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Key Points:

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

Supporting Information:

Supporting Information may be found in the online version of this article.

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

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Abstract Beaches are thought to be a large reservoir for marine plastics. 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 of plastic arriving on a specific beach. In this framework, we combine Lagrangian backtracking simulations of drifting particles with estimates of plastic input from coastlines, rivers and fisheries. The advantage over traditional Lagrangian simulations is that the Bayesian framework can consider information on known sources, and thus facilitates spatiotemporal source attribution for plastic arriving at the specified beach. We show that the main sources for our target beach in southwest Netherlands 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 floating time 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 (Morales-Caselles et al., 2021; Onink 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). 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 (Cózar et al., 2014; van Sebille, 2015). By locating and then mitigating at upstream sources (Robinson et al., 2017; van Gennip et al., 2019), 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 has been done before by using Lagrangian simulations (van Sebille et al., 2018) to compute virtual particle trajectories back in time. For example, Neumann et al. (2014) analyzed the sources of plastic beaching on the German Wadden Island of Sylt and Juist to find that there was a seasonal cycle in possible source regions. Gutow et al. (2018) analyzed the difference in source regions in the North Sea to find that these are sensitive to offshore locations and wind drag coefficient. Strand et al. (2021) analyzed the sources of plastic in the Arctic and northeast Atlantic, focusing particularly on fisheries sources. However, none of these studies took into account information on the spatial patterns of plastic input. There are studies that have combined source input data and Lagrangian simulations (Lebreton et al., 2012, 2018; Liubartseva et al., 2018; Kaandorp et al., 2020), but these studies only performed forward particle simulations. 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 normalize 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, specifically the beach near Domburg. We perform a general source attribution, study temporal variability, and assess the influence of assumed particle age (defined as the time the plastic has spent in the ocean from source to final destination on the beach) 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:

$$P\left(\mathbf{x}_S|\mathbf{x}_B, t_B\right) = \frac{P\left(\mathbf{x}_B, t_B|\mathbf{x}_S\right) P\left(\mathbf{x}_S\right)}{P\left(\mathbf{x}_B, t_B\right)}. \tag{1}$$

$P(\mathbf{x}_S|\mathbf{x}_B, t_B)$, the key quantity of interest in our framework, is the (time-varying) posterior probability: the probability that a given spatial location $\mathbf{x}_S$ is the source of a plastic particle, given that this particle ends up at the target beach $\mathbf{x}_B$ at time t_B. This posterior probability cannot be calculated directly from simulations but can be found through a combination of the likelihood and prior probability. $P(\mathbf{x}_B, t_B|\mathbf{x}_S)$ is the likelihood, the probability that a particle beaches at the target beach $\mathbf{x}_B$, given that it originates from a certain source location $\mathbf{x}_S$ at time $t < t_B$. This likelihood will be computed through Lagrangian backtracking simulations. $P(\mathbf{x}_S)$ is the prior probability, in this case the probability that a given location $\mathbf{x}_S$ is a source of plastics at time t. Here, we will determine $P(\mathbf{x}_S)$ for three different source types: coastal population, riverine sources, and fishing activity, as discussed in Section 2.2. The numerator in Equation 1 thus multiplies the probability that a particle originates from a location $\mathbf{x}_S$ (the "prior") with the probability that it reaches the beach at $\mathbf{x}_B$ from this location $\mathbf{x}_S$ (the "likelihood"). Lastly, we normalize the source probability using $P(\mathbf{x}_B, t_B)$, the total beaching probability per source type at time t_B. This normalization 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 $P(\mathbf{x}_B, t_B|\mathbf{x}_S)$ is calculated using Lagrangian backtracking simulations. The time evolution of the probability density function of a tracer in the ocean can be described (forwards in time) using the Fokker–Planck equation (van Sebille et al., 2018). The adjoint of this equation is the Kolmogorov backwards equation, which can be used to describe how a probability density function P evolves backwards in time. As shown in, for example, Shah et al. (2017), this can computed by reversing the sign of the Eulerian velocity field $\mathbf{v}$ and solving the advection–diffusion equation for P backwards in time. Taking a uniform diffusivity K, this yields:

$$\frac{\partial P}{\partial t} = -\nabla \cdot (-\mathbf{v}P) + K\nabla^2 P. \tag{2}$$

Instead of using Equation 2 to directly integrate the likelihood function P back in time, we approximate the likelihood function by a set of Lagrangian particles. This yields a stochastic differential equation, where each Lagrangian particle experiences a deterministic drift due to currents acting on scales larger than the grid size, as well as a stochastic forcing (Wiener process) modeling uncertainty introduced by sub-scale processes (van Sebille et al., 2018). The location $\mathbf{x}$ of each particle is integrated back in time using:

$$\mathbf{x}(t-\Delta t) = \mathbf{x}(t) - \int_{t-\Delta t}^{t} \mathbf{v}(\mathbf{x},\tau)d\tau + R\sqrt{2\ K\Delta t}, \tag{3}$$

where Δt is the integration time step, R is a random normally distributed number between -1 and 1, and K is the (uniform) eddy diffusivity.

We start with a uniform release of Lagrangian particles in the grid cell adjacent to the beaching location, at time t_B. This approximates the unit impulse function: a tracer released in this grid cell is defined as beached, that is,

$P(\mathbf{x}_B|\mathbf{x}_S, t_B) = 1$ at the release location. The Lagrangian particles are then tracked back in time to calculate the likelihood at previous times t, that is, $P(\mathbf{x}_B, t_B|\mathbf{x}_S, t)$: the probability that a tracer ends up on the beach at time t_B, given that it is at location $\mathbf{x}_S$ at time t. See Figure S1 in Supporting Information S1 for a schematic clarifying this procedure.

We evaluate Equation 3 using a fourth order Runge–Kutta integration scheme in the Parcels framework (Delandmeter & van Sebille, 2019) in a combined currents-Stokes-tides velocity field (see Section 2.5). 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 at x_B where they are released for backtracking. To prevent particles from getting stuck on land, we use the approach from Delandmeter and van Sebille (2019) where at each time step, the particle position is first updated following advection by the surface currents. Then we check whether the particle is located in a wet cell, otherwise it is displaced back to the sea. In a second step, the particles are moved according to their local Stokes drift and diffusion; and if the then particle beaches it stops moving.

In the simulation, we perform a daily release between 01–01–2015 and 01–01–2020 of 200 particles homogeneously spread over the coastal cell adjacent to the target beach x_B (see Section 2.5), for a total of 365k particles. Every particle is backtracked for maximum 2 years using an integration timestep $\Delta t = 2$ hr. The simulated particle trajectories are stored at daily frequency. The likelihood function is calculated for every day, by binning the particle locations using a 2D histogram on the same 1/15° × 1/9° resolution grid used for the surface currents (Section 2.5).

2.2. Prior

The value of Bayes' theorem lies in combining this likelihood with prior knowledge, in this case knowledge about possible plastic input for every cell in the domain at different times. We distinguish coastal population $P(\mathbf{x}_C, t)$, rivers $P(\mathbf{x}_R, t)$, and fisheries $P(\mathbf{x}_F, t)$ as sources, following the approach used by Kaandorp et al. (2020), where

$$P(\mathbf{x}_S, t) = P(\mathbf{x}_C, t) + P(\mathbf{x}_R, t) + P(\mathbf{x}_F, t). \tag{4}$$

An overview of plastic input per source can be seen in Figure 1a. Plastic sources located outside of this domain are not considered.

Coastal plastic sources $\mathbf{x}_C$ 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 $\mathbf{x}_R$ 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 $\mathbf{x}_F$ are defined as plastic litter coming from fisheries, for example, 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 1/15° × 1/9° 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 and river sources and fishery sources (Figures 1b and 1c).

2.3. Normalization

The denominator $P(\mathbf{x}_B, t_B)$ normalizes Equation 1 to the total probability that plastic found on the beach is from any of the three types of sources (coastal, riverine, and fisheries). According to data from 20 years of beach clean-up observations by Boonstra et al. (2021), 42% of the beached plastic along the Dutch coast originates from fishery sources. We assume that these proportions are similar at our target beach. Furthermore, Lebreton et al. (2018)

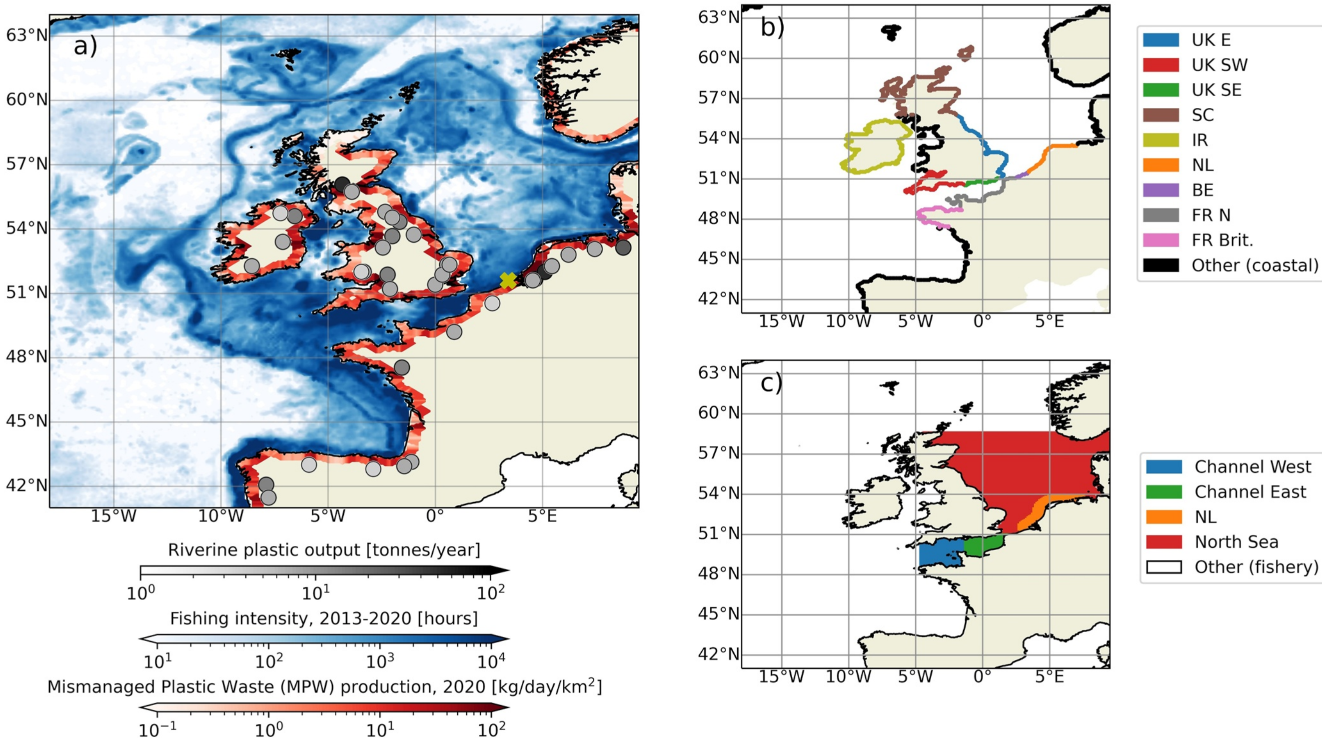

Figure 1. (a) Overview of relative contribution of coastal, river and fishery plastic sources. Yellow marker: target beach location $\mathbf{x}_B$. Rivers with a plastic output below 5 tonnes/year are not shown to prevent cluttering. The total fishing intensity over the whole simulation period is shown.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

estimate that on a global scale 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 5:1 ratio for coastal: riverine sources. Applying this ratio to the specific source percentages of Zeeland, and rounding to the nearest 10 to give a more appropriate representation in terms of significant figures, we thus assume that, integrated over all time, 50% of the beached plastic at Domburg comes from coastal population ($\mathbf{x}_C$), 10% from river transport ($\mathbf{x}_R$) and 40% from fisheries ($\mathbf{x}_F$). Further details on how the normalization $P(\mathbf{x}_B, t_B)$ is calculated is presented in the Supporing Information S1.

2.4. Posterior

With these three terms described above, we can now compute the posterior probability for a specific beaching time t_B. Since we have no information on the amount of time that a particle has spend at sea before t_B, we sum the likelihood, prior and normalization probabilities over all times $t < t_B$ in the domain. See Text S1 in Supporting Information S1 for more details and equations on the implementation.

2.5. Study Area and Data Description

We apply our framework to plastic beaching at a beach near Domburg (51.57°N, 3.49°E) on the southwestern Dutch province Zeeland, see also Figure 1a. 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 mean currents near the study area move from the southwest to the northeast along the Dutch coastline. Tidal currents move to the northeast during flood tide and southwest during ebb tide.

The surface current reanalysis data are provided by E.U. Copernicus Marine Service Information (2020) at a 1/15° × 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

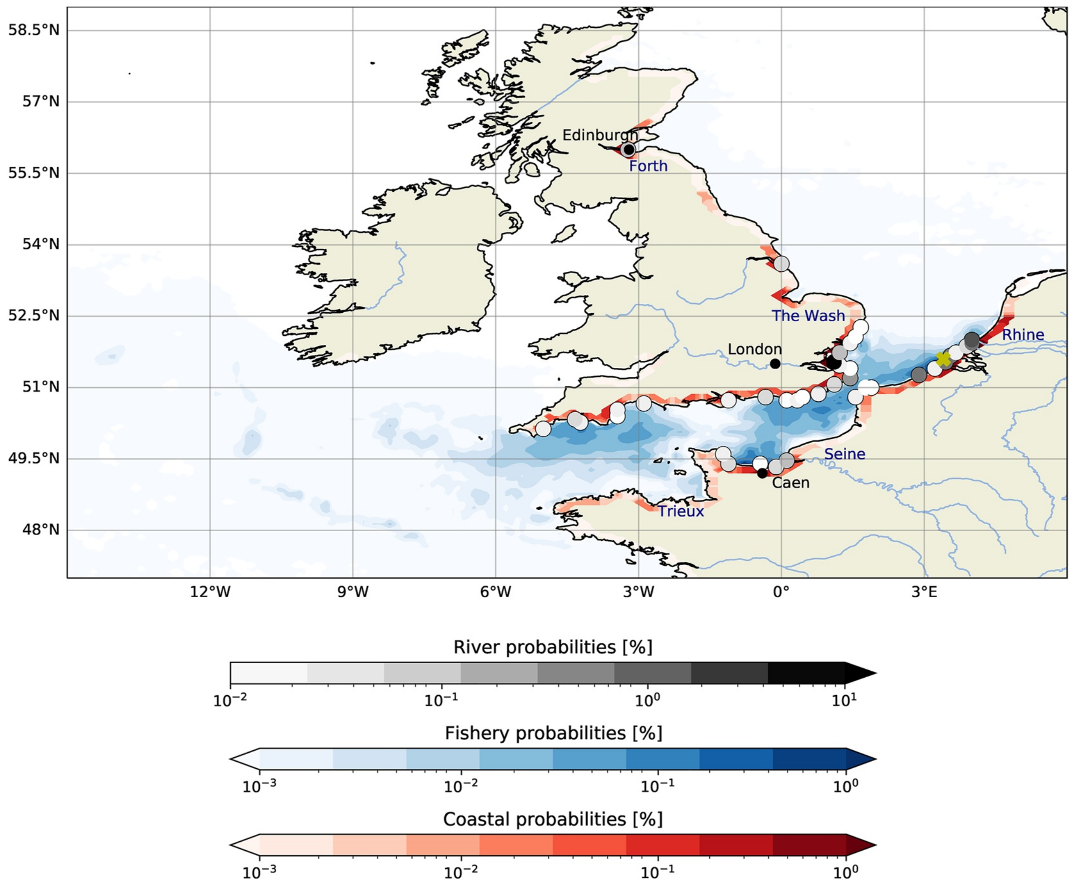

Figure 2. Source probabilities for particles beaching near marker between 2015 and 2020.

resolution and incorporation of tidal velocities. We use the formulation of Neumann et al. (2014) to add a small uniform eddy diffusivity $K = K_0(l/l_0)^{4/3}$, which with $K_0 = 1$ m^2/s for $l = 1$ km and a grid size of $l = 7$ km yields $K = 13.39$ m^2/s. Stokes drift reanalysis data are provided by E.U. Copernicus Marine Service Information (2021) on the European northwest shelf with a 1.5 km resolution in both directions.

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 variability in source locations $\mathbf{x}_S$, we analyze the source probability as a function of beaching week (which is the year-week of release in the backtracking simulation), 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. The main plume of source regions toward the southwest agrees with prior dispersion studies such as those of Ricker and Stanev (2020) and is driven by the dominant counter-clockwise circulation in the North Sea (see also, e.g., Neumann et al., 2014). 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

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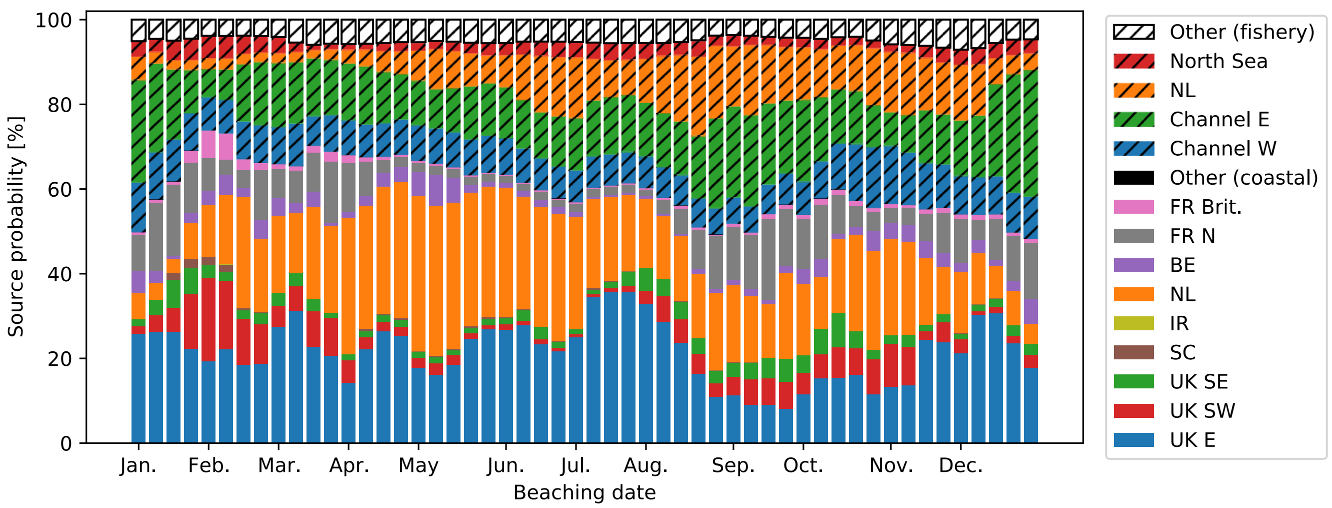

Figure 3. Source probabilities for particle beaching (i.e., release in the backtracking simulation) as a function of week of the year. Non-hatched: Coastal and riverine sources. Hatched: Fishery sources. Note that source probabilities of other (coastal) and Ireland (IR) are too small to be visible.

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 and rivers and fisheries. This generally causes Dutch plastic to be transported northward in winter and consequently not reaching the target beach $\mathbf{x}_B$.

Another interesting result is that Dutch coastal and riverine plastic have the highest source probability in April–June, whereas plastic from fisheries along the Dutch coast peaks in August. This can be explained due to temporal variability in the fishery prior $\mathbf{x}_F$. This prior is higher in Dutch waters for particles beaching in August than in other months (shown in Figure S2 in Supporting Information S1). 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

Using information on biofouling and degradation state, it is sometimes possible to estimate how long a plastic item has been in the ocean (Mesaglio et al., 2021). To investigate how this particle age, defined here as the time the plastic has spent in the ocean from source to final destination, can be used to further narrow the possible sources of plastic found, we have analyzed source probabilities as a function of particle age for any age between 0 and 24 months. The figure is not cumulative, that is, for an age of t months, we only study the part of the trajectory between t and $t + 1$ month before beaching.

During a backtracking simulation of 2 years, many particles leave the simulation domain, as shown in Figure S3 in Supporting Information S1. 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, 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 Plastic Adrift (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.

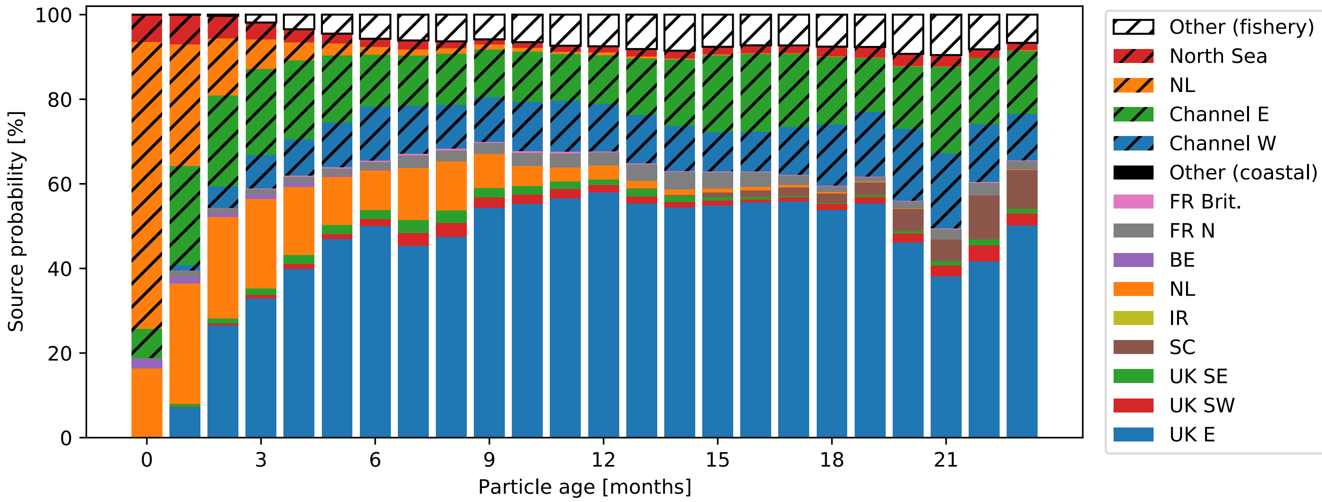

Figure 4. Source probabilities for different particle ages. Non-hatched: Coastal & riverine sources. Hatched: Fishery sources. Note that source probabilities of other (coastal) and Ireland (IR) are too small to be visible.

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 1a). 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 Netherlands initially, after which the Eastern UK starts dominating (see also Figure S4 in Supporting Information S1, which shows the sensitivity of the source probability maps to particle age).

4. Conclusions and Discussion

In this study, we provided a new Bayesian framework to identify sources for beached plastic, using backwards Lagrangian particle simulations combined with estimated plastic input data for coastal, riverine and fishery sources. The advantage of this Bayesian Framework over back-tracking-only simulations is that it can also ingest prior information about spatially explicit source distributions, and hence provide an estimate of sources that does not only depend on the ocean circulation but also on the estimates of the sources of plastic. 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 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 200 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. Normalization per source type can be performed to match observations of different litter types from beach clean-ups. These normalization constants were in our case based on rough estimations, but are easily adaptable to new information.

The framework is applicable to different scenarios, providing that information on the regional ocean circulation is available, as well as maps of possible sources in the region and an estimate of the probability for each source type. Using this Bayesian framework, knowledge about plastic sources for specific beaching locations (or, in fact, any location where plastic is found) can then be used for upstream prevention at the source and can thereby support environmental protection.

Data Availability Statement

The code used for the simulations and the data are publicly available at https://doi.org/10.24416/UU01-43ZKL3.

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