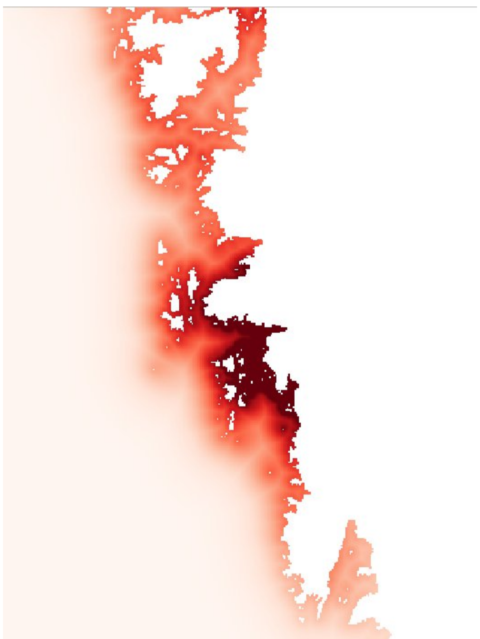
REPORT METEOROLOGY AND CLIMATOLOGY No. 122, 2025

Leisure boat activities and emissions in Sweden

Eef van Dongen[1], Tim Solig[1], Fredrik Windmark[1], Maria Lagerström[2], Erik Ytreberg[2]



[1] SMHI

[2] Chalmers University of Technology

Cover page figure:
Leisure boat fuel usage over Sweden and zoomed in around Gothen-
burg.

ISSN: 0347-2116 © SMHI

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Reviewer: Michaela Borg
Department: Community Planning Services, SMHI
Clients: This project has been funded by the Swedish Agency for Marine and Water Management (Havs- och Vattenmyndigheten) allocation 1:11 Measures for the marine and water environment (Åtgärder för havs- och vattenmiljö).

Summary

The Baltic Sea as a whole does not meet the criteria for good environmental status (GES) under descriptors 8 and 9 of the Marine Framework Directive based on a comprehensive evaluation of hazardous substances (HELCOM, 2018). Improved understanding of how human activities affect the Baltic sea is required to be able to more effectively target measures where they can have the greatest benefit.

Shipping has been identified as a significant source of emissions of metals and polycyclic aromatic hydrocarbons (PAHs) in particular to the marine environment. We have developed a new activity model for Swedish leisure boats, using a new mapping of moorings in combination with Automatic Identification System (AIS) data. AIS transmitters are mandatory for larger ships, with gross tonnage over 300, as well as for passenger ships in international traffic. The use of AIS among leisure boats is therefore generally lower than for commercial traffic, but many boat owners still use AIS voluntarily, for example for safety reasons. Therefore, AIS data does not provide full temporal and spatial coverage of leisure boats, but the data can be used, among other things, to produce a generic time variation for leisure boat activity.

The activity model combines AIS data for the year 2023, and a new dataset on Swedish moorings of leisure boats along the entire coast of Sweden, mapped using satellite imagery. The activity model is also based on information from the boating survey where boat owners estimated how often they use their boat, the distance sailed and what type of boat they use (Swedish Transport Agency, 2020). The model then assumes a Gaussian distribution of activity, concentrated at moorings and with a greater probability of boat activity closer to land. By modelling the activity for 232 963 leisure boats, we estimate a total fuel use of 27 330 tonnes. Antifouling paints release 18.9 tonnes of copper and 15.9 tonnes of zinc.

As a complement to the activity model, Shipair has also been used (Segersson, 2013) to model the emissions of larger leisure boats. Shipair models emissions based on time series of boat positions available through AIS. AIS data also tracks longer trips, between different ports, which are not covered by the activity model. Although only about 6 000 leisure boats are equipped with AIS transponders, 11.1 % of the entire fleet's travelled distance is covered by these boats. However, the modelled fuel consumption is only 5.2 % of the total fuel consumption estimated by the activity model, since a large proportion of the boats are assumed to be sailing boats.

The findings presented in this study can serve as input data for dispersion modelling to estimate atmospheric and marine pollutant concentrations. Moreover, the model can be adapted to assess additional environmental pressures on the marine ecosystem, including underwater noise, physical disturbances, and unburned fuel emissions from two-stroke engines. Additionally, it can be used to analyse the effects of different policy scenarios, offering valuable insights into how regulations influence emissions in both the atmosphere and marine environment.

Sammanfattning

Större delen av Europas havsområden når inte upp till en tillfredsställande miljöstatus enligt deskriptor 8 (farliga ämnen) och deskriptor 9 (farliga ämnen i livsmedel) i havsmiljödirektivet. Förbättrad förståelse kring hur olika mänskliga aktiviteter påverkar olika havsområden krävs för att mer effektivt kunna rikta åtgärder där de kan göra störst nytta.

Sjöfart har identifierats som en betydande källa till utsläpp av särskilt metaller och polycykliska aromatiska kolväten (PAHer) till havsmiljön. Vi har tagit fram en ny aktivitetsmodell för svenska fritidsbåtar med hjälp av en ny kartering av bryggor baserat på satellitbilder i kombination med Automatic Identification System-data (AIS). AIS-sändare är obligatoriska för större fartyg, med bruttodräktighet över 300, samt för passagerarbåtar i internationell trafik. Användandet av AIS bland fritidsbåtar är därför generellt lägre än för den kommersiella trafiken, men många båtägare använder ändå AIS frivilligt, till exempel av säkerhetsskäl. Därför ger AIS-data ingen full tidsmässig och rumslig täckning av fritidsbåtar, men uppgifterna kan bland annat användas för framtagandet av en generisk tidsvariation för fritidsbåtsaktivitet.

Aktivitetsmodellen kombinerar AIS-data för år 2023, och ett nytt dataset över svenska bryggor framtagen i tidigare projekt av Chalmers där förtöjningsplatser för fritidsbåtar längs hela Sveriges kust kartlagts med hjälp av ortofoton från Lantmäteriet tagna under 2020–2022. Aktivitetsmodellen bygger även på information från Båtlivsundersökningen där båtägare skattat hur ofta de använder sin fritidsbåt, seglad sträcka och vilken typ av båt de använder (Transportstyrelsen 2020). Modellen antar sedan en Gaussisk spridning av aktiviteten, koncentrerat vid förtöjningsplatser och med större sannolikhet för båtaktivitet närmare land. Genom att modellera aktiviteten för 232 963 fritidsbåtar, uppskattar vi en total bränsleanvändning av 27 330 ton. Från bottenfärger släpps 18,9 ton koppar och 15,9 ton zink.

Som ett komplement till aktivitetsmodellen har även Shipair används. Shipair modellerar emissioner baserat på tidsserier av båtpositionerna som är tillgängliga genom AIS. AIS-data visar även längre turer, mellan olika hamnar, som inte omfattas av aktivitetsmodellen. Trots att bara cirka 6 000 fritidsbåtar är utrustade med AIS-sändare, täcks 11,1 % av hela flottans färdsträcka av dessa båtar. Den modellerade bränsleförbrukningen utgör dock bara 5,2 % av den totala bränsleförbrukningen som estimeras av aktivitetsmodellen, eftersom det är en stor andel av båtarna som antas vara segelbåtar.

Resultaten från modellerna kan användas som indata för spridningsmodellering för att estimera atmosfäriska och marina koncentrationer av olika föroreningar. Dessutom har modellerna potential att inkludera och utvärdera andra miljöbelastningar på det marina ekosystemet, såsom undervattensbuller, fysiska störningar och oförbrända bensinutsläpp från tvåtaktsmotorer. Dessutom kan modellerna användas för att utvärdera effekterna av olika åtgärder, vilket ger insikter om lagstiftningens inverkan på utsläpp till atmosfären och den marina miljön.

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1 Introduction

Leisure boating is a significant and growing economic activity worldwide (Carreno and Lloret, 2021). However, it can also impact the marine environment in different ways by e.g. releasing biocides and chemicals from antifouling paints, causing underwater noise and turbidity (Moksnes et al. 2019). Moreover, leisure boating can affect human health by emitting air pollutants such as fine particulate matter (PM2.5), non-methane volatile organic compounds (NMVOCs), nitrogen oxides (NO_X) and sulfur oxides (SO_X). It also contributes to climate change through greenhouse gas emissions like carbon dioxide (CO_2).

Since 2007, ships in international traffic with a gross tonnage of over 300 GT, equivalent to a larger fishing boat, as well as passenger ships in international traffic are required to carry an Automatic Identification System (AIS) transponder. The AIS tracks the position and identity of ships. AIS data has been used to model emissions from the shipping sector through models such as the Shipair model (Segersson, 2013) and the STEAM model (Jalkanen et al. 2012; Johansson et al. 2017). In such models, each individual vessel's fuel consumption and emissions can be estimated with a high accuracy using the vessel's movement as tracked by AIS combined with data from a technical database such as IHS Fairplay Register of Ships. For leisure boats, use of AIS transponders is voluntary, and only about 6 000 leisure boats active at the Swedish coast used an AIS transponder in 2023, and comparatively little is known about the technical properties of these boats. The activity of the boats that do have an AIS transponder is also likely not representative for the total fleet of coastal leisure boats in Sweden. Consequently, modelling leisure boat activity presents significant challenges and requires additional data sources beyond AIS.

Johansson et al. (2020) conducted a study to estimate the activity and emissions of leisure boats in the Baltic Sea by using survey data to characterize the fleets operating within the region. The majority of the data originated from Swedish questionnaire surveys carried out in 2010 and 2015 published by the Swedish Transport Agency. These surveys provided comprehensive information on leisure boat activities in Sweden, including fleet characteristics, fuel consumption, and travel patterns.

For the Swedish coastline, Johansson et al. used digital mapping of marinas provided by the Swedish Environmental Protection Agency to define the geographic areas of the marinas. The data set, dated to 2010, contains information solely on leisure boat marinas. These areas were then converted into boat count estimates, which were manually verified through satellite image analysis. This method identified 114 000 leisure boats within marinas, while the Swedish boating survey in 2015 estimated approximately 228 000 boats are used in coastal areas (Swedish Transport Agency, 2015).

To enhance the accuracy of emissions estimations from Swedish leisure boats, it is necessary to update and improve this dataset. Specifically, all mooring locations for Swedish leisure boats must be mapped and linked to a more updated detailed description of boat characteristics (engine type, length, underwater hull surface area, etc.) and usage patterns (distance sailed, speed, etc.) to calculate emissions from the Swedish leisure boat fleet effectively. In addition, Johansson et al. (2020) only use AIS data indirectly, to simulate the temporal variability of leisure boat activity. Here, we also use AIS data directly to study the activity of those leisure boats that are equipped with an AIS transponder.

The aim of the study is to create a more accurate model of activities and emissions for leisure boats in Swedish coastal waters. The atmospheric emissions include PM2.5, NMVOC, NO_X, SO_x and CO, while the marine emissions include copper and zinc leached from antifouling paints.

2 Methodology

This study models leisure boat activity by combining two methods:

1. an activity model that indirectly uses AIS data to estimate temporal activity, combined with survey data, and
2. directly using AIS data by Shipair.

Both methods along with their input data are described in the following sections. The activity model used here is very similar to the Boat Emissions and Activities siMulator (BEAM, Johansson et al. 2020). The activity model is summarised in this section along with the improvements that have been done within this project. Thereafter, the handling of leisure boats in Shipair is described.

2.1 Activity model

The activity model assumes that the entire leisure boat fleet can be represented by diffuse movement around marinas. In this model, each marina accommodates a certain number of leisure boats that all operate within the surrounding area of that marina.

This model requires detailed mooring data along the Swedish coast, combined with statistics on leisure boat usage, properties and emission factors for different boat types as well as data on the temporal distribution throughout the year. These elements are all described below.

2.1.1 Model formulation

The model calculates the probability that a boat is active at a certain hour of the year p_t (Section 2.1.4). In addition, it calculates the probability that an active boat is located at a certain geographical location p_g (Section 2.1.2). The expected number of hours an active boat has been present in a grid cell (H_g) is calculated by summing

$$H_g(b) = \sum_t N_t S(b) T(b) p_t p_g$$

for each boat type *b*, where *S(b)* is the share of this boat type, *T(b)* the total active hours per year and N_t the number of boats in the marina at time *t.* The total fuel consumption and emissions of air pollutants is then calculated using the average engine power rating per boat type (Section 2.1.3) and emission factors (Section 2.1.5). Antifouling paints release copper and zinc both at their mooring location when inactive, and in the surrounding area when active.

2.1.2 Geographical distribution

The geographical distribution of Swedish leisure boat mooring locations was obtained from Lagerström et al. (2024). In that study, leisure boats were mapped in QGIS using orthophotos of the Swedish coast taken between April and September during the years 2020 to 2022 to identify active moorings. Moorings were recorded as points for single moorings and as lines for multiple berths, with orientation noted to estimate the number of moorings based on line length. Point layers represented one vessel per point, while line layers estimated boat numbers by line length. The analysis indicated that boats on the west coast are generally longer than those on the east coast, affecting the jetty length per boat ratio. Mooring locations were categorized into three regions based on national antifouling regulations: 'west' (Norwegian border to Trelleborg, 85 388 moorings), 'south-east' (Trelleborg to Örskär, 122 546 moorings), and 'north-east' (Örskär to the Finnish border, 25 029 moorings).

Locations of moorings are then grouped into 200 m x 200 m grid cells (Figure 1). Each grid cell that contains one or more moorings is regarded as a marina. If a line representing multiple berths is located across several grid cells, the number of boats is distributed relative to line length in each cell. In accordance with Johansson et al. (2020), boats are assumed to move within 50 km from their respective marina over all coastal waters.

Each boat has an activity probability for a certain location (p) that depends on the distance to its marina (r_m) and the nearest coast (r_c), given by:

$$p\left(r_m, r_c\right) = e^{-0.2\left(r_m + r_c\right)}.$$

The probabilities are normalised so that the value of each 200 m x 200 m grid cell represents the likelihood of finding a specific active boat in that grid cell. To simplify calculations, the straight distance to a marina is used, disregarding whether there is land in between the marina and the location for potential boat activity. This simplification can lead to errors along the complex geometry of the Swedish coast, but is overall not deemed to be a significant error.

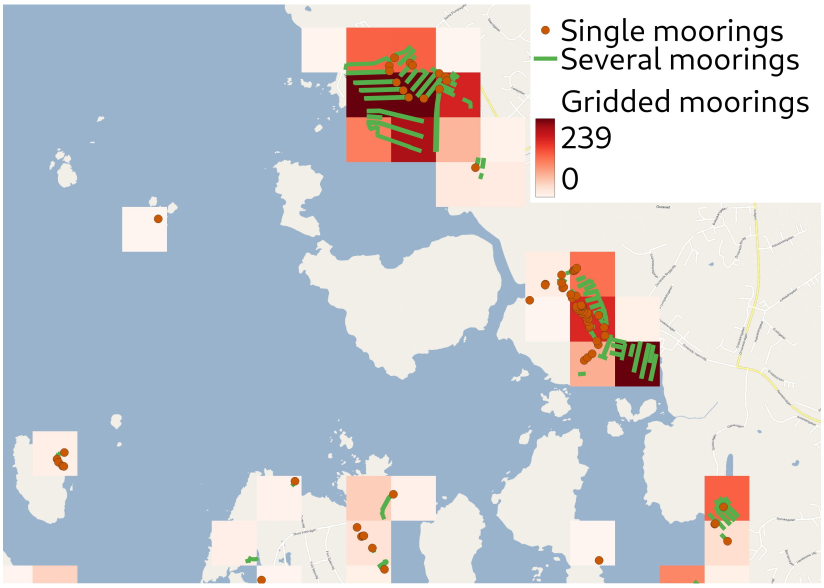

Figure 1 Moorings as mapped from ortophotos in lines and points, together with the 200 m x 200 m grid cells of grouped moorings, southwest of Gothenburg. Background: OpenStreetMap®.

2.1.3 Region-wise boat characteristics

The mapping of mooring locations gives a very detailed description of the geographical distribution of boats, but does not include any information on the boat types at each location. Boat characteristics were extracted from the Swedish boating survey published by the Swedish Transport Agency (2020). The survey includes data from 6 000 respondents, detailing boat ownership, boat length, and biofouling prevention methods. Information related to smaller crafts (such as kayaks, rowing boats, dinghies, jet skis) has been excluded in this study, focusing only on responses from boat owners with boats located along the Swedish west (n = 119 respondents), south-east (n = 176 respondents), and north-east (n = 45 respondents) coastal sections. The following boat types were used from the survey:

- OMB: Fully open boat with engine under 10 hp.
- MB: Motorboat without overnight accommodation, with an engine of at least 10 hp, including RIB boats.
- LMB: Large motorboat intended for overnight stays.
- LMSB: Large motorsailer intended for overnight stays.
- SB: Sailing boat with the possibility of only temporary overnight stays.

Parameters extracted from the survey include wet surface area (WSA), antifouling paint usage, total distance sailed per year, average speed, and engine type. Results from this compilation are presented in Table 1 and were further used to develop the activity and emission model. Distances reported as greater than 1 000 nautical miles per year were excluded, assuming these values to be erroneous or non-representative. Assumed average engine load was set at 70 % for open small boats, 50 % for other motorboats, and 10 % for sailing boats, similar to assumptions made by Johansson et al. (2020).

The WSA was derived from boat length using the 'length to wetted surface area' conversion described in the Marine Antifoulant Model to Predict Environmental Concentrations (MAMPEC) (Tukes, 2017). This conversion is based on data from 27 000 boats used in the Baltic Sea provided by the Finnish Sailing and Boating Association.

Table 1 Boat characteristics per boat type and region, as derived from Båtlivsundersökningen (Swedish Transport Agency, 2020). Two-stroke and four-stroke gasoline engines are denoted by "2S" and "4S". The newer engine types have a suffix "_2003", "DSL" stands for diesel and "EL" for electric engine.

Boat type	**OMB** Fully open motorboats	**MB** Motorboats without overnight accommodation	**LMB** Large motor-boats for over-night stays	**LMSB** Large motor-sailers for over-night stays	**SB** Sailing boats for temporary over-night stays
			North		
Share (%)	17.8	53.3	17.8	4.4	6.7
Water surface (m²)	9.3	13.0	17.8	31.0	10.8
Distance (km/yr)	4.6	156.8	126.5	69.5	72.6
Average speed (km/h)	17.7	28.3	34.1	11.0	3.9
			East		
Share (%)	9.1	38.1	25.6	15.9	5.7
Water surface (m²)	12.0	11.4	19.6	28.9	25.7
Distance (km/yr)	105.9	211.1	342.0	224.2	515.8
Average speed (km/h)	36.1	36.7	29.3	13.7	5.1
			West		
Share (%)	11.8	37.0	18.5	24.4	5.0
Water surface (m²)	10.7	11.4	21.6	23.9	33.0
Distance (km/yr)	58.3	154.1	308.4	424.7	354.3
Average speed (km/h)	19.9	35.7	37.8	11.2	3.9
			All		
Engine type					
DSL	11.8 % 6 kW	7.8 % 40 kW	35.1 % 150kW	64.5 % 150kW	64.5 % 150kW
DSL_2003	0.0 % 6 kW	0.0 % 40 kW	2.7 % 150kW	0.0 % 150kW	0.0 % 150kW
2S	35.3 % 6 kW	21.9 % 50 kW	18.9 % 80kW	16.1 % 50kW	16.1 % 50kW
2S_2003	0.0 % 6 kW	18.8 % 50 kW	2.7 % 80kW	6.5 % 50kW	6.5 % 50kW
4S	47.1 % 6 kW	50.0 % 50 kW	37.8 % 80kW	9.7 % 50kW	9.7 % 50kW
EL	5.9 % -	1.6 % -	2.7 % -	3.2 % -	3.2 % -

2.1.4 Temporal distribution

In addition to estimating where an active boat can be found, the model also estimates when boats are most likely to be active. Following Johansson et al. (2020), a statistical model is used to estimate the occupancy of marinas in Sweden throughout the year. The model estimates the season length (L) and the mid-season day (D_M), as functions of latitude (c). Additionally, the model evaluates the "ramp-up" (L_U) and "ramp-down" (L_D) periods, measured in days, which represent the time it takes for the marina occupancy to rise to 100 % and decline to 0 %, respectively. The linear statistical model is defined as follows:

$$D_M = 1.8c + 102, L = 720 - 9.1c, L_U = 0.2L, L_D = 0.33L.$$

As a specific example, consider a marina near Stockholm (c = 59.0°N). In Stockholm, the season lasts for 183 days, beginning April 25 and ending October 25. It takes 36 days to reach full capacity by May 31. After August 26, the number of boats gradually declines, and within approximately 60 days, the marina is expected to be empty until the start of the next season.

After the occupancy of the marina is found, the probability of a boat in the marina being active at a certain date and time is calculated based on AIS data and boat characteristics. The total hours per year that a boat is active is calculated from the average travel distance per year and the average speed, varying per boat type and region as shown in Table 1.

AIS data collected by the Shipair system is then used to estimate which dates and hours boats are most likely to be active. As previously mentioned, only about 2-3 % of all leisure boats have an AIS transponder. Boats that have a transponder are expected to travel further and more frequently than typical leisure boat activity. Therefore, representative leisure boats are selected that have activity statistics similar to the findings in the survey by the Swedish Transport Agency (2020). In accordance with Johansson et al. (2020), we set the selection criteria to:

- The boat can only be active during the ice free season from 1 April to 30 October.
- Total travel distance cannot exceed 1 000 km per year.
- The vessel is non-IMO-registered.
- The length must be less than 15 m.
- The relative monthly cruising time cannot exceed a selected threshold of 5 %.

This yields 1 143 boats satisfying the criteria for 2023. The average length of these boats is 10.3 m, and the average annual travel distance is 328 km. The travelled distance per hour for the entire fleet is calculated and normalized (Figure 2), to estimate the probability of a boat being active at a certain date and time.

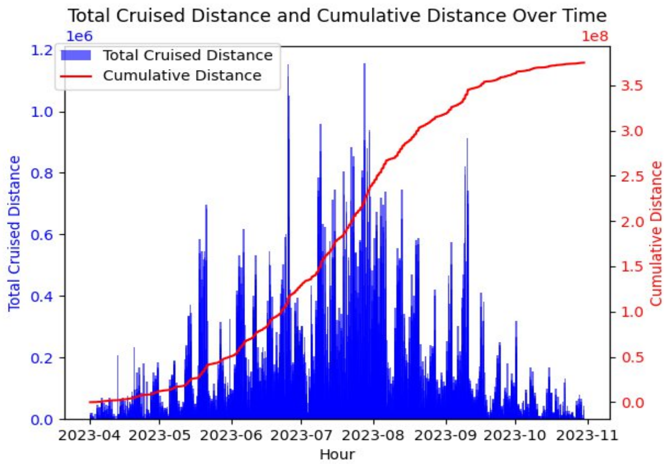

Figure 2 Cruised distance [km] per hour and cumulative distance [km] of representative leisure boats in 2023, using AIS data.

2.1.5 Emission factors

Emission factors for leisure boats have not been updated in the latest EMEP/EEA air pollutant emission inventory guidebook 2023. Therefore, Table 2 shows the same emission factors for air pollution for different combinations of boat types and engine setups as used in Johansson et al. (2020), based on the EMEP/EEA Guidebook for sector 1.A.3.d Navigation (shipping) 2023, with original data from Winther & Nielsen (2006).

In Sweden, biocidal antifouling paints can be used on boats heavier than 200 kg with main mooring on the west and south-east coasts. These paints contain inorganic copper species and zinc oxide. The paint market is divided into west coast paints and east coast paints; the latter leach lower copper amounts. In the latest Swedish boating survey, 90 % of respondents used paint approved for their home waters (Swedish Transport Agency, 2020).

Boaters were assumed to comply with all restrictions, and emissions were calculated for boats on the west and south-east coasts. Although east coast paints are permitted on the west coast, this is uncommon. Thus, all west coast boats were assumed to use west coast paints. Application rates of biocidal antifouling paint were found to be 62.2 % on the west coast and 41.5 % on the south-east coast (Swedish Transport Agency, 2020). For the north-east coast, it is assumed that no leisure boats are coated with biocidal antifouling paints.

Table 2 SFOC and emission factors to air for different leisure boat types and engine setups.

Boat type	Engine setup	SFOC (g kWh⁻¹)	PM2.5 (g kg⁻¹)	NOx (g kg⁻¹)	NMVOC (g kg⁻¹)	CO (g kg⁻¹)
LMSB & SB	2S	791	12.6	2.5	322.0	539.8
LMSB & SB	2S_2003	791	12.6	2.5	53.9	232.6
LMSB & SB	4S	426	0.2	16.4	50.7	348
LMSB & SB	DSL	281	5.0	64.1	7.7	19.8
LMSB & SB	DSL_2003	281	3.6	34.9	6.7	18.6
LMSB & SB	EL	0	0.0	0.0	0.0	0
LMB	2S	791	12.6	3.8	215.5	472.8
LMB	2S_2003	791	12.6	3.8	39.8	169.4
LMB	4S	426	0.2	28.2	21.1	293.4
LMB	DSL	275	4.4	31.3	7.2	19.8
LMB	DSL_2003	275	3.6	31.3	6.1	18.6
LMB	EL	0	0.0	0.0	0.0	0
MB	2S	791	12.6	2.5	322.0	539.8
MB	2S_2003	791	12.6	2.5	57.5	232.6
MB	4S	426	0.2	16.4	50.7	431.9
MB	DSL	281	5.0	64.1	7.7	19.8
MB	DSL_2003	281	3.6	34.9	6.3	18.6
MB	EL	0	0.0	0.0	0.0	0.0
OMB	2S	791	12.6	2.5	322.0	672.6
OMB	2S_2003	791	12.6	2.5	57.5	556.3
OMB	4S	426	0.2	16.4	50.7	1032.9
OMB	DSL	281	5.0	64.1	7.7	19.8
OMB	DSL_2003	281	3.6	34.9	6.3	18.6
OMB	EL	0	0.0	0.0	0.0	0.0

For copper, the release rate has shown to be governed by salinity. Therefore, release rate data for copper from coated panels statically immersed at seven different locations in Swedish waters was compiled from three field studies conducted between 2015 and 2023 (Lagerström et al. 2025a). The dataset, comprised of release rates from a total of 10 different leisure boat coatings, thus covering nearly half the products approved on the Swedish market at the time of the studies (Lagerström et al. 2018, 2020, 2025b). This dataset was subsequently utilized to evaluate the leaching rate of copper from individual leisure boats, considering the salinity levels of the areas where the boats are moored or active. For zinc, there is no dependency on salinity. Therefore, release rates of 5.07 µg cm^{-2} d^{-1} for vessels moored on the west coast and 7.43 µg cm^{-2} d^{-1} for those on the south-east coast were used.

To estimate the local salinity, observations and model results are combined. All salinity observations with a maximum water depth of five meters, obtained from the Swedish maritime archive SHARK[3], are averaged by coastal water body as defined by SVAR 2022 (Abdoush et al. 2024). Those coastal water bodies that do not have any published salinity observations, are set to the average salinity of its neighbouring coastal water bodies. Outside of coastal water bodies, farther offshore, the average salinity of the shallowest layer (0.5 m) modelled in the Baltic Sea Physicis Reanalysis[4] from 1993 to 2023 is used.

[3] Available at https://shark.smhi.se/

[4] Available at https://doi.org/10.48670/moi-00013

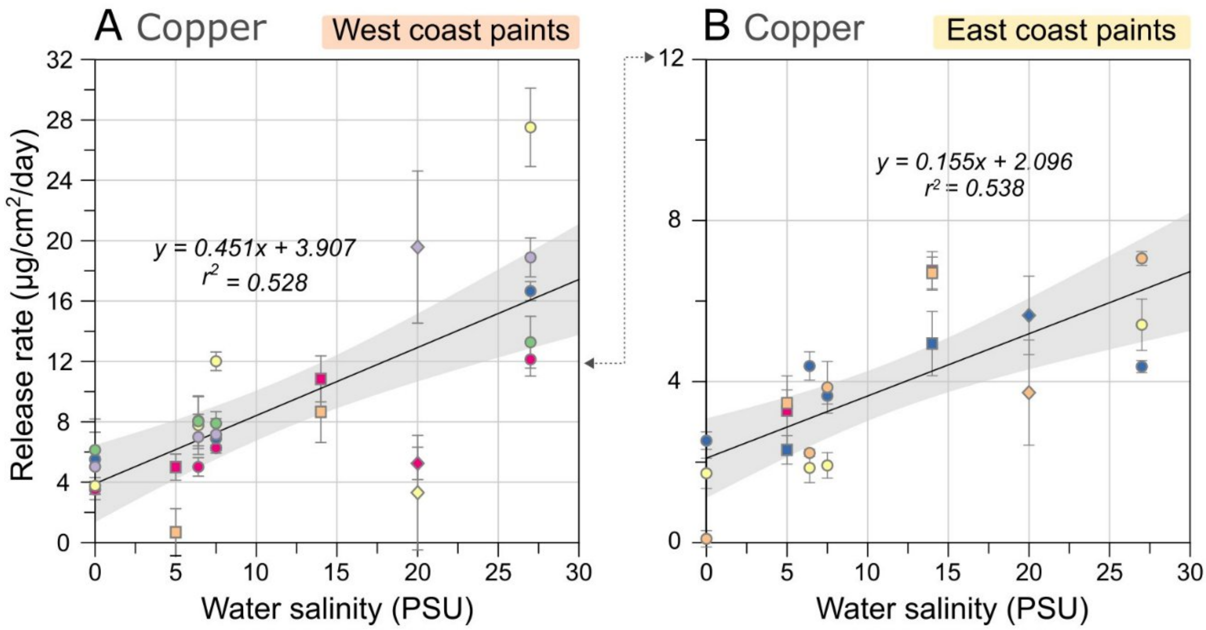

Figure 3 Average release rates (day 14-56 of exposure) of copper from west and east coast paints from field studies in Swedish waters, as a function of salinity at the immersion. From Lagerström et al. 2025a.

2.2 Shipair

The Shipair model is described in detail in Segersson (2013), and is therefore only briefly summarized here. In the model, AIS data is collected from the Swedish Maritime Agency (Sjöfartsverket) and the ship positions are stored as time-series with up to one minute resolution, using a high performance time-series database. Erroneous positions are filtered and each time step is assigned a navigational status:

- Cruise; the ship is moving and not located within a manoeuvring area,
- Manoeuvring; the ship is moving within a manoeuvring area,
- At Berth; the ship is not moving and within a manoeuvring area,
- Anchored; the ship is not moving but outside a manoeuvring area,
- OPS; the ship is not moving and is located within an on-shore power supply area.

Whereas Shipair models fuel usage and emissions for main engines, auxiliary engines and boilers during all navigational statuses for commercial vessels, leisure boats are only modelled during cruise and manoeuvering. In Shipair, the manoeuvring areas are mainly mapped for large ports. Leisure boat marinas have a poorer coverage. However, since leisure boats are not expected to have engines running while at berth or anchored, and emissions are similar when cruising and manoeuvring, it is not as critical to distinguish between these statuses for leisure boats compared to commercial vessels.

The power output P_t at time t is calculated based on the velocity V_t as

$$P_t = \frac{P_{tot}}{{V_{max}}^3} {V_t}^3$$

using the total installed power P_{tot} and maximum velocity V_{max}. Unlike commercial vessels, the installed power and maximum speed for specific leisure boats are unknown. Instead, the values in Table 1 for large motorboats (LMB) or large motorsailers (LMSB) are assumed for all leisure boats. For each of the engine types, the power output, fuel usage and emissions are modelled, and then weighted by the share of the respective engine type. For motorsailers, 90 % of the power output P_t is assumed to be provided by wind energy and the remaining 10 % by the engine, in agreement with Johansson et al. (2020).

Out of the 6 046 leisure boats with AIS transponder, the static AIS data tells that 2369 boats are sailing boats, 73 motor boats and the remaining 3604 are undefined. These undefined boats are split by their maximum speed. If the maximum speed exceeds 10 knots, Shipair regards them as motor boats and otherwise they are regarded as sailing boats.

Antifouling paint release is not modelled with Shipair, since copper and zinc are also emitted when boats are inactive. It is not likely that leisure boats keep their AIS transponder turned on when at berth, therefore, the activity model with the detailed mooring mapping gives a better estimate of antifouling emissions.

3 Results

The following sections present the results from the activity model and Shipair separately. The activity model should be seen as a total description of the entire boat population, while Shipair provides a more detailed analysis of 2.6 % of the most active boats in the fleet.

3.1 Activity model

Activity and emissions in the model strongly depend on the boat characteristics (Table 1). Updating characteristics according to the latest boating survey, and applying region-wise statistics instead of only national averages, results in different fuel usage and emissions compared to BEAM (Johansson et al. 2020), as summarized in Table 3 . In addition, totals for all modelled quantities are also presented per region and boat type (Tables 4 - 9).

Table 3 Results of the updated activity model compared to BEAM (Johansson et al. 2020), where AFP stands for antifouling paint.

	Fuel (10^3 kg)	**CO (10^3 kg)**	**NMVOC (10^3 kg)**	**NO_x (10^3 kg)**	**PM2.5 (10^3 kg)**	**AFPCu (10^3 kg)**	**AFPZn (10^3 kg)**	**Travel (10^6 km)**	**Boats**
BEAM	28220	6750	2030	520	198	15.9	18.6	67	227800
Update	27330	6614	2369	734	177	18.9	15.9	56	232963
Change	-3 %	-2 %	17 %	41 %	-11 %	19 %	-15 %	-17 %	2 %

The most significant change is seen for NO_x emissions, where we estimate a 41 % higher total yearly emission. The largest source of NO_x emissions in Johansson et al. (2020) comes from large motorboats, whereas we find comparable contributions from large motorboats, large motorsailers and smaller motorsailers (Table 7). This can be explained by the higher share of older diesel engines that we find compared to Johansson et al. (2020), since these sailing boat engines have the highest emission factor for NO_x (Table 2). In addition, the share of all sailing boats (LMSB and SB combined) is higher in the latest boating survey (Swedish Transport Agency, 2020) for the regions East and West than the previous survey used by Johansson et al. (2020).

Also NMVOC emissions have increased by 17 %. NMVOC emissions are largely dominated by older two-stroke engines (“2S” in Table 2). Johansson et al. (2020) estimated that 13 % of all boats have this engine type, whereas our findings show that 23 % in the north, 20 % in the east and 21 % in the west, use these engines, which explains the increase in NMVOC emissions. We find the largest NMVOC emission per boat type for motorboats without overnight accommodation (MB, Table 6).

The 11 % decrease of PM2.5 emissions is also related to differences in boat properties, with the emission per kg used fuel being higher for the smaller boats (OMB and MB) compared to the other categories.

Contrary to Johansson et al. (2020), we find higher loads of Cu from antifouling paint (18.9 tonne) than Zn (15.9 tonne). The load of Cu is highest at the west coast (15.5 tonne, 82 %) whereas the load of Zn is highest at the east coast (9.1 tonne, 57 %). The differences with Johansson et al. (2020) are due to different assumptions on release rates, and possible also as a result of different shares of moorings at the east and west coasts.

Table 4 Fuel usage (10^3 kg) per region and boat type.

	OMB		MB		LMB		LMSB		SB	
Fuel	**diesel**	**gasoline**	**diesel**	**gasoline**	**diesel**	**gasoline**	**diesel**	**gasoline**	**diesel**	**gasoline**
north	0	2	32	988	129	219	19	8	85	34
east	5	70	125	3805	3022	5146	921	373	2034	823
west	4	62	62	1888	1038	1767	2224	900	1099	445
total	9	133	219	6682	4189	7133	3164	1281	3218	1302

Table 5 CO emissions (10^3 kg) per region and boat type.

CO	**OMB**	**MB**	**LMB**	**LMSB**	**SB**	**total**
north	2	407	77	4	17	507
east	57	1568	1809	179	396	4010
west	51	778	621	433	214	2097
total	110	2754	2508	616	626	6614

Table 6 NMVOC emissions (10^3 kg) per region and boat type.

NMVOC	**OMB**	**MB**	**LMB**	**LMSB**	**SB**	**total**
north	0	139	25	2	8	174
east	15	535	587	85	187	1409
west	13	266	202	205	101	786
total	28	940	814	291	296	2369

Table 7 NO_x emissions (10^3 kg) per region, boat type and fuel type.

	OMB		MB		LMB		LMSB		SB	
NO_x	**diesel**	**gasoline**	**diesel**	**gasoline**	**diesel**	**gasoline**	**diesel**	**gasoline**	**diesel**	**gasoline**
north	0.0	0.0	2.1	7.9	4.0	3.4	1.2	0.0	5.4	0.2
east	0.3	0.6	8.0	30.6	94.6	80.5	59.1	1.9	130.3	4.2
west	0.3	0.5	4.0	15.2	32.5	27.6	142.6	4.6	70.5	2.3
total	0.6	1.1	14.0	53.7	131.1	111.5	202.8	6.5	206.3	6.7

Table 8 PM2.5 emissions (10^3 kg) per region and boat type.

PM2.5	**OMB**	**MB**	**LMB**	**LMSB**	**SB**	**total**
north	0.0	7.7	2.0	0.2	0.8	10.7
east	0.5	29.8	47.0	8.4	18.6	104.4
west	0.5	14.8	16.1	20.4	10.1	61.8
total	1.0	52.3	65.1	29.0	29.5	176.9

Table 9 Energy consumption (10^3 kWh) per region and boat type.

Energy	**OMB**	**MB**	**LMB**	**LMSB**	**SB**	**total**
north	5	1791	861	79	352	3088
east	137	6896	20200	3826	8445	39503
west	121	3422	6937	9236	4566	24281
total	262	12109	27998	13141	13363	66872

Energy consumption is the quantity most closely related to noise which the activity model provides (Table 9). Larger and faster boats typically produce more noise (Hao and Nabe-Nielsen, 2023), and the energy consumption of boats also increases with size and speed. Picciulin et al. (2022) find that engine power and engine type are more productive of underwater radiated noise than boat length and design. The highest energy consumption is found for large motorboats, which also have the highest average speed for most regions (Table 1).

Both antifouling emissions and boat activities (and thereby fuel usage and combustion emissions) vary strongly per month (Figure 4). Boat activities have their largest peak in July (34 % of the yearly activity). Antifouling emissions are more similar from June to August, since we assume that marinas have reached their full capacity then, and also inactive boats release Cu and Zn. There is a slight difference in the time variation of Cu and Zn, which is a result of the salinity dependence of Cu release, whereas Zn varies solely with marina capacity.

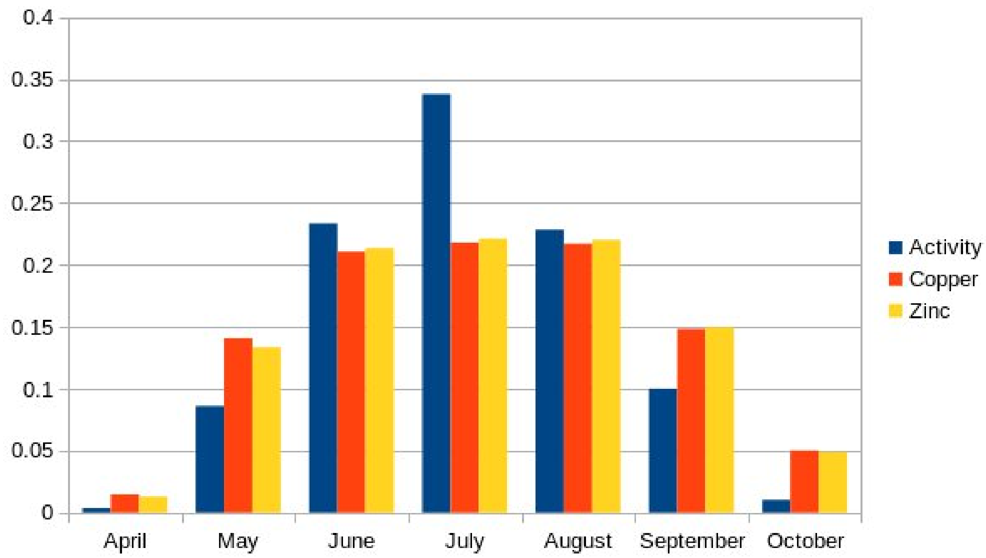

Figure 4 Share of activity (and thus fuel usage and combustion emissions), Cu and Zn emissions per month.

The effect of the latitude-dependent marina capacity is clearly visible in Figure 5, which shows no fuel usage in the north in April. In July, the geographical distribution is dominated by the density of marinas, which is clearly highest in the Gothenburg and Stockholm areas.

Emissions of Cu and Zn from antifouling paints occur mainly in marinas (Figure 6), since leisure boats spend the vast majority of their time at berth.

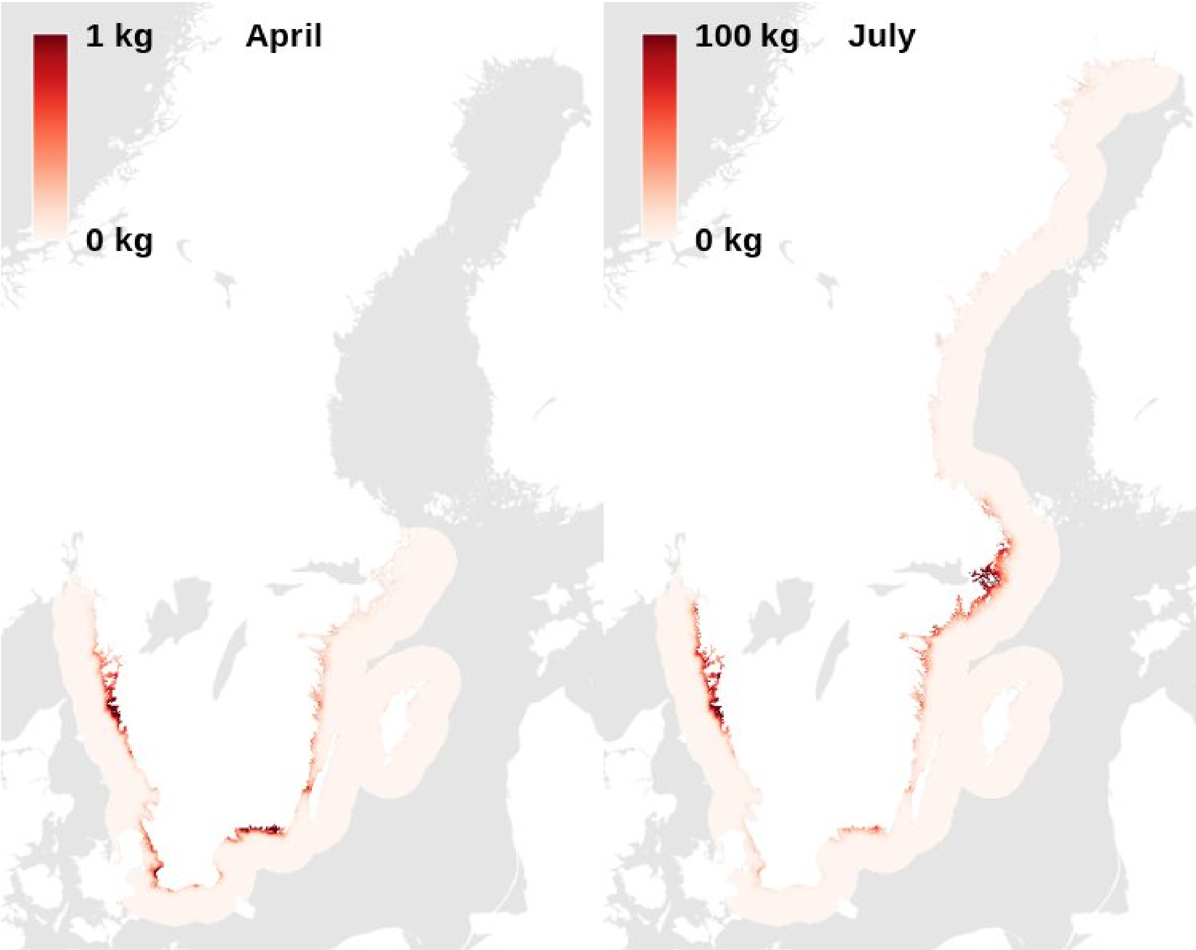

Figure 5 Geographical distribution of total fuel usage in April (left) and July (right), in kg per 200 m by 200 m grid cell.

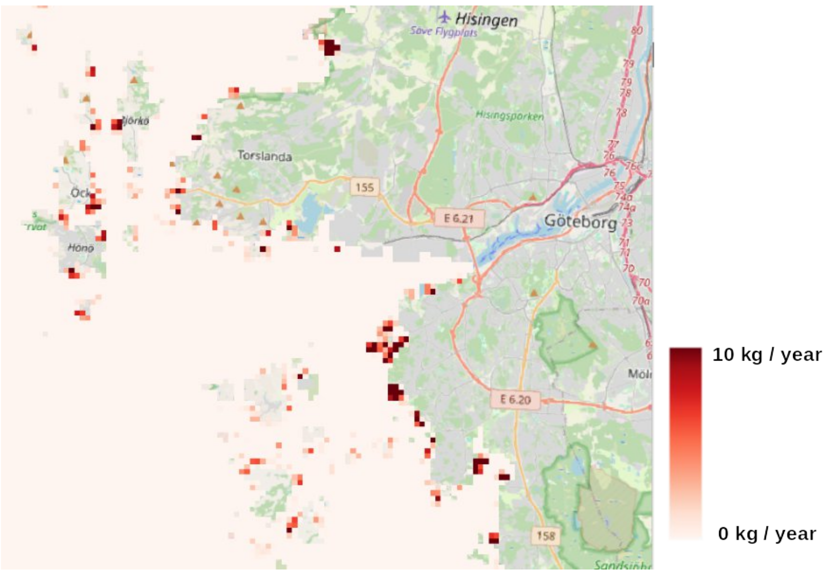

Figure 6 Geographical distribution of Zn load from antifouling paint in the Gothenburg area, in kg per gridcell (200 m by 200 m) per year. Background: OpenStreetMap®.

3.2 Shipair

Total fuel usage and emissions as modelled by Shipair are shown in Table 10. Despite representing only 2.6 % of the boats in the activity model, 11.1 % of the travelled distance is covered by boats equipped with an AIS transponder. Fuel consumption and emissions however are only around 5 % of the totals modelled with the activity model. This can be explained by a higher share of sailing boats modelled by Shipair. Out of the 3 604 boats of undefined type, 1 495 are regarded as sailing boats due to their maximum speed being below 10 knots. Hence, 64 % of the boats modelled with Shipair are assumed to be sailing boats, compared to 24 % in the activity model. Further research is needed to investigate whether the share of sailing boats is indeed higher among boats equipped with AIS transponder, or whether Shipair currently underestimates fuel usage and emissions.

Table 10 Emissions from Shipair compared to the updated activity model.

	Fuel (10^3 kg)	CO (10^3 kg)	NMVOC (10^3 kg)	NO_x (10^3 kg)	PM2.5 (10^3 kg)	Travel (10^6 km)	Boats
Shipair	1420	318	101	36	8	6	6046
Activity model	27330	6614	2369	734.4	176.927	56	232963
Shipair coverage	5.2 %	4.8 %	4.3 %	4.9 %	4.7 %	11.1 %	2.6 %

Whereas the activity model assumes leisure boats are distributed in a Gaussian spread around their marina, the AIS data in Shipair shows that boats also travel from one marina to another (Figure 7). Despite the lower coverage of AIS data, this clearly shows how using AIS data directly with an emission model provides a complement to an activity model around marinas.

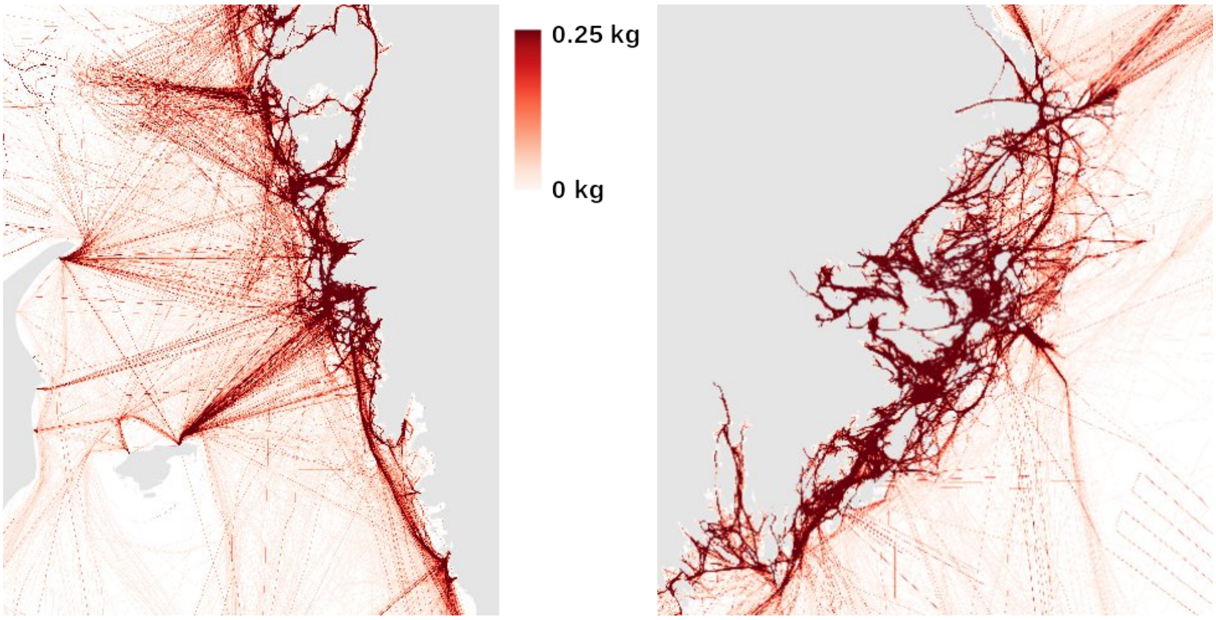

Figure 7 Fuel usage for 2023 modelled by Shipair, at the coast surrounding Gothenburg (left) and Stockholm (right), in kg per 100 m by 100 m gridcell.

4 Conclusions and outlook

This study presents the development of an advanced activity model for assessing activities and emissions from leisure boats in Swedish coastal waters. The model is capable of estimating atmospheric emissions of PM2.5, NMVOC, NO_X, SO_x and CO, as well as direct emissions of copper and zinc from antifouling paints.

Combining the activity model with Shipair provides an even higher level of detail for the share of the leisure boat fleet that is equipped with an AIS transponder, covering also traffic from one marina to another. However, the limited amount of data on engine characteristics and usage contributes to uncertainties in both the activity model and Shipair. The assumed engine type, size and load strongly affect the modelled emissions and should therefore be in focus for future improvements. Besides that, the parameters in the Gaussian spread of activity around marinas is based on a study performed in Florida (Montes et al. 2018). It would be interesting to compare this geographical distribution to leisure boat activities at the Swedish coast, for example with locations tracked in navigation apps.[5]

The results presented here can be utilized as input data for dispersion modelling to predict atmospheric and marine concentrations of various pollutants. Additionally, the model has the potential to incorporate and evaluate other environmental pressures on the marine ecosystem, such as underwater noise, physical disturbances, and unburned gasoline emissions from two-stroke engines. Furthermore, this model can be employed to evaluate the effects of various policy scenarios, providing insights into the impact of legislation on atmospheric and marine environment emissions.

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1)Correspondig author, e-mail: Nils.Gustafsson@smhi.se
2)Deceased 2010 3)Deceased 2006 4)Deceased 2015
5)Deceased 2005
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ISSN: 0347-2116

SE 601 76 NORRKÖPING
Phone +46 11-495 80 00 Telefax +46 11-495 80 01