

Contents lists available at [ScienceDirect](https://www.sciencedirect.com)

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

Baseline

Modelling of marine debris pathways into UK waters: Example of non-native crustaceans transported across the Atlantic Ocean on floating marine debris

P.J. Barry^{a,*}, C. Beraud^a, L.E. Wood^{b,1}, H.J. Tidbury^b^a Centre for Environment Fisheries and Aquaculture Science, Pakefield Road, Lowestoft NR33 0HT, United Kingdom^b Centre for Environment Fisheries and Aquaculture Science, The Nothe, Barrack Road, Weymouth, Dorset DT4 8UB, United Kingdom

ARTICLE INFO

Keywords:

Non-native species
Hydrodynamic modelling
Marine debris
Pathways
Vector

ABSTRACT

The long-distance transfer of non-native, potentially invasive species via floating marine debris is an increasing threat to biodiversity and conservation efforts. To address the lack of understanding around mechanisms and pathways of species transfer via marine debris, a novel modelling approach was applied to recreate the likely trajectory and source of a large piece of debris fouled by non-native species collected from UK marine waters. This approach applied the Oil Spill Contingency and Response (OSCAR) simulation tool, an adapted oil spill modelling programme, which was informed by a combination of biological trait information for the foulant species, marine debris characteristics and hydrodynamic data. The modelling output suggested an origin in the Western Atlantic, a scenario concurrent with the known distribution of the foulant species. This modelling approach represents a valuable tool with which to determine the origin and trajectory of invasive species transferred via marine debris.

1. Introduction

Effective prevention of non-native species (NNS) requires comprehensive understanding of introduction pathways in order to identify locations at high risk of introduction, and thereby inform decisions on NNS policy and management, including risk-based biosecurity and surveillance programmes (e.g. [Convention on Biological Diversity, 2014](#); [Essl et al., 2015](#); [Tidbury et al., 2016](#); [Cassey et al., 2018](#)). Previously, relatively few assessments of pathways have considered floating marine debris and the likely consequence of a lack of available data on marine debris as a transport vector. However, the increasing volume of marine debris in the ocean is becoming a major conservation concern that requires investigation ([Sutherland et al., 2019](#)). Human-generated marine debris provides a novel artificial habitat for foulant species ([Gündoğdu et al., 2017](#)), and thus is a vector that facilitates long-distance transport beyond their native distribution when the debris is moved by wind or ocean currents. The number of studies documenting the dispersal of NNS on marine debris is steadily increasing (e.g. [Marques and Breves, 2015](#); [Masó et al., 2016](#); [Carlton et al., 2017](#); [Gündoğdu](#)

[et al., 2017](#); [Miralles et al., 2018](#); [Rech et al., 2018](#); [De-la-Torre et al., 2021](#)). However, a clear understanding of the scale of the problem, and the underlying processes that drive this phenomenon, is lacking. A key but challenging evidence gap is the identification of origins ([Kiessling et al., 2015](#)) and dispersal pathways of floating marine debris ([Rech et al., 2016](#)).

Several approaches to identify the origin of marine debris have been developed – these include the: 1) use of natural distribution patterns of foulant species and their biological traits to inform origins ([Hoeksema et al., 2012](#)); 2) exploration of taxonomic profiles of fouling communities on debris on beaches close to areas of high maritime activity, such as ports, where NNS have been found ([Miralles et al., 2018](#); [Ibabe et al., 2020](#); [Rech et al., 2018](#)); 3) linking biological traces of animals on debris to local sites (e.g. debris was attributed to a local mussel farm source following detection of attached byssal threads on debris in [Campbell et al. \(2017\)](#)); and 4) examination of the characteristics of the debris itself ([Quigley and Hill, 2015](#); [Rumbold et al., 2020](#)). Occasionally, the origin of biofouled debris can be traced using meteorological information following a large-scale weather event or natural disaster such as the

* Corresponding author.

E-mail addresses: peter.barry@cefasc.gov.uk (P.J. Barry), claire.beraud@cefasc.gov.uk (C. Beraud), louisa.wood@port.co.uk (L.E. Wood), hannah.tidbury@cefasc.gov.uk (H.J. Tidbury).¹ Current address: Centre for Blue Governance, University of Portsmouth, PO1 2UP, United Kingdom.<https://doi.org/10.1016/j.marpolbul.2022.114388>

Received 24 June 2022; Received in revised form 14 November 2022; Accepted 16 November 2022

Available online 29 November 2022

0025-326X/Crown Copyright © 2022 Published by Elsevier Ltd.

This is an open access article under the CC BY-NC-ND license

<http://creativecommons.org/licenses/by-nc-nd/4.0/>.

2011 tsunami in Japan (García-Gómez et al., 2021). Numerical modelling methods have been used to assess global (Mountford and Morales Maqueda, 2019; Guerrini et al., 2021) and regional (Rosas et al., 2021) patterns in the transport of marine debris, but to date, few studies have examined how biological attributes of the NNS transported by debris can be used in combination with hydrodynamic modelling, to gain insight into the potential pathways and trajectories of marine debris.

The aim of this study was to develop a method that combines a hydrodynamic tracking model with species' biological trait information. This combined approach is demonstrated in a case study of the dense community of live crustaceans collected from the surface of a single, large piece of floating marine debris recovered from United Kingdom (UK) coastal waters.

2. Materials and methods

A large piece of floating debris was intercepted by the research vessel *RV Cefas Endeavour* (www.cefas.co.uk/about-us/facilities/rv-cefas-endeavour/) about 12 nautical miles off the southwest coast of the UK (latitude/longitude: 50.145 N 6.019 W) on 11 April 2018 (Fig. S1). Upon recovery, the object was identified as part of a metal shipping container (Fig. S2A), which comprised three adjoining but damaged steel panels, with an approximate total area of 280 cm × 250 cm. The inner surface of the panels was coated with a 10 cm thick layer of plastic foam insulation (Fig. S2B) that provided the piece with positive buoyancy.

The submerged foam surface was found to have dense colonies of goose barnacles attached. Animals and scrapings from the foam insulation were removed and preserved in a 70 % industrial methylated spirits solution (70 % ethanol, 20 % water, 10 % glycerol). In total, 45 individual barnacles and one isopod were retained and identified using the *Synopses of the British Fauna* identification guides (Naylor and Brandt, 2015; Southward, 2008) and a monograph of the Isopoda from North America (Richardson, 1905). Photographs were taken in the laboratory. The goose barnacles were measured along the capitellum, scutum and carina. Growth of barnacle plates can only occur after settlement, so an estimated barnacle growth duration was used as a proxy for the minimum floating duration of the recovered debris. The growth duration was calculated by dividing the length of the capitellum and scutum by published plate growth rates for *Lepas* species settled on free-floating rafts (Thiel and Gutow, 2005): Floating duration (days) = total length of barnacle plate (mm) ÷ relevant growth rate (mm day⁻¹). The fastest and slowest growth rates, respectively, were used for the capitellum (0.44 mm day⁻¹; Evans, 1958) and for the scutum (0.1 mm day⁻¹; Green et al., 1994). Both growth rates were used to estimate extreme floating durations to define scenarios for the model to run. For example, a capitellum length of 27.3 mm ÷ 0.44 mm day⁻¹ = 62.05 days of growth post-settlement on the floating debris, indicating a minimum floatation period of 62 days.

The floating object was parametrised for the Oil Spill Contingency and Response (OSCAR) numerical model (Aamo et al., 1997) as a passive-drifting, floating particle transported by the surrounding current and wind conditions. To 'back-track' the drift trajectory of the object, the forces acting on the floating object were reversed in time, permitting the drifting history of the object to be re-traced (method discussed in Kako et al., 2014; Suneel et al., 2016). The date of interception, April 2018, was used as the time end-point of the drift trajectory. The OSCAR driving forces included both hydrodynamics and meteorological (wind) conditions from the re-analysis products of Copernicus (EU Copernicus Marine Services Information, 2021a, 2021b) extracted at appropriate spatio-temporal windows. In the absence of a model dedicated to tracking large plastic debris, OSCAR was adapted in our study to reflect the behaviour of an inert floating plastic object. More specifically, particle density was re-parametrised so that the back-tracked debris was positively buoyant. Further dissolution and evaporation processes associated with oil were excluded. In the absence of calibration data, default drag and windage parameters were used. The maximum

duration of the simulation was equal to the longest estimated floating duration; but the variability in growth rates defined two different scenarios of settlement windows (see previous section and Table 1). To understand better the spatio-temporal variability in hydrodynamic and meteorological forcing, graphical representation of the trajectory is presented as seven sub-drifts, each of one month duration, in reverse chronology, from interception in April 2018 backward to September 2017 (i.e., Sub-drift -1 is one month prior to the interception date, Sub-drift -3 is three months prior).

A primary environmental constraint on goose barnacle growth and reproduction is water temperature. *Lepas* species occur in tropical and sub-tropical waters, where sea surface temperatures (SST) are ≥18 °C year-round (Patel, 1959; Patel and Crisp, 1960). The SST along the modelled track was examined to determine whether barnacle settlement and growth was likely (Inatsuchi et al., 2010). Mean SST data were downloaded from the EU Copernicus Marine Services Information (2021b) at monthly intervals corresponding to each sub-drift.

In total, 45 specimens of the goose barnacle, *Lepas (Anatifa) anatifera* Linnaeus, 1758 (Crustacea: Cirripedia: Lepadidae) and a single specimen of the isopod *Idotea metallica* Bosc, 1802 (Crustacea: Isopoda: Idoteidae) were recovered from the debris (see Supplementary Information). Note that although these species range across the Atlantic Ocean and Mediterranean Sea, populations are generally concentrated below 40° N, which in the case of *I. metallica* in particular, is along the east coast of the United States of America (Naylor, 1957; Noël and Jomard, 2011).

3. Results

Amongst the 45 individuals of *Lepas anatifera*, the size range of capitellum plates was 29.1 mm and that of scutum plates 22.1 mm (Table 1), with that for carina plates being 19.9 mm (minimum/maximum = 4.9/24.8 mm) (see Supplementary Information). From these measurements, estimated floating durations ranged from 13.86 to 80 days (i.e. <1 to 3 months; short scenario) and 45 to 266 days (<2 to 7 months; long scenario) using documented fast and slow growth rates, respectively (Table 1). The faster growth rate scenario or 'short scenario', represented by Sub-drift -1 to Sub-drift -3, predicted an origin west of Ireland (Fig. 1, Table 2). Such a scenario would have involved barnacle settlement, followed by rapid growth, under a water temperature regime of 9–11 °C. The slower growth rate scenario or 'long scenario', represented by Sub-drift -1 to Sub-drift -7, predicted an origin in the Western Atlantic, then a trans-Atlantic transit lasting five months followed by a slow drift around the coastal waters of the British Isles

Table 1

Debris floating duration in days (or months where indicated) estimated using the sizes of capitellum and scutum from 45 individuals of *Lepas anatifera*, collected from the intercepted marine debris, and reported growth rates (0.44 mm day⁻¹ for the capitellum, Evans, 1958; 0.1 mm day⁻¹ for the scutum, Green et al., 1994). Those durations were then subtracted from the interception date to estimate the barnacles' settlement window.

		Capitellum	Scutum
Size (mm)	Min	6.1	4.5 ^a
	Max	35.2	26.6
	Mean	20.78	16.45
	Median	21.35	17.3
Estimated floating duration (days)	Min (short)	13.86 (<1 month)	45 (1 – 2 months)
	Max (long)	80 (3 months)	266 (7 months)
	Estimated settlement window	Jan 2018–Mar 2018 (Fast growth, short scenario) Sept 2017–Feb 2018 (Slow growth, long scenario)	

^a The smallest scutum and capitellum were from different individuals. The largest capitellum and scutum were from the same individual (see Supplementary information).

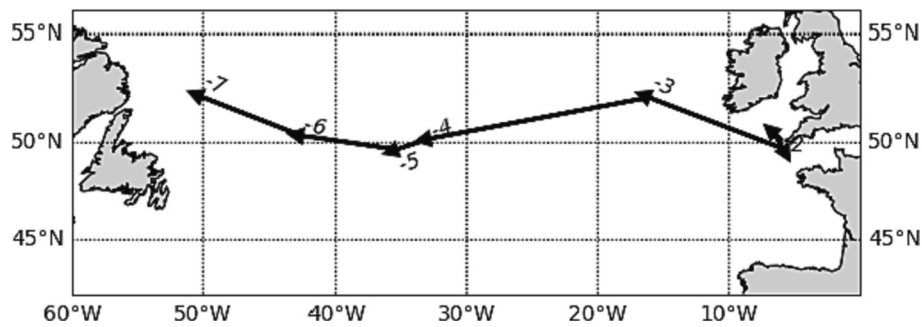


Fig. 1. Slow growth scenario model track.

Table 2

Model-projected sub-drifts for animals collected from the intercepted marine debris, with corresponding months and mean sea surface temperature derived from Copernicus (EU Copernicus Marine Services Information, 2021b) taken at monthly intervals before the interception date (11 April 2018).

Sub-drift	-7	-6	-5	-4	-3	-2	-1	0
Estimated month	Sept. 2017	Oct. 2017	Nov. 2017	Dec. 2017	Jan. 2018	Feb. 2018	Mar. 2018	Apr. 2018
Mean sea surface temperature (°C)	8.91	14.69	12.22	12.02	11.65	9.27	8.76	9.99

(Fig. 1, Table 2).

Under both scenarios, the forcing current and wind showed a gradient in magnitude from low in coastal areas to high in open sea. The forcing winter wind was also highly variable in direction. In Sub-drift -1 & -2 (February & March 2018) there was limited southward trajectory due to the proximity to the UK coast. In Sub-drift -3 (January 2018), strong easterly winds and surface currents influenced the trajectory of the debris. In Sub-drift -4 (December 2017), the wind and current were aligned in a westerly direction and resulted in the furthest drift portion. In Sub-drift -5 (November 2017), a spinning wind direction resulted in a variable trajectory, with the shortest distance travelled overall. In Sub-drift -6 & -7 (September & October 2017), wind and wave forces were westerly in direction, though wind variability remained high. In Sub-drift -7, the modelled track of the debris extended to the Labrador Sea off the North American continent; thus, under this simulated trajectory the debris is proposed to have originated in the Western Atlantic. The temperature range across the simulated track was relatively low. At the end of Sub-drift -7, the mean daily SST was 8.91 °C due to the high latitude and time of year; however, water temperatures were moderate across Sub-drift -6 to Sub-drift -3 (11.65 to 14.69 °C) until early in 2018, when the rafting colony would have been exposed to much colder winter water temperatures (<10 °C) prior to interception.

4. Discussion

Our study outlines a methodological approach that integrates species' biological trait information with hydrodynamic data. This combined approach has proved useful in the case of a single interception of debris of unknown origin, colonised by widespread oceanic species that have a range of thousands of miles of ocean. This approach contributes to efforts to determine a potential source and suggest different scenarios for the object's transit to the UK. Under the short scenario, model outputs suggest that barnacle settlement occurred west of Ireland, early in Winter 2018. The likelihood of viable planktonic larvae settling and growing rapidly under such relatively low SST (8–10 °C during the relevant months) is very low when considering the tolerances and measured growth rates of this and other *Lepas* species at such temperatures (Patel, 1959; Inatsuchi et al., 2010). Within this timeframe, and under the prevailing environmental conditions, the barnacles were unlikely to achieve the rapid growth rates required for adult specimens to attain a mean capitulum length of >20 mm (Table 1). As such, the long scenario of 266 days was considered more realistic. Laboratory-reared specimens of *L. anatifera* have been known to survive temperatures as

low as 8 °C; but observed moulting rates, when kept at 8–14 °C, were less than half of those observed when the barnacles were kept in water of 20–25 °C, simulating the tropical conditions where *L. anatifera* are concentrated (Patel, 1959). Therefore, a longer transit (over seven months) would permit the barnacles to achieve capitulum lengths of >20 mm under the lower SST. While the SST dropped very low during the transit, it would not have caused the total mortality of the entire barnacle colony (Inatsuchi et al., 2010). Lastly, since the end point of the model's track would still be above 50°N, with relatively low SST (<9 °C), an original settlement in the Western Atlantic but at more southerly latitudes must be considered. Barnacle settlement may have occurred outside the 266 days' floating duration used by the model, possibly in more southerly waters, before the debris joined the proposed track; however, such a scenario is beyond the timeframe that can be inferred from the available biological data. This uncertainty underscores the difficulty of calculating a likely origin of marine debris using a single point of interception and only two species.

While the presence of *Idotea metallica* supports the origin in the Western Atlantic theory, given its known distribution and wide environmental tolerances (Naylor, 1957; Franke et al., 1999; Quigley and Hill, 2015), this species was not included in calculations since it is mobile, capable of swimming between rafting objects (Abelló et al., 2004) and may have joined the raft at any time during its transit. This is in contrast to *L. anatifera* which can only grow once permanent attachment to an object is formed. It is unusual to recover just two species from floating debris, in particular given the presence of a foundation species, such as *L. anatifera* (Gil and Pfaller, 2016). However, the conditions encountered on trans-Atlantic transit on an abiotic substrate would have been challenging (Bravo et al., 2011) and outside the tolerance ranges of many rafting species over an extended time period (Tsikhon-Lukanina et al., 2001). Further, a trajectory through open ocean, thereby not passing coastal waters, makes colonisation during transit unlikely. Large marine litter sinks such as the North Atlantic garbage patch (Law et al., 2010) could provide a source of animals along the proposed trajectory, though it is unlikely for *L. anatifera*, as the spawning temperature required is above that in the location of the garbage patch.

Even with the data available, a number of assumptions had to be made about the growth of the barnacles and the behaviour of the floating object. Crustacean growth rates have been applied previously to generate what has been termed 'relatively reasonable estimates of floating duration' (p. 373; Thiel and Gutow, 2005) of fouled debris. However, this approach provides a 'minimum' period of floating, and

the true timeframe could have been much longer. Further, the rates estimated from laboratory studies were most likely based on the assumption of linear growth under relatively stable environmental conditions and no within-population variation. To account for this, growth rates from free-floating oceanic populations (not laboratory-reared specimens) were used (Evans, 1958; Green et al., 1994) in our study to estimate floating durations. However, the estimates used do not necessarily reflect conditions that could be viewed as similar to those in the Northern Atlantic during winter, because these animals are not regularly found outside the tropics and therefore would have faced much colder water temperatures, slowing metabolism and growth (Inatsuchi et al., 2010).

Further, an inhomogeneous change in the debris' surface roughness and density, with resulting variation in drag and/or windage, could potentially have occurred due to the alteration of the macrofaunal community structure following succession, and increased abundance and growth of the goose barnacles (Tsikhon-Lukanina et al., 2001; Thiel and Gutow, 2005). Similarly, biofouling can alter a floating object's behaviour and its position in, and trajectory through, the water column. Continuous oscillation of plastic debris near the water surface has been observed to result from biofouling and from the water column characteristics, e.g., stratification (Kreczak et al., 2021). Therefore, incorporation of the effect of biofouling and capture of the interaction with water column characteristics can be challenging. In addition to those biologically-induced changes, other processes such as weathering and erosion could alter the debris' characteristics (van Sebille et al., 2020), thereby affecting the drift dynamics. Plastic debris can drift over very long distances, and its characteristics are subjected to the ambient environmental conditions (e.g., meteorological, oceanic, biologic, chemical), which are dynamic. While some authors have already documented and quantified plastic degradation rates (Gerritse et al., 2020; Egger et al., 2020), these rates have rarely been included in tracking models. These uncertainties underline the difficulty in merging biotic and abiotic information with spatial hydrodynamic modelling – uncertainties that need to be addressed in order to improve modelling approaches to inform NNS monitoring and prevention. However, the general drift direction pointing to a Western Atlantic source, identified in this study, is supported by observations and re-analysed current and wind data (Garraffo et al., 2001; EU Copernicus Marine Services Information, 2021b; Laurila et al., 2021).

The approach described here to predict the debris likely origin relies on the correct identification of the colonising fauna and inclusion of their relevant biological trait information, including temperature tolerance, to parameterise the hydrodynamic- and meteorological-based numerical model. As such, this novel approach builds upon previously developed techniques that have been applied to investigate the potential origins and trajectories of marine debris, such as floating buoys (Astudillo et al., 2009). Complementary analysis of litter characteristics (e.g., labels, markings) to infer likely origin (e.g., Quigley and Hill, 2015) would have been valuable but was not possible in this instance given the lack of defining features on the intercepted debris. With the advance of more sophisticated numerical modelling techniques that can track drifting debris (e.g., Palatinus et al., 2019; Turrell, 2020; Vriend et al., 2020), combined with established techniques to gauge drift durations using attached biota (Thiel and Gutow, 2005; Mesaglio et al., 2021), more robust estimation of source location is now possible. This advance comes at a time of growing awareness of species rafting on marine debris, including NNS (García-Gómez et al., 2021; Haram et al., 2021; Póvoa et al., 2021). Future studies could employ the approach described here to inform on the likely origins of other drifting debris with attached or associated organisms if growth patterns have been established. The accuracy of model outputs will be best validated for organisms with a more narrowly defined distribution. Finally, in terms of the Convention on Biological Diversity (CBD) Pathway Classification, we recommend that floating marine debris be assigned to the “Transport – stowaway” category (Pergl et al., 2020), given that human-generated marine debris,

although transported by natural forces (pathway unaided), is effectively a form of hitch-hiking. We also recommend that increased effort is made to understand sources and sinks (Rech et al., 2016).

CRediT authorship contribution statement

P. J. Barry: Conceptualisation, methodology, data analysis, writing original draft; C. Beraud: Methodology, writing-review and edit; L. E. Wood: Conceptualisation, writing-review and edit; H. Tidbury: writing-review, edit.

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.

Data availability

Data will be made available on request.

Acknowledgements

The OSCAR model was forced using data from EU Copernicus Marine Service available from <http://marine.copernicus.eu/services-portfolio/access-to-products/>. We thank Alex Callaway for providing the original sample material and location map. We thank G.H. Copp for constructive comments on earlier versions of the manuscript.

Funding

This work was supported by the Department for Environment, Food & Rural Affairs [SLA29 and GIA 07] and Cefas' Internal Development Fund. Part of the work by L.E. Wood was supported by the Natural Environment Research Council [NERC Award No. NE/V009516/1].

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.marpolbul.2022.114388>.

References

- Aamo, O.M., Reed, M., Downing, K., 1997. Oil spill contingency and response (OSCAR) model system: sensitivity studies. *Int.Oil Spill Conf.Proc.* 1997, 429–438. <https://doi.org/10.7901/2169-3358-1997-1-429>.
- Abelló, P., Guerao, G., Codina, M., 2004. Distribution of the neustonic isopod *Idotea metallica* (Crustacea, Isopoda, Idoteidae) in the western Mediterranean. *J. Crustac. Biol.* 24, 558–566. [10.1651/C-2505](https://doi.org/10.1651/C-2505).
- Astudillo, J., Bravo, M., Dumont, C., Thiel, M., 2009. Detached aquaculture buoys in the SE Pacific: potential dispersal vehicles for associated organisms. *Aquat. Biol.* 5, 219–231. <https://doi.org/10.3354/ab00151>.
- Bravo, M., Astudillo, J.C., Lancellotti, D., Luna-Jorquera, G., Valdivia, N., Thiel, M., 2011. Rafting on abiotic substrata: properties of floating items and their influence on community succession. *Mar. Ecol. Prog. Ser.* 439, 1–17. <https://doi.org/10.3354/meps09344>.
- Campbell, M.L., King, S., Heppenstall, L.D., van Gool, E., Martin, R., Hewitt, C.L., 2017. Aquaculture and urban marine structures facilitate native and non-indigenous species transfer through generation and accumulation of marine debris. *Mar. Pollut. Bull.* 123, 304–312. <https://doi.org/10.1016/j.marpolbul.2017.08.040>.
- Carlton, J.T., Chapman, J.W., Geller, J.B., Miller, J.A., Carlton, D.A., McCuller, M.I., Treneman, N.C., Steves, B.P., Ruiz, G.M., 2017. Tsunami-driven rafting: transoceanic species dispersal and implications for marine biogeography. *Science* 357, 1402–1406. <https://doi.org/10.1126/science.aao1498>.
- Cassey, P., García-Díaz, P., Lockwood, J.L., Blackburn, T.M., 2018. Invasion biology: searching for predictions and prevention, and avoiding lost causes. In: Jeschke, J.M., Heger, T. (Eds.), *Invasion Biology: Hypotheses and Evidence*. CABI, Boston, pp. 3–13, 192 pp.
- Convention on Biological Diversity, 2014. Pathways of Introduction of Invasive Species, Their Prioritization and Management. UNEP/CBD/SBSTTA/18/0/Add. 1, Montreal, Canada, June 2014, 18 pp. www.cbd.int/doc/meetings/sbstta/sbstta-18/official/sbstta-18-09-add1-en.pdf.

- De-la-Torre, G.E., Dioses-Salinas, D.C., Pérez-Baca, B.L., Millones Cumpa, L.A., Pizarro-Ortega, C.I., Torres, F.G., Gonzales, K.N., Santillán, L., 2021. Marine macroinvertebrates inhabiting plastic litter in Peru. *Mar. Pollut. Bull.* 167, 112296 <https://doi.org/10.1016/j.marpolbul.2021.112296>.
- Egger, M., Sulu-Gambari, F., Lebreton, L., 2020. First evidence of plastic fallout from the North Pacific garbage patch. *Sci. Rep.* 10, 1–10. <https://doi.org/10.1038/s41598-020-64465-8>.
- Essl, F., Bacher, S., Blackburn, T.M., Booy, O., Brundu, G., Brunel, S., Cardoso, A.-C., Eschen, R., Gallardo, B., Galil, B., García-Berthou, E., Genovesi, P., Groom, Q., Harrower, C., Hulme, P.E., Katsanevakis, S., Kenis, M., Kühn, I., Kumschick, S., Martinou, A.F., Nentwig, W., O'Flynn, C., Pagad, S., Pergl, J., Pyšek, P., Rabitsch, W., Richardson, D.M., Roques, A., Roy, H.E., Scalera, R., Schindler, S., Seebens, H., Vanderhoeven, S., Vilà, M., Wilson, J.R.U., Zenetos, A., Jeschke, J.M., 2015. Crossing frontiers in tackling pathways of biological invasions. *BioScience* 65, 769–782. <https://doi.org/10.1093/biosci/biv082>.
- EU Copernicus Marine Services Information, 2021. Global Ocean Physics Analysis - CERSAT-GLO-BLENDED WIND L4 REP-V6-OBS FULL TIME SERIE.
- EU Copernicus Marine Services Information, 2021. Global Ocean Physics Analysis -GLOBAL REANALYSIS PHY_001_030/INFORMATION.
- Evans, F., 1958. Growth and maturity of the barnacles *Lepas hillii* and *Lepas anatifera*. *Nature* 182, 1245–1246.
- Franke, H.-D., Gutow, L., Janke, M., 1999. The recent arrival of the oceanic isopod *Idotea metallica* Bosc off Helgoland (German Bight, North Sea): and indication of a warming trend in the North Sea? *Helgol. Meeresunters.* 52, 347–357. <https://doi.org/10.1007/BF02908908>.
- García-Gómez, J.C., Garrigós, M., Garrigós, J., 2021. Plastic as a vector of dispersion for marine species with invasive potential: a review. *Front. Ecol. Evol.* 9, 1–28. <https://doi.org/10.3389/fevo.2021.629756>.
- Garraffo, Z.D., Mariano, A.J., Griffo, A., Veneziani, C., Chassignet, E.P., 2001. Lagrangian data in a high-resolution numerical simulation of the North Atlantic I. Comparison with in situ drifter data. *J. Mar. Syst.* 29, 157–176. [https://doi.org/10.1016/S0924-7963\(01\)00015-X](https://doi.org/10.1016/S0924-7963(01)00015-X).
- Gerritse, J., Leslie, H.A., de Tender, C.A., Devriese, L.I., Vethaak, A.D., 2020. Fragmentation of plastic objects in a laboratory seawater microcosm. *Sci. Rep.* 10, 1–17. <https://doi.org/10.1038/s41598-020-67927-1>.
- Gil, M.A., Pfaller, J.B., 2016. Oceanic barnacles act as foundation species on plastic debris: implications for marine dispersal. *Sci. Rep.* 6, 19987. <https://doi.org/10.1038/srep19987>.
- Green, A., Tyler, P.A., Angel, M.V., Gage, J.D., 1994. Gametogenesis in deep- and surface-dwelling oceanic stalked barnacles from the NE Atlantic Ocean. *J. Exp. Mar. Biol. Ecol.* 184, 143–158. [https://doi.org/10.1016/0022-0981\(94\)90001-9](https://doi.org/10.1016/0022-0981(94)90001-9).
- Guerrini, F., Mari, L., Casagrandi, R., 2021. The dynamics of microplastics and associated contaminants: data-driven Lagrangian and Eulerian modelling approaches in the Mediterranean Sea. *Sci. Total Environ.* 777, 145944 <https://doi.org/10.1016/j.scitotenv.2021.145944>.
- Gündoğdu, S., Çevik, C., Karaca, S., 2017. Fouling assemblage of benthic plastic debris collected from Mersin Bay, NE Levantine coast of Turkey. *Mar. Pollut. Bull.* 124, 147–154. <https://doi.org/10.1016/j.marpolbul.2017.07.023>.
- Haram, L.E., Carlton, J.T., Centurioni, L., Crowley, M., Hafner, J., Maximenko, N., Clarke Murray, C., Shcherbina, A.Y., Hormann, V., Wright, C., Ruiz, G.M., 2021. Emergence of a neopelagic community through the establishment of coastal species on the high seas. *Nat. Commun.* 12, 1–5. <https://doi.org/10.1038/s41467-021-27188-6>.
- Hoeksema, B.W., Roos, P.J., Cadée, G.C., 2012. Trans-Atlantic rafting by the brooding reef coral *Favia fragum* on man-made flotsam. *Mar. Ecol. Prog. Ser.* 445, 209–218. <https://doi.org/10.3354/meps09460>.
- Ibabe, A., Rayón, F., Martínez, J.L., García-Vazquez, E., 2020. Environmental DNA from plastic and textile marine litter detects exotic and nuisance species nearby ports. *PLoS ONE* 15, 1–20. <https://doi.org/10.1371/journal.pone.0228811>.
- Inatsuchi, A., Yamato, S., Yusa, Y., 2010. Effects of temperature and food availability on growth and reproduction in the neustonic pedunculate barnacle *Lepas anserifera*. *Mar. Biol.* 157, 899–905. <https://doi.org/10.1007/s00227-009-1373-0>.
- Kako, S., Isobe, A., Kataoka, T., Hinata, H., 2014. A decadal prediction of the quantity of plastic marine debris littered on beaches of the East Asian marginal seas. *Mar. Pollut. Bull.* 81, 174–184. <https://doi.org/10.1016/j.marpolbul.2014.01.057>.
- Kiessling, T., Gutow, L., Thiel, M., 2015. Marine litter as habitat and dispersal vector. In: Bergmann, M., et al. (Eds.), *Marine Anthropogenic Litter*. Springer, Heidelberg, pp. 141–181. https://doi.org/10.1007/978-3-319-16510-3_447 pp.
- Kreczak, H., Willmott, A.J., Baggaley, A.W., 2021. Subsurface dynamics of buoyant microplastics subject to algal biofouling. *Limnol. Oceanogr.* 66, 3287–3299. <https://doi.org/10.1002/lno.11879>.
- Laurila, T.K., Sinclair, V.A., Gregow, H., 2021. Climatology, variability, and trends in near-surface wind speeds over the North Atlantic and Europe during 1979–2018 based on ERA5. *Int. J. Climatol.* 41, 2253–2278. <https://doi.org/10.1002/joc.6957>.
- Law, K.L., Morét-Ferguson, S., Maximenko, N.A., Proskurowski, G., Peacock, E.E., Hafner, J., Reddy, C.M., 2010. Plastic accumulation in the North Atlantic Subtropical Gyre. *Science* 329, 1185–1188. <https://doi.org/10.1126/science.1192321>.
- Marques, R.C., Breves, A., 2015. First record of *Pinctada imbricata* Röding, 1798 (Bivalvia: Pterioidea) attached to a rafting item: a potentially invasive species on the Uruguayan coast. *Mar. Biodivers.* 45, 333–337. <https://doi.org/10.1007/s12526-014-0258-8>.
- Masó, M., Fortuño, J.M., De Juan, S., Demestre, M., 2016. Microfouling communities from pelagic and benthic marine plastic debris sampled across Mediterranean coastal waters. *Sci. Mar.* 80, 117–127. <https://doi.org/10.3989/scimar.04281.10A>.
- Mesaglio, T.P., Schilling, H.T., Adler, L., Ahyong, S.T., Maslen, B., Suthers, I.M., 2021. The ecology of lepas-based biofouling communities on moored and drifting objects, with applications for marine forensic science. *Mar. Biol.* 168, 21 <https://doi.org/10.1007/s00227-021-03822-1>.
- Miralles, L., Gomez-Agenjo, M., Rayon-Viña, F., Gyraitė, G., Garcia-Vazquez, E., 2018. Alert calling in port areas: marine litter as possible secondary dispersal vector for hitchhiking invasive species. *J. Nat. Conserv.* 42, 12–18. <https://doi.org/10.1016/j.jnc.2018.01.005>.
- Mountford, A.S., Morales Maqueda, M.A., 2019. Eulerian modeling of the three-dimensional distribution of seven popular microplastic types in the global ocean. *J. Geophys. Res. Oceans* 124, 8558–8573, [10.1029/2019JC015050](https://doi.org/10.1029/2019JC015050).
- Naylor, E., 1957. The occurrence of *Idotea metallica* Bosc in British waters. *J. Mar. Biol. Assoc. UK* 36, 599–602. <https://doi.org/10.1017/S002531540002587X>.
- Naylor, E., Brandt, A., 2015. *Intertidal Marine Isopods*. (Synopses of the British Fauna 3), Second edition. Field Studies Council, Shrewsbury, UK. 144 pp.
- Noël, P.-Y., Jomard, C., 2011. Présence du crustacé *Idotea metallica* (Isopoda: Valvifera) dans le Parc national de Port-Cros (France, Méditerranée). In: *Scientific Reports of the Port-Cros National Park*, France, 25, pp. 173–187.
- Palatinus, A., Kovač Viršek, M., Robić, U., Grego, M., Bajt, O., Šiljić, J., Suaria, G., Liubartseva, S., Coppini, G., Peterlin, M., 2019. Marine litter in the Croatian part of the middle Adriatic Sea: simultaneous assessment of floating and seabed macro and micro litter abundance and composition. *Mar. Pollut. Bull.* 139, 427–439. <https://doi.org/10.1016/j.marpolbul.2018.12.038>.
- Patel, B., 1959. The influence of temperature on the reproduction and moulting of *Lepas anatifera* L. under laboratory conditions. *J. Mar. Biol. Assoc. U. K.* 38, 589–597. <https://doi.org/10.1017/S0025315400007013>.
- Patel, B., Crisp, D.J., 1960. The influence of temperature on the breeding and the moulting activities of some warm-water species of operculate barnacles. *J. Mar. Biol. Assoc. U. K.* 39, 667–680. <https://doi.org/10.1017/S002531540001362X>.
- Pergl, J., Brundu, G., Harrower, C.A., Cardoso, A.C., Genovesi, P., Katsanevakis, S., Lozano, V., Perglová, I., Rabitsch, W., Richards, G., Roques, A., Rorke, S.L., Scalera, R., Schönrogge, K., Stewart, A., Tricarico, E., Tsiamis, K., Vannini, A., Vilà, M., Zenetos, A., Roy, H.E., 2020. Applying the convention on biological diversity pathway classification to alien species in Europe. *Neobiota* 62, 333–363. <https://doi.org/10.3897/neobiota.62.53796>.
- Póvoa, A.A., Skinner, L.F., de Araújo, F.V., 2021. Fouling organisms in marine litter (rafting on abiotic substrates): a global review of literature. *Mar. Pollut. Bull.* 166, 112189 <https://doi.org/10.1016/j.marpolbul.2021.112189>.
- Quigley, D.T.G., Hill, R., 2015. A further record of the marine isopod *Idotea metallica* Bosc, 1802 in Irish waters and a review of the species/habitats, trophic association and ecology in NW European waters. *Bull. Ir. Biogeogr. Soc.* 39, 222–242.
- Rech, S., Borrell, Y., García-Vazquez, E., 2016. Marine litter as a vector for non-native species: what we need to know. *Mar. Pollut. Bull.* 113, 40–43. <https://doi.org/10.1016/j.marpolbul.2016.08.032>.
- Rech, S., Salmína, S., Borrell Pichs, Y.J., García-Vazquez, E., 2018. Dispersal of alien invasive species on anthropogenic litter from European mariculture areas. *Mar. Pollut. Bull.* 131, 10–16. <https://doi.org/10.1016/j.marpolbul.2018.03.038>.
- Richardson, H., 1905. *Monograph on the isopods of North America*. Bull. U. S. Nat. Mus. 54, 1–727.
- Rosas, E., Martins, F., Janeiro, J., 2021. Marine litter on the coast of the Algarve: main sources and distribution using a modeling approach. *J. Mar. Sci. Eng.* 9, 412 <https://doi.org/10.3390/jmse9040412>.
- Rumbold, C.E., García, G.O., Seco Pon, J.P., 2020. Fouling assemblage of marine debris collected in a temperate South-Western Atlantic coastal lagoon: a first report. *Mar. Pollut. Bull.* 154, 111103 <https://doi.org/10.1016/j.marpolbul.2020.111103>.
- van Sebille, E., Aliani, S., Law, K.L., Maximenko, N., Alsina, J.M., Bagaev, A., Bergmann, M., Chapron, B., Chubarenko, I., Cózar, A., Delandmeter, P., Egger, M., Fox-Kemper, B., Garaba, S.P., Goddijn-Murphy, L., Hardesty, B.D., Hoffman, M.J., Isobe, A., Jongedijk, C.E., Kaandorp, M.L.A., Khattullina, L., Koelmans, A.A., Kukuika, T., Laufkötter, C., Lebreton, L., Lobelle, D., Maes, C., Martínez-Vicente, V., Morales Maqueda, M.A., Poulain-Zarcos, M., Rodríguez, E., Ryan, P.G., Shanks, A.L., Shim, W.J., Suaria, G., Thiel, M., van den Bremer, T.S., Wichmann, D., 2020. The physical oceanography of the transport of floating marine debris. *Environ. Res. Lett.* 15, 023003 <https://doi.org/10.1088/1748-9326/ab6d7d>.
- Southward, A.J., 2008. *Barnacles*. (Synopses of the British Fauna 57). Field Studies Council, Shrewsbury, UK, 152 pp.
- Sutherland, W.J., Fleishman, E., Clout, M., Gibbons, D.W., Lickorish, F., Peck, L.S., Pretty, J., Spalding, M., Ockendon, N., 2019. Ten years on: a review of the first global conservation horizon scan. *Trends Ecol. Evol.* 34, 139–153. <https://doi.org/10.1016/j.tree.2018.12.003>.
- Suneel, V., Ciappa, A., Vethamony, P., 2016. Backtrack modeling to locate the origin of tar balls depositing along the west coast of India. *Sci. Total Environ.* 569–570, 31–39. <https://doi.org/10.1016/j.scitotenv.2016.06.101>.
- Thiel, M., Gutow, L., 2005. The ecology of rafting in the marine environment. II. The rafting organisms and community. *Oceanogr. Mar. Biol.* 43, 279–418. <https://doi.org/10.1201/9781420037449.ch7>.
- Tidbury, H.J., Taylor, N.G., Copp, G.H., Garnacho, E., Stebbing, P.D., 2016. Predicting and mapping the risk of introduction of marine non-indigenous species into Great Britain and Ireland. *Biol. Invasions* 18, 3277–3292. <https://doi.org/10.1007/s10530-016-1219-x>.

- Turrell, W.R., 2020. Estimating a regional budget of marine plastic litter in order to advise on marine management measures. *Mar. Pollut. Bull.* 151, 110725 <https://doi.org/10.1016/j.marpolbul.2019.110725>.
- Tsikhon-Lukanina, E.A., Reznichenko, O.G., Nikolaeva, G.G., 2001. Ecology of invertebrates on oceanic floating substrata in the North-Western Pacific. *Russ. Acad. Sci. Oceanol.* 41, 550–555.
- Vriend, P., van Calcar, C., Kooi, M., Landman, H., Pikaar, R., van Emmerik, T., 2020. Rapid assessment of floating macroplastic transport in the Rhine. *Front. Mar. Sci.* 7, 1–8. <https://doi.org/10.3389/fmars.2020.00010>.