Identifying Marine Sources of Beached Plastics Through a Bayesian Framework: Application to Southwest Netherlands

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Abstract

Beaches are thought to contain a large part of plastics entering the marine environment. Here, they can cause harm to biota, and can potentially break down into smaller fragments over time. To protect vulnerable beaches, it is advantageous to have information on the sources of this plastic. Here, we develop a universally applicable Bayesian framework to map sources for plastic arriving on a specific beach, applied to a beach in southwest the Netherlands. In this framework, we combine Lagrangian backtracking simulations of drifting particles with data of plastic input from coastlines, rivers and fishing activity. This facilitates spatiotemporal source attribution for plastic arriving at the specified beach. We show that the main sources are the east coast of the UK, the Dutch coast, the English channel (fisheries) and the Thames, Seine, Rhine and Trieux (rivers). We also show that particle age is a major uncertainty in source attribution using backtracking.

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Key Points:

- Combined oceanic backtracking and Bayesian statistics supports source attribution of beached plastic
- Strong temporal variability in likely sources is found, due to variability in plastic input and currents
- Particle age remains a major uncertainty in determining the origin of beached plastic via backtracking

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Abstract

Beaches are thought to contain a large part of plastics entering the marine environment. Here, they can cause harm to biota, and can potentially break down into smaller fragments over time. To protect vulnerable beaches, it is advantageous to have information on the sources of this plastic. Here, we develop a universally applicable Bayesian framework to map sources for plastic arriving on a specific beach, applied to a beach in southwest the Netherlands. In this framework, we combine Lagrangian backtracking simulations of drifting particles with data of plastic input from coastlines, rivers and fishing activity. This facilitates spatiotemporal source attribution for plastic arriving at the specified beach. We show that the main sources are the east coast of the UK, the Dutch coast, the English channel (fisheries) and the Thames, Seine, Rhine and Trieux (rivers). We also show that particle age is a major uncertainty in source attribution using backtracking.

Plain Language Summary

A large part of plastic in the ocean is located at or near beaches. This plastic can break down into micro-plastics or be ingested by animals. Therefore, it is important to clean up these beaches. The easiest way to do so is to prevent the plastic from entering the oceans initially by interfering at the source. In this study, we develop a framework to find these sources for a given beach. We first simulate the path that plastic has taken to reach this beach. We do this by releasing virtual plastic particles at the beach where they end up. Next, we calculate their paths back in time, computing their trajectories until they reach this beach. We then combine these simulations with data on the sources of plastic: where and when did plastic enter the ocean? We apply this framework to a beach in southwest Netherlands, near the town of Domburg. We quantify seasonal effects, where time-varying currents cause the plastic to come from different sources. Lastly, we study how plastic sources vary with plastic age (the time between the plastic entering the ocean and beaching at its final location).

1 Introduction

Most buoyant marine plastics are either beached or afloat in coastal waters (Onink et al., 2021; Morales-Caselles et al., 2021). Beached macro-plastic can more easily degrade into smaller micro-plastics than floating or submerged plastics, for example due to a higher exposure to solar UV radiation (Andrady, 2011) and mechanical fragmentation (Chubarenko et al., 2020). These micro-plastics can contain high concentrations of pollutants present in the oceans (Frond et al., 2019) and can, due to their small size, easily be ingested by marine biota and thus enter the food web (Andrady, 2011). High concentrations of plastic are already found in many species in the marine environment (Franeker et al., 2011; Coe & Rogers, 1997; Ryan et al., 2009). The importance of cleaning up our beaches is therefore evident (Kataoka & Hinata, 2015). However, it is difficult to do this efficiently when much is unknown about the source and fate of the plastic (van Sebille, 2015; Cózar et al., 2014). By locating and then mitigating at upstream sources (van Gennip et al., 2019; Robinson et al., 2017), it may be possible to prevent this pollution and its consequences. Moreover, knowing the sources of plastic pollution enables 'naming and blaming' of the polluters.

Source attribution of beached plastics for specific beaching locations has been done before by for example Neumann et al. (2014) and Strand et al. (2021), who both used Lagrangian particle simulations (van Sebille et al., 2018) to compute virtual particle trajectories back in time. These studies did not take into account where plastic enters the ocean and how much, giving only a rough indication of the general source regions based on hydrodynamics. The combination of source input data and Lagrangian simulations has been used by for example Lebreton et al. (2012, 2018); Liubartseva et al. (2018) and

Kaandorp et al. (2020). These studies, however, only make use of forward particle simulations, which can be used to assess the general fate of plastic coming from certain sources (van Sebille et al., 2020). To assess the sources of plastic litter ending up on a specific beaching location, as in this study, backtracking simulations are more efficient.

In this study, we provide a Bayesian framework that allows for the combination of Lagrangian backtracking simulations with plastic input data and the possibility to normalise these results based on observations. Combining the scalability of simulations and the tangibility of observations allows for source attribution of plastic beaching on a target location. This framework is laid out in Section 2. We then showcase this framework for plastic beaching at the coast of the southwestern Dutch province Zeeland, more specifically the beach near Domburg. We perform a general source attribution, study temporal variability, and assess the influence of assumed particle age on the source attribution in Section 3. Finally, we provide our conclusions and discussion in Section 4.

2 Methods

In this study, we propose a Bayesian framework to map sources of plastic arriving on a given beach. Bayes theorem is a statistical method to calculate conditional probabilities taking prior knowledge into account (Downey, 2013). Here, this theorem is interpreted as follows:

$$P(Source|Beaching) = \frac{P(Beaching|Source)P(Source)}{P(Beaching)}. \tag{1}$$

$P(Source \mid Beaching)$, the key quantity of interest in our framework, is the posterior probability: the probability that a given location is the source of a plastic particle, given that this particle ends up at the studied beach. This posterior probability can not be calculated directly from simulations, but can be found through a combination of the likelihood and prior probability. $P(Beaching \mid Source)$ is the likelihood, the probability that a particle beaches at the specified location, given that it originates from a certain source location. This likelihood can be computed through Lagrangian backtracking simulations. $P(Source)$ is the prior probability, in this case the probability that a given location is a source of plastics. Here, we will determine $P(Source)$ for three different source types: coastal population, fishing activity and riverine sources, as discussed in Section 2.2. The likelihood in all locations is multiplied with the prior $P(Source)$ in the same location. This multiplies the probability that a particle origins from a location (prior) with the probability that it reaches the beaching location from this same starting location (likelihood). Lastly, we normalize the source probability using $P(Beaching)$, the total beaching probability per source type. This normalisation is based on estimated abundances of beached plastic per source type, as described in Section 2.3.

2.1 Likelihood and Lagrangian Framework

The likelihood $P(Beaching \mid Source)$ can be calculated from the Lagrangian backtracking simulation. Lagrangian particle trajectories can be described (forwards in time) using the Fokker-Planck equation (van Sebille et al., 2018), containing a deterministic drift due to currents acting on scales larger than the grid size as well as a random forcing (Wiener process) due to sub-scale processes (van Sebille et al., 2020). The backwards in time equivalent of this equation is the Kolmogorov backwards equation, describing the probability that an observed target state at time s is reached from a different starting state at time $t < s$. We approach the Kolmogorov backwards equation numerically, by releasing a large set of passive, floating virtual particles and tracking them back in time according to:

$$\mathbf{X}(t-\Delta t) = \mathbf{X}(t) - \int_{t-\Delta t}^{t} \mathbf{v}(\mathbf{x},\tau)d\tau + R\sqrt{2K\Delta t}, \tag{2}$$

where $\mathbf{X}$ is the particle location, $\Delta t = 2$ hours the integration time step, $\mathbf{v}(\mathbf{x},\tau)$ the Eulerian velocity field, R a random normally distributed number between -1 and 1 and $K = 13.39$ m^2/s the (uniform) eddy diffusivity (Neumann et al., 2014). The diffusion term has the same sign as when solving the forwards (Fokker-Planck) equation, see e.g. (Issartel & Baverel, 2002; Robertson, 2004). We evaluate Eq. (2) using a Runge-Kutta4 integration in the Parcels framework (Delandmeter & van Sebille, 2019) in a combined currents-Stokes-tides velocity field (see Section 2.4). We use only the surface velocities, thereby neglecting sinking or upwelling of particles. Moreover, the virtual particles are infinitesimally small and degradation of floating plastic is neglected. Beaching processes are not part of the simulation, since the particles are only expected to beach in the final location where they are released for backtracking. We use the approach from Delandmeter and van Sebille (2019) to prevent particles from getting stuck on land.

The simulated particle trajectories are stored at daily frequency. Every time a particle passes through a certain grid cell, there is a certain probability that this cell is the source cell. The more time a particle spends in a grid cell, the more likely it is that this is the starting location of that particle. Thus, using this backtracking approach, we find the likelihood/probability that the target state of plastic beaching in our studied location is reached from a certain starting state or source location. The procedure is shown schematically in Figure S1.

In the simulation, we perform a daily release between 01-01-2015 and 01-01-2020 of 100 particles homogeneously spread over the coastal cell adjacent to the studied beaching location (see Section 2.4). Every particle is backtracked for maximum two years.

2.2 Prior

The likelihood only contains information on how particles have moved through the environment and is in itself nothing but a backtracking simulation. The value of Bayes' theorem lies in combining this likelihood with prior knowledge, in this case knowledge about plastic input, as a map of plastic input quantities for every possible cell in the domain. We distinguish fisheries, rivers and coastal population as sources, following the approach used by Kaandorp et al. (2020). An overview of plastic input per source can be seen in Figure 1a. Plastic sources located outside of this domain are not considered. Note that different source types can not be compared to each other due to different units.

Coastal plastic sources are defined as plastic input coming from coastal population (population living within 50 km of the coast). These values are estimated by combining population density data (SEDAC et al., 2015) with data of mismanaged plastic waste per capita in the same region (Jambeck et al., 2015). Population density data from 2020 are used. Plastic input from coastal population is assumed to be constant over the year.

River sources are defined as plastic coming from inland population, entering the ocean through river transport. River inputs are specified based on a study by Meijer et al. (2021). River inputs are reported in tonnes of discharged plastic per year and are thus assumed to be constant over time.

Fishery sources are defined as plastic litter coming from fisheries, e.g. nets, ropes and fluff (used to protect nets when bottom trawling). Fishery inputs are based on spatiotemporal fishing intensity data by Kroodsma et al. (2018), assuming that a higher fishing intensity corresponds to a proportionally higher amount of plastic litter input from these fisheries. To take seasonal variability in fishing intensity into account, the fishing intensity is averaged per calendar week. This averaging is done over a period of 7 years, from 01-01-2013 up until 01-01-2020, matching the simulation period. The fishing intensity is gridded on the $1/9° \times 1/15°$ grid of the simulation.

In order to facilitate the analysis, we aggregate grid cells belonging to the same geographical area. This geographical division is done separately for coastal & river sources and fishery sources (Figures 1b and 1c).

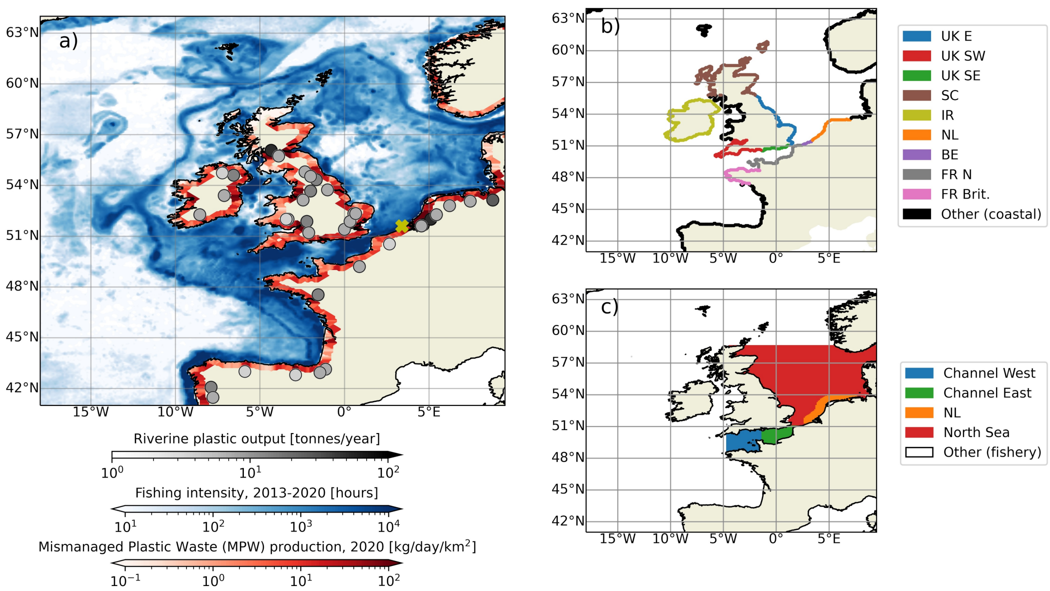

Figure 1. a) Overview of relative contribution of coastal, river and fishery plastic sources. Yellow marker: beaching location. Rivers with a plastic output below 5 tonnes/year are not shown to prevent cluttering. The total fishing intensity over the whole simulation period is shown. b) Division of coastal & riverine source regions, used for aggregation. c) Division of fishery source regions, used for aggregation.

2.3 Normalisation

The normalisation $P(Beaching)$ is constructed such that the accumulated probabilities per source type match the observed relative source abundances of plastic beaching in the Netherlands (Section 2.4 for more information), based on 20 years of beach cleanup observations by Boonstra et al. (2021). According to their observations, 42% of the beached plastic along the Dutch coast originates from fishery sources. Since we only assume two other source categories, riverine and coastal sources (ignoring for example shipping and aquaculture), we extrapolate that 58% of the plastic waste must come from these two sources. A study by Lebreton et al. (2018) estimates that globally, 59.8% of plastic originates from coastal population, 12.1% from riverine sources, 17.9% from fisheries, 8.9% from shipping and 1.3% from aquaculture. This gives a ratio of roughly 5/1 for coastal/riverine sources. Applying this ratio to the specific source percentages of Zeeland, we assume that roughly 50% of the beached plastic comes from coastal population, 10% from river transport and 40% from fisheries. Note that these values have been rounded to the nearest ten to give a more appropriate representation in terms of significant figures. This means that the summed source probability of all fishery sources should be 40%, the summed source probability of all riverine sources should be 10%, and the summed source probability of all coastal sources should be 50%. The normalisation is performed over the whole simulation period. This means, for example, that some periods can have a higher total fishery source probability, if those particles experience a higher than average fishing activity and thus are more likely from fishery sources. Normalisation of coastal & riverine sources is then adapted such that the total source probability sums to 100% and the 5/1 ratio of coastal/riverine plastic is maintained.

2.4 Study area and data description

We apply our framework to plastic beaching at the coast of the southwestern Dutch province Zeeland. More specifically the beach near Domburg (51.57 °N, 3.49 °E). This beach is often visited by local beach cleanups and is adjacent to the North Sea, which is part of the European northwest shelf (Northern Hemisphere). A detailed overview of the general circulation pattern in the study area can be found in for example Ricker and Stanev (2020) or Holt and Proctor (2008).

The surface current reanalysis data are provided by E.U. Copernicus Marine Service Information (2020a) at a $1/15° \times 1/9°$ resolution in latitudinal and longitudinal directions, respectively. These data are available on the European northwest shelf, limiting the simulation domain but compensating for this flaw by their relatively high resolution. Stokes drift reanalysis data are provided by E.U. Copernicus Marine Service Information (2020b) on a global scale with a $1/5°$ resolution in both directions. The M_2, S_2, K_1, O_1 (linear) and M_4, S_4 and MS_4 (non-linear) barotropic tidal velocity constituents from FES2014 data (Lyard et al., 2021) are taken into account using the approach from Sterl et al. (2020).

3 Results

First, we present a general overview of plastic sources, averaged over the whole simulation period, and making no assumptions on the particle age (i.e. every age between 0 and 2 years is just as likely). This averaged result is the most representative for the sources of plastic on an uncleaned beach at a random time. Next, to study seasonal effects in source locations, we analyse the source probability as a function of beaching week, taking a climatological average over 5 years. Lastly, we assess the influence of assumed particle age on the source attribution. If this age is known, for example from observing the state of degradation of beached plastic, a much more specific source attribution can be done.

3.1 Averaged sources

A general overview of plastic sources is shown in Figure 2. From this Figure, several source hot spots are clear: predominantly the eastern and western part of the English Channel, and in the North Sea along the Dutch coast (fishery sources). In terms of coastal plastic, the east coast of the UK near London, Edinburgh, the coast of Normandy near Caen and the Dutch coast near Amsterdam are important sources (coastal population). Furthermore, the Rhine, the Seine, the Trieux and the Forth belong to the most important riverine sources. It stands out that semi-enclosed regions often show a high (coastal) source probability, for example near Caen, London, Edinburgh and The Wash estuary (east coast UK).

3.2 Temporal Variability

Source probability as a function of beaching week is shown in Figure 3. Strong seasonal variation is clear, mostly in the source probability of the Dutch coast & rivers and fisheries. The lower source probability of Dutch plastic in winter months can be explained due to increased stratification starting in spring causing currents to be more southward along the Dutch coast (Holt & Proctor, 2008). This generally causes Dutch plastic to

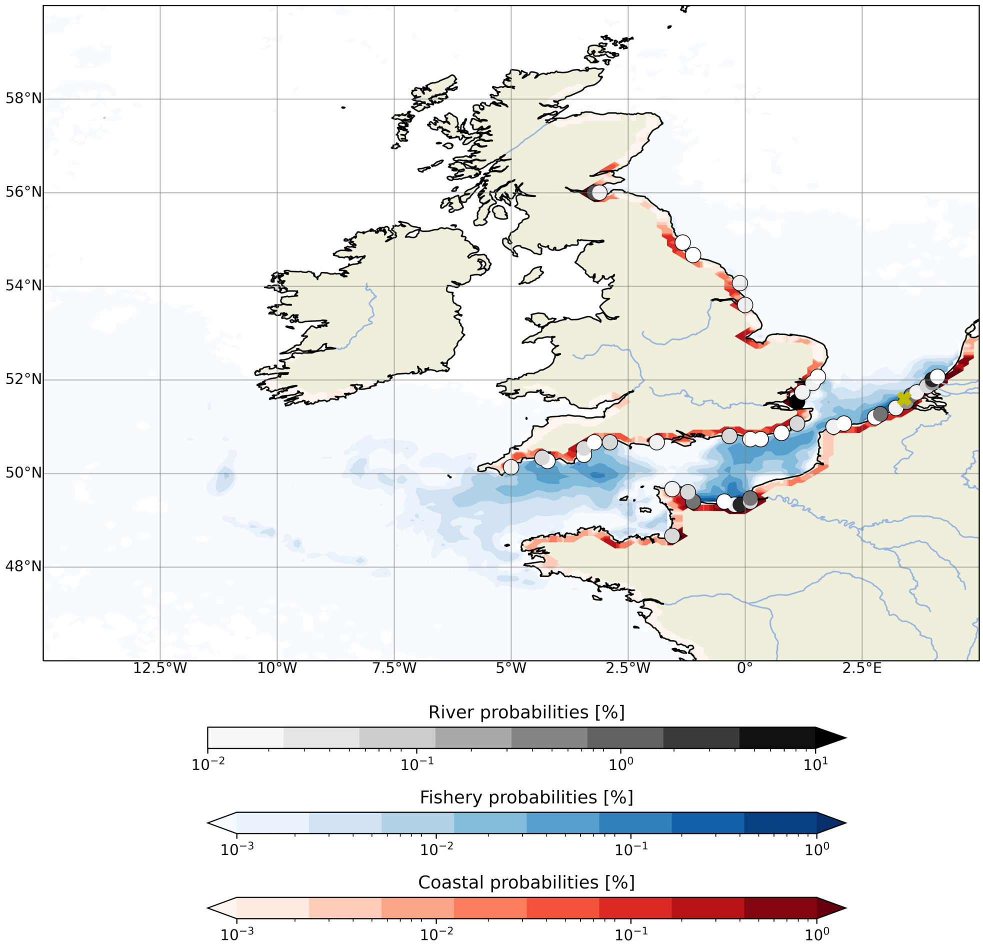

Figure 2. Source probabilities for particles beaching near marker between 2015 and 2020.

be transported northward in winter and consequently not reaching the studied beaching location.

Another interesting result is that Dutch coastal & riverine plastic has the highest source probability in June, whereas plastic from fisheries along the Dutch coast peaks in August. This can be explained due to temporal variability in the fishery prior. This prior is higher in Dutch waters for particles beaching in August than in other months (shown in Figure S2). Furthermore, fishing intensity is relatively high over the whole domain in the months up to August, causing a relatively high proportion of plastic to be attributed to fishery sources.

3.3 Age variability

To investigate the effect of particle age (defined as the time the plastic has spent in the ocean from source to final destination), we have analysed source probabilities as a function of particle age for any age between 0 and 24 months. The Figure is not cu-

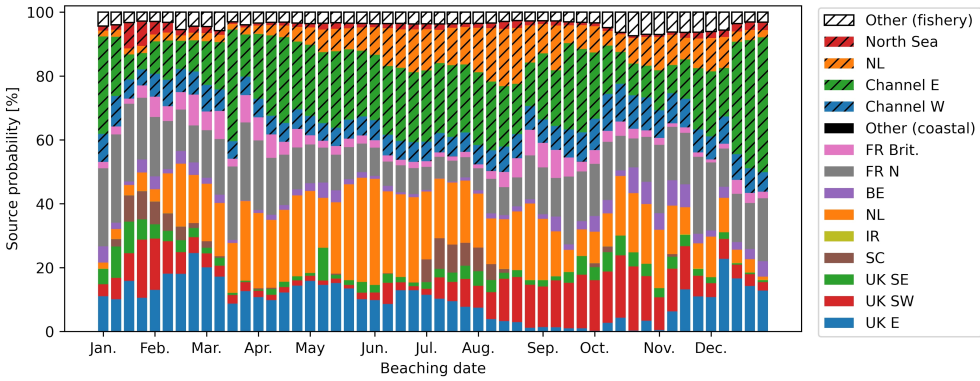

Figure 3. Source probabilities for particle beaching as a function of week of the year. Non-hatched: Coastal & riverine sources. Hatched: Fishery sources. Note that source probabilities of Other (coastal) and Ireland (IR) are too small to be visible.

mulative, i.e. for an age of t months, we only study the part of the trajectory between t and $t + 1$ months before beaching.

During a backtracking simulation of 2 years, many particles leave the simulation domain, as shown in Figure S3. The first particles leave the domain after backtracking for 5 months and after 24 months more than 80% of particles have left the domain. In this analysis, we will only consider the particles that are within the simulation domain for the assumed age, since we neglect sources located out of the domain. Particles almost exclusively leave the simulation domain at the Atlantic Ocean, west of the English Channel. No land is nearby at this region. Plastic originating from, for example, Newfoundland, Canada has less than 5% probability to reach the North Sea in under 2 years according to PlasticAdrift (van Sebille et al., 2012). It is therefore safe to assume that plastic coming from the Atlantic within 2 years of simulation is almost exclusively from fishery sources. We justify neglecting these out-of-bounds sources by the fact that fishing intensity is much lower in the Atlantic Ocean compared to the European northwest shelf (Kroodsma et al., 2018), so there is low probability that these areas are sources of plastic in the prior.

Figure 4 shows that for low particle age, there is a high probability that the plastic originates from fishery sources, likely because fishing intensity is relatively high near southwest NL (see Figure 1). With increasing age, the North Sea and fisheries along the Dutch coast become less likely sources and fishery plastic will most likely come from the English Channel. For coastal plastic, the most important sources are the east coast of the UK initially, then the north of France and Scotland for plastic of ages over 18 months. Since the coast of Scotland (near Edinburgh) is an enclosed region, particles circulate here for a longer time, causing high source probabilities.

It is interesting that, for high age, coastal sources are mainly located in Scotland, but fishery sources are located in the English Channel and the Atlantic Ocean (also shown on a map in Figure S4). This seems contradictory at first, as these regions are far apart, but can be explained based on plastic input data. While many particles reach the Atlantic (high likelihood), this area contains little possible sources of plastics such as fishing activity or coastlines (low prior). On the other hand, the coast of Scotland has a lower likelihood, but a high plastic input from coastal population (high prior).

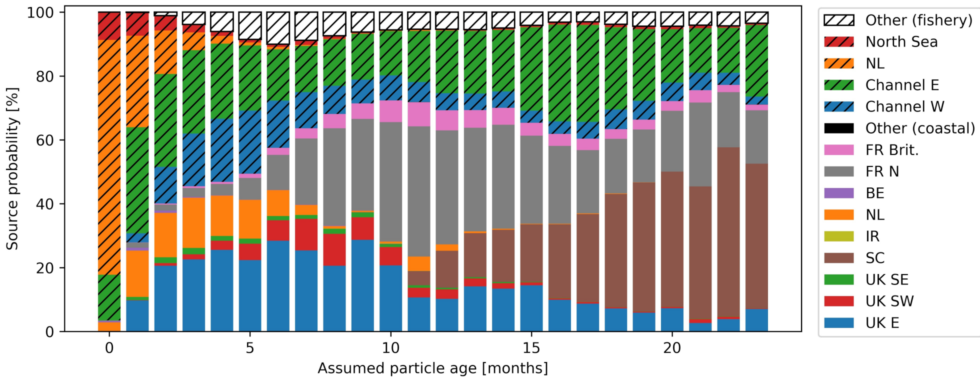

Figure 4. Source probabilities for different particle ages. Non-hatched: Coastal & riverine sources. Hatched: Fishery sources. Note that source probabilities of Other (coastal) and Ireland (IR) are too small to be visible.

4 Conclusions and discussion

In this study, we provided a new framework to identify sources for beached plastic, using backwards Lagrangian particle simulations combined with estimated plastic input data for coastal, riverine and fishery sources. To showcase this framework, we identified the sources for plastic beaching in Domburg, southwest Netherlands. Furthermore, we assessed how source locations depend on the time spent at sea, which facilitates a more refined source attribution when particle age is known.

Our framework can seamlessly be extended to more complex flows and larger domains, which would support source attribution for higher particle ages. In this study, the fine-resolution northwest European shelf hydrodynamic data meant that sources located out of the simulation domain could not be incorporated. On the other hand, the hydrodynamic data are too coarse for solving complex coastal dynamics accurately. Simulation results can therefore be improved if hydrodynamic data with a higher resolution becomes available. Moreover, particle transport was currently only modeled in 2D, neglecting upwelling and sinking. Also, windage, particle degradation and resuspension of beached particles were not explicitly included.

In our showcase, we assumed a constant flux of beached particles, since 100 particles were released daily. The Bayesian framework can be extended by releasing particles proportional to the amount of observed beached plastic in the corresponding period, if these data are available.

The framework is universally applicable and has the ability to combine backtracking simulations with (time-dependent) plastic input data. Normalisation per source type can be performed to match observations of different litter types from beach clean-ups. These normalisation constants are currently based on rough estimations, but are easily adaptable to new information. Knowledge about plastic sources for specific beaching locations can be used for upstream prevention at the source and can thereby support environmental protection.

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Supporting Information for "Identifying Marine Sources of Beached Plastics Through a Bayesian Framework: Application to Southwest Netherlands"

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Contents of this file

1. Figures S1 to S4

Introduction

In this document, we provide four Figures to get a more detailed understanding of the framework presented in the main paper.

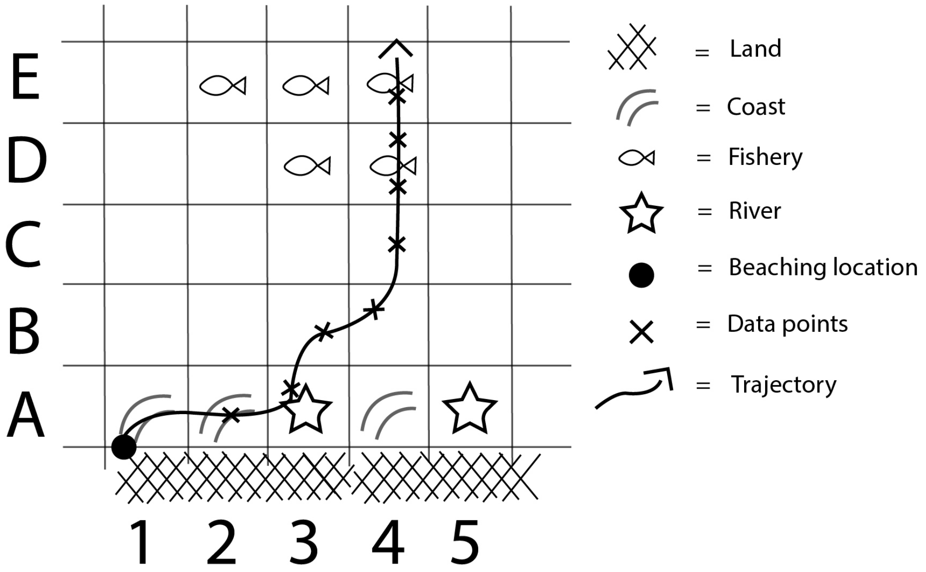

Figure S1. Schematic illustration of backtracking procedure for one particle.

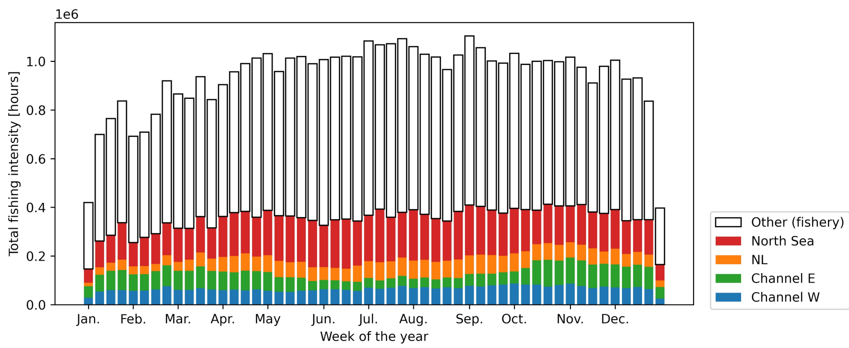

Figure S2. Total fishing intensity per fishery region shown as a function of week of the year. This is the time-dependent prior $P(Source)$ for fishery sources.

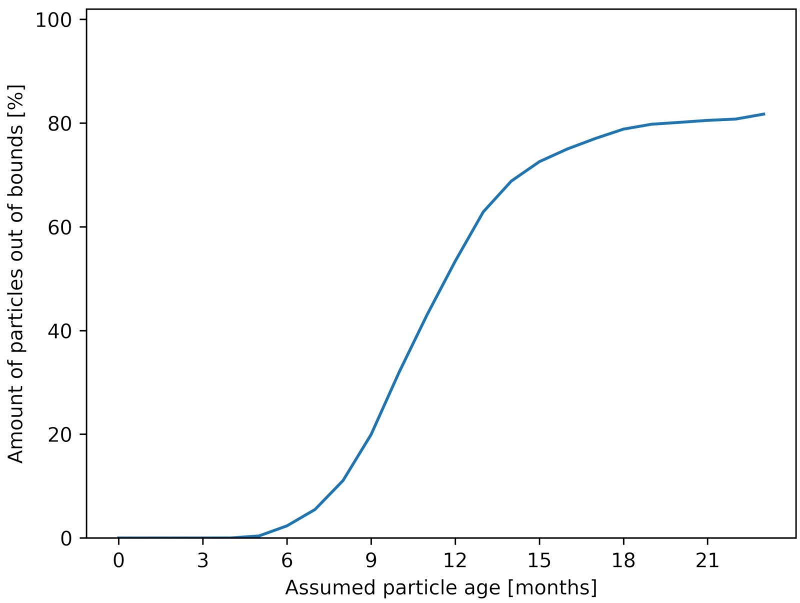

Figure S3. Percentage of particles out of bounds as a function of particle age.

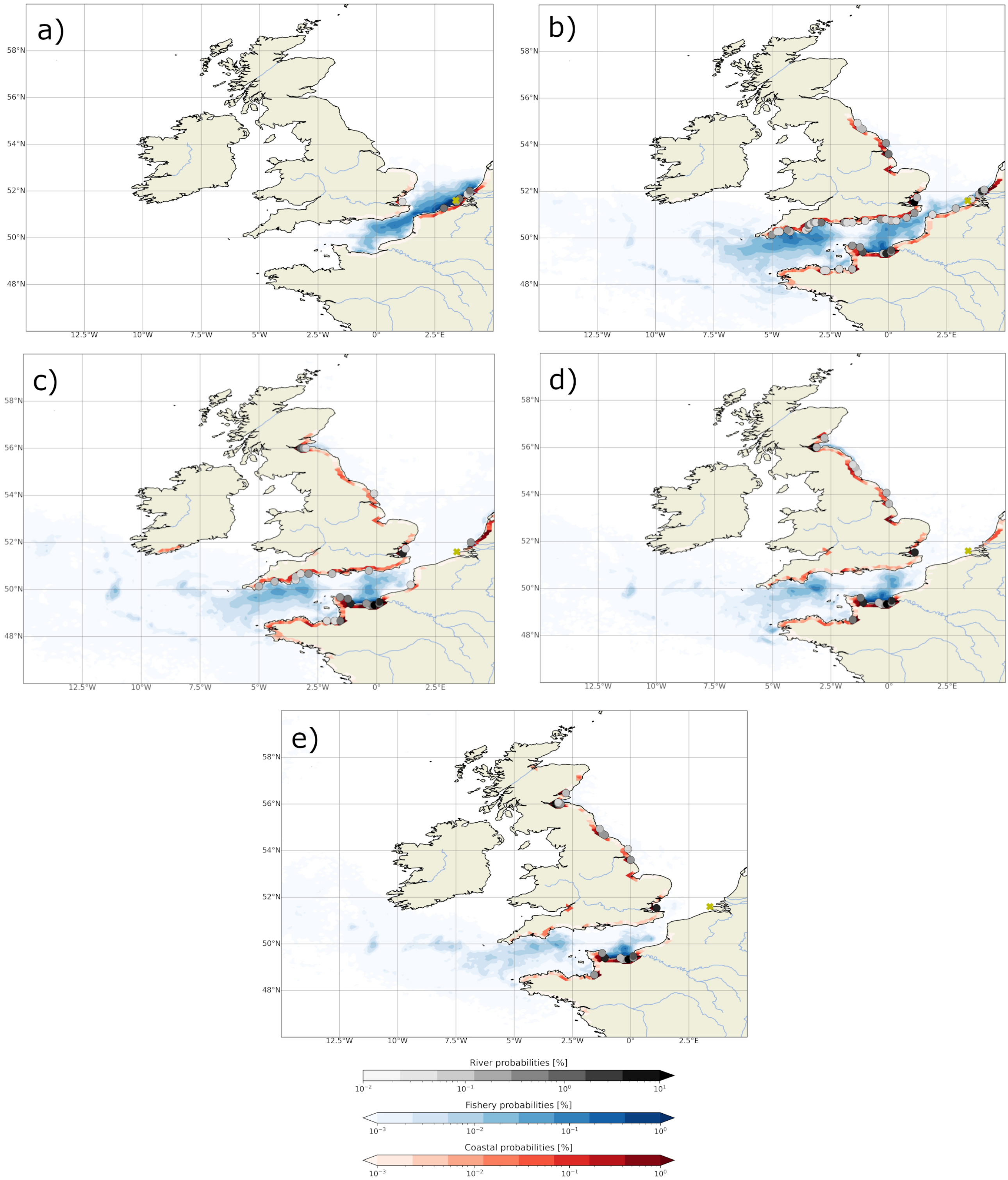

Figure S4. Source probability for different particle ages. a) age = 0-1 month, b) age = 5-6 months, c) age = 11-12 months, d) age = 17-18 months, e) age = 23-24 months.