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LETTER

Augmentation of global marine sedimentary carbon storage in the age of plastic

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Scientific Significance Statement

The impact of plastic on the marine environment is clear from polluting beaches and damaging marine life. Yet, little consideration has been given to the potential that plastic entering the global oceans could change the marine carbon (C) system. Through compiling current data on the flows and deposition of plastic in the marine environment in conjunction with the C content of different plastics, it is estimated that between 17.2 and 57.1 Mt of C is stored on the seabed. Additionally a further, 7.8 Mt C in the form of plastic is trapped each year which is equivalent to many natural hotspots for C burial in the marine environment.

Abstract

Plastic is entering the world's oceans at an unprecedented rate impacting the functioning of the natural marine environment. Yet little consideration has been given to the potential of carbon (C) in the form of plastic (C_{plas}) to augment the marine carbon system. Here it is shown that C_{plas} is an integral part of the anthropogenic marine C cycle. Annually, 7.8 ± 1.73 Mt of C_{plas} is deposited at the seabed with a further 17.2–57.1 Mt C_{plas} already present on the seafloor. The quantity of C_{plas} currently being deposited on the seabed annually exceeds the rate at which organic carbon (OC) is buried in some marine sediments and by 2050 it is possible that the rate at which C_{plas} is buried will match fjord sediments which are global hotspots for OC burial. Though unwanted this new anthropogenic pathway for C to reach the marine environment cannot be ignored.

Coastal, shelf, and deep-sea surficial sediments store an estimated 43,000 Mt of organic carbon (OC) and bury 169 Mt OC annually (Hedges et al. 1997; Smith et al. 2015; Lee et al. 2019). Coastal and inshore seas in particular are recognized as hotspots for the burial and storage of C (Smith et al. 2015; Bianchi et al. 2020). OC that is buried and stored within marine sediments originates from biospheric and petrogenic sources. Biospheric OC is produced by living organisms in the marine and terrestrial environments (Bianchi 2011; Krause-Jensen and Duarte 2016); petrogenic OC is sourced largely from sedimentary rocks (Galy et al. 2008). Recently the large-scale introduction of plastic to the marine environment potentially introduces a new yet unquantified pathway for large quantities of C to enter the world's oceans.

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

Current estimates place the quantity of plastic particles floating in the world's ocean at between 15 and 50 trillion with an estimated mass of between 93 and 236 t (Eriksen et al. 2014; Van Sebille et al. 2015; Lebreton et al. 2017). Yet, this only represents 1% of the plastic entering the oceans annually (Van Sebille et al. 2015; Lebreton et al. 2017). Multiple fates await the other 99% of the plastic that enters the marine environment. These include deposition along coastlines (Smith and Markic 2013; Ryan et al. 2014), transport to the deep ocean (Cózar et al. 2014; Courtene-Jones et al. 2019), consumption by fauna (Courtene-Jones et al. 2019), accumulation at the seabed (Pham et al. 2014; Jambeck et al. 2015), and potentially redistribution across the seafloor by natural and anthropogenic disturbance (Kane and Clare 2019).

There are multiple environmental implications for marine habitats due to the introduction of plastic (e.g., Gregory 2009), but the increased quantity of C entering the world's oceans in the form of plastic (C_{plas}) and the impact it may have on the wider benthic C cycle has not yet been considered or quantified. The majority of the plastic reaching the seabed is nonbiodegradable (Gregory and Andrady 2003); therefore, the plastic has been widely assumed to be inert and unlikely impact atmospheric CO_2 concentrations. Yet, there are avenues in which C_{plas} could positively or negatively affect benthic C cycle in global sediments. Ladewig et al. (2021) outline two potential scenarios:

i. C_{plas} is utilized as and energy source by the benthic microbes, increasing organic matter decomposition and CO_2 remineralization.
ii. C_{plas} is toxic and harmful to the benthic microbial life, reducing the decomposition of organic matter and associated CO_2 remineralization.

Many questions remain on the impact of C_{plas} on the C cycle, but first we must understand the magnitude of the C_{plas} already stored in the world's oceans. Here, the quantity of C stored on the seafloor in the form of plastic and the rate at which these C_{plas} stores form are estimated, laying the foundations for further research to understand the new role of C_{plas} in the benthic and wider marine C cycle.

Methods

Plastics were collected representing the six most common varieties alongside five more specialized types (Table 1). Each plastic type can come in multiple forms, for example, polystyrene (PS) can be found in expanded (Styrofoam) or ridged (i.e., yogurt pots) forms; different forms of each plastic were selected to ensure a representative sample set (Table 1).

The plastic samples were reduced in size (< 2 mm) and placed in ultra-pure Milli-Q water and sonicated for 10 min, drained, and the process repeated five times to reduce the chance of contamination. Once washed the samples were dried at 40°C for 24 h. The C content (%) of the different plastics was measured by Elemental analysis. Triplicate measurements for each type of plastic were undertaken following the standard methodology (Verardo et al. 1990). Briefly, a subsample (10 mg) of the plastic was placed in a tin capsule and sealed. The samples underwent elemental analysis using an Elementar Vario EL. Analytical precision was estimated from repeat analysis of standard reference material sulfanilamide. The measured standards (n = 20) deviated from a known value (C: 41.81% ± 0.21%) by 0.07% ± 0.03%.

Table 1. Details of the different materials used to quantify the C content of each plastic type.

Plastic type	Source material
Common plastic	
Polyethylene terephthalate (PET)	Fruit container, soft drink bottle
High-density polyethylene (HDPE)	Milk bottle, milk bottle cap (green), bottle cap (orange)
Polyvinyl chloride (PVC)	Bubble wrap, plastic bag, laboratory water bottle
Low-density polethylene (LDPE)	Gray pipe, clear vacuum tubing, card wallet
Polypropylene (PP)	Blue rope, document wallet, takeaway container
Polystyrene (PS)	Expanded PS packaging, egg box, yogurt pot
Specialized plastic	
Nylon	Blue sheeting
Polycarbonate	Lexan sheeting
Acrylic	Blue sheeting
Acetal C	Clear tile
Polyurethane	Black ridged tubing

Results and interpretation

The rates at which plastic enters the world's oceans and reaches sinks within sub- and intertidal environments are highly complex (Horton and Dixon 2018; Kane and Clare 2019). To facilitate a global first-order estimate of the C_{plas} entering and being stored in the marine environment, the flows of plastic data from the literature were condensed to their simplest form (Table 2). By simplifying these rates, we reduce the complexity; for example, significant quantities of plastic are found in epipelagic and mesopelagic water columns (Choy et al. 2019) yet the complex nature of vertical settling and lateral advection (Liubartseva et al. 2018) on plastic within water columns means that it is impractical to integrate such data into a first order estimate of C_{plas} in the world's

Table 2. Simplified plastic flows through the environment used to calculate the quantity of C_{plas} entering the world's oceans.

	Plastic flow (Mt yr^{-1})	% of total plastic	Reference
Source			
Land	9.50	77.87	Jambeck et al. (2015)
Maritime activities	1.75	14.34	Barnes et al. (2009)
Primary microplastics	0.95	7.79	Eunomia Research and Consulting Ltd (2016)
Total	**12.20**		
Sink			
Seabed	11.47	94.02	Pham et al. (2014)
Beach	0.61	5.00	Smith and Markic (2013), Ryan et al. (2014)
Ocean surface (floating)	0.12	0.98	Cózar et al. (2014), Eriksen et al. (2014)
Total	**12.20**		

oceans. By reducing the complexity of these rates, the uncertainties in the final C_{plas} estimates undoubtedly increase.

It was estimated that 12.2 Mt of plastic enters the marine environment annually (Jambeck et al. 2015) from various sources (Table 2). This plastic is deposited in sub- and intertidal habitats around the world with the majority (11.47 Mt) accumulating on the seabed (Table 2).

The C content varies with plastic type (Fig. 1A). The mean C content for the six most common plastics equals 74.63% ± 15.81%, while the more specialized plastics contain less C on average (59.72% ± 8.9%). Across this mix of all plastics, the mean C content is 68.05% ± 15.05%. Using the mean C content for all plastics (68.05% ± 15.05%) in combination with the quantified flows of plastic (Table 2), it is estimated that 8.3 ± 1.84 Mt C_{plas} yr^{-1} enters the marine environment with 7.8 ± 1.73 Mt C_{plas} yr^{-1} reaching the seabed.

The 7.8 ± 1.73 Mt of C_{plas} which reaches the seabed annually is greater than the natural annual OC burial in carbonate

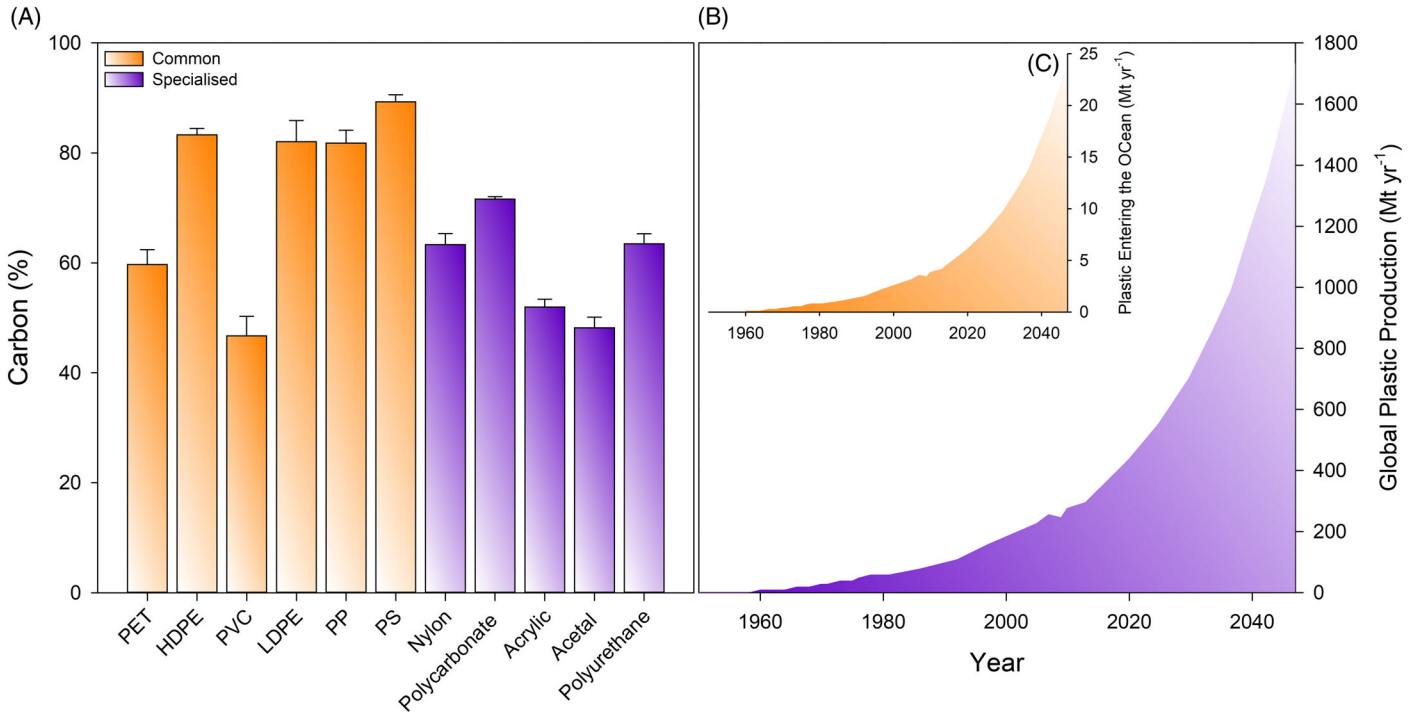

Fig 1. Plastic properties. (**A**) Carbon content (%) of the six most common plastics (PET, HDPE, PVC, LDPE, PP, PS) alongside five specialized plastics, error bars represent one standard deviation. (**B**) Current and predicted global plastic production (1960–2050) (plastics Europe 2016). (**C**) Current and future estimates of plastic entering the marine environment (Mt yr^{-1}). Annual plastic input to the world's oceans estimated as 1.4% of annual plastic production (Jang et al. 2015).

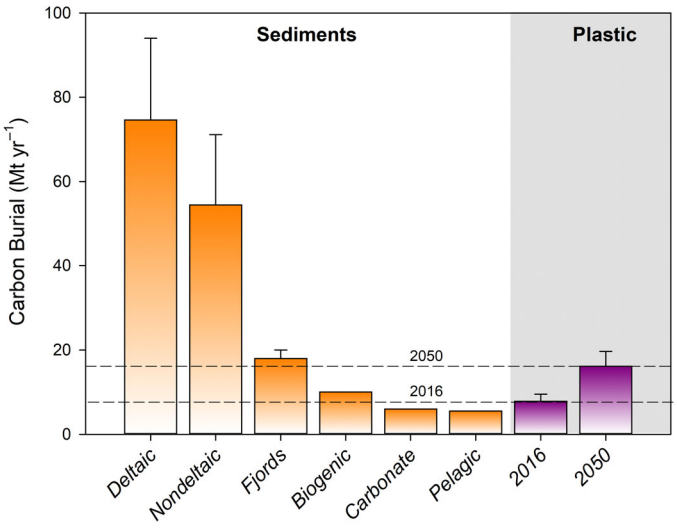

Fig 2. Annual OC burial in seabed sediments. Absolute yield of OC buried each year (Mt yr^{-1}) (Hedges et al. 1997; Smith et al. 2015) in comparison with the estimated C_{plas} accumulation on the seabed for 2016 and the predicted quantities for 2050.

and pelagic sediments globally (Hedges et al. 1997) and is equivalent to the OC buried each year in biogenic sediments (Fig. 2). Currently the annual accumulation of C_{plas} on the seabed does not exceed the natural burial of OC found in fjords or the continental shelf (deltaic and nondeltaic) (Hedges et al. 1997; Smith et al. 2015) but if plastic production continues to rise as predicted (Fig. 1B) this is likely to change.

Currently, production of plastic per annum exceeds 300 Mt (Plastics Europe 2016) and is predicted to significantly increase in the coming decades reaching approximately 1800 Mt yr^{-1} by 2050 (Plastics Europe 2016). Currently 1.4% of the annual production of plastic enters the marine environment (Jang et al. 2015), with 94% (Pham et al. 2014) of that plastic reaching the seabed. However, in reality, there is a lag between plastic entering the marine environment and it reaching its final storage location. These lags in plastic deposition are a product of physical, biological, and chemical processes. These range between the temporary storage of the plastic in intermediate locations prior to final deposition to the alteration of the plastics characteristics resulting in the retention of some plastics in the water column for extended periods (Horton and Dixon 2018; Kane and Clare 2019).

If plastic production continues as predicted (Fig. 1B) and if no interventions (i.e., plastic bans, widespread introduction of biodegradable plastics) are introduced, by 2050, it is estimated that 25 Mt yr^{-1} of plastic will be entering the world's oceans. ~94% (Pham et al. 2014) of that plastic will reach the seabed which equates to 16.3 ± 3.6 Mt C_{plas}. This is almost equivalent to the quantity of OC buried in fjord sediments (Fig. 2) which are recognized global hotspots for the burial and storage of OC (Smith et al. 2015; Bianchi et al. 2020).

Plastic has been entering and accumulating in the oceans since it was first produced, unlike beaches where there has been a concerted effort to remove the plastic waste; there is no foreseeable way to remove the significant quantities of plastic on the seabed. The material that has been deposited on seabed potentially remains in situ at the point of deposition or redistributed across the seabed or back to the water column through sediment disturbance driven by submarine currents (Pohl et al. 2020), extreme events such as earthquakes (Mountjoy et al. 2018), and anthropogenic disturbance such a bottom trawling (Oberle et al. 2016). It is estimated as of 2014 between 25.3 and 83.9 Mt of plastic is located on seafloor (Pham et al. 2014; Jang et al. 2015) which represents a C_{plas} stock of between 17.2 ± 3.8 and 57.1 ± 12.6 Mt. This is almost certainly an underestimate, when you consider that 11.47 Mt of plastic (7.8 ± 1.73 Mt C_{plas}) is estimated to have accumulated on the seabed annually (Table 1). By 2050 if current rates of plastic input to the oceans continue, the C_{plas} stock will increase by 124.4 ± 27 Mt. The C_{plas} stock found on the seafloor is relatively minor in comparison to the total natural sedimentary OC stocks (43,000 Mt OC; Lee et al. 2019), which has developed over millennia (Hedges et al. 1997; Smith et al. 2015; Bianchi et al. 2020). Yet, the rate at which the C_{plas} stock is developing is striking, when you consider that plastic has only been accumulating at the seabed for ~60 yr. Areas such as submarine canyons and Hadal trenches have been shown to be hotspots for the accumulation of plastic with up to 71.1 pieces of plastic bring observed in a kilogram of sediment (Pierdomenico et al. 2019; Peng et al. 2020). These deep-marine environments are efficient sedimentary OC traps in the short term but fail to preserve significant quantities of OC (Masson et al. 2010); therefore, the C_{plas} may represent a significant fraction of the total C being trapped and preserved in these sediments.

The nonbiodegradable (Gregory and Andrady 2003) nature of much of the plastic currently entering the world's oceans could potentially lead to a sizable long-term C store forming on the seabed which may persist across geological time. The recent relatively limited introduction of biodegradable plastics is unlikely to halt the development of these sedimentary C_{plas} stores but it has the potential to decrease the rate at which they are currently growing.

The seabed is the main repository for the majority (94%) of the C_{plas} in the oceans but there is plastic spread across both sub- and intertidal environments (Fig. 3), indicating that the plastic is now a ubiquitous source of C to these environments a kin to OC derived from terrestrial, marine, and petrogenic sources.

The scale and rate at which C_{plas} has been introduced to the marine environment is unprecedented. In the last ~60 yr, the quantity of C_{plas} that has accumulated on the seabed (17.2–57.1 Mt C_{plas}) exceeds the accumulation of biospheric C

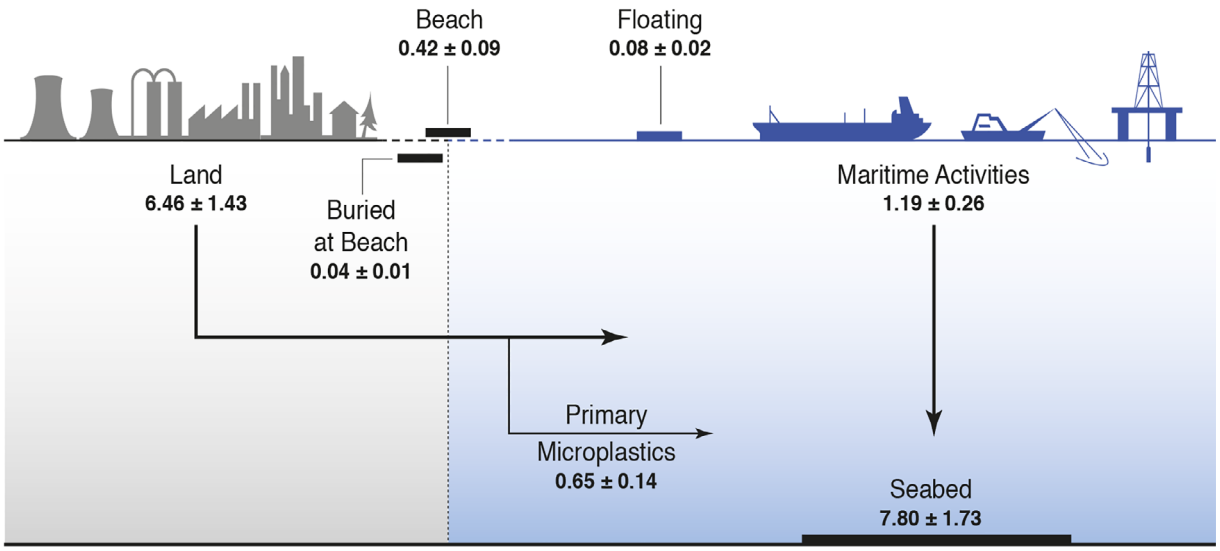

Fig 3. Global flows (Mt C_{plas} yr^{-1}) of plastic derived carbon in the marine environment. Arrows represent the flow of C_{plas} from different sources to the sinks (shaded rectangles). Data used to produce this figure can be found in Supporting Information Table S2.

in some sedimentary environments (Fig. 2). Going forward the role of plastic, as an anthropogenic pathway for C to reach the marine environment needs further exploration and attention especially in light of the potential changes in the benthic C cycle highlighted by Ladweig et al. (2021). If C_{plas} stocks on the seabed continue to grow as predicted it is not difficult to envisage in the near future the need for the C_{plas} to be included in C budgets alongside biospheric and petrogenic OC.

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Conflict of Interest

None declared.

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