paint = paint, lower amount, with low copper concentration and washing pad used, BW 30 min = brush washer located 30 min away, BW = brush washer located at home port, HC = hull cover)

same way (Fig. 4). The main difference was that there was no effect of the washing pad when using EDIP, since this method does not consider toxic emissions to soil to cause aquatic toxicity which all other methods tested do. In the ReCiPe method, zinc has a much lower toxic impact (characterization factor) compared to copper, resulting in a larger difference between high- and low-copper paint than when analyzed with USEtox. The brush washer scenario with a 30-min extra drive contributes more to freshwater eco-toxicity than the best case scenario for paint in the IMPACT method, because of the emissions from petrol consumption. Overall, we conclude that the ranking of treatments and conclusions are not affected by the choice of impact assessment method.

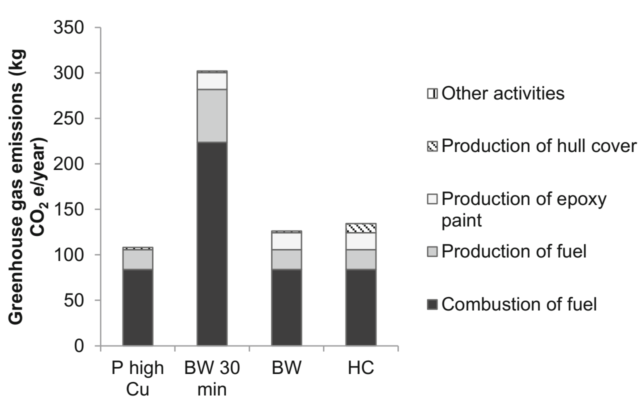

Fig. 3 Greenhouse gas emissions of different antifouling treatments per year (P high Cu = paint, average amount, with high copper concentration and no washing pad, BW 30 min = brush washer located 30 min away, BW = brush washer located at home port, HC = hull cover)

The second sensitivity analysis performed concerned the data used for fuel use per season, which was increased from approximately 40 to 160 l, which was in the upper range of reported fuel consumption among Swedish boaters (Swedish Transport Agency 2010). This led to proportionally increased greenhouse gas emissions and a reduced difference between treatments, implying the effect of the extra 30-min transportation to the brush washer meant less. Despite the increase, fuel-related toxic emissions were lower than emissions from paint biocides even in the best-performing paint scenario (Fig. 5). However, in this scenario, fuel-related toxic emissions were responsible for as much as 26% of the total emissions. We conclude that the fuel use data does not change major conclusions between treatments, but it has importance for the conclusion about the importance of where boat washers should be located in relation to major marinas.

The third aspect tested was the release rate used for copper and zinc, i.e., how much of the substances that leak to the surrounding water was left on the boat hull after the season. The original data on release rates calculated using the rotating cylinder and CEPE model was changed to release rates measured with the XRF method. While the choice of release rate data had a major influence on absolute toxic emissions (resulting in higher emissions when XRF-based values were used; Fig. 6), it did not change any conclusions regarding the relative performance of treatments. An observation is that even when the highest possible release rates are applied, there is leakage to soil from biocides left on the boat hull after the season without any antifouling effect (Fig. 6), indicating that concentrations are unnecessarily high.

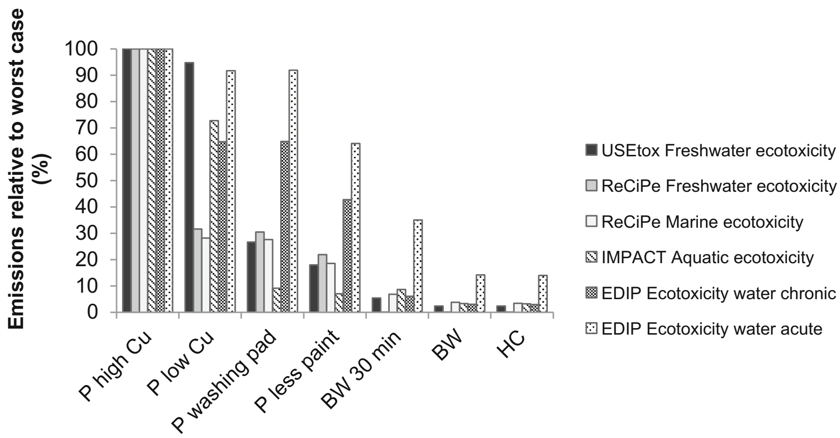

Fig. 4 Various impact assessment methods and impact categories applied to test sensitivity of results (P high Cu = paint, average amount, with high copper concentration and no washing pad, P low Cu = paint, average amount, with low copper concentration and no washing pad, P washing pad = paint, average amount, with low copper concentration and washing pad used, P less paint = paint, lower amount, with low copper concentration and washing pad used, BW 30 min = brush washer located 30 min away, BW = brush washer located at home port, HC = hull cover)

4 Discussion

This study shows that the choices boaters make on how to treat their boat hulls to keep them free from fouling have a major influence on resulting emissions. The choice between toxic and non-toxic methods is the most important one, followed by the choice of using a washing pad when the hull is cleaned before winter storage. When using toxic paints, the amount used and the release rate, which varies both with the paint (structure/formula) and with the environment in which it is used (salinity), is important (Valkirs et al. 2003). Another factor for overall aquatic toxic emissions is the paint's content of copper and zinc. The direct toxicity on aquatic organisms of zinc compared to copper has been found to be lower in toxicity studies (Ytreberg et al. 2010; Bighiu et al. 2017). However in the model used in this study, zinc is considered causing almost as much toxicity in aquatic ecosystems as copper. A new Life Cycle Impact Assessment method (that includes USEtox methodology) for calculating marine eco-toxicity for metals presented in Dong et al. (2015, 2018) found that zinc was almost ten times as toxic as copper in marine ecosystems due to the higher bioavailability of zinc, indicating that the pattern can be seen in different types of aquatic ecosystems. Thus, if paints with lower copper content designed for use in more sensitive areas like the Baltic Sea, instead contain more of the booster biocide zinc, they could in fact have a higher impact on aquatic toxicity than paints containing more copper. The uncertainty surrounding the comparative toxicity assessment of alternative toxic substances, in this case copper and zinc, further reinforces the advantage of avoiding their use altogether following the precautionary principle that if there is lack of knowledge whether a substance or activity will cause long-term environmental damage, it should be avoided.

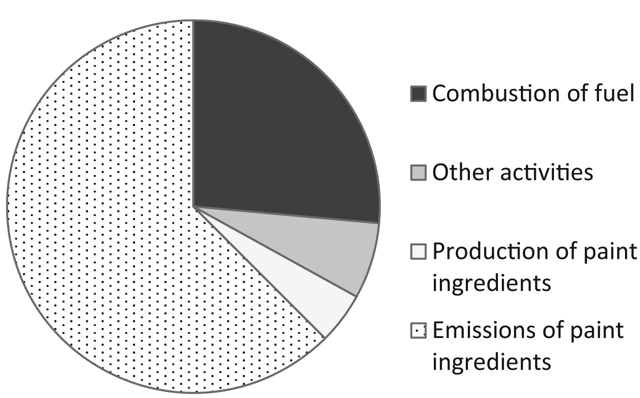

Fig. 5 Relative contribution to freshwater eco-toxicity from the paint less scenario (paint, lower amount, with low copper concentration and washing pad used) activities when increasing fuel consumption from 37.5 to 162.5 liters per year

If toxic substances are to be used, they should be applied in minimum amounts giving maximum effect, meaning the release rate should match the local fouling pressure and other environmental conditions (salinity) so that just enough active substance leaks out to prevent fouling. Panel tests of the CHANGE project showed that there was no additional antifouling effect of paints with higher than 7.5% copper oxides in the Baltic Sea, which means that higher concentration is a waste of money and leads to unnecessary emissions to the same ecosystems boaters go out to enjoy. Also, paints should be designed in a balanced way between content and release, so that as little toxins as possible is left on the hull after the season, to avoid or at least reduce the problem with toxic paint residues on land (Lagerström et al. 2016). If antifouling paints were used in this way broadly, the need to install (very costly) washing pads in

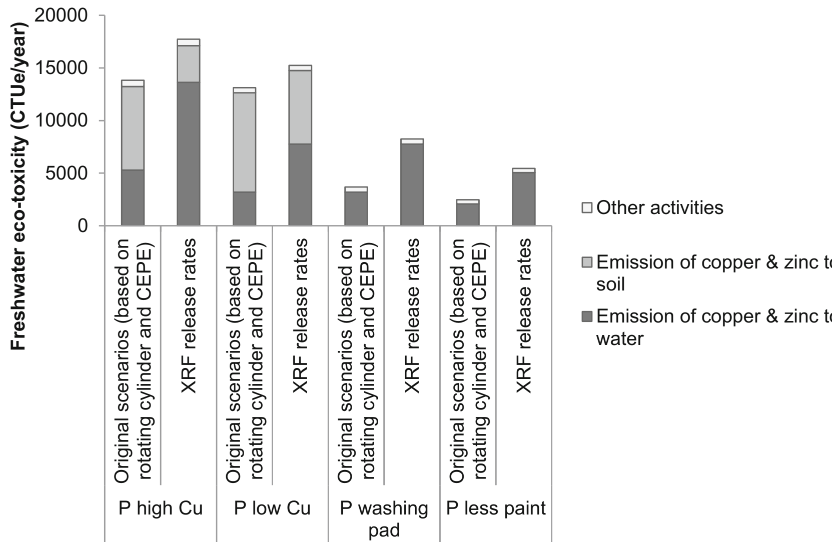

Fig. 6 Two different metal release rate datasets used to test sensitivity of results (P high Cu = paint, average amount, with high copper concentration and no washing pad, P low Cu = paint, average amount, with low copper concentration and no washing pad, P washing pad = paint, average amount, with low copper concentration and washing pad used, P less paint = paint, lower amount, with low copper concentration and washing pad used)

marinas would be less urgent. Still, even with stricter future regulations concerning biocide paints, washing pads could continue to be important for minimizing leakage of biocides for many years; 25 years after the EU ban of TBT in antifouling paints, it is still detected on leisure boats around the Baltic Sea (Lagerström et al. 2017). A negative effect of marinas investing in washing pads could be that they become less likely to invest in a brush washer as well. Efforts to build more washing pads should therefore be carefully analyzed as to not hinder a more progressive development.

Many ideas flourish about the relative roles of the use of biocide paint versus fuel for toxic and greenhouse gas emissions of shipping and boating, ideas that are surprisingly ungrounded in science. Here, we can demonstrate that toxic emissions from production and combustion of fuel in leisure boating, although not negligible, are much lower than those of the release of antifouling substances. It is important to note that the scenario here is based on a motorboat with the type of engine that causes the highest amounts of emissions (two-stroke outboard engine). For sailing boats which rely less on fuel the biocide emissions from paints would dominate the total impact even more. By using alkylate petrol instead of regular fuel in a motor boat the emission of toxic compounds could be further reduced (Cerne et al. 2008). Unfortunately, only 4% of Swedish boaters use alkylate petrol, the main reason it being too expensive or not accessible (Swedish Transport Agency 2016). Many impact assessment methods in LCA (including the one used) lack toxicity factors for a few of the polyaromated hydrocarbons that are released for example from the combustion of fuels, which means that their contribution is underestimated. Even though the toxic emissions from fuel do not exceed the ones from antifouling paints, increasing greenhouse gas emissions is still an issue as is the loss of maneuverability why our results do not suggest to avoid fouling prevention altogether.

The non-toxic treatments brush washer and hull cover were the best-performing alternatives analyzed, and these should be promoted for use wherever efficient. In more saline waters, the fouling pressure is stronger which requires more frequent brushing, which increases cost, inconvenience, and environmental impacts, especially if the brush washer is not located in the home port. A survey among Swedish boaters showed that very few were willing to travel further than 30 min to wash their boat (Dahlström et al. 2014). Our results show that if the brush washer is not located reasonably close, increased effects on climate change arise due to fuel-related emissions from transportation. Factors to weigh into decisions of location of new brush washers are therefore the vicinity to major marinas, but also the sensitivity of the area, i.e., how important it is to avoid toxic emissions. Today, the number of brush washers along Swedish coast bordering the Baltic Sea (approximately ten) is increasing and most of the brush washers in Sweden are situated in the Stockholm area. Building a new one is subsidized by the government, as is the construction of washing pads.

Many marinas, however, still lack brush washers and washing pads and some harbor masters hesitate to allow the use of hull covers fearing they will disturb other boat owners (Koroschetz et al. 2017). With that in mind, the boat owners' ability to make the different choices between antifouling methods and maintenance described in this study is sometimes limited by availability of this particular infrastructure in their vicinity. Hence, for a change to take place towards more sustainable practices, the role of infrastructure, culture, and policy/regulations in addition to individual boat owner choices need to be better understood. For example, today, large retail chains sell the same products in all of their stores, regardless of where they are located. Therefore, a boater can walk into a store on the Baltic coast and buy antifouling paint that is not approved for usage in the Baltic Sea; compliance is up to the boater. Research in environmental psychology suggests that by changing regulations, so that only paints allowed for usage in the Baltic Sea can be sold in stores on the Baltic coast, the illegal paint use would be more efficiently reduced than through information campaigns targeting paint consumers (Koroschetz et al. 2017). The availability of sustainability information has a limited effect on individual consumption (Bamberg and Möser 2007; Koroschetz et al. 2017). Information targeting boat owners could lead to faster change towards more sustainable practices if it helped building stronger support for new legislation, gave acceptance of new practices or highlighted maintenance that does not depend on new infrastructure or habits, such as the "paint less method." Major improvement is possible by recommending painting only the parts of the hull most prone for fouling and only every second year, without losing antifouling effect, in particular if using a low-copper paint. If this method is presented from an economic and health impact perspective to boaters rather than from an environmental perspective, it may have a larger effect. Therefore, to achieve a change from paint to brush washer or hull cover, the individual boat owners are not the ones to be targeted alone; the focus should also be on marinas, market actors, and policy makers.

5 Conclusions

We conclude that the policy direction taken by, e.g., the Swedish government supporting closer access to washing pads and brush washers, is appropriate to reduce emissions of copper and zinc to the Baltic Sea. Additional policy changes that are highly needed and could facilitate for compliant boat owners and reduce loads of excess copper and zinc to ecosystems are stronger regulations of the use of toxic antifouling paints. The issue deserves more public and policy attention, given the amounts of excess copper currently released to water and soil from leisure boats, without filling any function, while causing major harm to the same ecosystems of great recreational value to leisure boaters.

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References

Amara I, Miled W, Slama RB, Ladhari N (2017) Antifouling processes and toxicity effects of antifouling paints on marine environment. A review. Environ Toxicol Pharmacol 57:115–130

Andersson S, Kautsky L (1996) Copper effects on reproductive stages of Baltic Sea *Fucus vesiculosus*. Mar Biol 125(1):171–176

Bamberg S, Möser G (2007) Twenty years after Hines, Hungerford, and Tomera: a new meta-analysis of psycho-social determinants of pro-environmental behaviour. J Environ Psychol 27(1):14–25

Bighiu MA, Gorokhova E, Almroth BC, Wiklund AKE (2017) Metal contamination in harbours impacts life-history traits and metallothionein levels in snails. PLoS One 12(7):e0180157

Bonsdorff E (2006) Zoobenthic diversity-gradients in the Baltic Sea: continuous post-glacial succession in a stressed ecosystem. J Exp Mar Biol Ecol 330(1):383–391

Cerne O, Strandberg J, Fridell E, Peterson K, Allard AS, Rydberg T, Vaske B, Jägersten C, Östman N, Eklund B (2008) Rena Turen–Utvärdering av miljöanpassade bränslen i fritidsbåtar (Pure luck-Evaulation of environmentally adapted fueld in leisure boats, in Swedish). IVL Svenska Miljöinstitutet, Stockholm

Champ MA (2000) A review of organotin regulatory strategies, pending actions, related costs and benefits. Sci Total Environ 258(1):21–71

Cid A, Herrero C, Torres E, Abalde J (1995) Copper toxicity on the marine microalga Phaeodactylum tricornutum: effects on photosynthesis and related parameters. Aquat Toxicol 31(2):165–174

Dafforn KA, Lewis JA, Johnston EL (2011) Antifouling strategies: history and regulation, ecological impacts and mitigation. Mar Pollut Bull 62(3):453–465

Dahlström M, Elwing H, Ytreberg E, Solér C, Dahlström M (2014) Bland borsttvättar och fartygsfärger – En studie av fritidsbåtsägares attityder till och användning av olika antifoulingtekniker (Among brush washers and shiping paints- A study of boaters attitudes to and use of various antifouling techniques, in Swedish) http://changeantifouling.com/wp-content/uploads/2014/10/Ut%C3%B6kad_rapport_bilaga4.pdf

Diaz RJ, Rosenberg R (2008) Spreading dead zones and consequences for marine ecosystems. Science 321(5891):926–929

Dong Y, Rosenbaum RK, Hauschild MZ (2015) Assessment of metal toxicity in marine ecosystems: comparative toxicity potentials for nine cationic metals in coastal seawater. Environ Sci Technol 50(1):269–278

Dong Y, Rosenbaum RK, Hauschild MZ (2018) Metal toxicity characterization factors for marine ecosystems—considering the importance of the estuary for freshwater emissions. Int J Life Cycle Assess 23(8):1641–1653

Eklund B, Eklund D (2014) Pleasure boatyard soils are often highly contaminated. Environ Manag 53(5):930–946

Eklund BT, Kautsky L (2003) Review on toxicity testing with marine macroalgae and the need for method standardization—exemplified with copper and phenol. Mar Pollut Bull 46(2):171–181

Eklund B, Haaksi H, Syversen F, Eisted R (2013) Disposals of plastic end-of-life boats. TemaNord 2013:582, Nordic Council of Ministers 2013, ISBN 978-92-893-2651-3

European Commission (2010) Joint Research Centre - Institute for Environment and Sustainability: international reference life cycle data system (ILCD) handbook - general guide for life cycle assessment - detailed guidance. First edition march 2010. EUR 24708 EN. Luxembourg. Publications Office of the European Union

Gibbs PE, Bryan GW (1986) Reproductive failure in populations of the dog-whelk, *Nucella lapillus*, caused by imposex induced by tributyltin from antifouling paints. J Mar Biol Assoc UK 66(04):767–777

International Organization for Standardization (2006a) ISO14040:2006 environmental management – life cycle assessment – principles and framework. ISO, Geneva

International Organization for Standardization (2006b) ISO 14044:2006 Environmental Management – Life Cycle Assessment – Requirements and Guidelines. ISO, Geneva

IPCC (2013) Climate change 2013: the physical science basis: working group I contribution to the fifth assessment report of the

intergovernmental panel on climate change. Cambridge University Press, Cambridge
Jones B, Bolam T (2007) Copper speciation survey from UK marinas, harbours and estuaries. Mar Pollut Bull 54(8):1127–1138
Karlsson J, Eklund B (2004) New biocide-free anti-fouling paints are toxic. Mar Pollut Bull 49(5):456–464
Karlsson J, Ytreberg E, Eklund B (2010) Toxicity of anti-fouling paints for use on ships and leisure boats to non-target organisms representing three trophic levels. Environ Pollut 158(3):681–687
Katranitsas A, Castritsi-Catharios J, Persoone G (2003) The effects of a copper-based antifouling paint on mortality and enzymatic activity of a non-target marine organism. Mar Pollut Bull 46(11):1491–1494
Koroschetz B, Solér C, Mäenpää E (2017) Bonus Change Deliverable 2.2 Report/Scientific article on Leisure boat owners' ways of using of antifouling products and techniques and their understanding of environmental consequences
Lagerström M, Norling M, Eklund B (2016) Metal contamination at recreational boatyards linked to the use of antifouling paints—investigation of soil and sediment with a field portable XRF. Environ Sci Pollut Res 23(10):10146–10157
Lagerström M, Strand J, Eklund B, Ytreberg E (2017) Total tin and organotin speciation in historic layers of antifouling paint on leisure boat hulls. Environ Pollut 220:1333–1341
Lagerström M, Lindgren JF, Holmqvist A, Dahlström M, Ytreberg E (2018) In situ release rates of cu and Zn from commercial antifouling paints at different salinities. Mar Pollut Bull 127:289–296
Rosenbaum RK, Bachmann TM, Gold LS, Huijbregts MA, Jolliet O, Juraske R et al (2008) USEtox—the UNEP-SETAC toxicity model: recommended characterisation factors for human toxicity and freshwater ecotoxicity in life cycle impact assessment. Int J Life Cycle Assess 13(7):532–546
Schiff K, Diehl D, Valkirs A (2004) Copper emissions from antifouling paint on recreational vessels. Mar Pollut Bull 48(3):371–377
Srinivasan M, Swain GW (2007) Managing the use of copper-based antifouling paints. Environ Manag 39(3):423–441
Strandmark A, Bring A, Cousins SA, Destouni G, Kautsky H, Kolb G et al (2015) Climate change effects on the Baltic Sea borderland between land and sea. Ambio 44(1):28–38
Swedish International Development Authority/FAO Gulbrandsen O (1986) Reducing the fuel costs of small fishing boats
Swedish Transport Agency (2010) Båtlivsundersökningen 2010. En undersökning om svenska fritidsbåtar och hur de används (Boat survey 2010. A study on Swedish leisure boats and how they are used, in Swedish)
Swedish Transport Agency (2016) Båtlivsundersökningen 2015. En undersökning om svenska fritidsbåtar och hur de används (boat survey 2015. A study on Swedish leisure boats and how they are used, in Swedish) Report number TSG 2016–534
Swedish Transport Agency (2018) Ren båtbotten (Clean boat hull, in Swedish) https://www.transportstyrelsen.se/sv/sjofart/Fritidsbatar/Batlivets-miljofragor/Ren-batbotten/. Accessed 26 Feb 2018
Tedengren M, Arner M, Kautsky N (1988) Ecophysiology and stress response of marine and brackish water Gammarus species (Crustacea, Amphipoda) to changes in salinity and exposure to cadmium and diesel-oil. Mar Ecol Prog Ser 47:107–116
Valkirs AO, Seligman PF, Haslbeck E, Caso JS (2003) Measurement of copper release rates from antifouling paint under laboratory and in situ conditions: implications for loading estimation to marine water bodies. Mar Pollut Bull 46(6):763–779
Voulvoulis N (2006) Antifouling paint booster biocides: occurrence and partitioning in water and sediments. In: Antifouling paint biocides. Springer Berlin Heidelberg, pp 155–170
Watermann BT, Daehne B, Sievers S, Dannenberg R, Overbeke JC, Klijnstra JW, Heemken O (2005) Bioassays and selected chemical analysis of biocide-free antifouling coatings. Chemosphere 60(11): 1530–1541
Wernet G, Bauer C, Steubing B, Reinhard J, Moreno-Ruiz E, Weidema B (2016) The ecoinvent database version 3 (part I): overview and methodology. Int J Life Cycle Assess 21(9):1218–1230
Yamaha (2002) Yamaha körfakta. (Yamaha driving facts, In Swedish) http://www.batvaruhuset.se/documents/batvaruhuset/documents/korfakta_2002_tcm36-34329.pdf2002. Accessed 13 July 2015
Ytreberg E, Karlsson J, Eklund B (2010) Comparison of toxicity and release rates of cu and Zn from anti-fouling paints leached in natural and artificial brackish seawater. Sci Total Environ 408(12):2459–2466