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Review

A review of the use of microplastics in reconstructing dated sedimentary archives

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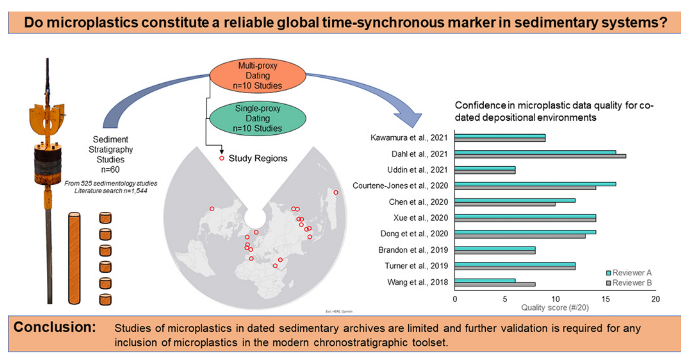
HIGHLIGHTS

- Field studies investigating microplastics in natural archives are scarce.
- Data quality issues are prevalent in microplastic sedimentation publications.
- The microplastic emissions' record in sediments is often incomplete.
- Microplastics as time-synchronous marker horizons require further validation.

GRAPHICAL ABSTRACT



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ABSTRACT

Buried microplastics (plastics, <5 mm) have been documented within the sediment column of both marine and lacustrine environments. However, the number of peer-review studies published on the subject remains limited and confidence in data reliability varies considerably. Here we critically review the state of the literature on microplastic loading inventories in dated sedimentary and soil profiles. We conclude that microplastics are being sequestered across a variety of sedimentary environments globally, at a seemingly increasing rate. However, microplastics are also readily mobilised both within depositional settings and the workplace. Microplastics are commonly reported from sediments dated to before the onset of plastic production and researcher-derived microplastics frequently contaminate samples. Additionally, the diversity of microplastic types and issues of constraining source points has so far hindered interpretation of depositional settings. Therefore, further research utilizing high quality data sets, greater levels of reporting transparency, and well-established methodologies from the geosciences will be required for any validation of microplastics as a sediment dating method or in quantifying temporally resolved microplastic loading inventories in sedimentary sinks with confidence.

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Contents

1. Introduction

Plastics represent an instantaneous event on the geological time scale. They are a solely artificial product almost entirely produced following the 'Great Acceleration' (post 1950s) (Waters et al., 2016). In this time hundreds of millions of metric tons (Mt) of plastics and hundreds of millions of Mt. of plastic waste have been produced (Geyer et al., 2017). Global plastic pollution from loss and inadequate disposal is now well documented. Small plastic pieces appear to have a ubiquitous presence. Known collectively as 'microplastics' (commonly described as synthetic polymer particles <5 mm), these small plastic pieces have been reported from urban to remote settings (Hale et al., 2020). This has led to microplastic pollution frequently being considered as a potential proxy material for the dating of stratigraphic sequences (Zalasiewicz et al., 2016; Ivar and Labrenz, 2021). Proposed studies on microplastics include their use as passive tracers of modern sedimentation regimes to a distinct stratigraphic marker for the onset of the 'Anthropocene Epoch' (Bancone et al., 2020; Harris, 2020). It has been suggested that extremely high-resolution depositional histories can be constructed using microplastic techno-fossils. For example, attribution of specific sediment strata to the various periods of plastic production based on the presence or absence of those types of microplastics may produce relative dating resolution on the scale of years to decades (Ivar and Labrenz, 2021). However, this is couched on the assumption that different plastics will exhibit equivalency in transport between environments and within the sediment column, as well as in their rate of decomposition (and that the rate of breakdown will in turn, not impact the potential mobility of aged plastics) (Bancone et al., 2020). The applications and limitations of established Quaternary sediment dating methods have been thoroughly reviewed elsewhere (e.g., Li et al., 2021). All available methods for developing age models for recent sedimentary sequences are susceptible to errors in precision and accuracy, misinterpretation, or the simple absence (at least below the lower limit of detection) of the requisite datable proxy material (Zou et al., 2019). Therefore, the development of a larger suite of available dating methods has been a priority in recent decades (Li et al., 2021). Any acceptance of a new chronostratigraphic marker as standard reference material will require extensive validation against already established techniques. Mesocosm experiments and environmental observations indicate microplastic remobilisation within the sediment column and into overlying waters may be extensive (e.g., Martin et al., 2017; Gebhardt and Forster, 2018; Näkki et al., 2019; Xue et al., 2020; Coppock et al., 2021). Therefore, the presence of in situ microplastics in stratigraphic sequences may be rare, despite their nature as a long-lasting pollutant.

To understand microplastic transport, deposition, and sequestration it must first be clarified what microplastics are and are not. Microplastics are not a classical chemical contaminant, but a complex array of anthropogenic debris, composed of different sizes, polymers, chemical additives, and sorbed pollutants (Rochman et al., 2019). Microplastics are not mineralogical grains, but insoluble synthesized compounds, which have different morphologies; principally pellets, beads, fibres, films, foams, and fragments (Hartmann et al., 2019). The densities of the most common plastics (0.9–1.4 g/cm^3) do not overlap with those of the most commonly formed minerals (1.7–3.0 g/cm^3) and encompass a broader range than those of typical organic detritus in terrestrial and marine settings (0.9–1.3 g/cm^3) (Harris, 2020). Microplastics are readily mobilised and remain in suspension longer than the sediment which may contain them. This is the principal behind one of the most common methods for microplastic extraction from sediment matrices; density separation with a saturated salt solution (Prata et al., 2019; Lusher et al., 2020). The distinct properties of the different microplastics pose a unique challenge in establishing the mechanisms driving their transport and deposition, where knowledge of sedimentary environments and chemical pollutants may not be analogous.

Ultimately, microplastics represent a potentially harmful anthropogenic pollutant, for which environmental clean-up is practically impossible, especially in complex matrices such as sediment (Padervand et al., 2020). As sedimentary systems are often deemed the final sink for lost microplastics, an understanding of their rate of sequestration (loading inventories), environmental degradation, and potential for remobilisation is necessary for developing future plastic pollution scenarios (Rochman and Hoellein, 2020). Studies addressing microplastic sedimentation are an emerging research topic without standardized practices (Cowger et al., 2020). Therefore, questions of quality assurance regarding microplastic analysis have been raised (Torres and De-la-Torre, 2021). Issues of reproducibility, precision, accuracy, and sensitivity must all be addressed to limit systematic errors and to allow for comparison between research outcomes. Weight-of-evidence scoring has previously been applied to microplastic studies of biotic, freshwater, and sediment matrices where data reliability was found to be limited (Hermsen et al., 2018; Koelmans et al., 2019; Belontz and Corcoran, 2021). While plastics have received critique as a potential environmental reconstruction tool (e.g., Waters et al., 2016; Zalasiewicz et al., 2016; Bancone et al., 2020;

Ivar and Labrenz, 2021; Li et al., 2021; Torres and De-la-Torre, 2021; Uddin et al., 2021), a systematic critical review of the current body of evidence for their inclusion in the chronostratigraphic toolset has yet to be undertaken. Thus, confidence in the current state of knowledge on microplastics in natural sediment archives remains unclear. Therefore, this review aims to assess the current state and debate of microplastic use in paleoenvironmental reconstruction. Specifically, this near systematic critical review aims to (1) identify the available literature on microplastics in stratigraphic records; (2) evaluate the identified methods in terms of reliability, data reporting, and confidence for establishing microplastic time-synchronous markers and loading inventories in sedimentary environments; (3) establish the current visibility of microplastics within the proposed Anthropocene horizon in the environmental record; (4) investigate the current visibility of individual polymer depth horizons within the environmental record; and (5) synthesize lessons learned, best practices, and future recommendations, including potential microplastic target groups (i.e., recommended size fractions, morphologies, and polymer types for geoscience applications).

2. Methods

2.1. Literature review

Scientific articles investigating the presence of microplastics in sedimentary archives were reviewed in a near systematic procedure. Searches were carried out using the Web of Science Core Collection (Indexes: SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, ESCI) with the keywords, “microplastic*” AND “sediment*” to generate a broad list of peer-reviewed articles. Articles were retrieved for the period 1st January 2004 to 27th July 2021. This date range represents the start of the proliferation of literature on microplastics, as exemplified by the seminal publication of Thompson et al. (2004). Additional articles were subsequently added from a Google Scholar search and in-text citation searches of the reviewed articles. Articles were screened for review relevance by title, abstract, and full text. Only studies which presented original data on microplastic accumulation in natural or semi-natural sedimentary environments were considered. Criteria for exclusion were as follows: investigations of rock encrustations, holding tanks, pipes, retention ponds, landfills, raw manure and sewage sludge; investigations using models, meta-analysis/reviews, or method development papers without an environmental case study; investigations using laboratory experiments and experimental plots; investigations using sediment traps, sand rakes, or visual picking of microplastics without collection of bulk sediment samples; investigations of plasticizers (microplastics being defined here as insoluble debris); investigations of single type microplastic (microplastics being a heterogeneously distributed family of pollutants generally reported in low concentrations, with any single morphology having limited applicability in temporally resolving commonly encountered sedimentary settings). Lastly, papers had to adequately report their field methods (sample position, sample date, sampling equipment, sample size, and depth data) for inclusion in this review. Only English language papers were considered.

2.2. Study characteristics

For papers relevant to this review, information on sampling methods (grabs/benthic sleds, excavations, coring) and whether multiple sections of the sediment column were investigated were tabulated. Where microplastic concentrations were reported in more than one environmental matrix and/or included surficial bulk sampling in their analysis, and/or reported on several topics; for example, climate variability, in addition to sedimentation of microplastics: only study objectives related to the occurrence of microplastics within stratified deposits were considered. Sediment stratigraphy studies were grouped into either disturbed (high-energy, dynamic) environments or low-energy depositional environments (primarily inert). For studies on disturbed environments, the depth of microplastic pollution within sediment and the environment investigated were tabulated. For studies of depositional environments, all dating methodologies applied were tabulated, including whether they were successful. Studies of aggregational, low-impact depositional systems were then further categorized into single proxy and multiproxy dating approaches. The studies applying two or more cross-validated co-dating techniques (i.e., multiproxy dating of the same sedimentary sequence used to investigate microplastics) were grouped into the categories of *Full Anthropocene* (capturing the entire post 1950 sediment profile or earlier) and *Partial Anthropocene* (capturing a portion of the proposed Anthropocene epoch within a sediment profile) (Inkpen, 2008; Waters et al., 2016; Drexler et al., 2018; Li et al., 2021).

For articles categorized as *Full* and *Partial Anthropocene Co-Dated* the following relevant study characteristics were summarized in tabular form: *Reference* (publication), *study environment* (matrices arc-type), *study location* (country/area), *core type employed* (all quality assessed studies collected field samples using coring techniques), *investigated sediment depth* (core length or excavated depth below surface from which microplastics were extracted), *sediment sampling intervals* (lengths of core sections investigated), *sample mass* (subsample sizes for microplastic investigation, not including subsamples used only for dating or other multiproxy analysis), *experimental controls* (positive and negative procedural controls relating to microplastic procedural contamination and recovery rates), *contamination mitigation* (level of avoidance of procedural contaminants relating to microplastics in workspaces), *organic digestion and heating* (sample treatment), *microplastic extraction* (sample treatment), *microplastic size fraction investigated* (targetable size range of microplastics based on the methods employed), *polymer identification* (analytical method used to identify microplastic polymers), *dating methods* (discussed above), *sedimentary environment* (primary size fraction of sediment samples), *sedimentation rates* (depositional environment), *deepest layer with microplastic pollution* (depth of observed microplastic pollution in sediment), *general depositional trends* (overall trends in microplastic concentrations with sediment depth), *polymer horizons* (when specific microplastic polymers first appear in the record), and *reporting of error propagation* (uncertainty for both microplastic concentration data and environmental reconstruction procedures).

2.3. Quality assessment

The *Full Anthropocene* and *Partial Anthropocene* papers were quality reviewed independently by two experienced microplastics investigators using an adaptation of Koelmans et al. (2019) criteria (Table 1). In short, minimum quality criteria were assigned to critical aspects of the analytical procedure for microplastics research in sediment. The rubric covered the following aspects: *Sampling methods*, *Sample size*, *Processing and Storage*, *Laboratory preparation*, *Clean air conditions*, *Negative controls*, *Positive controls*, *Treatment*, *Polymer ID*, and *Limitations*. *Limitations* is an additional category than previously presented by Koelmans et al. (2019). This aspect was added to facilitate current recommendations in microplastic data reporting, longstanding recommendations in paleoenvironmental reconstruction reporting, and to promote greater comparability between studies employing a diversity of methodologies through the reporting of margins of error and discussions in line with the work and results achieved (Drexler et al., 2018; Zou et al., 2019; Cowger et al., 2020; Provencher et al., 2020). Below significant deviations from the methods of Koelmans et al. (2019) are justified in the context of sedimentology.

- *Sampling methods*: Due to sedimentation rates spanning tens of cms to <1 mm per century depending on the environment, only reporting the year of the sampling campaign was deemed sufficient for study contextualisation. Where sediment cores were retrieved

Table 1
Quality assessment criteria for microplastic research in sediment cores.

Score	2	1	0
Sampling methods	- Date - Location - Materials - Water depth (if applicable) - Sediment sampling depth and interval parameters (core sections)	- Only a subset of 2 reported (but still fairly reproduceable)	- Insufficient reporting
Sample size	≥400 g	<400 g, but with good cause e.g., high concentrations, clear trends.	- <400 g for >300 μm microplastics with no cause
Sample processing	- Sample containers rinsed with filtered water or sediment sides cut away - Sample handling avoided before laboratory or negative controls used if excavated or sliced in the field - Compatible chemicals for sample preservation if used - Lab chemicals pre-filtered	- Only a subset of 2 reported (but still fairly reproduceable) - Citizen scientists used with validation	- Samples handled outside lab without negative controls - Citizen science without validation
Laboratory conditions	- Natural fibre clothing worn during sample handling - Equipment and lab surfaces cleaned	- Only a subset of 2 reported with parallel negative samples	- No precautions
Air conditions	- Clean room or laminar flow cabinet	- Keeping samples covered where possible with negative controls in parallel	- No air controls (fume hoods do not count unless they are laminar flow).
Negative control	- At least three parallel negative controls - Sample concentrations corrected for controls	- Only negative air controls run (at least three)	- No negative controls
Positive control	- At least three recovery tests performed	- Only part of the protocol tested for recovery	- No positive controls
Sample treatment	- Validated digestion protocol (see: Hurley et al., 2018; Pfeiffer and Fischer, 2020) - Sample temperatures ≤50 °C - Validated microplastic extraction technique	- Digestion (any) or visual sorting of organics in samples discussed - Offshore sample (low organics) - Validated microplastic extraction technique	- No digestion or discussion of rational for treatment of the sample matrices
Polymer ID	- >50 particles analysed using spectrographic techniques or pyrolysis	- Unrepresentative sample chemically analysed - SEM/EDX only	- No polymer ID
Study limitations	- Error propagation for dating and microplastics	- Only a subset of 2 reported	- No error propagation - Discussion does not match results

Scoring criteria used for the assessment of papers that fulfilled the requirements of Co-dated *Full Anthropocene* and *Partial Anthropocene*. Full Anthropocene papers are those that reconstruct depositional histories to 1950 or earlier using two or more independent proxies, whereas partial Anthropocene papers reconstructed depositional histories for a period post 1950 using two or more independent proxies. The review criteria were adapted from criteria put forward previously by Koelmans et al. (2019), whereby each paper could score a maximum of 2 points across 10 scoring criteria. 0 = unreliable, 1 = limited reliability, 2 = reliable.

from marine or lacustrine environments, water depth becomes important as it impacts the depositional environment as well as the potential settling rate of microplastics. Therefore, this criterion has been included. Sediment sampling depth and the resolution of a sediment profile (e.g., core segment lengths) can significantly impact results and therefore this criterion has also been included (Prata et al., 2019; Cowger et al., 2020).

- *Sample size*: Sedimentary environments differ from other environmental compartments and sample mass requirements will depend on the pollutant being investigated. There is limited validation for sediment mass requirements in microplastics studies. Therefore, the precautionary approach has been taken and the NOAA recommended mass of 400 g ww has been used here (Marine Debris Program, 2015). However, as validation is lacking, if meaningful results have been achieved using smaller sample sizes the publication has been deemed reliable to an extent. Still, study robustness can be assumed to be impacted by smaller sample sizes due to the low concentrations of microplastics typically recovered and their heterogenous distribution in the environment. A highly polluted sample may be required to capture microplastic pollution trends from small sediment sample masses or only the typically abundant <300 μm size fraction of microplastics may need to be investigated (Koelmans et al., 2019).
- *Processing*: As there are several pathways for procedural contamination to enter sediment samples, including from field stations and field personnel, contamination mitigation protocols must be in place from the time of sample collection, particularly in instances where cores are sliced in the field rather than a controlled laboratory setting. Following this, it is also recommended to remove the outer edge of sediment samples from analysis as they me be contaminated or disturbed by the sampling equipment (Zou et al., 2019). Lastly, the filtering of chemicals and liquids used in microplastics analysis is a crucial step in controlling for this contamination pathway and has been added as a criterion (Cowger et al., 2020).

Scoring criteria on reporting and methods followed Koelmans et al. (2019) with a score of 2 = reliable, 1 = limited reliability, and 0 = unreliable. The highest possible total score was 20 across 10 criteria. A data set with no zero scores can be considered sufficiently reliable for studies on microplastic sequestration. The quality assessment was a mixed quantitative-qualitative process. Even with explicit scoring thresholds discretion is often required in consideration of study context and in a reviewer's tolerance regarding the level of acceptable reporting. This is particularly true for the more qualitative categories, e.g., limitations in discussion of results, where an understanding of what has been achieved remains an important assessment to make in understanding research outcomes, regardless of the difficulties in quantifying such an aspect. In this regard two reviewers performed the task based upon previously agreed criteria to promote objectivity. Results were then used to assess the current level of confidence and extent of ground truthing available for the validation of microplastics as a datable proxy in sedimentary environments outside of theoretical perspectives (e.g., Bancone et al., 2020; Ivar and Labrenz, 2021; Li et al., 2021). Lessons learned, the current debate, available best practices, and knowledge gaps were then synthesized and presented in the Discussion (Section 4).

3. Results

3.1. Microplastics in sedimentary sequences

One thousand, five hundred and forty-four citations were identified by the search strategy once duplicates were removed (Table S1). In the first screening step, 598 articles were excluded from the review by title relevance. Three hundred and thirty-five articles were then excluded from the review in the second screening step by abstract relevance. Finally, 86 articles were excluded in the third screening step by full text. Of the remaining 525 articles, 60 studies were identified which investigated the sediment column for microplastics. Twenty of these studies exclusively investigated environments that can be considered largely disturbed or reworked by either natural or anthropogenic processes (Table S2). This precludes their use as a long-term environmental record. The remaining 40 studies reconstructed the depositional environment using microplastics, 20 of which employed robust dating methodologies to temporally constrain the sediment record (Table S3). The review process is presented schematically in Fig. 1.

All 20 high-energy site investigations reported microplastic presence throughout the sediment column, including the deepest sediment layers investigated. Within global high-energy or heavily disturbed environments microplastics have now been reported within sediment profiles as deep as 135–143 cm (beach, Chubarenko et al., 2018), 40–60 cm (riverine hyporheic zone, Frei et al., 2019), and 30 cm (farmland soil, Ji et al., 2021), and 5–10 cm (energetic tidal flat, Wu et al., 2020). These results represent a function of sampling effort (depth investigated) rather than the potential total extent of microplastic burial (to zero incidence) in these settings.

The earliest attempt to establish a history of microplastic deposition in sediment was reported by Claessens et al. (2011) from two, heavily trafficked Belgian beaches. Beaches are generally dynamic, high-energy environments, which are difficult to reconstruct geochronologically due to frequent reworking of sediment in the foreshore. Consequentially, age-depth relationships were estimated based on beach progradation derived from line surveys (which do not capture disturbance events). Claessens et al. (2011) suggested that these sites may be highly bioturbated and anthropogenically modified, impacting results. Only partial records projected to represent 4- and 16-years of deposition were constructed under these conditions. The 16-year record indicated an increase in microplastic deposition over time, while the 4-year record captured no trends. The first complete microplastic depositional history based on the sampling of sediment cores to zero microplastic incidence, with reference to local sedimentation rates for the determination of core ages, was reported by Corcoran et al. (2015) from two box cores taken in Lake Ontario, North America. The onset of significant microplastic deposition in Lake Ontario was estimated to have started between the 1970s–1990s based on previously determined sediment accumulation rates. However, this study did not construct age models specific to the investigated core environment.

Direct dating of sediment investigated for microplastics was not reported until 2017; first by Matsuguma et al. (2017), then Martin et al. (2017), and Willis et al. (2017). These studies investigated sediment cores from inland waterways to distal continental shelf settings. Matsuguma et al. (2017) resolved core ages using the local historical emission record of chemical contaminants, while Martin et al. (2017) derived sedimentation rates from radiocarbon dating of Holocene sediment. Willis et al. (2017) investigated a core dated with ^{210}Pb measurements. All three studies utilized different dating methods and from different sedimentary environments, reported anachronistic microplastic content in the core record. This finding was variously attributed to disturbance events (Matsuguma et al., 2017), the reworking of surficial sediment (Martin et al., 2017), and procedural contamination (Willis et al., 2017).

As of July 2021, twenty studies have applied chronostratigraphic methods to sediment investigated for microplastics, see Table 2. This breadth of reporting covers the main environments used to construct chronological records except for peat bogs and ice cores (which have no chronostratigraphic publications on microplastics) and abyssal plains (which accumulate too slowly to produce a meaningful record of microplastics within the immediate future) (Zou et al., 2019; Bancone et al., 2020). In areas with high sedimentation rates, microplastic burial may already be extensive. Microplastic pollution has been reported as deep as (and potentially more than) 157–162 cm

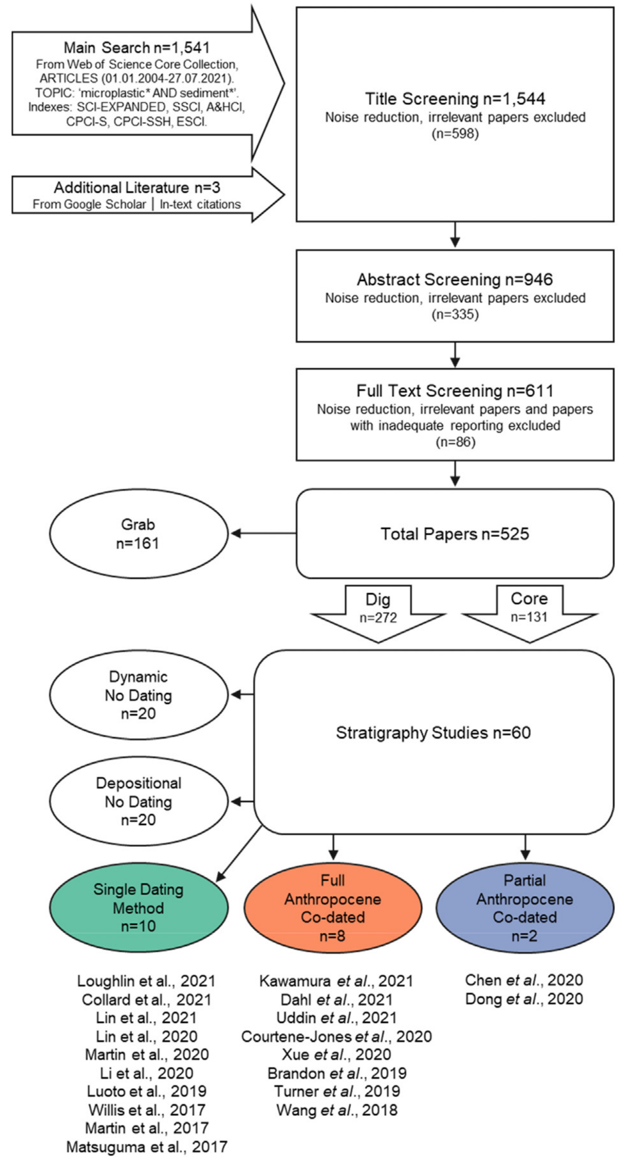

Fig. 1. A literature search was conducted to identify papers investigating microplastics which capture a profile of the Anthropocene in (semi)natural sedimentary depositional sinks co-dated using two or more independent methods (bottom row: 'Full Anthropocene' - multiproxy records extending earlier than 1950 & 'Partial Anthropocene' multiproxy records starting after 1950). 'Grab' refers to homogenised samples collected using samplers such as a grab or benthic sled – these cannot provide information on sedimentary layers. 'Dig' refers to excavated sediments (often employing quadrats) in which a discrete sedimentary layer may be preserved. 'Core' refers to studies employing coring equipment to collect sediments. A single study may employ multiple techniques. Stratigraphy studies are defined as studies which investigated more than one discrete depth layer of a sediment deposit. The studies which constrained microplastic deposition with dating methods are listed on the bottom row. Studies employing chronology are cross-referenced by colour with the data table of S3. Studies in the column to the left were not included in the quality review.

within a sediment core; taken from a salt marsh proximal to Hangzhou Bay, Zhejiang, China (Li et al., 2020).

3.2. Validation of chronological records in microplastic studies

Ten studies applied two or more independent dating methods (or utilized previously validated varve structures to count annually deposited sediment layers) to co-date microplastic deposits by constructing

Table 2
Use of multiproxy evidence in microplastic environmental reconstruction.

Method	Description	Study application	Study environment (region)	Study reference
^{210}Pb	210-Lead (half-life: 22.3 years) is a radioisotope resulting from natural ^{238}U decay.	Dating	Shelf sediments (18)	Kawamura et al., 2021
		Dating	Seagrass soils (16)	Dahl et al., 2021*
		Dating	Shelf sediments (13)	Uddin et al., 2021
		Dating	Shelf sediments (15)	Lin et al., 2021
		Dating	Shelf sediments (5)	Lin et al., 2020
		Dating	Mangrove sediments (13,14)	Martin et al., 2020
		Dating	Deep-sea sediments (12)	Courtene-Jones et al., 2020
		Dating	Shelf sediments (11)	Chen et al., 2020
		Dating	Salt marsh (5)	Li et al., 2020
		Dating	Coastal sediments (10)	Xue et al., 2020
		Dating	Lacustrine sediments (9)	Dong et al., 2020
		Dating	Lacustrine sediments (7)	Turner et al., 2019
		Dating	Delta sediments (5)	Wang et al., 2018*
		Dating	Estuary sediments (4)	Willis et al., 2017
^{137}Cs	Caesium-137 (half-life: 30.05 years) is an artificial radionuclide with a global fallout peak in 1963 (see also ^{241}Am & $^{239+240}$Pu).	Dating	Shelf sediments (18)	Kawamura et al., 2021*
		Dating	Shelf sediments (13)	Uddin et al., 2021
		Dating	Fjord sediments (6)	Collard et al., 2021
		Dating	Deep-sea sediments (12)	Courtene-Jones et al., 2020
		Dating	Shelf sediments (11)	Chen et al., 2020*
		Dating	Coastal sediments (10)	Xue et al., 2020
		Dating	Lacustrine sediments (9)	Dong et al., 2020*
		Dating	Lacustrine sediments (7)	Turner et al., 2019
		Dating	Lacustrine sediments (6)	Luoto et al., 2019
		Dating	Delta sediments (5)	Wang et al., 2018*
		Dating	Shelf sediments (2)	Matsuguma et al., 2017†
^{241}Am	Americium-241 (half-life: 4.32 × 10^3 years), *see above*.	Dating	Deep-sea sediments (12)	Courtene-Jones et al., 2020*
		Dating	Lacustrine sediments (7)	Turner et al., 2019
$^{239+240}$Pu	Plutonium-239 (half-life: 2.4 × 10^4 years) + 240 (half-life: 6.5 × 10^3 years), *see above*.	Dating	Delta sediments (5)	Wang et al., 2018*
AMS C^{14}	Accelerator Mass Spectrometry measurement of residual carbon-14 content (half-life: 5.7 × 10^3 years) in organics.	Sedimentation rate	Shelf sediments (17)	Loughlin et al., 2021
		Sedimentation rate	Seagrass soils (16)	Dahl et al., 2021
		Sedimentation rate	Coastal-shelf sediments (3)	Martin et al., 2017
Varves	Annual depositional beds.	Dating	Coastal sediments (8)	Brandon et al., 2019
OSL	Optical Stimulated Luminescence: luminescence signal strength correlated to burial time.	Dating	Delta sediments (5)	Wang et al., 2018*
Pollution history (non-nuclear)	A comparison of sediment concentrations to emissions' records. This includes the use of spheroidal carbonaceous particles (SCP), polychlorinated biphenyls (PCBs), and Alkylbenzenes (surfactants).	Correlate cores – SCP	Coastal sediments (5)	Lin et al., 2020†
		Dating – SCP	Lacustrine sediments (9)	Dong et al., 2020
		Dating – SCP	Lacustrine sediments (7)	Turner et al., 2019
		Dating - PCBs + Alkylbenzenes	Canal-shelf sediments (1–2)	Matsuguma et al., 2017†

Description column modified from Li et al. (2021) and studies reviewed here. 'Dating' refers to direct dating of an Anthropocene deposit, 'Sedimentation rate' refers to the direct dating of earlier Holocene deposits from which sediment accumulation within the proposed Anthropocene was then estimated. 'Correlate cores' refers to the practice of matching observations in different cores to the same depositional bed at a site. Part of the ^{238}U decay series ^{226}Ra was also utilized by Wang et al. (2018), Chen et al. (2020), Courtene-Jones et al. (2020), Dong et al. (2020), Xue et al. (2020), and Kawamura et al. (2021) to support ^{210}Pb age models. As such, it has not been included here as an independent proxy. *Reported erroneous measurements or a lack of datable material for this method. †Application: Matsuguma et al. (2017) applied different dating techniques to different cores rather than co-dating individual cores. Lin et al. (2020) used black carbon measurements solely to correlate depositional sequences between cores rather than co-date the cores. Regions where microplastic depositional fluxes have been dated within the sedimentary record. In order of publication on each environment: 1 – Tokyo, Japan; 2 – Gulf of Thailand; 3 – Irish Shelf; 4 – Tasmania; 5 – Eastern China; 6 – Svalbard; 7 – London, UK; 8 – Santa Barbra Basin; 9 – Central China; 10 – Beibu Gulf; 11 – South China Sea; 12 – Rockall Trough; 13 – Persian Gulf; 14 – Red Sea; 15 – Yellow Sea; 16 – Western Mediterranean; 17 – Icelandic self; 18 – North-eastern Japan.

a robust temporal record of the depositional environment (Table S4). These ten studies were subsequently assessed using the scoring criteria. Applying weight-of-evidence scoring to the studies indicated mixed results on the reliability of microplastics data. On completion of the quality assessments, it was still found to be necessary to discuss results between reviewers to ensure an even application of the scoring criteria where work performed remained unclear. However, this did not result in major revisions of the original 'blind' scoring. No cumulative revised scores changed by more than a total of two points. The average quality score for the reviewed studies following consultation between the reviewers was 55% (11/20) with individual scores ranging from 6 to 17 out of a possible 20 (Table 3). Even though a small selection of papers were evaluated in this review, average scores reported here (11/20, 55%) are similar to previous investigations into biota (8/20, 40%, Hermsen et al., 2018) and freshwater (8/18, 44%, Koelmans et al., 2019) matrices. Belontz and Corcoran (2021) previously applied a different style of scoring matrix to fifty microplastic sedimentology studies, but similarly found that half of the studies reviewed were not reporting essential QA/QC practices. The average scores per criterion where scores were <1 (<50%) in this review were for *sample size* (0.95), *sample processing* (0.95), *air conditions* (0.95), and *positive controls* (0.45). Interestingly, polymer identification, which scored

Table 3
Quality review assessments for microplastic geochronology studies whereby each paper could score a maximum of 2 points across 10 scoring criteria. 0 = unreliable, 1 = limited reliability, 2 = reliable.

Reference	Turner *et al.,* 2019		Wang *et al.,* 2018		Brandon, *et al.,* 2019		Xue *et al.,* 2020		Uddin *et al.,* 2021		**Courtene-Jones *et al.,* 2020**		Dong *et al.,* 2020		Chen *et al.,* 2020		Kawamura *et al.,* 2021		**Dahl *et al.,* 2021**		
Reviewer	A	B	A	B	A	B	A	B	A	B	**A**	B	A	B	A	B	A	B	**A**	**B**	Mean Scores (#/2)
Sampling Methods	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**1**	**2**	**1**	**2**	**2**	**2**	**2**	**2**	**2**	**1**	**1**	**2**	**2**	**1.80**
Sample Size	1	1	1	1	1	1	1	1	1	1	**2**	1	1	1	0	0	1	1	**1**	**1**	0.95
Sample Processing	0	0	0	0	1	0	1	1	0	0	**2**	2	2	2	2	0	1	1	**2**	**2**	0.95
Laboratory Conditions	1	2	1	1	0	0	2	2	0	0	**1**	2	2	2	1	1	2	2	**2**	**2**	1.30
Air conditions	1	1	0	0	0	0	2	2	0	0	**1**	1	1	1	1	2	1	1	**2**	**2**	0.95
Negative control	2	2	0	0	0	0	1	2	0	0	**1**	1	2	1	2	1	1	1	**1**	**2**	1.00
Positive Control	0	0	0	0	0	0	0	0	0	0	**1**	0	2	2	0	0	0	0	**2**	**2**	0.45
Sample Treatment	2	1	1	2	1	2	1	1	2	2	**2**	1	1	0	1	1	1	1	**2**	**1**	1.30
Polymer ID	2	2	1	1	1	2	2	2	1	1	**2**	2	1	2	2	2	0	0	**1**	**1**	1.40
Study Limitations	1	1	0	1	2	1	2	2	0	1	**2**	2	0	0	1	1	1	1	**1**	**2**	1.10
TOTAL (#/20)	12	12	6	8	8	8	14	14	6	6	**16**	14	14	13	12	10	9	9	**16**	**17**	

particularly low in both reviews for biota (0.66/2, Hermsen et al., 2018) and freshwater (0.89/2, Koelmans et al., 2019), received the second highest score of all criteria in this review (1.40/2). However, assessment of microplastic recovery rates (*positive control*) remains the lowest scoring criteria for sedimentary sequences (0.45/2, this study), biota (0.17/2, Hermsen et al., 2018), and freshwater (0.21/2, Koelmans et al., 2019). *Sampling methods* (1.80) had the highest average score in this study and was the only criteria not to receive a 0 across any of the assessed studies (co-dated study quality assessments were not impacted by the field methods exclusion criteria of the literature screening process). The average number of zeros per study was 2. However, the number of zeros between individual studies also ranged widely (0–6/10). Only two studies scored on every criterion (>0), by at least one reviewer: Courtene-Jones et al. (2020) and Dahl et al. (2021).

Mixed results were also encountered in reconstructing the depositional environment. Six of the ten co-dated studies reported encountering disturbed sediment or inapplicable dating techniques. The degradation of sediment cores as geochronometers in microplastic studies has been variously attributed to sediment reworking in deltas and in continental shelf settings (^{210}Pb measurements, Kawamura et al., 2021; Wang et al., 2018); marine input of ^{137}Cs (Wang et al., 2018); incomplete bleaching of fine-grained quartz deltaic sediment (Optically Stimulated Luminescence, Wang et al., 2018); low sedimentation rates on the continental shelf (^{210}Pb measurements, Dahl et al., 2021); dredging of urban lakes (^{137}Cs measurements, Dong et al., 2020); and mismatched or unclear ^{241}Am/^{137}Cs peaks in continental shelf and deep-sea sediment (Chen et al., 2020; Courtene-Jones et al., 2020; Kawamura et al., 2021).

In a South China Sea core sediment examined immediately below the uppermost layer (at 2–4 cm) contained the highest concentration of microplastics. (Xue et al., 2020). This was attributed to the unstable dynamic interface of the surface layer (0–2 cm) causing a resuspension of microplastics. Microplastics have previously been reported to reside in or be readily suspended into the layer of water immediately above the surface of marine sediment elsewhere (Martin et al., 2017; Coppock et al., 2021). Xue et al. (2020) also considered their core extensively bioturbated based on the presence of anachronistic microplastics. In the Xue et al. (2020) study, microplastics were hypothesised to occur no deeper than 22 cm (1933 CE deposit) but were documented to core refusal at 60 cm (1897 CE deposit). Sediment reworking by local invertebrates was attributed to this finding.

Five of the seven co-dated studies which investigated sediment profiles extending to periods earlier than 1950 reported finding anachronistic microplastics. Turner et al. (2019) reported microplastics as deep as 50 cm below sediment dated to 1950 (45 cm versus 95 cm depth), representing the mid-nineteenth century and decades before the onset of plastic production. These fibres were chemically matched to fibres in modern layers, supporting the conclusion that microplastic fibres were reworked within the sediment column. However, procedural contamination could also account for these results. In comparison, microplastic fragment morphologies were constrained to post-1950 deposits, indicating microplastic fragments were relatively immobile within the core and did not significantly contribute to procedural contamination (Turner et al., 2019). In a similar study, Courtene-Jones et al. (2020) suspected interstitial pore water transport to have significantly reworked anthropogenic fibres within their sandy silty North Atlantic cores. This was based on a correlation observed between core porosity and microplastic abundance. Despite historical production trends indicating microplastic occurrence should be limited to the top 4 cm of sediment, microplastics were reported in all investigated sediment layers (to 10 cm depth). Anachronistic microplastic deposits in sediment of the North Atlantic with low sedimentation rates have also been reported elsewhere (Martin et al., 2017; Loughlin et al., 2021). Downward transport and surficial reworking of microplastics in the sediment column may therefore be extensive in this environment. Brandon et al. (2019) reported no sediment disturbance in their near urban, USA coastal basin core. All anachronistic microplastics were thus assumed to be procedural contaminants. Brandon et al. (2019) therefore subtracted the average number of microplastics in pre-1945 sediment deposits from the post-1945 deposits as an experimental control. Similarly, Dahl et al. (2021) reported procedural contaminants in almost all sediment samples investigated, while Wang et al. (2018) and Kawamura et al. (2021) did not report microplastics in sediment pre-dating 1950.

3.3. Global trends in marine and lacustrine sediment

Microplastic presence in sediment was reported in all studies considered ($n = 525$) for this review. While available studies on sediment stratigraphy are limited and generally incomparable (due to different methodologies and levels of confidence in the data set) a qualitative downcore decreasing trend in microplastic concentrations was reported for all ten investigations quality assessed here. This general trend was previously highlighted from a metadata analysis of five microplastic stratigraphy studies (Torres and De-la-Torre, 2021). However, variable downcore concentrations of microplastics are also frequently reported within individual cores. Turner et al. (2019) reported variable downcore microplastic concentrations that were generally decreasing, with a slight microplastic peak in the 1960s. Microplastic deposition was considered to reflect the variable historical usage of plastics within the small lake catchment area (0.7 km^2) of the study. Similarly, an irregular but generally decreasing concentration of microplastics downcore from urban lake sediment in Wuhan, China was reported by Dong et al. (2020). The same study also reported a minor dip in microplastic concentrations in the period around 1971 with a rapid rise in microplastic concentrations after 2010. Unfortunately, the period post 2010 is not captured by several co-dated studies included in this review, with three studies using 2009 cores (Brandon et al., 2019; Turner et al., 2019; Uddin et al., 2021). This prevents a comparison in recent pollution trends from other regions. Nevertheless, this period may represent an important point of escalation in the degree of global microplastic deposition (Torres and De-la-Torre, 2021). The turbidite beds studied by Kawamura et al. (2021) also evidenced heightened microplastic (mostly fibres) transport from coastal settings to the depositional environment of the shelf in the modern environment. It is noteworthy that fibres often dominated the microplastic inventories of the reviewed studies (100% of microplastics in some instances) (Dong et al., 2020). Fibres and/or smaller microplastic morphologies were also commonly found to represent a larger proportion of the total microplastics reported in successively deeper sediment layers (Brandon et al., 2019; Turner et al., 2019; Dong et al., 2020; Uddin et al., 2021). Variable, but generally decreasing, downcore microplastic counts with an increase in the ratio of smaller microplastics with sediment depth have also been reported in studies utilizing undated sediment cores (Fan et al., 2019; Zheng et al., 2020) and in a PhD thesis chapter utilizing co-dated sediment cores (Belontz, 2021).

Reporting of polymer type as a function of depth in stratigraphic sequences is scarce. Qualitatively, there appear to be no global trends in individual polymer stratigraphy other than that once microplastics emerge in stratigraphic records the polymer types present quickly diversify in line with their rapid introduction, largely between 1950 and 1970 (Geyer et al., 2017). Polystyrene, discovered in the 1800s, may make an early appearance in the record where conditions allow (Turner et al., 2019; Bancone et al., 2020; Dahl et al., 2021). For the embayments and marginal seas of China, polymer diversity has been found to increase up-core (Chen et al., 2020; Zheng et al., 2020), whereas a general increase in polymer diversity downcore was observed in the deep North Atlantic (Courtene-Jones et al., 2020). Nevertheless, Courtene-Jones et al. (2020) still reported the greatest single instance of polymer diversity in the stratigraphically youngest (uppermost) sediment of their North Atlantic site.

4. Discussion

4.1. Uncertainty in microplastic sedimentary records

Despite a recent proliferation in microplastics research, a limited number of peer-reviewed publications describe microplastics within stratified sediment. To date, most literature on microplastic sedimentation has focussed on surficial concentrations. This research effort has led to the recognition of microplastics as a globally spread sedimentary particle, which in turn, has prompted interest in microplastic pollution as a potential stratigraphic marker for an emerging epoch: the Anthropocene (Waters et al., 2016). However, a diversity of sample treatments for extracting microplastics from sediment matrices and a lack of consistent reporting prevents direct comparison between studies. A quality assessment of microplastic investigations for the ten studies employing robust dating methods indicates generally limited microplastics data reliability. Both reviewers produced comparable total scores for each article with general agreement across most criterion. Differences in scoring between the two reviewers highlight the qualitative aspect of conducting a weight-of-evidence critical review. This is inherent in the process, even where explicit standards have been employed. Where large differences in scoring existed, they were primarily related to issues surrounding the level of reporting in the paper and the confidence reviewers held in a studies' capacity to account for procedural contaminants (Tables S5–S24). Nonetheless, only two quality reviewed studies were found to have no zeros in any category by either reviewer, limiting confidence in the ability of most studies to chronologically constrain the microplastic sedimentary record with a high degree of confidence. The exceptions were Courtene-Jones et al. (2020) and Dahl et al. (2021), which were scored >0 for all criterion by at least one reviewer.

The remaining microplastic stratigraphy studies ($n = 50$) were not quality assessed for microplastic recovery. They cannot be considered of such a level of reliability for the validation of microplastics as a chronostratigraphic tool due to a lack of cross-validated dating of the investigated sediment (Drexler et al., 2018; Zou et al., 2019; Li et al., 2021). Sedimentary sequences reflect only the conditions at the time of coring and preservation of microplastic inputs into the environment may only be partial in any depositional bed. Sediment mobility and environmental disturbance are frequent issues when attempting to reconstruct depositional histories. This issue is further exacerbated by pervasive quality control concerns within the current body of microplastics literature (Provencher et al., 2020). Matters of study reliability and reproducibility continue to be a broader problem within microplastics research, a trend which needs to be addressed with some urgency. Therefore, the factors influencing microplastic mobilisation and their potential for sequestration in long-term environmental sinks remain poorly understood. Only broad general trends in relative concentration can therefore be discussed from the current body of evidence.

The finding of relatively reliable polymer identification here as compared to reviews of other environmental matrices may be a methodological artefact resulting from the screening process before reviewing select studies, the scoring process of the different reviewers, or it could result from the relative recency of papers on this topic (indicating a general improvement in this criterion in microplastics research since 2018) (Hermsen et al., 2018; Koelmans et al., 2019). However, appropriate employment of experimental controls (particularly positive controls) continues to be infrequent in microplastics research. A lack of negative controls impedes the ability to develop a robust lower limit of detection (LLD) for microplastics, potentially blurring the accurate identification of the initial point of microplastic pollution within a core record, where loading inventories are expected to be low. Turner et al. (2019) was the only co-dated study here that established a LLD for microplastics by correcting for methodological blank results. Dong et al. (2020) and Xue et al. (2020) found no procedural contaminants in their blank controls matching the size fraction of investigated microplastics and therefore reported all instances of observed microplastics throughout their core profiles. Brandon et al. (2019) (in a procedure like the methods of Willis et al., 2017) subtracted microplastic abundances below intervals dated to before the onset of plastic production as a corrective measure. However, this method is not a recognised step in analytical chemistry, and its reliability has been questioned (Dong et al., 2020). Positive controls provide a reference for the efficiency of the diverse extraction techniques, which are currently being employed across a variety of sedimentary settings. A lack of positive and negative experimental controls within microplastics research remains a primary obstacle in establishing accurate and comparable environmental microplastic inventories. As such, whether a representative inventory of microplastics in environmental matrices is being reported remains unclear in biology and earth sciences disciplines. Given these issues, a microplastics budget for transport and accumulation between environments cannot currently be estimated with confidence. Without rigorous detection limits the point of the onset of microplastic pollution in the sediment record can remain uncertain. Robust experimental control and data correction are therefore crucial for establishing a reliable and comparable microplastics data set. Greater chemical analysis of recovered microplastics and reporting per sediment depth interval examined would help towards resolving these issues for sedimentation studies.

These brief quality reviews, however, are not an assessment of the overall quality of a paper nor can they be used to rank their value (Hermsen et al., 2018; Koelmans et al., 2019). This is also the case for the unassessed studies, where a lack of dating should not impede the estimation of environmental loading inventories for microplastics (Zou et al., 2019). Several instances of zero scores are attributed to a lack of reporting on work performed rather than an overt procedural error. This metric is applied solely to give an indication of the level of uncertainty in reported microplastics data and on methodological trends in research. One example of uncertainty in establishing quality evaluations is the use of organic digestion. As organics can obscure microplastics or be misidentified as microplastics during analysis, their removal via organic digestion methods is often deemed essential quality criteria (Koelmans et al., 2019; Lusher et al., 2020). However, digestive measures can also degrade microplastics or be incomplete, leading to their deliberate exclusion from certain studies (Turner et al., 2019). Four of the ten studies reviewed here utilized an organic digestion step. Three employed 15%–30% hydrogen peroxide (H_20_2) for sample treatment (Wang et al., 2018; Xue et al., 2020; Uddin et al., 2021), while Dahl et al. (2021) used enzymatic digestion. Oxidizing agents, such as H_20_2 (with or without the addition of an iron catalyst), are one of the most efficient treatments for the removal of organics from sediment samples while still preserving microplastics (Hurley et al., 2018). However, H_2O_2 alone has also been linked to the discolouration of microplastics, which may negatively impact the ability of a researcher to successfully identify microplastics (Pfeiffer and Fischer, 2020). Furthermore, it has been reported that H_2O_2 treatment can introduce C═O groups into natural materials, potentially leading to their misidentification as an -ethylene based plastic when chemical analysis is performed. Excluding -ethylene signatures from a sample could in turn lead to an underestimation of weathered polyethylene, which may be important in studies with aged plastic deposits (Matsuguma et al., 2017). The C—H spectra of polyamide (nylon), polystyrene, and polyethylene terephthalate (PET) have also been found to be altered by sample treatment. However, spectral signatures have not been found to be altered beyond recognition due to this process (Pfeiffer and Fischer, 2020). The continued debate on appropriate sample treatment extends to this review, where *sample treatment* received the greatest number of disparate review scores between the two reviewers ($n = 6/10$ studies), thus highlighting the challenges in establishing harmonized microplastics protocols amongst researchers. Therefore, study design decisions for microplastic analysis should be reported and justified within the context of individual study objectives.

4.2. Representativeness of core records

Another major issue facing microplastics studies which utilize core samples (all quality reviewed studies here) is the trade-off between sample mass requirements for statistical rigor and core sampling resolution (the down-core interval at which samples are taken, e.g., sectioned at 1 cm vs. 10 cm) (Drexler et al., 2018). This is reflected in the reliability scores for *sample size*. The multiple proxies required to validate core chronologies typically require mutually exclusive treatments, leading to subsampling, which further reduces the available sample mass for each proxy measurement (Turner et al., 2019). The heterogenous distribution and low concentrations typical of environmentally lost microplastics mean sample mass requirements can be relatively large compared to core capacity (Prata et al., 2019; Cowger et al., 2020). Where sample mass is reported, core studies frequently employ not only small sample sizes, but samples with large mass variance between individual core sections. Several studies homogenised unconsolidated sediment strata to increase sample mass at the expense of core resolution for microplastic analysis. Even so, Wang et al. (2018) and Turner et al. (2019) still acquired relatively small interval masses (50 g dw and 20–90 g dw respectively) after performing this task as a result of equipment parameters and additional subsampling for other analyses that were necessary for reconstructing the core record. Nonetheless, Fan et al. (2019) found similar microplastic depositional trends compared to other studies in an undated core using substantial 1 kg samples. Therefore, smaller sample masses may be appropriate for determining general trends in microplastic pollution. Multiple studies were also affected by the processing of cores for other types of analyses before being turned over for microplastic investigations (Brandon et al., 2019; Turner et al., 2019). As microplastics studies require tailored procedures throughout the investigative process - to limit background contamination - a lack of implementation of microplastic related protocols until a later research stage harms study reliability (Cowger et al., 2020). This issue is reflected in the quality scores for *sample processing* and *air conditions*.

In addition to methodological concerns, issues of reporting standards also remain. Whether reported as total microplastic weight or individual particle counts, the measurement criteria used for determining the concentration of microplastics in sediment come with specific drawbacks. As plastics almost always have lower densities than sediment, measurements of plastic as percentage weight by sediment underrepresent the total volume of plastic within the sediment matrix (Carson et al., 2011). Counting microplastics similarly does not inform on the mass of plastic in a sediment layer. As the proportion of smaller microplastics may increase with sediment depth this method can misrepresent the actual quantity of plastic in each sediment layer (Fan et al., 2019; Dong et al., 2020; Zheng et al., 2020). It is therefore possible to encounter a situation where plastic mass decreases downcore while individual microplastic counts increase. This issue requires careful consideration when determining appropriate reporting criteria in consideration of a study's objectives.

4.3. The microplastic sedimentary record

A third of the microplastic stratigraphy studies reviewed here were conducted in environments potentially so disturbed that historical trends may be indiscernible. These do not contribute to an understanding of microplastics as a sediment age marker. However, the consistent observation of microplastics buried in high energy environments, often at depth, demonstrates their potential for repeated remobilisation into overlaying ecosystems, impacting taphonomic processes, and requiring the inclusion of high energy depositional systems in any quantification of microplastic sinks (Bancone et al., 2020). The study of energetic settings has relevance to low-energy depositional settings in understanding delays of microplastic input from transfer zones to long-term sinks. Investigation of these dynamic settings will therefore help further develop microplastic depositional models.

For settings with limited disturbance (i.e., potential long-term sinks), a general decrease in microplastic concentration with sediment depth appears to be a global trend (albeit with limited study, mostly focussed on the Atlantic and East Asian coastal settings of the Northern Hemisphere). Where basins of sufficient size and morphology to act as a representative sink for plastic pollution have been investigated, positive correlations have been observed between historical population density, global plastic production, gross domestic product, and microplastic concentrations in the sediment column (Brandon et al., 2019; Fan et al., 2019). However, the use of historical emissions' indicators to construct temporal records has been criticized as overly simplistic models of the depositional environment, easily susceptible to misinterpretation (Zou et al., 2019; Bancone et al., 2020). The variability reported in downcore microplastic concentrations reflects this complexity (Turner et al., 2019; Chen et al., 2020; Courtene-Jones et al., 2020; Dong et al., 2020). Microplastic provenance is an important consideration. Pollution events are usually temporally and spatially discrete. Depositional systems cannot capture what has not been sourced. Neither can they capture material which the acting processes of the system keep in suspension/transport. Thus, there is little basis for individual sedimentary deposits reliably reflecting global plastic production trends. This also limits the utility of propagating centimetre scale observation over metre and kilometre scales. The use of multiple sampling stations to interpret a setting is therefore encouraged (Zou et al., 2019). The need for site-specific constraints on sourcing and potential transport-deposition pathways is also an important consideration for evaluating microplastic emissions' records in natural archives (Clayer et al., 2021). Furthermore, results also need to be interpreted within the context of data reliability and potential biases introduced by methodological choices (Provencher et al., 2020).

Based on the limited available literature, microplastic fibres and those in smaller size fractions (<1000 μm, the 'true' microplastics by metric definition, Hartmann et al., 2019) may be particularly susceptible to remobilisation or diffusion downcore (Brandon et al., 2019; Fan et al., 2019; Turner et al., 2019; Courtene-Jones et al., 2020; Zheng et al., 2020; Uddin et al., 2021). However, such results could be a methodological artefact introduced by small fibrous microplastics being predisposed to becoming procedural contaminants. Fibrous particles can be abundant in workplace settings and have a high potential for mobilisation based on the reviewed literature. Where older deposits (particularly those dated to pre-1950s) are found to exclusively contain fibres the possibility of procedural contamination cannot be dismissed (Belontz and Corcoran, 2021). The application of a variety of robust procedural controls to contain this problem in several studies critically reviewed here indicates that microplastics are, however, likely the subject of sediment reworking events. This is supported by the frequent reports of disturbed sedimentary environments in microplastic investigations (in studies capable of identifying such events: i.e., sedimentology studies with multi-proxy evidence). Therefore, greater environmental interpretation alongside microplastic analysis is required to contextualize the microplastic depositional record.

4.4. Microplastics as a chronostratigraphic marker

Microplastics are a diverse suite of chemically and morphologically distinct insoluble particles heterogeneously dispersed across the environment and subject to complex patterns of production, usage, disposal, and loss (Rochman et al., 2019). The main prerequisites for reconstructing microplastic depositional records from natural sedimentary archives are inert sediment with limited post-depositional mobility; targeted microplastic forms that are persistent and immobile within the sediment column; reliable analytical procedures; and accurate dating techniques (Zou et al., 2019). Factors that can destroy or distort this record include: a lack of source material; variable sedimentation rates; the vertical and horizontal migration of particles through pore spaces; disturbance and erosion caused by fluctuating energy levels (e.g., storms, strong currents, landslides, submarine landslides); bioturbation; and microplastic structural degradation through wear, decay, and microorganism colonisation. Evidence for post-depositional mixing of pollutants can be difficult to elucidate from sediment profiles due to often-variable rates of local emission and sourcing, blurring major trends in favour of discrete events (Zou et al., 2019). Furthermore, radionuclide dating techniques are validated on being relatively homogenously dispersed monotype radioactive isotopes with fixed rates of decay (Drexler et al., 2018). Many plastic polymers are environmentally persistent. However, their emission and estimated rates of decay are highly variable (Andrady, 2011, 2017). Evidence of mechanical weathering and the microbial colonisation of microplastics in the sediment column indicate microplastic degradation may be significant even after burial, despite plastics being long-lasting materials (Dong et al., 2020; Niu et al., 2021). The diversity of plastic types and their potential origins complicates interpreting source-to-sink processes. Currently, there is little ground truthing evidence to suggest polymer specific stratigraphic sequences are forming, which can be reliably utilized in a relative dating methodology. These issues all pose problems for the use of microplastics as chronostratigraphic markers and require further investigation.

The presence of anachronistic pollutants dated to before the period of emission is often the most reliable indicator of downward reworking within sediment or soils (Zou et al., 2019). However, the upward migration of pollutants within a stratified sequence can be less reliably investigated or may not be detectable where concentrations are expected to increase towards the present. In the studies presented here all instances of microplastic reworking within cores were evidenced by the presence of plastics in sediment dated to before the onset of their production, except for Xue et al. (2020) who reported presumed microplastic loss at the dynamic sediment surface interface. Therefore, greater constraint on microplastic mobility needs to be established before any microplastic morphology can be accepted as relatively inert within sediment deposits.

Furthermore, reliable microplastic recovery from sediment matrices can be challenging. Large sample sizes are likely required to quantify microplastic loading inventories, ideally with the use of multiple sample stations and replicates to propagate microplastic extent within a setting. Successful microplastic extraction often requires expensive chemical treatments, clean air spaces, and the use of non-plastic equipment, followed by the chemical confirmation of a large quantity of recovered particle compositions (e.g., Cowger et al., 2020). Microplastics also demonstrate a propensity for generating depositional beds that do not necessarily reflect emissions' records. Therefore, microplastics should never be used independently for the interpretation of a sedimentary environment. It is likely that a detailed assessment of projected local and distal sourcing will also be required to interpret microplastics in the sediment record (Clayer et al., 2021). These challenges make microplastics far from an economical bootstrapping alternative for researchers hoping to perform low cost, in-house, sediment dating with confidence. Interlaboratory positive control experiments using seawater indicate that the visual identification of plastic particles >2000 μm can be successfully conducted by both trained observers and citizen scientists (Isobe et al., 2019). Therefore, analytical limitations may be partially overcome by exclusively targeting larger (>2000 μm) microplastic fragments. However, this requires that >2000 μm plastic particles are environmentally present in sufficient quantities for record interpretation, a criterion which is unsupported by the current body of evidence. Fibres <1000 μm in size are often the major microplastic constituent of sedimentary environments (Turner et al., 2019; Courtene-Jones et al., 2020; Dong et al., 2020), as exemplified by microfibres representing 99–100% of total microplastics content in urban lake cores (Baldwin et al., 2020; Dong et al., 2020). Therefore, excluding fibres to constrain the vertical migration of microplastics in the sediment column could lead to false identification of pristine environments in addition to significantly underestimating loading inventories.

Given these issues, calls for the standardization of methods relating to microplastics analysis have been put forward for almost as long as the current expansion of literature on the topic has been ongoing (Hidalgo-Ruz et al., 2012; Hartmann et al., 2019; Cowger et al., 2020). However, the continuous development of improved methods, differences between researchers and laboratories, and the unique circumstances of each environment sampled, make standardization of methods an impractical goal (Provencher et al., 2020). Specific samples and research goals will need tailored responses to achieve results with high statistical power (Pfeiffer and Fischer, 2020). Therefore, clear transparency of data at the most general level for each sediment layer analysed, correction of results based on positive and negative controls, and the propagation of error for both microplastics and dating techniques, with clear reporting on study limitations, are the most impactful and immediately actionable steps towards defining the Anthropocene in microplastic sedimentary records.

5. Conclusion

Microplastics appear to be accumulating over time in sediment globally. However, increased methodological rigor and further investigation are required before historical microplastic loading inventories can be established with confidence. Additionally, the diversity of microplastics, their sources, and modes of transport may make them a less than robust chronostratigraphic marker as compared to radionuclide options for modern sediment dating. Great care should be taken in the future use/analysis of microplastics within the geosciences and in the discourse surrounding their limitations. Further research into the processes governing the sedimentation of different microplastic morphologies and on their remobilisation both within sediment and into other environmental compartments is necessary. Historical trends in microplastic deposition can only be reliably investigated with the support of multiple independent proxies and consideration of available source points and the depositional setting. Existing methodologies from the geosciences can inform this work. However, robust microplastic-specific procedures will also be required to account for the small and fibrous plastics that are often abundant and environmentally persistent.

CRediT authorship contribution statement

Jake Martin: Conceptualization, methodology, formal analysis, investigation, data curation, writing, visualization. **Amy L Lusher**: Conceptualization, methodology, formal analysis, writing, visualization, funding acquisition. **Francis Chantel Nixon**: writing, visualization, funding acquisition.

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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