Deliverable 4.6 Report/Scientific article on the Environmental impacts of alternative antifouling methods for leisure boats and use patterns of boat owners

RISE Research institutes of Sweden

Project acronym: BONUS CHANGE

Project title: Changing antifouling practices for leisure boats in the Baltic Sea

Work package: 4

Deliverable 4.6 Comparison of the different use patterns of antifouling paints identified using Life Cycle Assessment methodology

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1. Background

The negative environmental impacts from biocides used in boat hull paints are well documented (Cid et al. 1995, Dafforn et al 2011, Eklund and Kautsky 2003, Gibbs and Bryan 1986, Karlsson et al. 2010, Katranitsas et al 2003). Not using biocide paint on boats and ships however, results in organisms attaching and settling on the hull, causing drag that make vessels more difficult to maneuver as well as consume more fuel. The combustion of fuel will in turn result in emission of greenhouse gases and toxic substances. The occurrence of such a trade-off is well illustrated with the holistic approach of assessing different types of environmental impacts that Life Cycle Assessment offers.

The aim of the BONUS CHANGE project is to provide tools and research results that support a change of antifouling practices for leisure boats in the Baltic Sea towards more environmentally sustainable practices with less use and spread of biocides to the marine environment. It is obvious that boating related activities are popular in the countries surrounding the Baltic Sea as the number of leisure boats only in Sweden and Finland is 1.5 million. In addition, plenty of marinas are situated all along the coasts of the Baltic Sea to harbor the boats. The potential toxic impact from biocide paints and ways to reduce it are therefore important to study and communicate. Other tasks in the BONUS CHANGE project have shown that the amount of biocides used on leisure boats in the Baltic Sea in many cases is more than enough to prevent fouling. A large part of the project has therefore been to evaluate ways of decreasing biocide use and trying out innovative biocide-free methods to prevent fouling as a mean to reduce toxic substances being spread in the Baltic Sea.

In this study, we have assessed the environmental consequences of using two of these biocide-free methods compared to using biocide paints. We have also analysed different use patterns for biocide paints to illustrate how environmental impacts of leisure boating can vary depending on how the individual boat owner chooses to maintain the boat.

1.2 The purpose

The study presented herein is a part of Work Package 4 in the BONUS CHANGE project. The purpose of this study is to compare the environmental impacts of alternative and conventional anti-fouling methods using Life Cycle Assessment. We also wanted to study the effect of boat owner behaviour concerning how to apply these methods and potential trade-offs.

1.3 Method

Life Cycle Assessment is an internationally standardized framework for environmental assessment of products or processes following these from cradle-to-grave, i.e. from raw material extraction over production, distribution and use to waste management. It sets out to cover all environmental aspects relevant for a specific production system. The unit of assessment (the functional unit), shall reflect the function of the product. In the case of food, the functional unit is often a typical consumer package, a kilo of product or a nutritional function of the food. For paints, the functional unit could, rather than a liter of paint, be the coverage of a certain area over a certain time (m2*year) or it could be related to the purpose of using the paint, like keeping the boat free from fouling in the example of antifouling paints. These definitions will however always depend on the goal of the study, i.e. what is to be compared.

Undertaking an LCA comprises four main phases, as defined in the ISO standard (ISO 2006a,b) 1) Goal and Scope definition, 2) Inventory, 3) Impact assessment and 4) Interpretation. It is an iterative process in that early steps often need to be revisited after the first results are obtained. Goal and scope definition comprises of framing the study in terms of setting the system boundaries (which flows to be included), defining the product to be studied as well as the types of environmental impacts to be covered. Data inventory involves collecting data on inputs and outputs, of every activity included in the production system, and aggregation of them often using a dedicated LCA software (e.g. SimaPro). During impact assessment, inventoried data is translated into resource use and emissions, weighed together into impact categories to which they contribute (e.g. Cumulative Energy Demand, Global warming, Eutrophication, Acidification, Aquatic ecotoxicity etc.). Interpretation involves drawing conclusions from the results in relation to e.g. data quality and performing a sensitivity analysis, possibly resulting in a second iteration of refining important data used. LCA results can and are used for product development, for policy-making and as a basis for certification both by companies and public organizations on a totally voluntary basis.

1.4 Outline of report

This report is made up of a manuscript that will be published as a scientific article. It will be submitted in September 2017.

2. Manuscript:

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

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Abstract
As a basis for policy advice, we compared the environmental impacts of conventional antifouling methods with alternative antifouling methods using Life Cycle Assessment methodology. Two non-toxic methods were compared with two biocide paints used in different ways, resulting in four different paint scenarios. The non-toxic methods, brush washer and hull cover, were the best performing options and the only tradeoff situation identified was when an extra transport of 30 minutes was required to go to the brush washer, as greenhouse gas emissions increased. The additional resources required for the non-toxic methods (production of materials and electricity used), do not by far compensate for the intentional toxic emissions from paint. When using toxic paint as antifouling method, using a minimum amount of paint and cleaning the boat over a washing pad before winter storage reduces aquatic emissions dramatically. It was also shown that emissions from fuel production and combustion were lower than paint-related emissions. In the best of the paint scenarios, fuel related emissions represented 40% of total toxic emissions.

We suggest that support to marinas for investments in brush washers and washing pads be further developed to enable boat owners to choose more sustainable antifouling methods and information campaigns specially designed for boaters and marinas on the combined economic, health and ecosystem impacts of antifouling.

1. Introduction

The use of conventional antifouling paints to prevent fouling on boat hulls causes intentional emissions of toxic substances to marine ecosystems (Schiff et al. 2004, Karlsson et al. 2010). 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 also on other than fouling 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). In a number of algae 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 copper based paint has also been showed to cause 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 slow water exchange with the Atlantic and the high inflow of freshwater the salinity is very low, (on average 7.7 psu) (Strandmark et al. 2015) as is the number of species able to survive under those special circumstances. Organisms living in the Baltic Sea are exposed to widespread eutrophication and hypoxia and several species have been showed to have lower tolerance to heavy metal exposure in brackish water compared to marine (Tedegren 1988).

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 the soil where boats are kept during winter as well. Around 2500 marinas are estimated to be 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 marine Kattegat and Skagerrak on the west side (implying a higher fouling pressure), has different legislation for antifouling paints depending on which area the boat will be used in. Further complicating the matter, other countries, like Finland and Germany have legislation concerning paints used in the Baltic Sea. The main problem, however, is the fact that many boat owners use more paints and more toxic paints than are actually needed, 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).

Not preventing fouling at all leads to tradeoffs, as growth of barnacles, algae and other fouling organisms on the boat hull results in increased drag, which increases fuel consumption. Data on this tradeoff is, however, very sparse and only available for shipping, not for leisure boats. Literature values on increased fuel consumption for ships as a consequence of fouling vary between 0.3 % and 88 % (Champ 2000, SIDA 1986). According to a study by Voulvoulis et al. (2006) a ship expends 40 % more fuel after 6 months of fouling (corresponding to an average boating season in the Baltic Sea). This tradeoff 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 (addition of Zn makes it possible to reduce content of Cu while maintaining the same antifouling effect), as well as paints marketed as biocide free have been shown to be highly toxic also to non-target organisms (Karlsson et al. 2010, Karlsson and Eklund 2004). 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 and thereby preventing biofouling by limiting oxygen and light supply. 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.

Given the urgency to reduce release of toxic substances in the Baltic Sea and the time horizons involved in developing and approving new antifouling products, we cannot rely solely on the development of new paints. An integrated analysis of various kinds of existing antifouling methods, taking into account potential environmental tradeoffs (e.g. related to fuel consumption), could inform boat owners, marinas and policy-makers. Life Cycle Assessment (LCA) is a suitable method for this purpose. It is a recognized and widely used method for environmental assessment of products and processes, standardized by ISO (ISO 2006a,b). Within the European Union it forms the basis for the ongoing development of Product Environmental Footprinting methods. LCA quantifies a defined set of environmental impacts in relation to a defined function of a product. 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 also toxic emissions of upstream activities (such as the production of fuel and paint are included; not only emissions during use of the final product. LCA has successfully been applied to behaviours as well (Kaiser et al 2003). A comparison of different technological solutions and behaviours related to antifouling using LCA could provide a base for guidelines for future policy-making on various levels (from information campaigns targeting boat owners to legislation).

1.2 Aim

We aimed to compare the environmental impacts of alternative and conventional antifouling methods using Life Cycle Assessment. We also wanted to study the effect of boat owner behaviour concerning how to apply these methods, and potential trade-offs.

2. Materials and Methods

2.1 Goal and scope

The goal of this study was to quantify and compare the environmental impacts of alternative methods to prevent fouling on leisure boats, including two biocide free, mechanical antifouling methods and to investigate the influence of consumer choices on how to apply these methods. The functional unit (FU) was defined as *one boating season without fouling* of an average Swedish leisure boat (motor boat). The FU was related to a timespan without fouling to enable comparisons of the very different antifouling methods. Another FU was also considered; *one boating day without fouling.* However, using a boating day as FU leads to that the eco-toxicity potential increases and decreases with the number of days the boat is assumed to be used, although in reality, e.g. antifouling paint emits copper throughout the boating season. Also arguably, the function of having a boat is to be able to go out whenever and not just to have a fouling free boat the days when one does use it.

The two impact categories studied were freshwater eco-toxicity and climate change. These impact categories were selected to analyse if a tradeoff between toxic emissions and energy use, as described earlier, exists also for leisure boats.

Data from a national study on leisure boat life in Sweden from the Swedish Transport Agency (2016) as well as a study on boating habits in Sweden (Dahlström et al. 2014) was used to construct both the base case and a number of scenarios for leisure boat usage. The boating season was e.g. set to 152 days in all scenarios and emissions from production and combustion of 38 liters of petrol was included. Building of boat and engine were not included due to expected low contribution compared to the use of petrol and antifouling in the categories studied.

We compared two paints with different copper content and usage of a brush wash and hull cover as antifouling methods. We assumed that all methods were equally successful at preventing fouling. To study the influence of consumer choices, different scenarios for usage of copper-based paint and for brush washer were created (Table 1). Release rates of copper and zinc in the two commercial paints are presented in Lagerström et al. (submitted manuscript).

2.2 Scenarios

Table 1. Assumptions seven antifouling strategy scenarios.

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 $\mu g/cm^2/day$. Paint scrape-offs end up on bare land. 1.24 liters 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 $\mu g/cm^2/day$. Paint scrape-offs end up on bare land. 1.24 liters of paint used per year.
Paint scenario: paint with low copper concentration, washing pad and ground protecting foil used during maintenance, average amount of paint used	Commercial paint with 7.5 % copper content and Cu release rate of 0.41 $\mu g/cm^2/day$. Paint scrape-offs collected and treated as hazardous waste (through use of ground protecting foil and washing pad). 1.24 liters of paint used per year.
Paint scenario: paint with low copper concentration, washing pad and ground protecting foil used during maintenance, less paint used	Commercial paint with 7.5 % copper content and release rate of 0.41 $\mu g/cm^2/day$. Paint scrape-offs collected and treated as hazardous waste (through use of ground protecting foil and washing pad). 0.81 liters of paint used per year (65 % less than average).
Brush wash scenario: 30 min distance	Epoxy paint used, 3 visits per season, maximum acceptable driving distance for boat owners assumed.
Brush wash scenario: 0 min distance	Epoxy paint used, 3 visits per season, brush wash situated at home marina.
Hull cover scenario	

2.3 Life Cycle Impact Assessment

Method for eco-toxicity: USEtox (recommended + interim) version 1.04. (Rosenbaum et al. 2008)
Method for climate change: IPCC 2013 (Stocker et al. 2013) using the SimaPro 8.3 software (pre-sustainability.com) and the included databases for background data.

2.4 Sensitivity analysis

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

Dong et al. (2015) have 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. The method was not used as CFs for substances other than metals which has not yet been calculated to our knowledge. That makes it unsuitable to use in this study as we want to compare the impacts on eco-toxicity from the antifouling paints to other activities possibly contributing to eco-toxicity by emissions of non-metal substances.

The effect of higher fuel consumption per season was also analysed, as it was predicted to change the relative contribution to freshwater eco-toxicity of petrol emissions in comparison to paint emissions. It was also predicted to even out the scenarios contribution to climate change.

Release rates of copper and zinc in the paint determine how much of the biocides are emitted to the water during one season and how much remains on the hull. There are several methods for measuring and calculating release rates used by the paint industry; in our study we have used the same release rates as the Swedish Chemicals Agency receives from paint manufacturers in their approval procedure of the antifouling paints. However, a new method of measuring release rates for antifouling metal biocides, i.e., X-Ray Fluorescence spectrometer (XRF), has been suggested since the commonly used methods by the paint industry underestimate release rates. In the sensitivity analysis we investigated the impact on results from using different release rates.

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. 1). When biocide paints were used, the potential impact on eco-toxicity was much higher than non-toxic treatments irrespective of the toxic content as well as the way the paint was used, i.e. whether or not a washing pad and ground protecting foil were used when the hull was cleaned in fall and how many layers of paint were applied (Fig. 1). The use of a washing pad and ground protecting foil greatly reduce total emissions by more than two thirds by eliminating the emissions to soil of both copper and zinc, which eventually leak to water and cause aquatic toxicity. The difference between paints with high and low copper contents is smaller than one would expect (Fig. 1) 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 in the same range as that of copper in the methods used here. As mentioned, the non-toxic methods boat washer or hull cover lead to even lower toxic emissions than the best case paint treatment, which was using a low-copper paint sparsely and cleaning the boat over a washing pad with water treatment in the fall. For 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 analysed 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. 2). The main contributing processes are now, for all treatments, fuel production and combustion. For the boat washer, production of the epoxy paint used on the hull also contributes. Due to the importance of fuel use, need for additional transportation becomes very important and the worst case here is a brush washer that requires an extra transport of 30 minutes. 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. 1), but not enough to make it reach the paint scenarios. The production of materials and energy for operating the brush washer gave rise to negligible emissions in both impact categories.

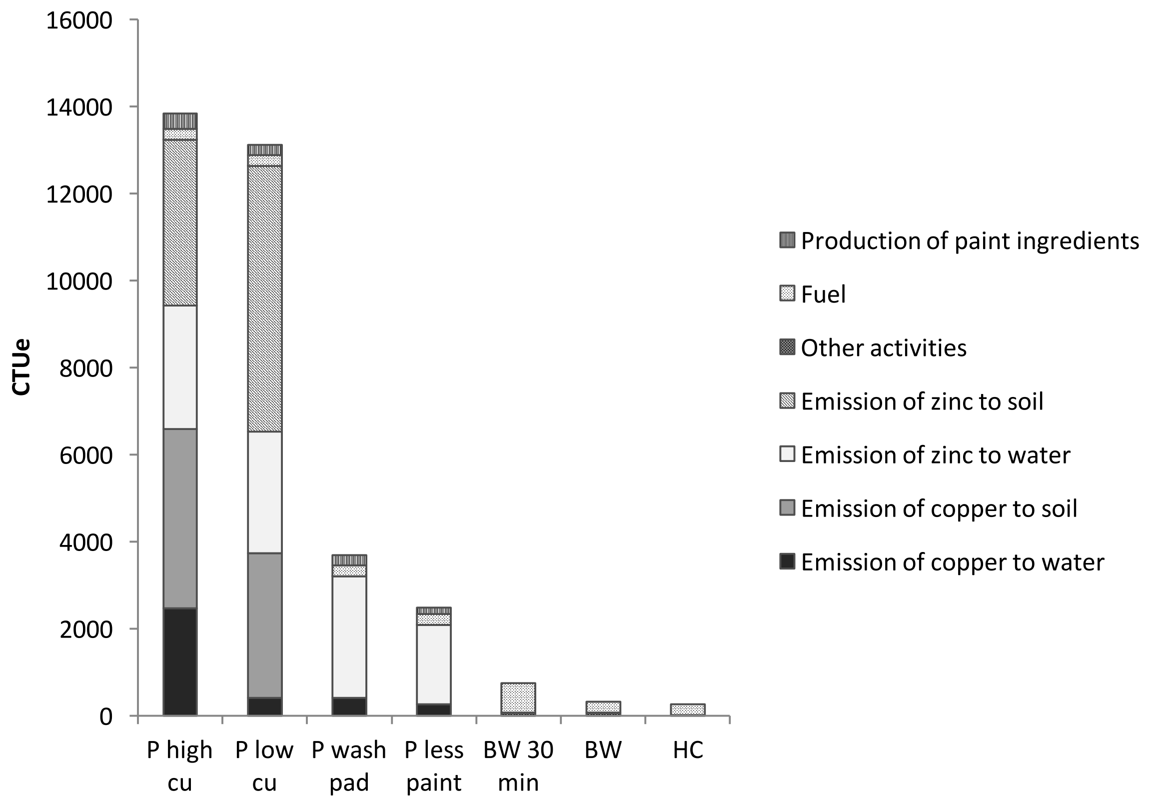

Fig.1 Aquatic eco-toxicity of different antifouling treatments per boating season (P high cu=average amount of paint with high copper conc. and no wash pad, P low cu= average amount of paint with low copper conc. and no wash pad, P wash pad=average amount of paint with low copper conc. and wash pad used, P less paint=less paint with low copper conc. and wash pad used, BW 30 min=brush washer located 30 min away, BW=brush washer located at home port, HC=hull cover).

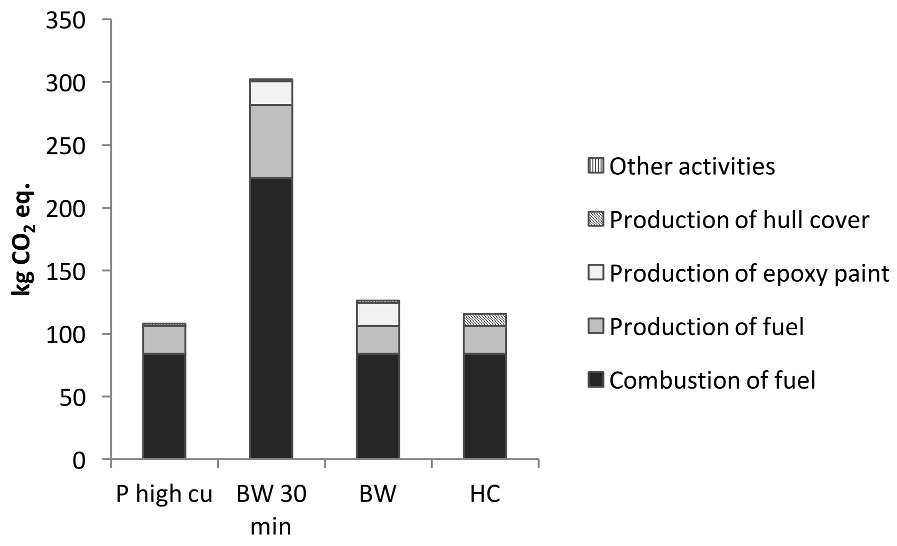

Fig.2 Greenhouse gas emissions of different antifouling treatments per boating season (P high cu=average amount of paint with high copper conc. and no wash pad, BW 30 min=brush washer located 30 min away, BW=brush washer located at home port, HC=hull cover).

3.1 Sensitivity analysis

We first analysed 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 the same decrease in toxicity from high-copper paint to the hull cover and ranked the treatments in the same way (Fig. 3). The main difference was that there was no effect of using the washing pad and ground protecting foil 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 in eco-toxicity potential than when analysed with USEtox. The brush washer scenario with a 30 minutes extra drive contributes more to freshwater eco-toxicity than the best case scenario for paint in the IMPACT method, because of the emissions from fuel production and combustion. Overall, we conclude that the ranking of treatments and conclusions are not affected by the choice of impact assessment method.

The second sensitivity analysis performed concerned the data used for fuel use per season, which was increased more than fourfold (statistically the second most common fuel consumption average by Swedish boaters). This led to proportionally increased greenhouse gas emissions and a reduced difference between treatments, implying the effect of the extra 30 minutes transportation to the brush washer meant less. Despite the increase, fuel-related toxic emissions did not reach emissions from paint biocides even in the best-performing paint scenario (Fig. 4). However, in this scenario, fuel-related toxic emissions were responsible for as much as 40 % of the emissions of paint ingredients. 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 are located in relation to major boatyards.

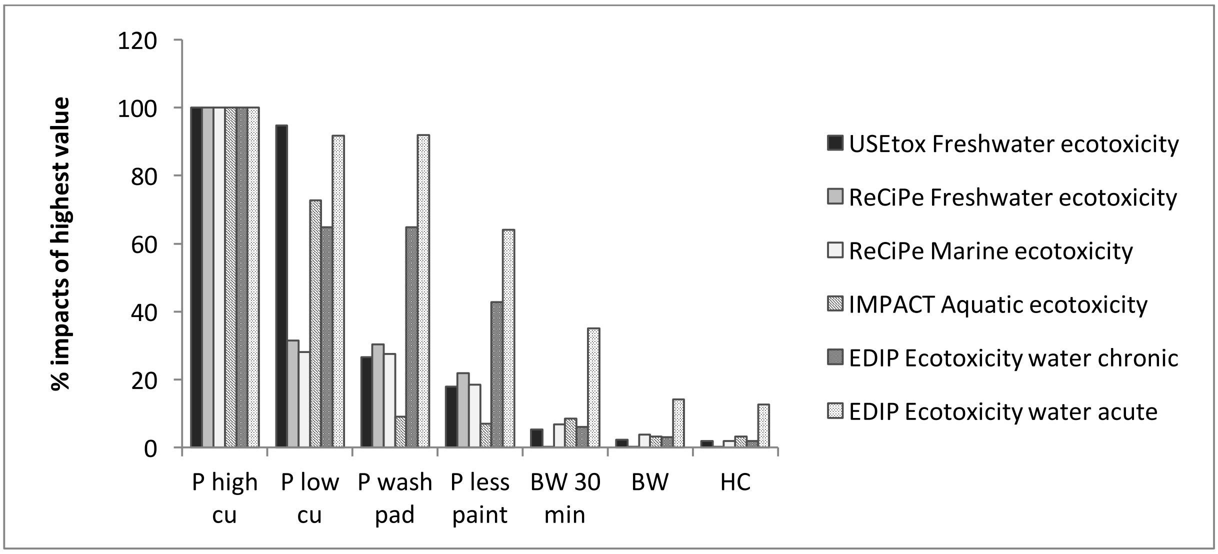

Fig. 3 Various impact assessment methods and impacts categories applied to test sensitivity of results (P high cu=average amount of paint with high copper conc. and no wash pad, P low cu= average amount of paint with low copper conc. and no wash pad, P wash pad=average amount of paint with low copper conc. and wash pad used, P less paint=less paint with low copper conc. and wash pad used, BW 30 min=brush washer located 30 min away, BW=brush washer located at home port, HC=hull cover).

The third aspect tested was the release rate used for copper and zinc, i.e., how much of the biocides that were leaking to the surrounding water vs. was left on the boat hull after the season ended. The original data on release rates calculated using the rotating cylinder and CEPE model (tier 2) was changed to release rates measured with the XRF method. While the choice of data on release rate data had a major influence on absolute toxic emissions (resulting in higher emissions when XRF-based values were used), 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 are biocides left on the boat hull without any antifouling effect, indicating that concentrations are unnecessarily high.

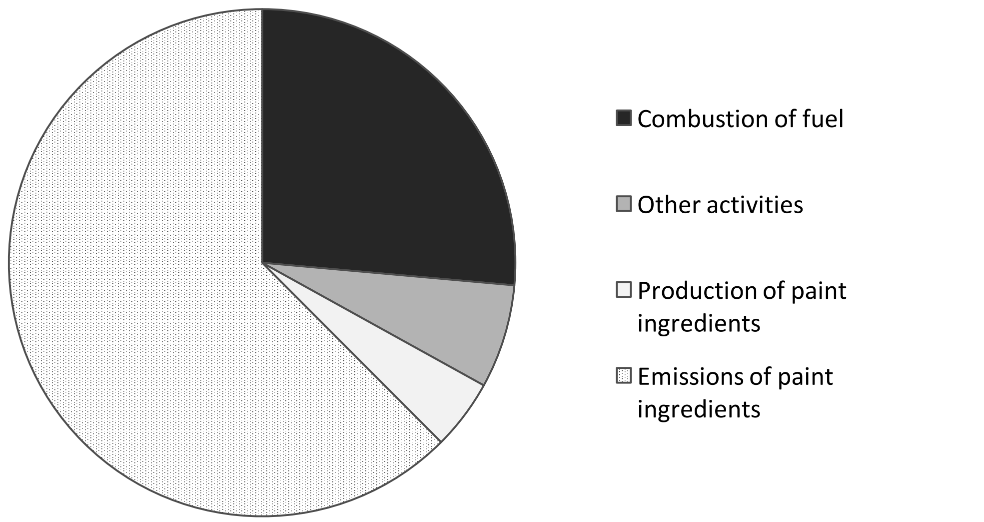

Fig. 4 Relative contribution to freshwater eco-toxicity from the P less paint scenario (less paint with low copper conc. and wash pad used) activities when assuming a higher fuel consumption per season.

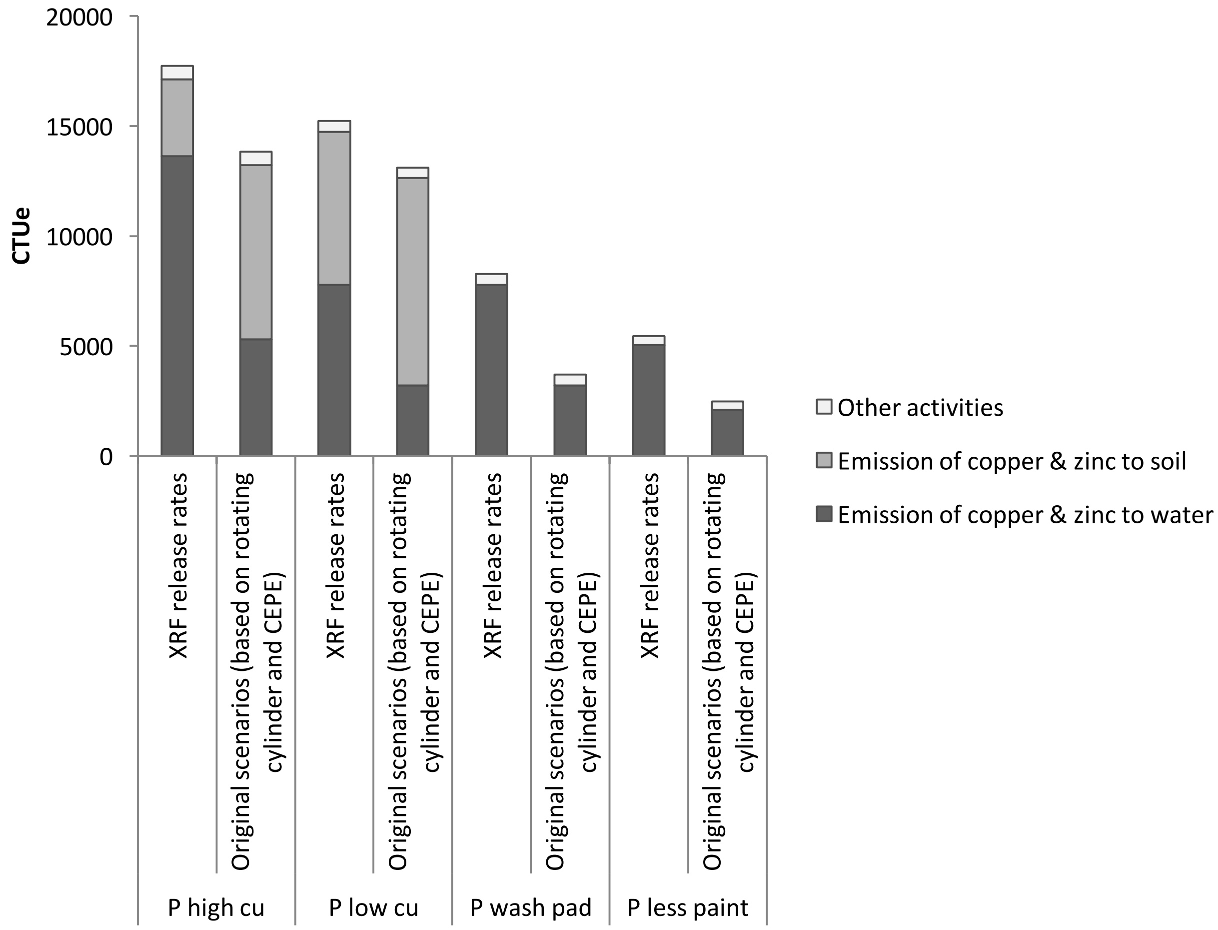

Fig. 5 Two different metal release rate datasets used to test sensitivity of results (P high cu=average amount of paint with high copper conc. and no wash pad, P low cu= average amount of paint with low copper conc. and no wash pad, P wash pad=average amount of paint with low copper conc. and wash pad used, P less paint=less paint with low copper conc. and wash pad used).

4. Discussion and Conclusions

This study shows that the choices boaters make on how to treat their boat hulls to keep them foul-free 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 and protective foil on the ground when paint is being scraped or sanded off the hull. 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. Another factor for overall aquatic toxic emissions is the paints content of copper and zinc. A low-copper paint does not necessarily cause less eco-toxicity if copper is replaced by zinc, which is considered causing almost as much toxicity in aquatic ecosystems by the model used in this study. A new Life Cycle Impact Assessment method (that includes USEtox methodology) for calculating marine eco-toxicity for metals presented in Dong et al. (2015 and 2017) found that zinc could cause almost ten times as toxic as copper in marine ecosystems due to higher bioavailability of zinc, indicating that the pattern can be seen in different types of aquatic ecosystems. The direct toxicity on aquatic organisms of zinc compared to copper was however lower, which has been found in toxicity studies before (Bighiu et al 2017). Thus, paints with lower copper content designed for use in more sensitive areas like the Baltic Sea, instead containing more of the booster biocide zinc, could in fact have a higher impact on aquatic toxicity than a paint 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.

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 just about prevent fouling. Panel tests of the BONUS CHANGE project showed that there was no difference in antifouling performance between a paint with 7.5% cuprous oxide (Cu_2O) and a paint with 34.6% cuprous oxide deployed for 150 days in the Baltic Sea during the boating season. This means that higher concentrations of copper in AF paints are a waste of money and leads to unnecessary emissions to the very ecosystems boaters go out to enjoy. Also, paints should be designed so that all toxic ingredients leak to water during one season to avoid or at least reduce the problem with toxic paint layers being built up on the boat hull and toxic paint residues entering land. If antifouling paints were used in this way broadly, the need to install (very costly) washing pads with water treatment in boatyards would be less urgent. As used today, washing pads with water treatment are important to reduce major emissions to soil of excess toxins.

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 and these ideas 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 intentional 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 reduced much as well (Cerne et al. 2008). Unfortunately, only some 4 % of Swedish boaters claim they use alkylate petrol, the main reason being that it is too expensive or not available nearby (Swedish Transport Agency 2016). Many impact assessment methods in LCA (including the one used) lack toxicity factors for a few of the poly-aromatic hydrocarbons that are released for example from the combustion of fuels, which means their contribution is underestimated.

The non-toxic treatments brush washer and hull cover were the best-performing alternatives analysed and these should be promoted for use. In more saline waters, the fouling pressure is stronger which requires more frequent cleaning when using a brush washer, 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 minutes to wash their boat (Dahlström et al. 2014). Our results show that if the brush washer is not located reasonably close, tradeoffs with increasing fuel-related emissions can arise due to 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, most of the brush washers in Sweden are situated in the Stockholm area (approximately ten brush washing stations) and the number of brush washers along the Swedish coast is increasing. Installing a new brush washing station in a marina in Sweden is subsidized by the government, as is the installation of a washing pad (Swedish Agency for Marine and Water Management).

Many marinas still lack brush washers and washing pads however and some harbour 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 limited by availability of this particular infrastructure in their vicinity. Furthermore, for a change to take place towards more sustainable practices, the role of infrastructure, culture and policy/regulations versus individual boat owner choices for maximum effect need to be understood. For example, today, it is up to the boater him-/herself to buy any type of antifouling paint in a store and large retailers sell the same products in all of their stores, regardless of if located close to the Baltic Sea or more marine areas. Research in the environmental psychology field suggest that by changing regulations, in this example so that only paint allowed for usage in the Baltic Sea can be sold in stores on the Baltic coast, the illegal paint use could be more efficiently reduced than through an information campaign targeting paint consumers (Koroschetz et al. 2017). The availability of sustainability information has been showed to have limited effect on individual consumption (Koroschetz et al. (manuscript), Bamberg and Möser 2007) Fast changes towards more sustainable practices could possibly be reached by information targeting boat owners on maintenance that does not depend on new infrastructure or habits, for example the "paint less method". Major environmental improvement is possible by recommending painting only the parts of the hull that are most prone to be fouled and paint only every second year, which is possible without losing antifouling effect. However, to achieve a change from paint to brush washer or hull cover, the individual boat owners are not the ones to be targeted alone but the focus should be on municipalities, marinas and market actors. To achieve that major shift there is a need for new material infrastructure in marinas as well as economic and legal policies.

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 the supply of excessive amounts of copper and zinc to the marine ecosystems would be to regulate 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 brackish and marine ecosystems providing recreational ecosystem services to leisure boaters.

5. References

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