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Research article

Monitoring biofouling as a management tool for reducing toxic antifouling practices in the Baltic Sea

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ABSTRACT

Over two million leisure boats use the coastal areas of the Baltic Sea for recreational purposes. The majority of these boats are painted with toxic antifouling paints that release biocides into the coastal ecosystems and negatively impact non-targeted species. Regulations concerning the use of antifouling paints differ dramatically between countries bordering the Baltic Sea and most of them lack the support of biological data. In the present study, we collected data on biofouling in 17 marinas along the Baltic Sea coast during three consecutive boating seasons (May–October 2014, 2015 and 2016). In this context, we compared different monitoring strategies and developed a fouling index (FI) to characterise marinas according to the recorded biofouling abundance and type (defined according to the hardness and strength of attachment to the substrate). Lower FI values, i.e. softer and/or less abundant biofouling, were consistently observed in marinas in the northern Baltic Sea. The decrease in FI from the south-western to the northern Baltic Sea was partially explained by the concomitant decrease in salinity. Nevertheless, most of the observed changes in biofouling seemed to be determined by local factors and inter-annual variability, which emphasizes the necessity for systematic monitoring of biofouling by end-users and/or authorities for the effective implementation of non-toxic antifouling alternatives in marinas. Based on the obtained results, we discuss how monitoring programs and other related measures can be used to support adaptive management strategies towards more sustainable antifouling practices in the Baltic Sea.

1. Introduction

Biofouling (i.e. colonisation by sessile organisms of submerged surfaces, from now on referred to simply as fouling) on vessels is a major problem causing increased fuel consumption, lower manoeuvrability and higher operational costs, as well as a higher risk of spreading invasive species (Yebra et al., 2004). The most common strategy to avoid fouling on boat hulls is the application of toxic antifouling paints, which contain biocides (mainly copper oxide) that are continuously released into the environment and have well-known negative impacts on marine ecosystems (e.g. Dafforn et al., 2011; Turner, 2010).

Leisure boating is considered an important source of heavy metals in shallow coastal areas (Dafforn et al., 2011). Leisure boats usually stay most of the time in the marinas, resulting in high levels of contamination of nearby waters and sediments (e.g. Biggs and D'Anna, 2012; Lagerström et al., 2016). Pollution from antifouling paints also results from maintenance activities, e.g. scraping and high-pressure hosing of boat hulls (Turner, 2010). In temperate coastal regions, the release of biocides from antifouling paints is often higher during spring and early summer, coinciding with the peak of boating activity (Jones and Bolam, 2007; Konstantinou and Albanis, 2004), as well as with the main reproductive and recruitment season of many species (e.g. Bonsdorff

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et al., 1995; Sokołowski et al., 2017).

Over two million leisure boats have their homeports in the countries bordering the Baltic Sea (ICOMIA, 2018). The Baltic Sea has been classified as a "particularly sensitive sea area" (PSSA) by the International Maritime Organization, due to the high sensitivity of this marine region to anthropogenic impacts (IMO, 2006, 2014). Despite the general awareness of politicians, stakeholders and scientists and their joint efforts in the frame of the Helsinki Commission (HELCOM) to improve the environmental status of the Baltic Sea (Reusch et al., 2018), major differences in the authorisation of biocides and antifouling products still persist among circum-Baltic countries. For example, paints with high-copper content (in the range of 20-35% Cu_2O; w/w) are allowed on leisure boats in Finland, Denmark and Germany, but not on the Baltic coast of Sweden, where most authorised paints contain ~8.5% Cu_2O (Daehne et al., 2017; Swedish Chemicals Agency, 2019). The authorisation of antifouling products is based on national risk assessments where predicted environmental concentrations of biocides are compared to the sensitivity of the environment. However, the criteria for risk assessments are not the same for all countries, highlighting the need for better understanding of the fouling dynamics in the Baltic Sea and to what extent toxic antifouling practices are needed at all to prevent fouling.

The Baltic Sea is one of the largest brackish water bodies in the world, with a salinity gradient spanning from approximately 30 in the transition to the North Sea to 0.5–2 in the Bothnian Bay and inner Gulf of Finland (Snoeijs-Leijonmalm et al., 2017, Fig. 1). Many marine species reach their osmotic tolerance limit in the Baltic Sea and several others show decreasing performance as salinity drops, resulting in an overall decline of species richness (Barboza et al., 2019; Ojaveer et al., 2010; Sanders et al., 2018; Wrange et al., 2014). Therefore, a higher fouling load is expected with increasing salinities due to more fouling species, higher reproductive output and faster growth under more favourable osmotic conditions.

Beyond the regional role of salinity, other variables of relevance have been identified as drivers of fouling intensity and composition. Seasonality, temperature, nutrient enrichment, type of substrate, coastal hydrodynamics, and biological interactions (e.g. competition, predation) can shape the structure of fouling communities in the Baltic Sea (Franz et al., 2019a; Qvarfordt et al., 2006; Sokołowski et al., 2017; Wahl et al., 2013). The numerous environmental drivers acting at different scales, in addition to the fragmented available ecological information, have prevented simple predictions of fouling composition and abundance in the Baltic Sea. In this context, generating reliable knowledge about spatial and temporal patterns of fouling communities may help to adapt more sustainable antifouling strategies and promote a transition from toxic to non-toxic antifouling practices.

The aim of the present study was to extensively describe the spatial and temporal variation of fouling in Baltic leisure boat marinas. With the information generated from 17 marinas along the coasts of four different countries, and during three consecutive boating seasons we: (i) evaluated the implementation of alternative monitoring strategies, (ii) generated a fouling index (FI) for the classification of marinas according to the fouling load and expected maintenance requirements - considering the perspective of boat owners -, and (iii) assessed the role of environmental and marina-specific drivers in the explanation of spatial and temporal changes in fouling. Based on the obtained results, we provide a number of recommendations for the use of monitoring information in combination with other measures as a management tool for supporting the implementation of non-toxic antifouling practices.

2. Methods

2.1. Study area and monitoring setup

During three consecutive boating seasons (2014, 2015 and 2016), polymethyl methacrylate (PMMA) panels were deployed in 17 leisure boat marinas around the Baltic Sea. The marinas were located in Sweden, Denmark, Germany and Finland, covering most of the major subbasins in the outer, central and inner Baltic Sea (Fig. 1, see exact coordinates in Table S1).

The settlement panels were hung from jetties at a depth of 1 m during the entire boating season (i.e. from mid-May to mid-October). This time frame was selected to estimate the maximum fouling that can settle on boat hulls during a boating season in the Baltic Sea. The panels were

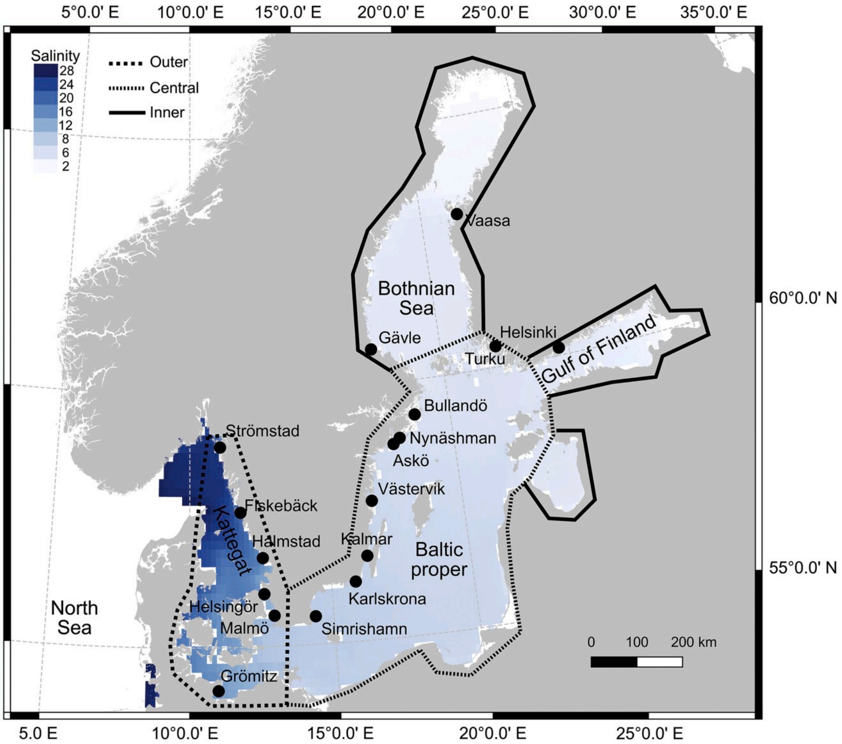


Fig. 1. Location map of the 17 marinas where fouling was monitored for three consecutive boating seasons (2014, 2015 and 2016) along the Baltic Sea. The colour ramp indicates the salinity gradient along the major sub-basins. The solid and dashed contours indicate the marinas and major sub-basins located in the outer, central and inner Baltic Sea (classified according to Kotta et al., 2020). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

deployed within the same week in all marinas. To identify the most suitable substrate for monitoring fouling, two different sets of panels were used: (i) transparent PMMA panels (15 × 15 cm) and (ii) PMMA panels painted, using a fine roller, with a biocide-free commercial black underwater paint (Lago Racing, International), recreating a surface similar to that of a painted boat hull. The surface of both types of panels was roughened using sandpaper (60 grade). PMMA panels (but also polyvinyl chloride - PVC - panels) have been successfully used for the monitoring of fouling (Berntsson and Jonsson, 2003; Franz et al., 2019a; Smale, 2013; Wahl et al., 2013). Four replicate panels of each type were hung vertically every 20 cm from polypropylene lines (PP, Ø 3.8 mm) using cable ties. The lines were attached alongside a jetty edge (mainly pontoon jetties) at the outer end when possible. The approximate depth under the selected jetties was at least 2 m. The panels were always placed in a central position of the marina.

2.2. Collection and processing of samples

The panels were collected at the end of the boating season, within the same week, in mid-October 2014, 2015 and 2016 and carefully placed in freezer bags. Upon arrival to the laboratory, the back of the panels was cleaned to provide an even surface for optimal photo documentation of the side facing outwards from the jetties, which was the analysed side. The panels were carefully dipped in seawater to remove any non-attached sediment. Each panel was tagged with an individual number and photographed using a SONY α6000 camera with an E3.5/30 Macro lens (24.3 megapixels). Each photo was analysed in order to estimate the coverage (in percentage) of the different fouling groups based on the categories presented in the standardized method of the American Society for Testing and Materials (ASTM, 2011), which was initially developed to evaluate fouling rates of submerged surfaces with antifouling coatings. The main fouling taxa recorded on the panels were: barnacles, mussels, tubeworms, bryozoans, hydroids, tunicates, sponges and algae (green, brown and red). In contrast to the ASTM method, biofilm was not recorded, as it does not constitute a major problem for most leisure boat owners. A grid of 100 cells was placed over each image and the coverage of the different taxa was recorded in relation to the total area of each panel. The outer 10 mm of the panel was not included in the analysis to avoid edge effects. Following the ASTM method, panels with multiple layers were carefully analysed under a stereomicroscope and most secondary layers were removed, keeping the layer of organisms attached to the surface of the panels for the estimation of coverage.

2.3. Classification of marinas using a fouling index

In order to define “fouling hotspots” and classify marinas according to the fouling load considering the perspective of boat owners, we defined a Fouling Index (FI), where both the coverage and type of fouling were taken into account (inspired by the N index from the Association Française de Normalisation, AFNOR, 1996). The suggested FI was calculated as the weighted sum of the recorded coverage for different types of fouling. Since the hardness of the organisms and strength of attachment determine how difficult it is to remove them during cleaning activities, these two characteristics were used for the classification of fouling. Hence, fouling was classified into three categories: (i) hard fouling strongly attached (HFS), which comprises encrusting organisms strongly attached to the substrate by heavily calcified structures (e.g. barnacles and tube worms); (ii) hard fouling weakly attached (HFW), i.e. organisms that generate calcareous exoskeletons or shells but are attached by semi-hard structures (e.g. threads made of proteins or lightly calcified structures) to the substrate (e.g. mussels and bryozoans); and (iii) soft fouling weakly attached (SFW), which includes organisms that do not generate calcareous structures and are more loosely attached (e.g. filamentous algae and tunicates). Although bryozoans are encrusting organisms, we classified them as HFW since most species in the Baltic Sea are lightly calcified and require a relatively low effort to be mechanically removed from boat hulls in comparison to barnacles or tube worms. The estimated coverage for each of the described categories was multiplied by a weighting value assigned to each fouling type (0.5 for soft fouling, 1 for hard fouling softly attached and 2 for hard fouling). Weights were defined based on current knowledge and gathered experience on the difficulties to detach each fouling type during maintenance activities (i.e. HFS represents a larger problem and in consequence received a higher weight). Values were then summed and divided by the maximum possible weighted fouling coverage (200, i.e. 2 × 100% of HFS), to obtain a standardized index between 0 and 1. Therefore, the formula for the FI is:

$$FI = \frac{2\,HFS + HFW + 0.5\,SFW}{200}$$

The FI for a marina was the average of the values calculated for each of the separate monitoring panels deployed in the marina during each boating season.

2.4. Marina-specific and environmental variables

Data on mean annual surface salinity (from now on referred to as salinity), the main driver of spatial changes in biological communities along the Baltic Sea (Ojaveer et al., 2010), were provided by the Swedish Meteorological and Hydrological Institute (SMHI) using the HIROMB model (see a full description of the model in Axell and Liu, 2016). Information on mean temperature during May–October (from now on referred to as temperature), a relevant driver of reproduction and recruitment of fouling species in the Baltic Sea (Sokołowski et al., 2017), was also generated using the HIROMB model. For those marinas - or close by coastal locations - where monitoring data was available (e.g. the SHARK database provides monitoring data in Swedish marine areas, SMHI, 2019), this information was used to corroborate the modelled data. The volume of the marina (estimated from the area and average depth) as well as the number of berths in each marina were included as proxies of the maximum number of boats and the potential concentration of antifouling compounds (Daehne et al., 2017; Dunn et al., 2007). These parameters were estimated using sea chart measurements or provided by the local authorities or marinas.

2.5. Statistical analyses

2.5.1. Comparison between types of monitoring panels

A generalized linear mixed model (GLMM) was implemented to compare the coverage of total fouling between monitoring painted and not painted panels. The same comparison was also done for barnacle coverage only (main component of hard fouling). The analysis was performed using the pre-defined function glmer from the package lme4 in R (Bates et al., 2018). The Gamma distribution and log link function were used for fitting the models. The coverage of total fouling and barnacles were included as response variables and the type of panel (painted or not painted with Lago racing) as fixed effect. The nested structure of boating season (2014, 2015 and 2016) within station (i.e. the 17 marinas) was included as random effect (see a detailed description of the used random effect and its purpose in section 2.5.3).

2.5.2. Fouling structure among Baltic sub-regions

In addition to the graphical description of the composition of fouling in different marinas and boating seasons, the relative contribution of the different fouling types was compared among the outer, central and inner Baltic (see details in Fig. 1) using GLMM with Gaussian distribution and identity link function (see R function and package in section 2.5.1). In these models the coverage of HFS, HFW and SFW were included as response variables, and the Baltic sub-regions (outer, central and inner) as explanatory variable (fixed effect). Once again, the nested structure of boating season within marina was included as a random effect (see a detailed description of the used random effect and its purpose in section

2.5.3). The coverage of the different fouling types was logarithmically transformed to fulfil the normality assumption, since the use of alternative distributions and link functions was not effective for modelling the skewed distribution of the analysed response variables. For the multiple comparisons of the coverage of different fouling types among the outer, central and inner Baltic Sea we applied a Tukey HSD post-hoc test using the function glht from the R package multcomp (Hothorn et al., 2019).

2.5.3. *Influence of marina-specific and environmental variables*

The importance of different environmental and marina-specific variables in determining the observed changes in fouling (summarized by FI) along the Baltic Sea was evaluated using GLMM. The Gaussian distribution and identity link function were used for all fitted models. Salinity, temperature, volume of the marinas and number of berths were included as fixed effects. The identity of marinas was included as random effect in order to cope with potential auto-correlation problems of the data (since all panels deployed in each marina were considered in the analysis) and to account for local sources of variability for which information was not available or could not be quantified. Thus, the inclusion of the marinas as a random effect was used to account for potential differences in, e.g., background levels of antifouling biocides, eutrophication, characteristics of associated urban areas and benthic habitats (among others) between marinas. In addition, by nesting boating season within the identity of the marinas we accounted for the inter-annual variability in fouling observed in the different locations. Information on other drivers of local relevance such as high-resolution costal hydrodynamics, distribution and density of predators, concentration of pollutants or availability of natural and artificial hard substrates (among others) is still highly fragmentary or missing for most areas in the Baltic Sea.

Sixteen candidate models (including full and null models) were automatically generated by running all potential additive combinations of salinity, temperature, volume of the marina and number of berths, using the function dredge from the package MuMIn (Bartoń, 2018). Models were ranked according to the Akaike information criterion with a correction for small sample sizes (AICc). Based on the AICc, the AICc difference (ΔAICc) between the most parsimonious model and the other adjusted models, and the respective AICc weights (AICcw), were calculated. Only the effects estimated for the most parsimonious model (i.e. the model with the lowest AICc) are presented. The marginal R^2 (i.e. variance explained by the fixed effects, $_mR^2$) and conditional R^2 (i.e. variance explained by the fixed and random effects, $_cR^2$) were calculated according to Nakagawa and Schielzeth (2013), using the function r.squaredGLMM from the package MuMIn. A detailed visual inspection of the diagnostic plots of residuals, generated with the package DHARMa (Hartig, 2019), was performed for the most parsimonious model.

3. Results

3.1. *Differences in fouling load between types of panels*

The coverage of total fouling (and especially for barnacles) was significantly higher on panels painted with Lago Racing than on not painted ones (Fig. S1; Table S2). The total fouling was 1.17 times higher on painted than on not painted panels and the coverage of barnacles was 2.41 times higher (Fig. S1). To avoid underestimating the fouling loads that boat owners may experience (and especially barnacles which are the main problematic hard fouling species in the Baltic region), the rest of the analyses were therefore performed using only data collected with painted panels.

3.2. *Spatial and temporal variation in fouling along the Baltic Sea*

The coverage and structure of fouling communities showed a high inter-annual variation in most of the monitored marinas (Fig. 2). In marinas from the outer and central Baltic Sea, fouling communities mainly alternated between states dominated either by HFS or HFW. In contrast, the inter-annual variation in fouling communities from the inner Baltic Sea was mainly driven by changes between HFS or HFW and SFW (Fig. 2). The structure of fouling communities was stable in time only in four marinas. Fiskebäck was consistently dominated by HFS, with mean coverages above 80% in all boating seasons (HFW and SFW were always below 10%). HFW presented coverages above 70% during the entire study period in Kalmar, while HFS and SFW never reached 10%. The fouling communities in Turku were dominated in a 90% or more by HFS (consisting of only barnacles). In Gävle, SFW exceeded a mean coverage of 70% in the three boating seasons (Fig. 2).

Beyond the high inter-annual and local variability described, differential trends in the coverage of the different fouling types (HFS, HFW and SFW) can be observed among Baltic sub-regions when the information collected in different boating seasons is integrated into a single mean value per marina. The fouling in marinas from the outer Baltic Sea was mostly dominated by HFS (mean coverages between 43 and 85%), followed by HFW (mean coverages between 6 and 46%) and SFW (mean coverages between 2 and 15%) (Fig. 3A). The contributions of HFS (mean coverage between 6 and 92%), HFW (mean coverage between 4 and 79%) and SFW (2 and 16%) to the composition of fouling communities in the central sub-basins did not significantly differ from those in the outer Baltic Sea (Fig. 3A, Table S3). In contrast, SFW was the main component of fouling communities in the inner Baltic (mean coverages between 22 and 76%) and its contribution was significantly higher than in the outer and central sub-basins (Fig. 3A, Table S3). The coverages of HFS (mean coverages between 8 and 30%) and HFW (mean coverages between 0 and 37%) were significantly lower in the inner Baltic Sea than in the other two sub-regions (Fig. 3A, Table S3).

The highest FI values were observed in Turku (0.94), Fiskebäck (0.91), Karlskrona (0.75), Strömstad (0.74) and Grömitz (0.72), all marinas located in outer and central sub-basins (Fig. 3B). Marinas in the inner Baltic Sea (Gävle and Vaasa), with the exception of Helsinki, were mainly dominated by SFW (Fig. 3A) and exhibited FI values below 0.40 (Fig. 3B).

3.3. *Environmental parameters explaining fouling patterns*

The most parsimonious GLMM retained salinity as the main and only environmental predictor - of those directly considered in the models - of the changes in FI along the Baltic Sea (Table S4). Based on the AICcw, this model was 1.76 times more likely than the next best model, which included temperature as the only predictor (Table S4). The FI followed a logarithmic function with salinity, slowly decreasing down to a salinity of 5, below which the index decreased more rapidly (Fig. 4, Table S5). Salinity explained, as fixed effect, 10% of the variance ($_mR^2$, Fig. 4). The nested structure of boating season within marina, included as a random effect, contributed with an additional 70% to the overall explained variance of the model ($_cR^2$, Fig. 4). The high variance explained by the identity of the marinas and the boating season highlights the relevance of local factors - not explicitly considered in the constructed models - and inter-annual variability in explaining spatial and temporal changes in fouling along the Baltic Sea coasts (see Fig. S2 for a detailed description of the contribution of each model component to the explained variance and Fig. S3 for the plots of model residuals).

4. Discussion

There are a few studies so far that have documented spatial and temporal patterns of fouling in the Baltic Sea and most of them are limited to the southern region and focused on ecological questions (Franz et al., 2019a; Wahl et al., 2013). Therefore, this study represents the first large-scale effort to describe geographic and inter-annual changes of fouling in leisure boat marinas at a Baltic Sea scale. The obtained data were analysed in order to provide relevant knowledge for

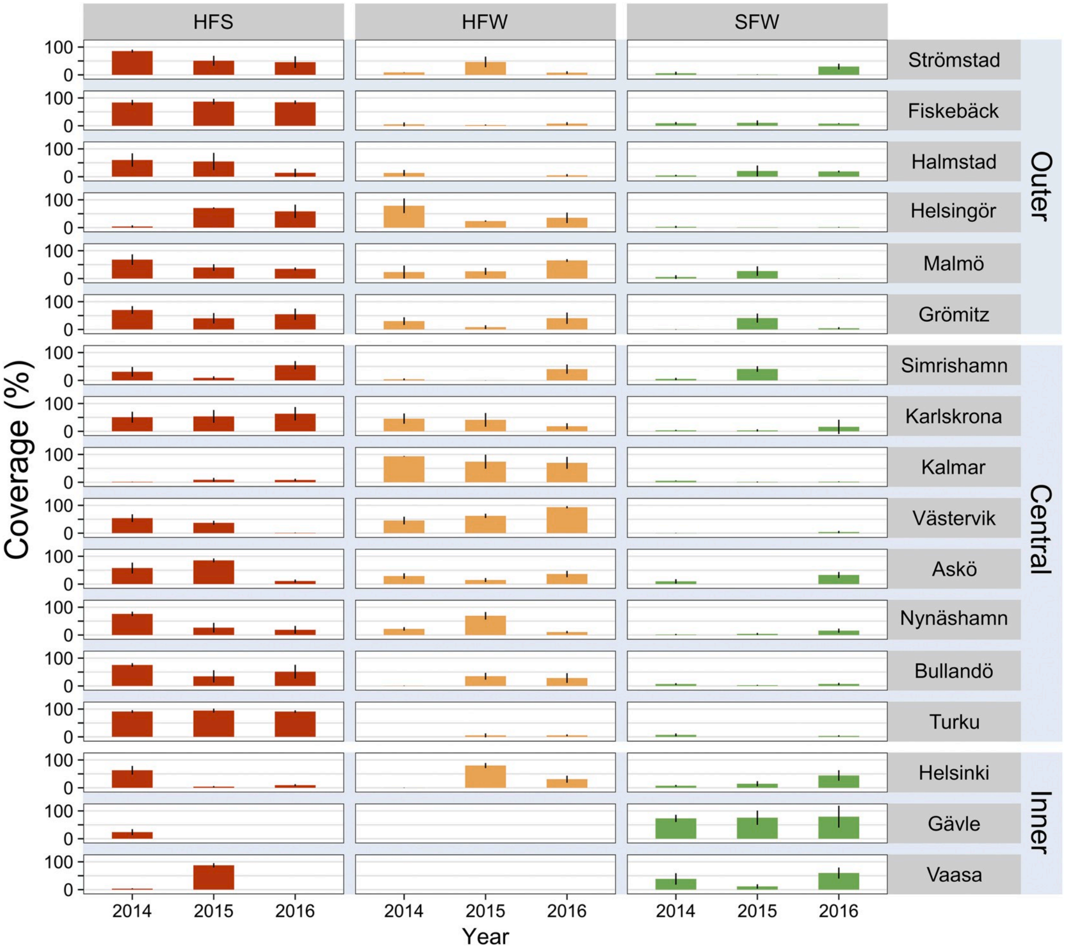


Fig. 2. Inter-annual changes in the coverage of hard fouling strongly attached (HFS), hard fouling weakly attached (HFW) and soft fouling weakly attached (SFW) in the 17 marinas monitored during three consecutive boating seasons (2014, 2015 and 2016) in the outer, central and inner Baltic Sea. Bars represent mean coverages and the whiskers 95% confidence intervals. See the exact location of the marinas and Baltic sub-regions in Fig. 1.

boat owners and authorities, which could support future policy and decision-making concerning the implementation of more sustainable antifouling practices in the Baltic Sea region.

Our results revealed that most of the variation in fouling type and coverage is explained by local drivers and their fluctuations between years, making the generation of general and effective large-scale management strategies for entire Baltic sub-regions difficult. The regional salinity gradient had a significant but secondary contribution to the observed variation, accounting for the transition from HFS or HFW-dominated communities in the outer and central sub-basins to SFW-dominated communities in the inner Baltic Sea - where salinity drops to values below 5 (Fig. 1). The lower calcium ion availability and increased energetic demands for osmoregulation under low salinity conditions impair the calcification and growth rates of hard foulers and may provide a competitive advantage to non-calcifying organisms in the inner Baltic Sea (Sanders et al., 2018; Thomsen et al., 2018). Therefore, low salinities favour the prevalence of non-problematic SFW which could motivate boat owners to use biocide-free techniques. However, our results suggest that considering the salinity gradient as the main driver of fouling composition and loads would not properly address the variation among marinas and boating seasons.

The coastal areas of the Baltic Sea are characterised by strong spatial and temporal environmental changes, with multiple natural and anthropogenic factors, which affect biological communities including fouling ones (Franz et al., 2019b; Reusch et al., 2018). As suggested in previous studies, inter-annual differences in fouling communities in the Baltic Sea are driven by, e.g., changes in prevailing seasonal temperatures between years and the stochastic occurrence of disturbance/recovery cycles and founder species (Franz et al., 2019a; Wahl et al., 2013). In marinas, environmental changes are additionally boosted by the partially enclosed nature of these water bodies and the concentration of human activities and associated urbanized areas. Here, the limited currents and water exchange, freshwater run-off, eutrophication, increased temperature, shading from jetties, re-suspension of sediments and pollution from boating activities (as well as other sources) could lead to highly variable environmental conditions (Hanninen, 2019). Therefore, any successful management of antifouling practices in marinas should explicitly address the uncertainties in the dynamics of these environments. Adaptive management strategies have been implemented successfully in systems with low predictability worldwide (Lewison et al., 2015). The key aspect of these “dynamic” or “adaptive” schemes of management is the active monitoring of the system of interest to facilitate an iterative decision-making process (Williams and Brown, 2014, 2018). In the framework of this emerging management paradigm, active monitoring of fouling in local leisure boat marinas using plastic panels could support the implementation of non-toxic mechanical antifouling practices in the Baltic Sea.

Data on fouling obtained using dark panels (to maximize barnacles settlement as suggested here and in previous studies, e.g. Bighiu et al., 2017) with different temporal resolutions can serve various management purposes, which are summarized in Fig. 5. Long-term monitoring in marinas during a full boating season (e.g. May–October in the Baltic) and over multiple years, as described in this study, can provide reliable baselines for grading marinas in terms of the problem that fouling

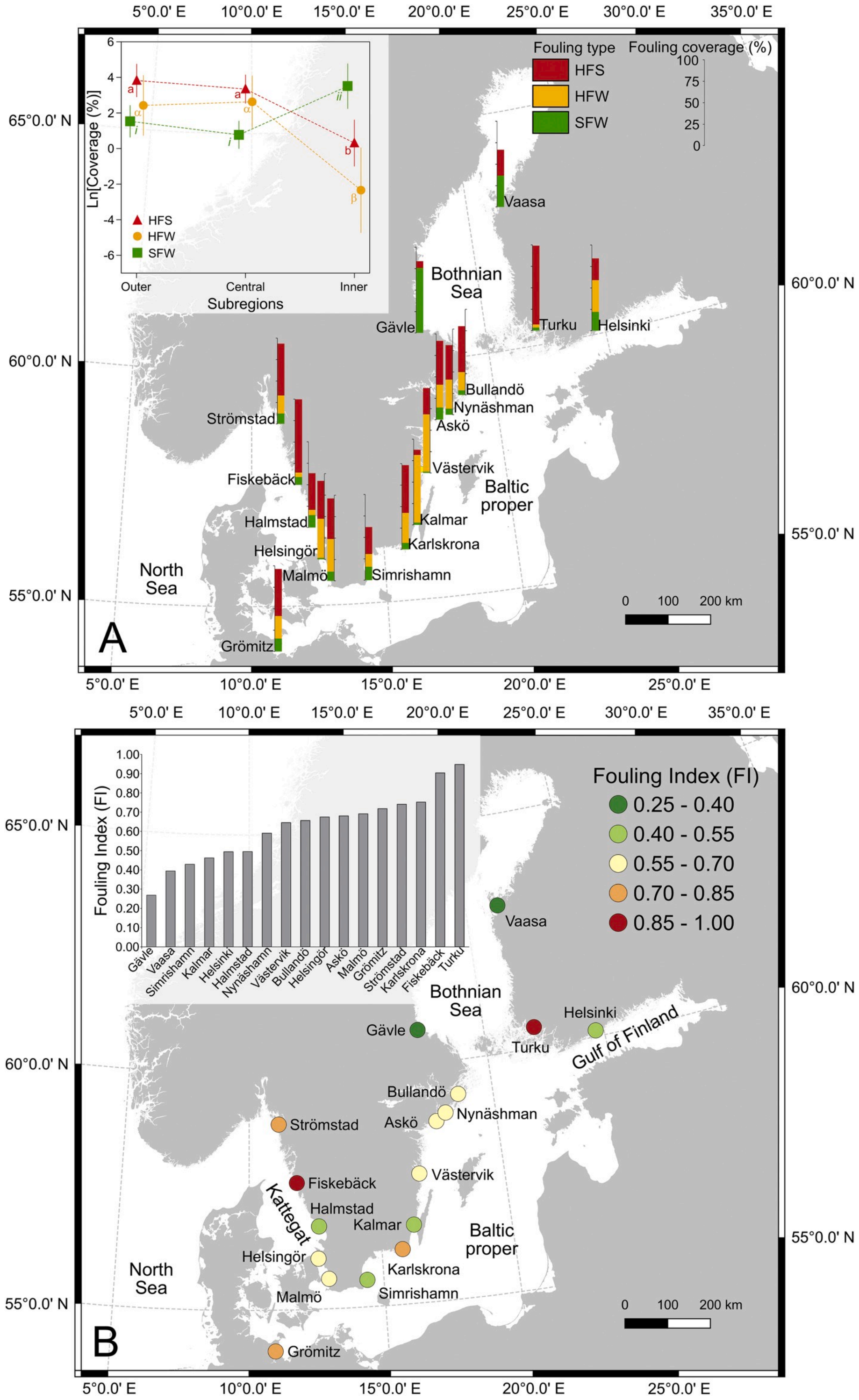


Fig. 3. A: Mean coverage of hard fouling strongly attached (HFS, red), hard fouling weakly attached (HFW, yellow) and soft fouling weakly attached (SFW, green) in the 17 marinas monitored along the Baltic Sea across all boating seasons. Notice that the mean coverage of total fouling and the contribution of the fouling types are represented as stacked bar plots with comparable scales (see a detailed representation of the scale in the upper-right corner of the map). The plot in the inset shows the results of the generalized linear mixed models (GLMM) applied for the comparison of the coverage (in logarithmic scale, Ln) of the fouling types among the outer, central and inner Baltic Sea (see in Fig. 1 the marinas located in these sub-regions). The dots represent mean values and whiskers 95% confidence intervals. Significant differences between Baltic sub-regions in the coverage of a given fouling type are indicated by different letters (see further statistical details in Table S3). B: Classification of 17 marinas based on the fouling index (FI, see details in the main text). The plot in the inset shows the exact mean FI for each station. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

represents for boating activities. In this regard, the fouling index (FI) defined in the present study, could be used to summarize the type and coverage of fouling observed in marinas in a single value, weighting the relative contribution of different fouling types from the perspective of boat owners. The obtained information on fouling composition and inter-annual dynamics, translated into a simple index, can be useful for authorities when discussing the need for using toxic antifouling paints and for local marinas when planning investments on infrastructure such as boat washers. Further improvements of the FI should be explored with the aim to balance the need for a simple metric that considers the characteristics of fouling communities and has the predictive power for defining the cleaning efforts required. The weights used in the present calculation of FI were based on current knowledge and experience of cleaning efforts for different fouling types since comparative data on attachment strength and persistence of marine fouling organisms is very limited (Oliveira and Granhag, 2016). Therefore, future modifications of the FI could include the calibration of weights against actual estimations of cleaning effort required for different types of fouling as well as fouling biomass. In addition to the aforementioned applications, long-term monitoring of marinas using plastic panels represents an effective

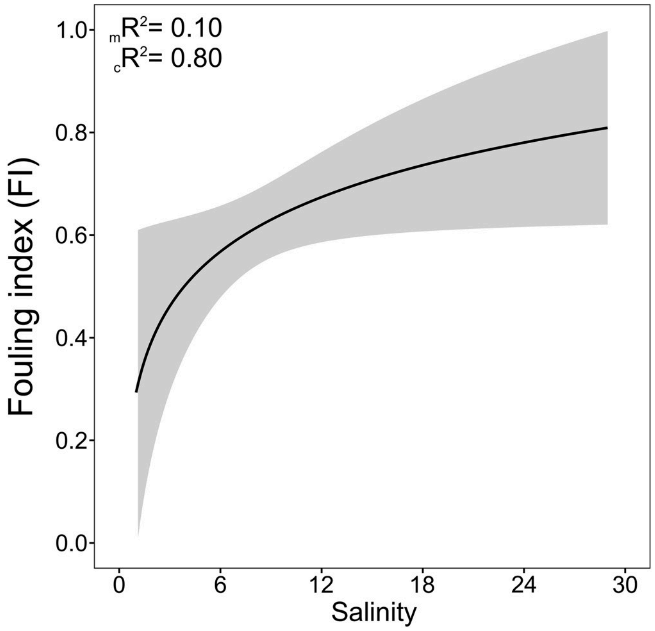
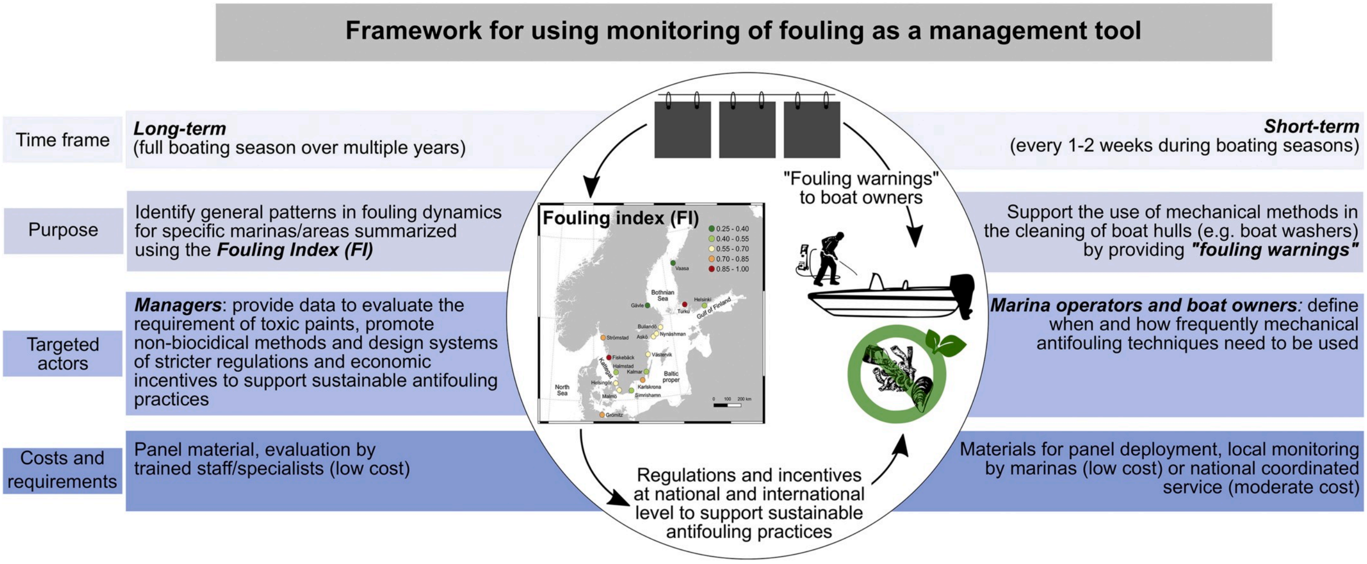


Fig. 4. Best generalized linear mixed model (GLMM) relating fouling index (FI) and salinity. The grey shaded area indicates the 95% confidence interval. The marginal R^2 (i.e. variance explained by salinity as fixed effect, $_{m}R^2$) and conditional R^2 (i.e. variance explained by salinity as fixed effect and the nested structure of boating season within the identity of the marinas as random effects, $_{c}R^2$) are presented. See further statistical details in Table S5.

strategy for the detection of invasive species, in particular those that could represent a problem for boat owners (Fernandes et al., 2016; Piola et al., 2009). For example, the Australian tubeworm *Ficopomatus enigmaticus* was observed for the first time in Sweden (Malmö) during our study, a species that has caused dramatic ecological and economic impact in areas where it was introduced (Bazterrica et al., 2012; Yee et al., 2019).

Panels can be also used for short-term monitoring (where panels are checked every 1 or 2 weeks) as part of either a nationally coordinated service, providing information about settlement events for boaters, or as an initiative run by local marinas to support the use of mechanical antifouling methods (e.g. boat washers). "Real time" information on fouling settlement is essential to define if and how frequently boat owners have to clean their boats to guarantee the successful application of mechanical methods such as boat washing stations. To speed-up the identification of problematic fouling and its communication to boat owners, panels should be analysed directly at marinas by trained staff or volunteers (e.g. boat owners). Training workshops could be held by state agencies, universities, research institutes or non-governmental organizations, focussing in the identification of HFS, HFW and SFW. This simple classification system does not require in-depth knowledge of taxonomy and provides relevant qualitative information on the hardness and strength of attachment of different fouling organisms and maintenance requirements. Developing a manual describing the method and examples of fouling could also support the monitoring. Based on this information, cleaning activities could be organized by providing warnings on the occurrence of HFS and HFW via social media, centralized websites and/or text messages (as SMS) (see Chou et al., 2017; Hausmann et al., 2018; Levin et al., 2015; Werts et al., 2012 for examples on the implementation of social media for conservation and management purposes). Some successful cases already exist in Sweden where The Archipelago Foundation in Stockholm (Skärgårdsstiftelsen) initiated a citizen science-based monitoring program almost 20 years ago that provides weekly information on barnacle settlement along the Swedish east coast, through a website and text messages. This monitoring program has been successful especially in the area around Stockholm where barnacle settlement occurs only 2 to 3 times per season and each settlement period lasts for 1–2 weeks (Skärgårdsstiftelsen, 2019). Several boat clubs in Sweden have recently worked actively to phase out the use of toxic anti-fouling paints by adopting monitoring systems with panels in combination with the installation of a mechanical boat washer (Strand et al., 2018). However, these valuable but isolated efforts require further standardization and implementation of monitoring methods based on results and recommendations provided here and in future studies.

A successful transition from toxic to non-toxic antifouling practices will only be possible if the proposed alternatives are shown to be as effective as traditional practices and/or provide additional benefits to boat users (e.g. reduced cost, see Salminen, 2019; Strand et al., 2018). Estimated costs for implementing monitoring systems in order to efficiently establish the use of mechanical antifouling methods are reasonably modest. Long-term monitoring using painted panels requires approximately 180 euro per location and year for the provision and distribution of required materials and analysis of panels, based on



Framework for using monitoring of fouling as a management tool

Time frame	***Long-term*** (full boating season over multiple years)	***Short-term*** (every 1-2 weeks during boating seasons)
Purpose	Identify general patterns in fouling dynamics for specific marinas/areas summarized using the ***Fouling Index (FI)***	Support the use of mechanical methods in the cleaning of boat hulls (e.g. boat washers) by providing ***"fouling warnings"***
Targeted actors	***Managers***: provide data to evaluate the requirement of toxic paints, promote non-biocidical methods and design systems of stricter regulations and economic incentives to support sustainable antifouling practices	***Marina operators and boat owners***: define when and how frequently mechanical antifouling techniques need to be used
Costs and requirements	Panel material, evaluation by trained staff/specialists (low cost)	Materials for panel deployment, local monitoring by marinas (low cost) or national coordinated service (moderate cost)

Fig. 5. Framework for the use of the monitoring of fouling for supporting the implementation of sustainable antifouling practices in the Baltic Sea.

estimations from similar initiatives in Germany (B. Watermann, pers. comm., 2020). Costs for a national coordinated system based on short-term monitoring to provide "real time" information on fouling settlement are estimated to between 30,000 and 40,000 euro per year including staff, material provision, communication and travelling expenses (110 locations) according to estimations from Sweden (A. Ehn, Skärgårdsstiftelsen, pers. comm., 2020).

To make the change towards more sustainable antifouling practices attractive, a combination of stricter regulations for the use of toxic paints and economic incentives for "biocide-free" methods should be considered. Costal managers should investigate ways of making polluting activities costlier through e.g., the enforcement of high pollution fees for marinas and boat owners that persist in using toxic methods. This could be accompanied by information campaigns to make boat owners aware of alternatives to painting. A successful example of this can be seen in the Stockholm Archipelago in Sweden, where many boat owners have moved away from biocidal coatings to non-toxic techniques. One key driver for this shift, were the stricter requirements set by local authorities for the management of wastewater and paint particles derived from maintenance activities in marinas. In this context, the implementation of wash pads with advance filtering systems that capture biocides was less economically convenient for marinas than becoming "biocide-free", i.e. not allowing antifouling paints and removing old paints from hulls as well as using mechanical cleaning in combination with the monitoring of fouling. Authorities could also provide directed funding that marinas can apply for to support their investments in necessary infrastructure for non-toxic antifouling practices (e.g. boat washer or land storage facility) as well as provide funding for coordination of a national fouling monitoring program, similar to the aforementioned example in Sweden (Skärgårdsstiftelsen, 2019). Finally, marina operators can also create incentives for boaters by having, e.g., reduced harbour fees to boat owners that use and promote biocide-free methods.

Reducing the use of antifouling paints has the potential to remove a large part of the new pollution that occurs each year in shallow bays around the Baltic Sea. However, without verifying that suitable infrastructure and practices are in place, it may also cause higher fouling loads on boat hulls leading to more organic material mixed with old paint layers to remove and dispose of correctly. In addition, the risk of transferring species between locations may increase. However, most leisure boats are relatively stationary, making day trips not far from their home port (Lagerqvist and Andersson, 2016) and are therefore not likely to introduce alien species from other regions (Moksnes et al., 2019). Long-distance travellers (mainly sailing boats) could represent a higher risk (Peters et al., 2017). Nevertheless, cleaning the hull of these boats in a designated enclosed area upon arrival to a marina could minimise species transfer. Precautionary actions should be taken particularly in marinas close to major commercial ports, where shipping (main vector of invasions in marine environments) may lead to secondary transfer of alien species by leisure boats (Ferrario et al., 2017).

Several complementary measures at an international level could support the efforts to reduce the use of toxic antifouling paints. Authorities in countries around the Baltic Sea should share monitoring data from marinas and discuss how these data can support biocide-free solutions. Within HELCOM, strategic policies and goals should be developed, aiming to reduce pollution from boating and establish fouling monitoring as part of the Baltic Sea Action Plan that aims to restore the good ecological status of the Baltic marine environment (HELCOM, 2007). Furthermore, recent studies have highlighted problems with current evaluation methods used for risk assessment of antifouling paints, where paints have been shown to release more toxic compounds than previously estimated (Lagerström et al., 2019). This should be considered when discussing authorisation criteria for paints and alternative methods in the future. Finally, further funding opportunities for research focussing on development and evaluation of non-biocidal methods should also be prioritized.

All in all, the existence of proactive boating communities that successfully use monitoring of fouling and mechanical cleaning methods with the support from local authorities provide encouraging examples that participative management in combination with a system of stringent regulations and economic incentives could be the key for the transition from toxic to non-toxic antifouling practices (Watermann and Eklund, 2019). Future research efforts that evaluate the performance of this management strategy in marinas along the Baltic Sea will be fundamental in the assessment of their success and applicability.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Anna-Lisa Wrange: Conceptualization, Data curation, Methodology, Formal analysis, Validation, Writing - original draft, Writing - review & editing. **Francisco R. Barboza:** Investigation, Formal analysis, Visualization, Writing - original draft, Writing - review & editing. **Joao Ferreira:** Investigation, Writing - review & editing. **Ann-Kristin Eriksson-Wiklund:** Conceptualization, Funding acquisition, Writing - review & editing. **Erik Ytreberg:** Conceptualization, Investigation, Writing - review & editing. **Per R. Jonsson:** Conceptualization, Writing - review & editing. **Burkard Watermann:** Conceptualization, Funding acquisition, Writing - review & editing. **Mia Dahlström:** Conceptualization, Project administration, Funding acquisition.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2020.110447.

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