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Estimating a regional budget of marine plastic litter in order to advise on marine management measures

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ABSTRACT

Using simple models, coupled with parameters extracted from published studies, the annual inputs of macro and micro plastics to the Scottish Atlantic Coast and the Scottish North Sea Coast regions are estimated. Two estimates of land-based sources are used, scaled by catchment area population size. The oceanic supply of floating plastic is estimated for wind-driven and general circulation sources. Minimum, typical and maximum values are computed to examine the magnitude of uncertainties. Direct inputs from fishing and the flux of macroplastic onto the seabed are also included. The modelled estimates reveal the importance of local litter sources to Scottish coastal regions, and hence local management actions can be effective. Estimates provide a scale against which removal efforts may be compared, and provide input data for future more complex modelling. Recommendations for research to improve the preliminary estimates are provided. Methods presented here may be useful elsewhere.

1. Introduction

The growing problems posed by plastics in the sea are now well documented (e.g. Galgani et al., 2015; Lebreton and Andrady, 2019). Most coastal nations are attempting to manage in some way this form of marine pollution and its associated environmental and economic harm (e.g. Ogunola et al., 2018; Williams and Rangel-Buitrago, 2019). In Scotland, there is currently a national strategy to reduce terrestrial litter and mis-managed waste (SG, 2014a), as well as a strategy directly aimed at managing marine litter (SG, 2014b). Both implement aspects of regional marine litter strategies (e.g. OSPAR, 2014), and global strategies, such as the Honolulu Strategy (UNEP/NOAA, 2011). All of these policies require managers to take actions to reduce sources of marine plastic, and remove marine plastic where it does occur.

When marine managers are tasked by such strategies with responding to plastic in the sea, two basic questions quickly arise: How much plastic is in the sea we manage? Where does it come from? To a manager, these are simple, basic questions. To a marine scientist they pose quite complex challenges. Marine plastics are not a static feature of the seascape. In order to answer the basic managerial questions, a dynamic system must be quantified, where plastics are constantly being supplied to regional seas by a range of local and remote sources (e.g. Jambeck et al., 2015; Schmidt et al., 2017), and are then subject to dynamic processes in the sea including advection and dispersion (e.g. Critchell and Lambrechts, 2016), settlement onto and removal from foreshores (e.g. Browne et al., 2015; Turrell, 2018), sinking to and re-suspension from the sea bed (e.g. Critchell and Lambrechts, 2016), and mechanical and chemical breakdown (e.g. Corcoran et al., 2009).

Many scientific studies describe the stock of marine plastics in a region (or on a beach) at a single point in time (e.g. Asensio-Montesinos et al., 2019), or at multiple times, through a year for example, in order to generate average loadings or patterns of loadings (e.g. Simeonova and Chuturkova, 2019; Turrell, 2019a). Studies have described the concentration and composition of floating macro plastic at the sea surface using visual or trawl surveys (e.g. Arcangeli et al., 2018; Gewert et al., 2017), the density of sinking plastics on the seabed at a certain time using trawl or camera surveys (e.g. Buhl-Mortensen and Buhl-Mortensen, 2017; Maes et al., 2018), or the amount and composition of floating macro plastic on foreshores using beach surveys (e.g. Asensio-Montesinos et al., 2019; Simeonova and Chuturkova, 2019). While these types of studies are useful up to a point, they fail to capture the flux of plastics through a region. For example, they cannot inform a manager of a coastline how frequent beach cleans need to be in order to maintain low litter loadings on foreshores. Hence removals, in terms of weight of macro plastic removed per unit time (e.g. one year), need to be compared in scale to inputs of macro plastic to the region over the same time period.

Hence, in order to manage marine plastics in any sea region, a total plastic budget is needed which quantifies (at least to an order of magnitude) the local and remote sources inputting plastic into the

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region, and the sinks removing plastic out from the region per unit time. Ignoring actual chemical dissolution of plastic to the elements it is composed of, plastic will be conservative by mass, i.e. the weight of plastic entering a region during a unit time should equal the weight of plastic leaving the region over the same time period plus the weight of plastic retained by the region.

One way of obtaining a regional budget of marine plastic is through modelling. Models have been used on the scale of ocean basins (e.g. Lebreton et al., 2012), regional seas (e.g. Mansui et al., 2015; Neumann et al., 2014) and individual coastlines (e.g. Critchell et al., 2015). These studies focus on the dispersion of floating plastic at sea, and predicting densities both at sea and on beaches. They do not attempt to arrive at closed budgets for a region, i.e. quantifying all inflows and outflows in terms of mass or number of plastic items per unit time (e.g. one year).

Budgets, or partial budgets, have been attempted on a global scale. For example, Jambeck et al. (2015) estimated the global input of plastic into the sea making assumptions about population size, waste produced per person, and waste management efficiencies. Koelmans et al. (2017) attempted a whole-ocean mass balance for marine plastic, and used this to suggest the importance of mechanical breakdown of plastic followed by sinking as the ultimate fate of most marine plastic. Law (2017) proposed a framework to estimate the global mass balance of marine plastics, but found a large variation in available model parameters and the resulting estimates could not account for the inputs suggested by Jambeck et al. (2015).

There are very few attempts at generating regional scale marine litter budgets (UNEP/NOAA, 2009). One was conducted by Jang et al. (2014) for the Sea of Korea. Jang et al. estimated the regional budget of all marine debris, not just the plastic component. They attempted to quantify all inflows and outflows from the region of marine debris, although they considered estimating fluxes through the open sea boundaries too difficult. Land-based inflows were estimated from catchment area population sizes. Sea-based inflows included from fishing activity and domestic litter discharged directly from shipping and fishing boats. Jang et al. (2014) concluded by hoping their information would aid debris management in the region.

1.1. Study aim

The aim of this study is to use simple desk-based methods in order to obtain preliminary regional budgets of macro and micro plastics, both in terms of mass and numbers of litter items, for two areas of the northwest European continental shelf, in order to: 1) compare the magnitude of land-based within-region plastic (local) sources to external oceanic (remote) sources; 2) compare the magnitudes of plastic sources to the magnitudes of current removal efforts; 3) investigate the nature of the greatest uncertainties in the plastic source estimates; 4) suggest further research which might reduce these uncertainties; and 5) advise marine managers on possible priorities for action. It is hoped that the simple approaches adopted may be useful elsewhere.

2. Methods

2.1. Conceptual model

Fig. 1 summarises the flows of macro and micro plastic into and out from a sea region, which in this study is either the Scottish west coast (Scottish Atlantic Coast Model; Fig. 2a) or the Scottish east Coast (Scottish North Sea Coast Model; Fig. 2b). The following sections describe the calculations performed within a set of sub-models to estimate each individual source described in Fig. 1, and the parameters used in these calculations. The Supplementary material gives detailed calculations and all data sources used. The models and sub-models calculate the flux of marine plastics into and out from the modelled regions over a period of one year.

2.1.1. Floating v. sinking plastics

The oceanic inflows in the model were assumed to be floating plastic. The riverine inputs were total plastic loads, and the non-floating component was removed to the seabed in the modelled sea regions by the sinking sub-model. Thus the outflowing plastic loads were also floating plastic. This is discussed further in sections below.

2.1.2. Microplastics

Although the principal aim of this study is to investigate macro plastics in Scottish waters, the possible typical flux of microplastics was also considered in order to compare orders of magnitudes between these two marine plastic size ranges.

2.1.3. Uncertainties

Where possible, the potential uncertainty of the macro plastic flux estimates was determined using minimum, base and maximum values of the various model parameters, determined from the supporting literature. The base values were selected as being most representative of current typical conditions in the modelled regions. Owing to the large uncertainties currently involved in the estimates of microplastic sources and concentrations, only base (i.e. typical) values were used for this plastic item size range.

2.2. Model region definitions

2.2.1. Atlantic Coast

The Atlantic Coast model domain was defined as a region west of Scotland, with a simple straight offshore boundary along the edge of the continental shelf approximately 400 km long and 100 m deep along its length (Q_3, Fig. 2a). Two further open sea boundaries exist, one connecting the Irish Sea to the Atlantic Coast region through the North Channel (Q_1, Fig. 2a, 35 km wide, 80 m deep) and one west of Ireland across the continental shelf (Q_2, Fig. 2a, 140 km wide, 100 m deep). In general terms there is a northwards flow of water through the modelled region, fed by flow through the open boundaries to the south (Q_1, Q_2) and inflow from the west through the oceanic western boundary (Q_3, e.g. Hill et al., 2008). The only outflow from the region occurs through the northern boundary (Q_{ACout}, Fig. 2a, 200 km wide, 100 m deep).

The region receives freshwater from the coast, principally through the River Clyde (QR_1), and through many small rivers spread along the west coast (QR_2). The River Clyde drains a mixed urban/rural catchment area dominated by the major city of Glasgow. Otherwise west coast river catchments are almost entirely rural in nature. Table 1 summarises the freshwater inflows from, and the population sizes of, the landward catchment areas discharging into the Atlantic Coast Model region.

2.2.2. North Sea Coast

The North Sea Coast Model was also defined with a simple long straight offshore boundary, with additional shorter boundaries to the north and south (Fig. 2b). Unlike the Atlantic Coast Model, which has its offshore edge defined by the edge of the continental shelf, there is no clear bathymetric feature defining the offshore boundary of the North Sea Coast Model domain. However, the coastal box defined in Fig. 2b has been described previously as being somewhat isolated from offshore waters (e.g. ICES, 1983), with a persistent southerly flowing current through its length originating from the northern boundary (e.g. Otto et al., 1990; Holt and Proctor, 2008). The region is marked to some extent by low salinities (i.e. < 34.9, Turrell, 1992a) extending out from the Scottish coast. The semi-isolated North Sea coastal strip has been identified by multiple authors. For example, Hainbucher et al. (1987) used the region to examine the transport of passive tracers. Lenhart et al. (1995) and Lenhart and Pohlmann (1997) used the region within a linked hydrodynamic – ecosystem model, and Vermaat et al. (2008) used the region to estimate nutrient budgets of the area. The model area was revealed as a distinct ecohydrodynamic region inshore of a

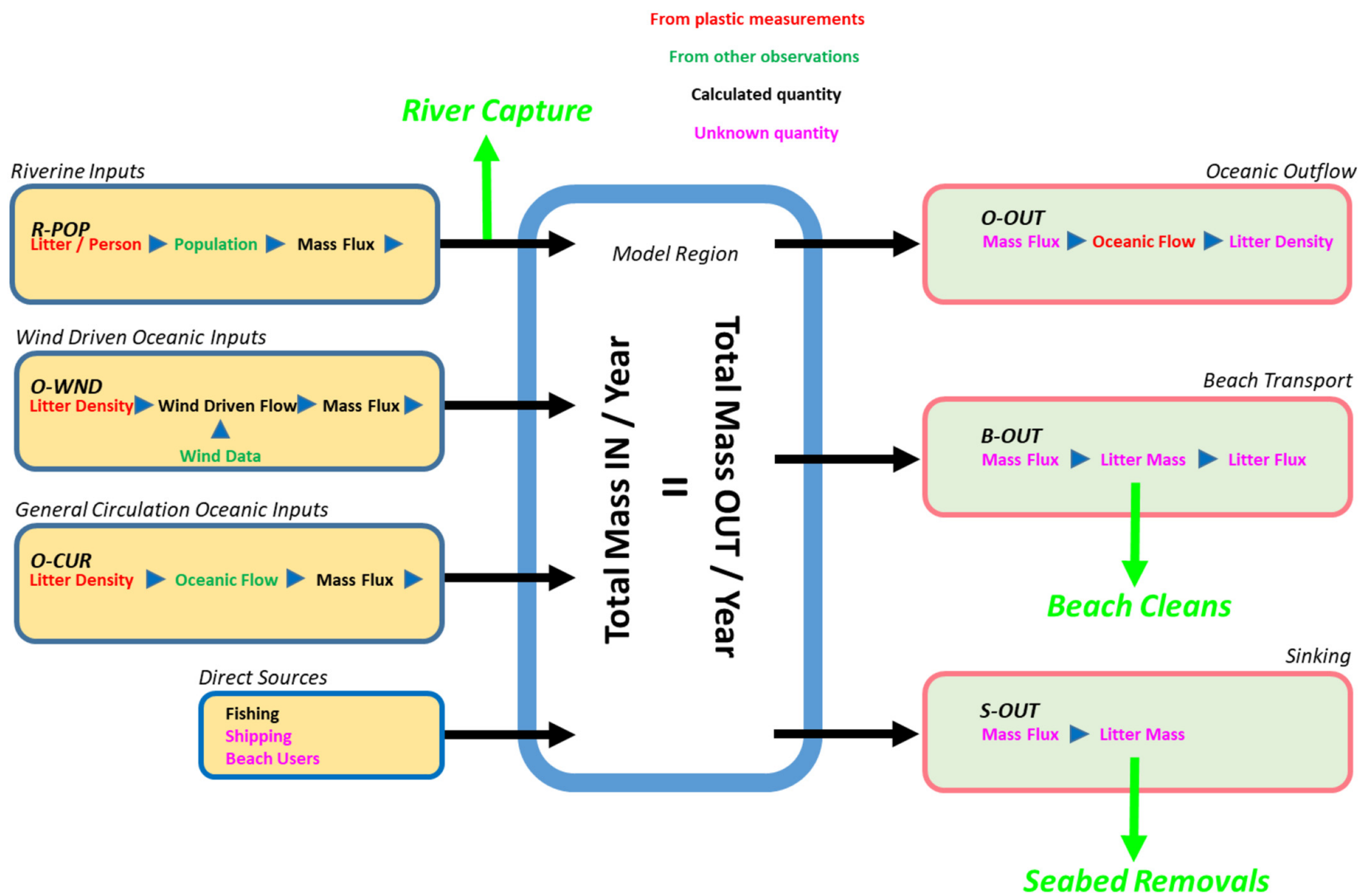

Fig. 1. Schematic showing the different contributions to the total budget of marine plastic in the Scottish Atlantic Coast and North Sea Coast model regions. Capitalised acronyms refer to sub-models used in this study (see text for full descriptions).

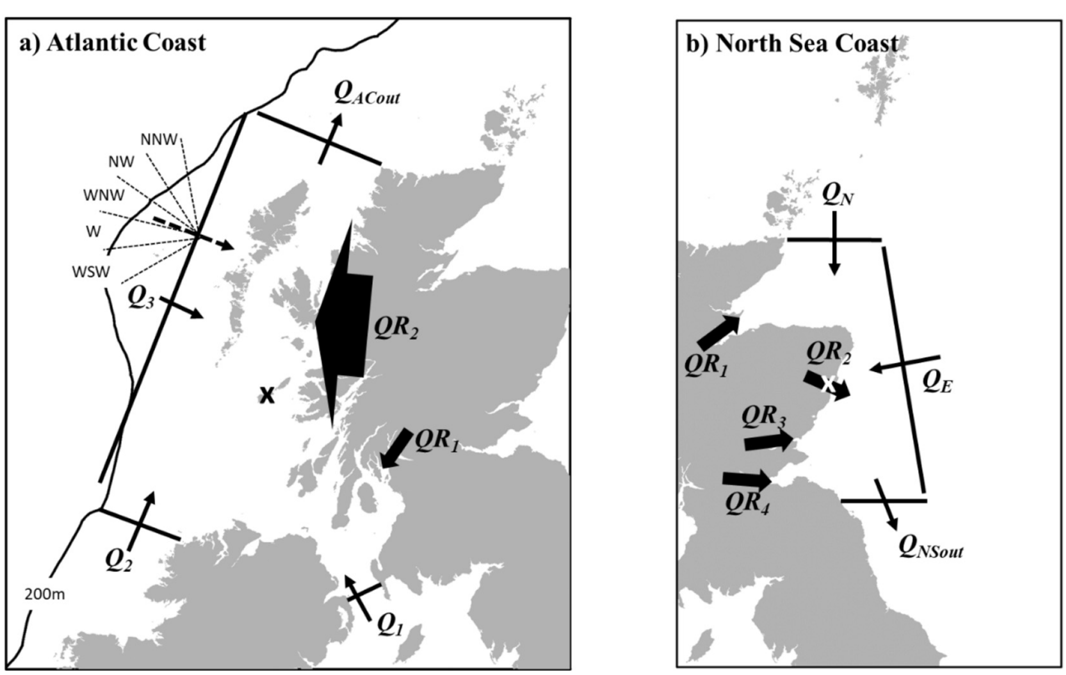

Fig. 2. Schematic of the a) Atlantic Coast Model, and b) North Sea Coast Model domains on the Scottish continental shelf showing principal flows of marine plastics used in this study (*Q* – oceanic, *QR* – riverine). Also shown within the left hand figure is the method of calculating the direct wind-driven surface flux using a wind-rose sector approach as described in the text. Cross symbols indicate the locations of the meteorological data sources (Atlantic Coast – Tiree; North Sea Coast – Aberdeen).

Table 1
Summary of river catchment area populations (NRS, 2019) and river flows (Bresnan et al., 2016) for the Atlantic Coast Model (Fig. 2a) and North Sea Coast Model (Fig. 2b). Fig. 2 shows the approximate locations of the river inflows (see labels in left hand column).

	Region	Population	River flow ($m^3 s^{-1}$)
Atlantic Coast Model			
QR_1	Clyde	2,027,247	139
QR_2	N Clyde	148,473	338
	Total	2,175,720	477
North Sea Coast Model			
QR_1	Moray Firth	514,017	386
QR_2	North East Coast	343,600	127
QR_3	Tay	300,040	176
	Tay-Forth	371,910	–
QR_4	Forth	1,317,783	63
	Total	2,847,350	752

seasonally stratified region defined by van Leeuwen et al. (2015).

Hence the North Sea Coast Model region used in this study is as shown in Fig. 2b. It has an offshore eastern edge 300 km long and approximately 80 m deep (Q_E; Fig. 2b) and a northern boundary 130 km long and 80 m deep (Q_N; Fig. 2b). All outflow occurs through the southern boundary (Q_{NSout}; Fig. 2b; 140 km long; 80 m deep).

Several large rivers discharge into the North Sea Coast Model region; the River Dee and Don through the city of Aberdeen (QR_2, Fig. 2b); the River Tay through the city of Dundee (QR_3); and the River Forth past the city of Edinburgh (QR_4). All inflows and population sizes of the landward catchment areas discharging into the North Sea Coast Model region are summarised in Table 1.

2.3. Sub-model - population-scaled riverine sources [R-POP]

For this study two population-based sub-models (R-POP, Fig. 1) were used to estimate the land-based sources of marine plastics entering the sea from rivers. The first method used, based on that of Jambeck et al. (2015), makes assumptions about the mass of waste each person in Scotland generates per year, the percentage of that waste which is plastic, the percentage of the plastic waste that is either mismanaged or littered (i.e. enters the environment), and finally the percentage of the mismanaged and littered plastic that enters the sea. Hence there are at least four parameters which can introduce uncertainty to estimates using this method.

Jambeck et al. (2015) based their values of the model parameters on sources such as World Bank data for waste generation figures, and a US study of littering for the mismanaged waste proportions. For the UK, and hence Scotland, they suggested that mismanaged plastics, from leakage from landfill sites for example, are virtually zero. For the UK, the principal source of mismanaged plastic is from littering. They suggested that each person in the UK (and hence Scotland) produces 1.79 kg/person/day of waste, of which 12% is plastic and, of this plastic waste, 2% is littered. A certain percentage of the littered component then gets into the sea as "marine leakage". Jambeck et al. (2015) suggested this leakage is between 15% and 40% of the littered plastic waste. Taking 15%, 20% and 40% as the minimum, base and maximum marine leakage percentages, this gave 0.64, 0.86 and 1.72 g/person/day of plastic waste entering the sea from a population in a Scottish river catchment area (i.e. L_{POP}, see below).

The second population-based sub-model used directly observed values of macro plastic litter in rivers, as measured by Tramoy et al. (2019). Studying the River Seine in France, they used the masses of macro plastic litter collected by a series of surface booms, coupled with the flow of the river, to provide estimates of the total mass of plastic (i.e. surface and sub-surface) reaching the sea via the Seine, i.e. between 1100 and 1700 tonnes per year (mean of 1400 tonnes per year). They gave the total population of the Seine inshore catchment area as 16.7 million people. Combining these values gives estimates of plastic waste entering the sea from an inland mixed urban/rural population of 0.18, 0.23 and 0.28 g/person/day (minimum, base and maximum; L_{POP}, see below). The values used from Tramoy et al. (2019) are for the total plastic load from the population of 16.7 million, not just the floating component. The removal of plastic load by sinking once rivers discharge into the adjacent coastal waters was accounted for by the sinking sub-model [S-OUT] described below.

For the above two sub-models, if the inshore population in a river catchment is R_{POP} (persons), then the total flux of plastic into the sea, MR kg s^{-1}, is given by

$$MR = R_{POP}.\ L_{POP}.\ (24.60.60)/1000\ (\text{kg s}^{-1}) \quad (1)$$

where L_{POP} is the mass of plastic released to the sea per person per day (g/person/day). To convert kg s^{-1} to tonnes per year we multiply by (60.60.24.365) / 1000.

To convert the mass of plastic released into the sea to the total numbers of plastic items released into the sea, the average mass of a floating plastic litter item, M_{river} g, is needed. The rate of inflowing plastic in terms of numbers of litter items, RR np s^{-1} is then given by

$$RR = MR/(M_{river}.\ 1000)\ (\text{np s}^{-1}) \quad (2)$$

Note that in this study both mass flux and number flux were estimated (see Supplementary material for discussion of the advantages and disadvantages of these two parameters). Note that when estimating the minimum number of plastic items released into the sea by rivers, the maximum value of M_{river} is used, and vice versa. For the two population-scaled methods of estimating riverine inputs of plastics to the sea, the same loading per head of population is assumed for both urban and rural rivers, in the absence of any evidence to the contrary. When a sea region receives inputs from multiple rivers, the total plastic litter input is simply the sum of the individual river inputs.

2.3.1. Microplastics

The Jambeck et al. (2015) method did not consider the emission of microplastics. However, the Tramoy et al. (2019) method (i.e. scaling observed river concentrations by catchment population size) can be used to estimate microplastic discharges. Lebreton et al. (2017) present thirty observed values of river macro (> 5 mm) and micro (< 5 mm) floating plastic litter, from thirteen rivers around the world (although some values were modelled using various assumptions). In order to estimate the amount of microplastics emitted by Scottish rivers per head of population, the mean ratio between macro and micro river concentrations was calculated using the Lebreton et al. (2017) data, after the exclusion of five rivers which appeared to give anomalous results (see Supplementary material). The results suggested that microplastic river concentrations (by mass) are typically 22% that of macro plastic concentrations. Thus it was assumed that in Scotland, microplastic inputs to the sea from rivers are, by head of population, 22% by mass those of macro plastics.

2.4. Sub-model - wind-driven oceanic sources [O-WND]

This sub-model estimates the direct wind-driven input of floating macro marine plastics at the sea surface (O-WND, Fig. 1). Wind-driven estimations of the surface transport generally assume that floating matter on the surface of the sea moves at a certain percentage of the wind speed (C_w), generally between 1% and 5% (e.g. Duhec et al., 2015). For this study, a simple method of estimation was chosen which used readily available data (i.e. a wind-rose) in order to calculate the maximum typical offshore supply of marine litter by direct wind forcing. The simple wind-rose based sub-model is compared to a more physically realistic method in the Supplementary material and is found to give good results.

The simple method assumes that wind from a predefined radial sector, whose axis is perpendicular to an open boundary, drives floating litter across the boundary, and it does so for a period of one year. For convenience, based on compass points, we will assume this sector is 112.5^0 wide, i.e. $\pm 56.25^0$ from the perpendicular direction (e.g. Fig. 2a). We divide this sector up into i sub-sectors, in our case each sub-sector is 11.25^0 wide. For each sub-sector we find the number of hours in a year (T_{wind} (i, j)) that wind blows from that sub sector at speeds between a minimum and maximum speed, the average of which is U_{wind} (i, j) ms^{-1}, as there are j wind speed "slots", from zero to the maximum wind speed of the annual period. In each sub-sector i, and for each wind speed slot j, the distance floating litter is moved by direct wind forcing, $d(i, j)$ km is given by

$$d(i,j) = (T_{wind}(i,j).60.60).(U_{wind}(i,j)/1000)\ (\text{km}) \tag{3}$$

If the width of the boundary is W_1 km, the floating litter moves at C_w percent of the wind speed and the average floating plastic litter density at the boundary is N_1 np km^{-2}, then the wind-driven transport of litter across the offshore boundary in the (i, j) sub-sector wind speed slot, R_{wind} (i, j) np s^{-1} is given by

$$R_{wind}(i,j) = N_I.(C_w/100).W_I.d(i,j)\ (\text{np s}^{-1}) \tag{4}$$

The wind does not blow from the offshore sector all year. If we estimate that wind comes from directions, and with speeds, within each defined sector for P_w (i, j) percent of the year, then R_{wind} becomes

$$R_{wind}(i,j) = R_{wind}(i,j).(P_w(i,j)/100)\ (\text{np s}^{-1}) \tag{5}$$

and if the average mass of a floating piece of litter at the surface is M_{float} g, then the mass of floating litter entering per second, M_{wind}, is given by

$$M_{wind} = \sum_{i,j} M_{float}.R_{wind}(i,j)/1000\ (\text{kg s}^{-1}) \tag{6}$$

To convert kg s^{-1} to tonnes per year we multiply by (60.60.24.365) / 1000.

2.5. Sub-model - residual circulation oceanic sources [O-CUR]

The estimation described in the last section is that for the direct wind-driven component at the very surface of the sea. However, there may also be a contribution from the general background residual circulation of a region, often driven by other forces other than wind (e.g. density, tides). If a region has multiple inflows of oceanic water, we can assess the contribution of each separately as they will be additive. If we take the first inflow, inflow 1, then the flow of water into the region from this inflow is Q_1 Sv (Sv is the oceanographic unit Sverdrups, or 10^6 m^3 s^{-1}). If we assume this flow takes place through a section perpendicular to the flow which has a width of W_1 km and an average depth of D_1 m, then the inflow has a characteristic inflow speed, U_1 ms^{-1}, of.

$$U_I = (Q_I.10^6)/(W_I.1000.D_I)\ (\text{ms}^{-1}) \tag{7}$$

Now if the density of floating plastic at the boundary is N_1 np km^{-2}, then the rate of input of plastic to the region, R_1 np s^{-1}, is given by

$$R_I = N_I.(U_I.W_I.1000)/(1000.1000)\ (\text{np s}^{-1}) \tag{8}$$

If the average mass of a piece of floating plastic is M_{float} g, then the inflowing mass of plastic M_1 kg s^{-1}

$$M_I = (R_I.M_{float})/1000\ (\text{kg s}^{-1}) \tag{9}$$

To convert kg s^{-1} to tonnes per year we multiply by (60.60.24.365) / 1000.

2.6. Sub-model - oceanic outflow from region [O-OUT]

Once all inflows of plastic to a modelled region have been estimated, their total (R_{total}) is additive. If we make the assumption that only the general circulation carries floating plastic out from a region, and if D_{out} is the depth (m) of the outflow region, then the area of the surface layer of the sea leaving the region in one year, A_{out} (km^2/year) is given by

$$A_{out} = (Q_{out}/D_{out}).60.60.24.365\ (\text{km}^2) \tag{10}$$

and hence the typical average litter density of the outflow (N_{out} np km^{-2}) is given by

$$N_{out} = R_{total}/A_{out}\ (\text{np km}^{-2}) \tag{11}$$

where, R_{total} is the total annual input of floating litter to the region, in number of litter items in one year (np/year).

The assumption that only the general circulation is responsible for outflow of plastic from the modelled regions holds for the Atlantic Coast and North Sea modelled regions, as the prevailing winds there act in directions parallel to the outflow open boundaries. This may not be the case in other regions, and hence direct wind-driven transport may also have to be taken into account for these areas.

2.7. Sub-model - direct sources (fishing)

Direct sources of marine plastic to the modelled regions include that from shipping, beach users and fishing (Fig. 1). As Scotland has a large and active fishing industry (e.g. SG, 2017), a method was devised to estimate this direct source. If, as in Eq. (11) above, R_{total} (np/year) is the total annual input of floating macro plastic to a modelled region from all sources except for that from fishing, and R_{fish} is the total number of pieces of floating plastic released by the activity of fishing into the same region, then the proportion of floating litter that comes from fishing, P_{fish}, is given by

$$P_{fish} = R_{fish}/(R_{total} + R_{fish}) \tag{12}$$

rearranging gives

$$R_{fish} = R_{total}.P_{fish}/(1 - P_{fish}) \tag{13}$$

In the absence of any physical process affecting floating plastic derived from fishing in a different manner to other floating plastic, it is a fair assumption that the ratio of plastic washed up on a foreshore should be in the same proportion as that floating at sea, i.e. P_{fish}. Hence values of P_{fish} can be derived from foreshore surveys. This same ratio method was employed by Lebreton et al. (2018) when estimating global sources of plastics from marine sources (see their Supplementary material, Method 4). However, it should be noted that the observed ratios between fishing and non-fishing beach plastics may be modified by local sources. At the current time there is insufficient information to estimate microplastics released by fishing activity in Scottish waters.

2.8. Sub-model - sinking [S-OUT]

Oceanic inflows to the modelled regions were assumed to be of floating plastic only, as the sinking component was assumed to have been removed before the plastics reached Scottish waters. However, riverine inputs were total plastic loads. Hence an estimate of the amount of plastic sinking to the sea bed was attempted. This sub-model simply assumed that a certain percentage of inflowing land-based plastic sinks to the seabed. Sinking percentages were obtained from literature, and are described in Section 2.14 below.

2.9. Model parameters - ocean transports

The sub-model described (O-CUR) above requires knowledge of the residual ocean input to a region (Q) through each and every open sea boundary. This section describes values of Q for the Atlantic Coast and North Sea Coast models, from published studies.

2.9.1. Atlantic Coast

There are three major oceanic inflows to this region: from the Irish Sea through the North Channel (Q_1, Fig. 2a); along the strip of shelf

Table 2
Values of the oceanic inflows to a) the Atlantic Coast Model region, b) the North Sea Coast Model region (Fig. 2). Sv - Sverdrup, i.e. 10^6 m^3 s^{-1}. Estimates were made using numerical models ("Model") or direct in-situ observations ("Obs."). Where ranges of values were given, minimum ("Min.") and maximum ("Max.") values are given. These can be the mean +/− a standard deviation. When no range is given, only mean ("Base") values are presented.

Atlantic Coast Model				Transport (Sv)		
	Inflow	Source		Min.	Base	Max.
Q_1	Inflow from Irish Sea	Prandle (1984)	Model	0.06	–	0.09
		Brown and Gmitrowicz (1995)	Obs.	0.11	–	0.14
		McKay et al. (1986)	Obs.	–	0.05	–
		Knight and Howarth (1999)	Obs.	0.06	0.08	0.09
		This study	Q_1	0.06	0.10	0.14
Q_2	Inflow from west Irish shelf	Fernand et al. (2006)	Obs.	0.12	–	0.24
		This study	Q_2	0.12	0.20	0.24
Q_3	Inflow across shelf edge	Huthnance et al. (2009)	Obs.	0.61	–	1.00
		Porter et al. (2018)	Obs.	0.70	–	1.20
		This study	Q_3	0.61	1.00	1.20
Q_{ACout}	Outflow	McKay et al. (1986)	Obs.	–	1.12	–
		Turrell (1992b)	Obs.	–	1.70	–

North Sea Coast Model				Transport (Sv)		
	Inflow	Source		Min.	Base	Max.
Q_N	Inflow from north	ICES (1983)	Model	–	0.03	–
		Turrell (1992a, 1992b)	Obs.	–	0.02	–
		This study	Q_N	0.02	0.03	0.04
Q_E	Inflow from east	ICES (1983)	Model	–	−0.01	–
		Turrell (1992b)	Obs.	–	0.00	–
		This study	Q_E	0.00	0.00	0.00
Q_{NSout}	Outflow south	ICES (1983)	Model	–	0.02	–
		Turrell (1992b)	Obs.	–	0.02	–
		Lenhart et al. (1995)	Model	–	0.02	–
		Lenhart and Pohlmann (1997)	Model	–	0.02	–

west of Ireland (Q_2); and across the offshore edge of the continental shelf (Q_3). Table 2 summarises the estimates of oceanic inflows to the region from literature.

There have been a number of estimates of the northward flow of Irish Sea water through the North Channel. The examples selected include a numerical model estimate by Prandle (1984), and three estimates obtained by direct observation; McKay et al. (1986) inferring transport from radiocaesium distributions; Brown and Gmitrowicz (1995) using an array of current meter moorings across the channel; and Knight and Howarth (1999) using land-based remote sensing (HF radar) coupled with a moored current meter (a Doppler profiling current meter). From these studies the minimum, base and maximum values of Q_1 were taken as 0.06 Sv, 0.10 Sv and 0.14 Sv respectively (Table 2).

Fernand et al. (2006) confirmed the northward flow along the west coast of Ireland using extensive deployments of drifters and current meter moorings. The flow there can be seasonal, with a range in transport of 0.12 to 0.24 Sv. Hence these two values were selected as the minimum and maximum values of Q_2, with a base value of 0.20 Sv.

Estimating the transport of water across the shelf edge to the west of the Atlantic Coast Model region (Q_3) is not a trivial task, but has been attempted by several previous studies. Huthnance et al. (2009) reviewed multiple modelling and observational studies and presented several estimates of the total transport, which is complicated by a general on-shelf transport near the surface, and a net off-shelf transport near the seabed. He suggested that on-shelf net transports were between 0.61 Sv and 1.0 Sv. A more recent study by Porter et al. (2018) updated values presented by Huthnance et al. (2009) by including an estimated inflow of water from the shelf edge in leakage from the slope current (a persistent flow of oceanic water flowing polewards above the edge of the continental shelf), suggesting that the net inflow was between 0.7 Sv and 1.2 Sv. From the various published values (Table 2), the minimum, base and maximum values for Q_3 used in this study were 0.61 Sv, 1.00 Sv and 1.21 Sv respectively.

The sum of $Q_1 + Q_2 + Q_3$ gives the total inflow to the region, and hence should equate to the total outflow (Q_{ACout}, Fig. 2a), given that river flows are small compared to oceanic flows (i.e. total river flow into the Atlantic Coast Model region is 0.0006 Sv). Usefully, McKay et al. (1986) also estimated the total outflow from the region northwards (1.12 Sv), using the transport of radiocaesium as a tracer and Turrell (1992a, 1992b) estimated the outflow using direct observations (1.70 Sv). These observed values were used as a check that the total inflows used in this study were of a realistic order of magnitude. Using the values selected above for Q_1, Q_2 and Q_3, The minimum, base and maximum total transport into the shelf region west of Scotland using the values cited above was 0.79 Sv, 1.30 Sv and 1.58 Sv respectively which compares well with the observed outflow values.

2.9.2. North Sea Coast

The North Sea Coast model box lies wholly within the North Sea, with an outer boundary internal to that shelf sea. The principle circulation feature is the coastal current flowing through the box, southwards along the coast, with little flow perpendicular to the coast. A study using a box model of the North Sea coastal zone, described in ICES (1983), concluded that the flow of water into the North Sea Coast Model region through the northern open boundary (i.e. Q_N, Fig. 2b) was 0.03 Sv, with zero persistent flux through the eastern offshore boundary (Q_E). This estimate was made using a mixture of observations and modelling. For the current calculations, a variation of ± 10% was used to estimate the minimum, base and maximum values of Q_N used in this study and hence these were 0.02 Sv, 0.03 Sv and 0.04 Sv respectively. Q_E was assumed to be zero.

2.10. Model parameters - wind climates

The direct wind-driven sub-model (O-WND) required wind-rose data typifying the wind forcing over the two model domains. For the Atlantic Coast Model domain, wind from Tiree was used, and for the North Sea Coast Model winds from Aberdeen were used. Fig. 3 presents the wind-roses for these two locations derived from 10 years of data, 2008 to 2017 (Met Office, 2006). Location of Tiree and Aberdeen may be seen in Fig. 2.

2.11. Model parameters - typical mass of floating macro plastic litter item

As noted above, in order to convert an estimated mass flux of floating plastic (macro plastic or microplastic) to a flux of numbers of litter items, the typical mass of a floating litter item (M_{float}) is needed. This same mass is needed in order to convert the density of floating plastic in terms of numbers of litter items (np) per unit area into a mass of floating plastic per unit area. For example, in order to perform number-mass conversions, van Emmerik et al. (2018) used two standard litter item masses (3.2 g/np and 5.9 g/np) when estimating mass flux into the sea from the Saigon River in Vietnam, although van Emmerik et al. (2019) when considering a full year of observations including a monsoon season, used the larger value of 19 g/np. Eriksen et al. (2014) assumed an average weight of 10 g per floating plastic litter in their global modelling study.

No direct in situ measurements of floating macro plastics yet exist in Scottish rivers or in offshore waters. Rather, in order to get an indication of the possible extremes of offshore mass fluxes within the two Scottish regions used in this study, and noting the observed range seen in published particle mass values (Table 3), minimum, base and maximum values of 0.2 g/np, 5 g/np and 12 g/np were used. The same

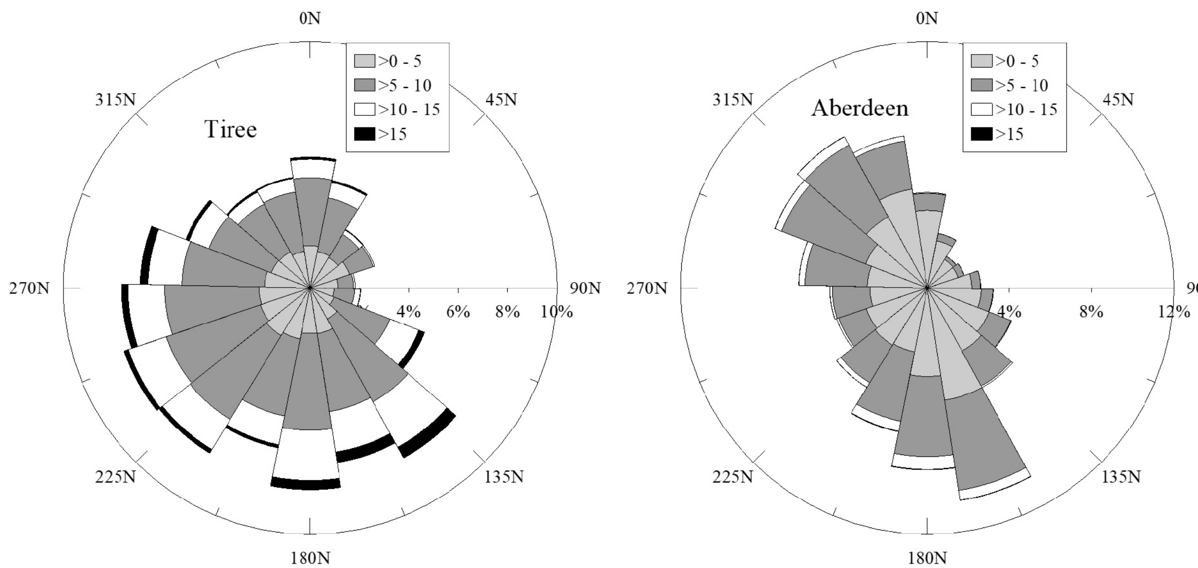

Fig. 3. Wind-roses from Tiree (left) and Aberdeen (right). See Fig. 2 for locations. Speeds are in ms^{-1}. Wind direction is from. Percentage times for each sector are calculated over the ten year period 2008 to 2017.

range was used for riverine macro plastics (i.e. M_{river}).

2.11.1. Microplastics

A large range of masses of microplastics is possible, depending on exact size and composition. A survey of some of the relevant literature found quoted values of between 1 and 70 mg per particle (particle size < 5 mm. See Supplementary material), although often the associated size of the microplastic particle was difficult to determine from the information presented. For this study, a standard mass of 10 mg per microplastic particle was assumed for M_{float} and M_{river}. This is about one-third the mass of a typical pre-production plastic pellet (nurdle), and lies within the lower end of the published observational values.

2.12. Model parameters - offshore floating plastic number densities

The sub-models which estimate the direct wind-driven oceanic input of floating plastic litter (O-WND) and the input due to the residual circulation (O-CUR) both require the density of offshore floating plastic items. Table 4 summarises observed values of floating macro plastic at various locations in the North and South Atlantic and the North Sea. No observed values exist as far as we know for the Irish Sea. From Table 4, for all open sea boundaries of both the Atlantic Coast model and the North Sea Coast model, typical minimum, base and maximum densities of floating macro plastic items were assumed to be 2, 5 and 15 np km^{-2}.

2.12.1. Microplastics

In Scottish waters, direct observations have been made of floating microplastic densities. Since 2014, tows of a manta net supported by a surface catamaran have been made around the Scottish coast and adjacent offshore areas as part of the standard Marine Scotland Science environmental monitoring programme. (M. Russell, pers. comm., SG in press and Supplementary material). The surface-following net was of 300 μm mesh size. Results have been averaged over various Scottish sea regions, and for the current study three values were used to typify floating microplastic concentrations: for the two offshore Atlantic Coast model boundaries (Q_2, Q_3), 1700 np km^{-2}; for the Irish Sea boundary (Q_1), 7100 np km^{-2}; and for all North Sea model boundaries (Q_N, Q_E), 1100 np km^{-2}.

2.13. Model parameters - direct sources (fishing)

The Marine Conservation Society (MCS) organises foreshore surveys in the modelled regions used in this study. Turrell (2019a) analysed this data to investigate spatial patterns of foreshore litter in the area, and Turrell (2019b) used the same data to develop indicators of beach litter abundance and composition in order to inform local managers. The MCS surveys use the OSPAR classification of litter items (OSPAR, 2010). This classification scheme has 118 individual classes of litter, of which 54 are plastic items, and eight of these were assumed to relate to fishing (i.e. nets and pieces of net, floats/buoys, tangled nets/cord/rope and string, fish boxes, lobster and fish tags, crab/lobster pots. See Supplementary material for full MCS list).

Using values presented in Turrell (2019b), the ratio of numbers of plastic identified during MCS beach surveys as being derived from fishing (np/100 m) to total plastic items, P_{fish} in Eq. (13), varied from

Table 3
Summary of a selection of published typical masses of macro plastics derived from in situ observations.

Type	Source	Sea area	Location	Sampling site	mg/np
River	van Emmerik et al. (2019)	Vietnam Coast	Saigon River	Within River	19,000
Beach	Duhec et al. (2015)	Indian Ocean	Seychelles (Island)	Low-use, remote beach facing into trade winds	11,700
Open Sea	Lebreton et al. (2018)	North Pacific	Open Sea	Gyre centre	5900
Beach	Simeonova and Chuturkova (2019)	Black Sea	Bulgarian Coast	8 beaches within bathing zones	4100
River	van Emmerik et al. (2018)	Vietnam Coast	Saigon River	Within River	3200
Beach	Moore et al. (2001)	North Pacific	Californian Coast	43 random sites, Orange County	2900
Beach	Madzena and Lasiak (1997)	Indian Ocean	Transkei Coast	6 rural, remote beaches	1500
Beach	van Cauwenberghe et al. (2013)	North Sea	Belgian Coast	4 beaches, varying tourist pressure	1200
					200
River	Lebreton et al. (2017)	–	EU/US rivers	39 river studies	193

Table 4
Density (number of litter items per square kilometre, np km^{-2}) of floating macro marine plastic litter from previous studies, observed at sea. Values have been rounded up to nearest whole number. Values for Turrell (2018) were from a model of macro plastic as defined by beach surveys.

Region	Sub-region	Size range (cm)	Floating plastic density (np km^{-2})			References
			Min.	Base	Max.	
North Atlantic	Eastern Basin 30^0–50^0 N	> 10	2	–	13	Barnes and Milner (2005)
	Mid Atlantic 0^0–30^0 N	> 10	0	–	9	Barnes and Milner (2005)
North Sea	German Bight	> 2	18	–	27	Thiel et al. (2011)
	German Bight	n.d.	1	2	6	Herr (2009)
	Belgium	n.d.	–	1	–	van Cauwenberghe et al. (2013)
	Scottish east coast	Model	1	–	7	Turrell (2018)
	Aberdeen - Shetland	> 10	1	–	4	Barnes and Milner (2005)
	All North Sea	> 10	1	2	3	Dixon and Dixon (1983)
All Open Ocean Boundaries – this study		> 1	2	5	15	Selected for this study
South Atlantic	Western Basin 10^0–30^0 S	> 10	0	–	9	Barnes and Milner (2005)
	Western Basin 30^0–50^0 S	> 10	0	–	1	Barnes and Milner (2005)
	Eastern Basin 30^0–35^0 S	> 1	5	6	8	Ryan (2014)
	Central Atlantic 30^0–35^0 S	> 1	1	1	2	Ryan (2014)

1% (minimum) to 6% (maximum) with an average of 4% (base) around the Scottish coast. These values were used in Eq. (13) to estimate minimum, base and maximum values of the number of plastic items released by fishing in the modelled regions per year (R_{fish} np/year). In order to convert from numbers of fishing related litter items to mass of this plastic litter and in the absence of specific data, the weight per item (g/np) for floating macro plastic associated with fishing was taken as the base value used in sections above, i.e. 5 g/np.

2.14. Model parameters - sinking rate

There are more published studies of the sinking rates of microplastics than of macro plastics. Certainly macro plastics reach the seabed, as evidenced by macro plastic litter caught in demersal fish trawls throughout the northwest European continental shelf (e.g. Maes et al., 2018; Moriarty et al., 2016). Cózar et al. (2014) suggested that 60 to 64% of land-based plastic entering the sea via rivers traverses the coastal ocean and enters the open ocean. Hence between 36% and 40% sinks to the seabed on first entry to sea or soon thereafter. Frias et al. (2016), citing UNEP figures, suggest that up to 70% of plastic litter ends up on the seabed. Ryan (2015) noted that owing to the effect of biofouling on floating plastics, smaller items sink sooner than larger ones.

Plastics which reach Scottish waters by sea have most likely already had the majority of the sinking component removed from the plastic population owing to the length of time in the water. However, a component of the plastics entering the sea from land-based sources may certainly sink during the initial phase of marine existence. Hence for this study it has been assumed that 40%, 55% and 70% (minimum, base, maximum) of the land-based inputs of plastics settle to the seabed within the modelled region. The base value of 55% is applied to microplastics. Plastics sinking to the seabed are removed prior to estimating the input from fishing activity, as the fishing load is estimated using statistics derived from beach survey data, and hence mostly well after first entry to sea for land-based sources. Percentages are applied to land-based inputs in terms of both numbers per year and weights per year.

2.15. Model parameters - summary

Table 5 summarises the principal sub-model parameters used in this study.

3. Results

3.1. Inputs - Atlantic Coast

Using the base sub-model parameter values, a total of 601 tonnes of plastic enters the Atlantic Coast region each year from both land-based and ocean-based sources, 477 tonnes of which is macro plastic and 124 tonnes of which is microplastics (Table 6 and Fig. 4). This represents approximately 96 million items of macro plastic, and 12 billion pieces of microplastic.

Using the current model, approximately 91% of the macro plastic entering the Atlantic Coast sea region comes from littering by the Scottish public on land and 7% from offshore oceanic sources and 2% directly from fishing activity. For microplastics, 77% of the total annual input comes from the land and the remainder from remote sources transported through the sea. For the land-based sources, approximately 93% originates from the River Clyde catchment area (Supplementary material).

The uncertainty in the model parameters used in this study results in a possible variation of the total input of macro plastics (i.e. 477 tonnes base value) to the region of between a possible minimum of 328 tonnes per year and a maximum of 1,373 tonnes per year. The variability is largely due to the uncertainties in the land-based sources.

Using the maximum values of the sub-model parameters increases the proportion of the region's floating macro plastic provided by the sea. This becomes 39% (32% direct wind driven, 7% residual circulation) compared to 7% when using the base model parameters.

3.2. Inputs - North Sea Coast

A total of 709 tonnes of plastic enters the North Sea Coast region each year, 582 tonnes of which is macro plastic and 127 tonnes of which is microplastics (Table 7 and Fig. 4). This represents approximately 116 million items of macro plastic, and 12.7 billion pieces of microplastic.

Using the current model, 97% of the macro plastic in the North Sea Coast region comes from littering by the Scottish public on land, 1% from remote sources transported by the sea, and 2% directly from fishing activity. For microplastics, 98% comes from the land-based sources.

For the land-based sources, approximately 46% originates from the River Forth catchment area (Supplementary material), with the remainder coming fairly equally from the other catchment areas.

The uncertainty in the model parameters used in this study results in a possible variation of the total input of macro plastics (i.e. 582 tonnes per year base value) to the region of between a possible minimum of

Table 5

Summary of sub-model parameters used in this study. For R-POP plastic input/person, the full plastic load is included (i.e. surface and sub-surface from Tramoy et al., 2019). For offshore floating microplastics, three average values have been estimated using Marine Scotland Science direct observations (M. Russell, pers. comm., SG in press). Left hand column – sub-model codes, see Fig. 1. Superscripts: A – Irish Sea Boundary (Q_1); B - Atlantic open boundary and Irish Shelf Boundary (Q_2, Q_3); C – All North Sea open boundaries (Q_N, Q_E). Full details of data sources and associated calculations in Supplementary material.

Model	Parameter	Min.	Base	Max.	Micro.	Unit
R-POP	Plastic input/person (Jambeck)	0.64	0.86	1.72	0.19	g/person/day
R-POP	Plastic input/person (Tramoy)	0.18	0.23	0.28	0.05	g/person/day
R-POP	Typical mass of a floating riverine plastic item	200	5000	12,000	10	mg
O-WND	Wind drag factor	1	2	5	–	% 10 m wind
O-WND	Typical mass of a floating marine plastic item	200	5000	12,000	10	mg
O-CUR	Typical offshore density of floating marine plastic	2	5	15	7100[A] 1700[B] 1100[C]	np km^{-2}
Direct source	Ratio of fishing-related plastic to total plastic load on Scottish beaches	1	4	6	–	%
S-OUT	Sinking percentage of land-based plastic inputs	40	55	70	55	%

Table 6

Summary of the estimated total budget of plastic for the Scottish Atlantic Coast region. The separate components (unshaded) and sub-components (shaded) of the total budget are shown in Fig. 1, and explained in the text. For the land-based sources (i.e. via rivers), the final total value is the average of the two different estimation methods used (i.e. the Jambeck and Tramoy methods, see text). For the oceanic wind-driven inflows, and the oceanic general circulation driven inflows, the final totals are the sum of the fluxes through all open offshore boundaries. The "Base" values provide estimates of typical values, while the "Min." and "Max." values provide an indication of the possible uncertainty in those estimates. The "Micro." values is an estimate of typical conditions (i.e. "Base") with respect to microplastics. Note that totals were calculated before rounding to nearest significant digit, hence some small discrepancies are apparent in totals.

Budget component	Budget sub-component	Input of plastic							
		By number (10^6 np/year)				By mass (tonnes/year)			
		Min.	Base	Max.	Micro.	Min.	Base	Max.	Micro.
R-POP	Jambeck	42	137	6830	15,025	508	683	1366	150
R-POP	Tramoy	12	37	1112	4018	143	183	222	40
Total Land	Average	27	87	3971	9522	326	433	794	95
O-WND	Q_1-*Wind*	0	0	2	447	0	2	28	4
	Q_2-*Wind*	0	1	11	482	0	7	128	5
	Q_3-*Wind*	0	3	23	1064	0	16	282	11
Total Wind	Sum	1	5	36	1993	0	24	438	20
O-CUR	Q_1	0	0	1	280	0	1	10	3
	Q_2	0	0	1	107	0	2	14	1
	Q_3	0	2	6	536	0	8	68	5
Total Circ.	Sum	1	2	8	923	0	10	92	9
Total Direct	Fishing	0	2	10	–	2	10	49	–
TOTAL IN		**29**	**96**	**4025**	**12,438**	**328**	**477**	**1373**	**124**
S-OUT	To Seabed	11	48	2780	5237	130	238	556	52
(O-OUT + B-OUT)		19	48	1245	7201	198	238	817	72
TOTAL OUT		**29**	**96**	**4025**	**12,438**	**328**	**477**	**1373**	**124**

429 tonnes per year and a maximum of 1,150 tonnes per year. As with the Atlantic Coast the uncertainty is driven by the uncertainty associated with the estimates of land-based sources.

Using the maximum values of the sub-model parameters increases the proportion of the region's floating macro plastic provided by the sea. This becomes 7% compared to 1% when using the base model parameters.

3.3. Outputs – Atlantic Coast

In the Atlantic Coast region it was estimated that of the 433 tonnes of macro plastics that enter the region from land-based sources, 238 tonnes settle onto the seabed within the region each year. When the supply from the sea and from fishing is included, this leaves 238 tonnes of floating macro plastics to exit the region each year through the open northern boundary (Q_3, Fig. 2b). The flux to the seabed represents about 48 million pieces of macro plastic per year.

For microplastics, it is estimated that 52 tonnes settle to the seabed within the region each year, representing approximately 5.2 billion particles of plastic. This leaves 72 tonnes of microplastics (approx. 7.2 billion particles) to exit the region through the northern boundary each year.

3.4. Outputs – North Sea Coast

Similarly, for the North Sea Coast region it was estimated that of the 582 tonnes of macro plastics that enter the region from land-based sources, 311 tonnes settle onto the seabed within the region each year. When the supply from the sea and from fishing is included, this leaves 271 tonnes of floating macro plastics to exit the region each year through the open southern boundary (Q_3, Fig. 2b). The flux to the seabed represents about 62 million pieces of macro plastic per year.

For microplastics, it is estimated that 69 tonnes settle to the seabed within the region each year, representing approximately 6.9 billion particles of plastic. This leaves 58 tonnes of microplastics (approx. 5.8 billion particles) to exit the region through the northern boundary each year.

3.5. Summary – all Scotland

Combining results from the two modelled regions for macro plastic only, a number of facts and figures can be estimated that will be useful to disseminate to managers and the public. More than 90% of plastic in Scottish seas typically come from Scottish littering on land. Scottish littering puts about 1000 tonnes of macro plastic into Scottish seas each

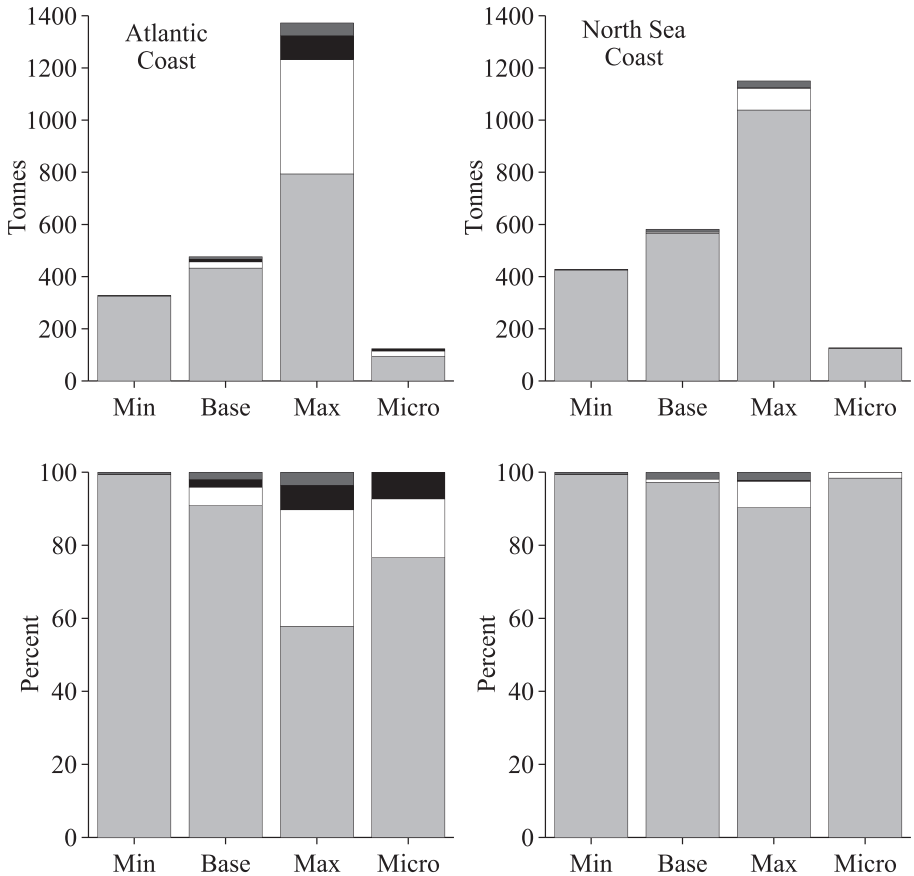

Fig. 4. Summary of model results. Left hand figures – Atlantic Coast modelled region; right hand figures North Sea Coast. Upper figures – inputs of plastic per year (tonnes). Lower figures – percentage contributions from different sources: total plastic contributions from rivers (i.e. coastal population) – grey; ocean – direct wind driven – white; ocean – general circulation – black; direct source (fishing) - red. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

year, which is about 200 million pieces of macro plastic. Another 40 tonnes (8 million pieces) of macro plastic litter enters Scottish seas from remote sources, carried by the sea. Fishing releases about 20 tonnes (4 million pieces) of plastic into Scottish seas each year and this is about 2% of the total plastic inputs. 93% of the plastic entering the sea from the land on the west coast comes from the Clyde catchment area, while 46% of the plastic entering the sea from the land on the east coast comes from the Forth catchment area. About 550 tonnes of plastic from land-based littering (110 million pieces) ends up on the seabed around Scotland each year. Beach cleans remove somewhere between 50 and 220 tonnes of plastic each year, although there are no accurate records, representing between 5% and 20% of the total macro plastics entering Scottish seas.

4. Discussion

Using some basic assumptions about oceanic circulation, wind surface forcing and land-based sources of marine plastic, coupled with the best currently available published values of key parameters, estimates of the various inputs of macro plastic, as well as microplastics, to two regions of Scottish waters (the Atlantic Coast region and the North Sea Coast region) were made. Although these estimates are limited by the associated simplifying assumptions, and the accuracy of the parameters used, they are the first published estimates and hopefully provide at

Table 7
Summary of the estimated total budget of plastic for the Scottish North Sea Coast region. See Table 6 legend for details.

Budget component	Budget sub-component	Input of plastic							
		By number (10^6 np/year)				By mass (tonnes/year)			
		Min.	Base	Max.	Micro.	Min.	Base	Max.	Micro.
R-POP	Jambeck	55	179	8938	19,663	665	894	1788	197
R-POP	Tramoy	16	48	1455	5259	187	239	291	53
Total Land	Average	36	113	5196	12,461	426	566	1039	125
O-WND	Q_N-*Wind*	0	0	3	91	0	2	37	1
	Q_E-*Wind*	0	1	4	111	0	3	45	1
Total Wind	Sum	0	1	7	202	0	5	83	2
O-CUR	Q_N	0	0	0	13	0	0	3	0
	Q_E	0	0	0	0	0	0	0	0
Total Circ.	Sum	0	0	0	13	0	0	3	0
Total Direct	Fishing	1	2	5	–	3	11	25	–
TOTAL IN		**37**	**116**	**5208**	**12,676**	**429**	**582**	**1150**	**127**
S-OUT	To Seabed	14	62	3637	6854	170	311	727	69
(O-OUT + B-OUT)		22	54	1571	5822	258	271	423	58
TOTAL OUT		**37**	**116**	**5208**	**12,676**	**429**	**582**	**1150**	**127**

least order of magnitude accuracy.

One reason why the simple models proposed here are appropriate for the task of estimating plastic loads, especially those from remote sources transported by the sea, is due to the oceanography of the region which has been studied for decades, is relatively well understood and is simple, in the sense that there is a clockwise residual circulation around the land-mass of Scotland (e.g. Hill et al., 2008). The "box model" approach taken here has been used before, for example to estimate the budgets of nutrients, including those from rivers and from the sea (Lyons et al., 1993; Heath et al., 2002). The north coast of Scotland, Orkney and Shetland have been omitted from the current study as they sit in much more complex waters, where a simple "box" approach would not be appropriate. However, the regions modelled here encompass about 99% of Scotland's population.

4.1. Absolute loadings

This study provides, for the first time, estimates of the total masses of macro plastic entering Scottish marine regions, i.e. Atlantic Coast region, 477 tonnes per year; North Sea Coast region, 582 tonnes per year. The North Sea Coast region receives more owing to the greater population on that coast (2.85 M, Table 1) than on the Atlantic Coast (2.18 M). The North Sea Coast receives a small percentage from the sea owing to two factors, the wind is primarily directed offshore, and the general circulation on average is weak within the coastal region. The Atlantic Coast receives greater proportions from the sea as the wind there is predominantly onshore, and there is a more active cross-boundary circulation.

4.2. Local cf. remote sources

For the Atlantic Coast region, it was estimated that between 58% and 99% of marine macro plastic is supplied by littering by the Scottish public, entering the sea through rivers. The same figures for the North Sea Coast were between 90% and 99% (Fig. 4).

It might be considered that the high percentage contributions for land-based sources of marine plastics are unexpected, as Scottish waters and coasts are exposed to the North Atlantic and the North Sea and hence to contributions from remote sources. Nelms et al. (2017) considered the composition of UK beach litter collected during citizen science surveys and also concluded that land-based littering was the principal source. For most of the Atlantic Coast region they suggested that 40% of the beach litter was able to be attributed to land-based sources with a further 40% not able to be attributed to any specific source. For the North Sea Coast region, 50% could be attributed to land-based sources, with a further 40% unattributed. Hence on both coasts their data is not inconsistent with the percentages of land-based sourced litter suggested by this study, if unattributed litter is from land-based sources.

4.3. Direct sources - fishing

In the models presented here, just one local direct source of plastic was estimated, that from the activity of fishing as, when beach litter data is considered, plastics associated with fishing represent between 1% and 6% of the total plastic loads (Turrell, 2019b). These percentages of marine plastics allocated to fishing-related sources are small compared to the percentage found in the Great Pacific Garbage Patch by Lebreton et al. (2018), i.e. 46%, indicating conditions differ between the two areas.

In order to provide enough floating plastic to maintain the observed Scottish ratios, the models suggest that on the Atlantic Coast fishing must release about 10 tonnes of macro plastic pieces per year (with an uncertainty of between 2 and 49 tonnes), and release 11 tonnes (3 to 25 tonnes) in the North Sea Coast region. Some of the fishing related plastic on Scottish beaches could well have come from remote sources, which would reduce the masses released by local fishing. Conversely, a certain percentage of plastics from fishing will immediately sink, which has not been accounted for here, and this would raise the masses needed to be released from fishing to explain the observed beach loadings. Some of the litter items that were associated with fishing by Turrell (2019b) may also originate from non-fishing sources (e.g. rope pieces), which would also reduce the contribution from fishing. Hence there is still much uncertainty associated with the estimates presented here of the contribution of floating macro plastics from fishing. These estimates do not include any domestic waste plastics discharged directly into the sea from fishing vessels, as this is indistinguishable in the beach litter record from land-based litter.

4.4. Direct sources – others

One possibly significant missing direct source is that of sewage related plastics, which in Scotland mainly comes from storm-related overflows. In the MCS/OSPAR beach litter database (e.g. OSPAR, 2010), there are separate categories for sanitary-related items, and these are composed of a mixture of materials including plastics and non-plastics. Turrell (2019b) found that in the Clyde and Forth regions, about 20% of the total beach litter load (plastics and non-plastics) was composed of sanitary items, indicating the potential in these regions of direct input from waste water treatment facilities. For other parts of the Scottish coastline, the percentage of sanitary litter fell to < 4%. This implies that a large proportion of sewage related litter is removed from the floating load soon after entry into the sea, i.e. it sinks to the seabed. Hence, for much of the Atlantic Coast and North Sea Coast regions, sewage related debris may be a locally important rather than a regionally important source. Nevertheless, its total contribution still needs to be estimated. Other direct sources that still require estimation for the modelled regions include that from shipping, and that from beach users.

4.5. Outputs – sinking

The assumptions made concerning the percentage of floating litter entering the modelled regions from land-based sources that sinks soon after first entry to the sea resulted in estimates that, in total, about half the total plastic load which enters each region ends up on the seabed, and the rest leaves through an open boundary, to the north on the west coast and to the south on the east coast. This prediction needs to be tested further through analysis of seabed litter observations (e.g. Moriarty et al., 2016; Maes et al., 2018).

4.6. Outputs – the role of beaches

Up until now the role of litter on the foreshores of the two modelled regions has not been discussed or estimated. Understanding beach litter is one of the ultimate aims of this study, and it is hoped the estimates presented here will help progress the work of Turrell (2018) and Turrell (2019a). Turrell (2018) proposed that for Scottish beaches (in fact all mid-latitude, macro tidal beaches) the net accumulation rate is zero. If this is correct beaches are not a sink for floating plastic litter in a static sense. However, beaches do hold a standing stock of litter at any one time, but in Scotland at least this is not great. Using the median observed loadings along the beaches of the North Sea Coast modelled region from Turrell (2019a) (see Supplementary material) and raising these loadings using the number and length of foreshores present along the entire coast, it is estimated that on average, the beaches of the North Sea Coast model region hold 2.5 tonnes of floating macro plastic (assuming 5 g per litter item) at any one time. The situation in the Atlantic Coast region is probably not too dissimilar, but awaits detailed estimates of beach numbers and size. The model of Turrell (2018) also suggests that at any one time, owing to previous tidal and wind conditions, loadings on beaches may be much greater than the median, and at other times much less.

The mechanism of floating litter capture by beaches described in Turrell (2018) predicts a net zero accumulation rate on beaches, but also suggests there can be a flux of litter along a coast, from beach to beach. This means that, although the median total standing stock on all beaches in the North Sea Coast region is just 2.5 tonnes at any one time, the flow of litter along the beaches over the course of a year may be much greater. However, this flux has not yet been quantified, and further work is needed to do so.

4.7. Output – a paradox

There remains a paradox using the models presented here. Assuming that the estimates of the inputs of macro plastic for a year are at least correct to an order of magnitude, after the removal of plastics to the seabed through sinking and assuming a net zero flux associated with the foreshores of both regions, using Eq. (11) tells us that the outflow from the Atlantic Coast model region should have a floating litter content of 117 np km^{-2} (using base parameter values) and the outflow from the North Sea Coast model region should have a macro plastic content of 105 np km^{-2}. These are obviously about 30 times greater than the concentrations assumed for Scottish waters from Table 4 (i.e. of the order of 5 np km^{-2}). It is clear that, in the presence of land-based sources discharging into a coastal region, concentrations in the outflow will be higher than in the oceanic inflow, but a factor of 30 seems too high as such values have not yet been observed in the region. The following explanations are possible: 1) the inputs estimated here are too large; 2) the oceanic transports out from the region are too small; 3) the assumed sinking rates are too small; 4) the net flux onto the foreshores is not zero; 5) there is a flux of plastic out from the modelled regions along the foreshores as well as in the water; 6) the outflowing water does have high loadings although these have not been observed as the outflow regions have yet to be surveyed. In reality, it may be some combination of the above, but it is clear more investigation is needed.

For completeness, when Eq. (11) is applied to microplastics, the outflow from the Atlantic Coast model region should have a floating microplastic content of approximately 17,600 np km^{-2} and the outflow from the North Sea Coast model region should have a microplastic content of 11,400 np km^{-2}. These values are three to four times larger than those observed (Table 5).

4.8. Absolute loadings cf. removals

A typical beach clean in Scotland removes from a stretch of beach a mixture of plastic and non-plastic materials, as well as beach sediment, water and biofouling associated with the waste. There is no accurate data either for the number of beach cleans in any one year in a specific region of the Scottish coast, nor the weight of waste removed by each beach clean. Hence currently it is difficult to obtain the total weight of plastics removed from beaches in Scotland.

The Marine Conservation Society (MCS) does record accurately the beach cleans they organise. In 2017, the MCS organised 85 beach cleans in the Atlantic Coast region, and 142 beach cleans in the North Sea Coast region (Turrell, 2019a). A typical MCS beach clean, using public volunteers, recovers between 1 and 5 tonnes of mixed beach waste (C. Paris *pers. comm.*). If we assume 10% of this by weight is actual plastic, but we also assume that local authorities and other volunteer groups do as many beach cleans in both regions as MCS organised events, then beach cleans in Scotland remove a maximum of between 20 and 80 tonnes of plastic from the Atlantic Coast region, and between 30 and 140 tonnes of plastic from the North Sea Coast region, i.e. 4%–17% of the annual input of macro plastic on the Atlantic Coast and 5%–24% on the North Sea Coast (assuming base values for model parameters). These figures are low, but not insignificant, and the huge efforts of the volunteers must be acknowledged.

Owing to the "capture" of floating plastics by a foreshore (e.g. Turrell, 2018), it can be beneficial to remove plastic litter from the marine environment using beaches as concentrating mechanisms, although, as Tramoy et al. (2019) note, it may be even easier to remove litter from rivers before it enters the sea. In Scotland, as rivers are a principle source, perhaps more emphasis might be placed on removal of litter from our rivers, and such efforts have commenced, e.g. the Water Witch debris recovery vessel on the River Clyde (BBC, 2003), and the Upstream Battle project (KSB, 2019).

4.9. Additional uncertainties

There are a number of additional reasons why the results presented in this study may be in error. The assumption that all plastics in the sea are found at the surface (i.e. that oceanic inputs are of floating plastics only) may be incorrect. For example, Kukulka et al. (2012) showed using modelling that plastics could be distributed throughout the upper mixed layer of the sea, and this would result in surface observations of plastics significantly underestimating the amounts of marine plastics. If the densities of macro plastic used in the models used in this study are assumed to represent the plastic in the upper 10 m of the sea, and these same densities persisted throughout a water column 100 m deep, then the oceanic inputs to the coastal modelled region due to the general circulation (i.e. Fig. 1, O-CUR) would be a factor of 10 greater than presented here.

A range of other processes have not been included. For example, Stokes drift might enhance the landward transport of floating plastic, particularly on the Atlantic Coast (e.g. Fazey and Ryan, 2016). Horizontal dispersion due to processes such as oceanic eddies may increase the landward flow of marine plastics. Macro plastic can break down to create smaller particles (e.g. Critchell and Lambrechts, 2016). Additionally for microplastics, recent work has suggested the importance of atmospheric deposition (e.g. Liu et al., 2019) which is not included here.

5. Conclusions

By using very simple models of the supply of floating plastic to Scottish coastal waters some basic characteristics of marine plastics in the region were derived. The main result of this preliminary estimate of the budget of marine plastics in Scottish seas is that > 60%, and more typically > 90%, is supplied by littering by the Scottish public, entering the sea through rivers. If the results are correct, it is clear that local management measures (e.g. litter reduction campaigns, beach cleans, river litter interception) of macro plastic can be effective.

However:

1) Marine processes not included in the current estimations (e.g. sub-surface marine plastics, stokes drift, oceanic dispersion) may result in greater estimates of the contributions from remote sources to Scottish beach plastics.
2) A larger sinking rate than used here of plastics on entering the sea may reduce the estimated contribution of land-based sources to Scottish beach plastics.
3) Direct sources not included in these estimates (e.g. direct from shipping vessels, direct from coastal wastewater treatment plant overflows) could increase the total amounts of plastic entering Scottish seas.

In order to improve upon the preliminary estimates of the flux budgets of floating plastic macro plastic for Scottish waters presented here we need:

1) Better estimates from observations or oceanographic models of the annual average inflows and outflows, and their characteristic variability between years, across the open sea boundaries of the Scottish sub-regions.

2) Statistically robust measurements at sea of the areal density (i.e. np km^{-2}) of floating plastic litter items at the open boundaries where inflows and outflows take place. Measurements should include average mass of the litter items. Hence capture and weighing of litter is needed to compliment visual surveys. Ideally some estimate of the variability between sub-areas/seasons/years of these parameters would be made.
3) Investigation of sub-surface plastics at sea. Is there a significant component of marine plastics entering Scottish waters throughout the water column? Investigation of the sinking rate of plastics on first entry to the sea from land-based sources.
4) Statistically robust measurements of the average weight per unit item of the plastic debris on Scottish beaches.
5) Statistically robust measurements of the amount of floating plastic litter items in the major rivers entering the Scottish coastal zone. Measurements should include both the average number of litter items per cubic metre of river water, and the average mass per cubic metre of river water. Numbers and mass by volume are probably best for riverine litter observations as the shallow and turbulent nature of many Scottish rivers may result in plastic being dispersed throughout the water column. In deeper, slower moving rivers where plastic litter is able to remain at the surface, areal density in terms of number and mass of items per unit surface area would also be appropriate. In this case the average flow speed of the river (ms^{-1}) will be needed to compute flux rather than the flow ($m^3 s^{-1}$). Measurements would ideally be taken as close to the tidal limit of the river as possible.
6) Estimates of direct inputs of floating macro plastics from land based sources (e.g. coastal littering, coastal discharges outwith rivers) and marine sources (e.g. shipping, fishing vessels, offshore platforms).
7) A full three-dimensional hydrodynamic model of Scottish seas which reproduces the principle physical driving mechanisms (i.e. wind, density, tides) coupled to a particle tracking model of floating plastic litter which includes a realistic beaching/unbeaching submodel (e.g. based on the VaWWL effect; Turrell, 2018), variable sinking rates and with realistic riverine inputs. Such a model could also include direct litter sources, both land-based and marine.

Declaration of competing interest

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

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Appendix A. Supplementary data

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