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How to quantify algal turf sediments and particulates on tropical and temperate reefs: An overview

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ABSTRACT

Algal turfs are the most abundant benthic covering on reefs in many shallow-water marine ecosystems. The particulates and sediments bound within algal turfs can influence a multitude of functions within these ecosystems. Despite the global abundance and importance of algal turfs, comparison of algal turf-bound sediments is problematic due to a lack of standardisation across collection methods. Here we provide an overview of three methods (vacuum sampling, airlift sampling, and TurfPods), and the necessary equipment (including construction suggestions), commonly employed to quantify sediments from algal turfs. We review the purposes of these methods (e.g. quantification of standing stock versus net accumulation) and how methods can vary depending on the research question or monitoring protocol. By providing these details in a readily accessible format we hope to encourage a standardised set of approaches for marine benthic ecologists, geologists and managers, that facilitates further quantification and global comparisons of algal turf sediments.

1. Introduction

Algal turfs are multispecies assemblages of short macroscopic algae (Connell et al., 2014; Filbee-Dexter and Wernberg 2018), that form an inconspicuous but extensive component of many tropical, subtropical and temperate marine ecosystems (Connell et al., 2014; Filbee-Dexter and Wernberg 2018; Tebbett and Bellwood 2019) (Fig. 1a and b). Algal turfs can be highly productive benthic primary producers (Carpenter 1986; Klumpp and McKinnon 1989; Copertino et al., 2005) that compete for space with other benthic organisms (Vermeij et al., 2010; O'Brien and Scheibling 2018; Liao et al., 2019) and shape a range of ecosystem functions including recruitment, productivity, herbivory/detritivory and sediment dynamics (Alestra et al., 2014; Burek et al., 2018; Speare et al., 2019; Ng et al., 2021). As human impacts on the world's marine ecosystems have intensified, algal turf coverage has increased in most geographic areas leading to mortality and decreased cover of more complex habitat forming organisms such as scleractinian corals (Goatley and Bellwood 2011; Jouffray et al., 2015) and kelps (Moy and Christie 2012; Vergés et al., 2016; Wernberg et al., 2016; Feehan et al., 2019). Unlike these habitat formers, algal turfs can be more tolerant to disturbance and stress (Hay 1981) and are expected to expand as humans increasingly modify the marine environment (Falkenberg et al., 2015). Indeed, the future of many shallow-water hard-bottom marine ecosystems already appears to be intimately intertwined with the cover and form of algal turfs (Filbee-Dexter and Wernberg 2018; Bellwood et al., 2019; Pessarrodona et al., 2021).

Increased sediment inputs from terrestrial sources (e.g. via river runoff) as well as increased sediment mobilisation from coastal development (e.g. via dredging activities) represent pervasive stressors in many shallow-water marine ecosystems, globally (Bainbridge et al., 2018; Magris and Ban 2019; Andrello et al., 2022). Such sediments can directly interact with algal turfs because turfs have a remarkable propensity to trap and retain organic particulate material and sediments within their complex architecture (Airoldi 2003; Latrille et al., 2019;

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Pessarrodona et al., 2021). Turfs slow water movement (Carpenter and Williams 1993) and the mucilage of some turf communities may assist in retaining and binding deposited sediments (Neumann et al., 1970; Stal, 2003). Importantly, if sediment retention and trapping increases in algal turfs (which may occur even without increased sediment input [Wernberg et al., 2005; Layton et al., 2019; Tebbett et al., 2020c]), this can result in the formation of sediment-laden algal turfs (Gorgula and Connell 2004; Goatley et al., 2016; Filbee-Dexter and Wernberg 2018). These sediments can have substantial negative effects on ecosystem functioning and resilience as they can compromise critical ecosystem processes (Ricardo et al., 2017; Tebbett et al., 2017a; Fong et al., 2018; Speare et al., 2019). For example, algal removal by herbivorous fishes on coral reefs can be significantly impaired by increased algal turf sediment loads (Tebbett et al., 2017a; Duran et al., 2019). Similarly, the organic particulate material that is also trapped within algal turfs and targeted by detritivorous organisms can be diluted by inorganic sediments, decreasing the nutritional quality of particulates (Purcell and Bellwood 2001; Tebbett et al., 2020b). In addition, the settlement of habitat forming organisms including hard corals (Birrell et al., 2005; Speare et al., 2019; Wakwella et al., 2020) and macroalgae (Umar et al., 1998) on tropical reefs, as well as kelp (Kennelly 1987; Connell and Russell 2010; Layton et al., 2019) and macroalgae (Gao et al., 2019) on temperate reefs, can be inhibited by high loads of algal turf sediments.

Despite the detrimental effects of algal turf-bound sediments, the widespread coverage of algal turfs, and increases in coastal sediment delivery (McCulloch et al., 2003; Filbee-Dexter and Wernberg 2018; Andrello et al., 2022), algal turf sediments have received relatively little attention in the scientific literature and they are rarely considered in ecosystem management and monitoring programmes (Tebbett and Bellwood 2019; Schlaefer et al., 2021). Indeed, while algal turf coverage is frequently quantified and monitored on both tropical (Holbrook et al., 2016; Ford et al., 2018; Kennedy et al., 2020) and temperate reefs (Irving and Connell 2006; Bennett et al., 2015; Gorman et al. 2020), there is a distinct lack of baseline information on algal turf sediment loads, as well as other properties of algal turf sediments and how they influence reef dynamics (reviewed in Tebbett and Bellwood 2019; Vergés et al., 2019; Schlaefer et al., 2021). Nevertheless, the importance of algal turf sediments are beginning to receive growing attention in the literature (e.g. Alestra et al., 2014; McAndrews et al., 2019; Speare et al., 2019; Bowden et al., 2022), building on the findings of earlier

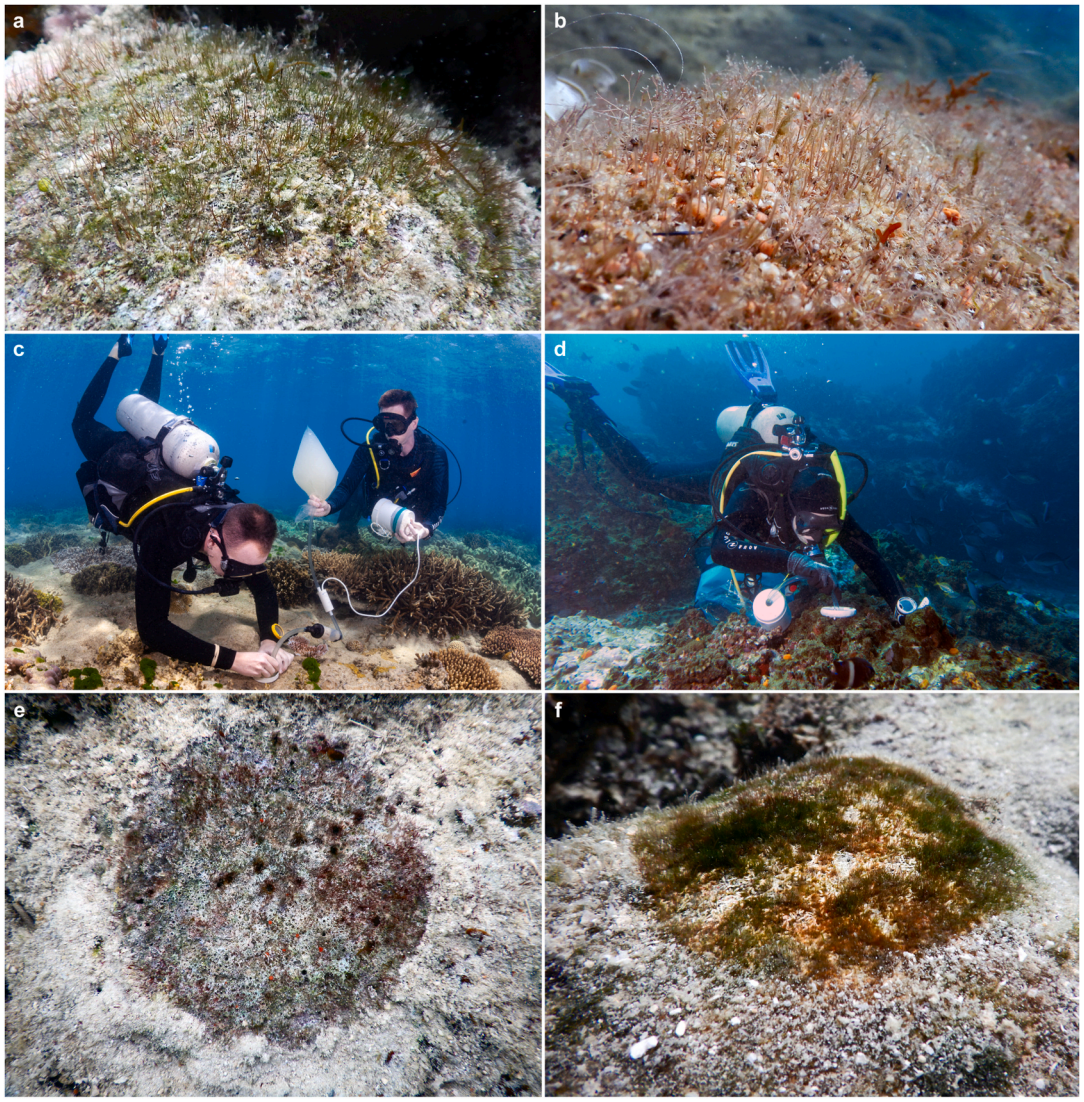

Fig. 1. Algal turf communities on a) a coral reef at Lizard Island, Australia and b) a temperate rocky reef in the Mediterranean, off Tossa de Mar, Spain. Sampling benthic particulates from algal turfs with vacuum samplers on c) a coral reef at Fantome Island, Australia and d) a subtropical rocky reef in the Solitary Islands, Australia. e, f) Sediment-laden algal turf communities at Lizard Island that have had their particulates removed using a vacuum sampler; note the distinct area cleared of sediments in the shape of the sampling ring, and the fact that the algae remains intact following sampling. Photographs: S.B. Tebbett (a, b, e, f), V. Huertas (c), A. Vergés (d).

pioneering studies (e.g. Kendrick 1991; Airoldi and Virgilio 1998; Purcell 2000). However, research into these algal turf sediments is currently relying on a wide variety of different methods (cf. Prathep et al., 2003; Tebbett et al., 2020c; Hayes et al., 2021) that are not necessarily comparable as they capture different sediment fractions and are processed in different ways (Supplemental Text S5).

Importantly, there is no single source that provides clear information on the various methods of quantifying algal turf particulates and sediments, limiting comparative and collaborative endeavours. To address this issue, we provide an overview of methods that can be used to accurately quantify algal turf sediments and particulates in marine ecosystems. This overview provides information on when, why and how to use specific methods (namely vacuum sampling, airlift sampling and TurfPods) as well as providing information regarding the construction and use of different types of equipment pertaining to these methods. Such equipment may also have uses beyond quantifying algal turf sediments and particulates, including the collection of a range of benthic organisms and abiotic components (e.g. Kramer et al., 2012; Max et al., 2013). This review may therefore be of use to marine benthic ecologists, marine geologists, marine archaeologists and environmental managers in general.

2. Quantification of algal turf particulates: what and how

All algal turfs contain particulate material within their complex structure. However, the amount of particulate material can range from <10 g m^{-2} to $>10{,}000$ g m^{-2} depending on the nature of the algal turfs, the habitat, and the ecosystem in question (Purcell 2000; Connell and Russell 2010; Filbee-Dexter et al., 2016; Tebbett et al., 2018b). It is this particulate material that we want to collect and quantify from algal turfs, i.e. all inorganic and organic material <2 mm, and is generally referred to as 'particulates'. This <2 mm size cut-off includes all grain size fractions considered sands, silts, and clays under the ISO 14688–1:2017 scheme. In terms of algal turfs, the inorganic particulate material is generally referred to as 'sediment' while the organic component is largely composed of detritus (<125 μm) (see Tebbett and Bellwood [2019] for a full overview of definitions).

There are two primary processes that can be measured regarding particulates and sediments in algal turfs: standing stock and net accumulation. Standing stock refers to the total amount of particulates that have accumulated in a given area over an extended but unknown time frame. As such, this is commonly measured in standardised mass units per unit area (e.g. g m^{-2}) (Table 1). By contrast, net accumulation refers to the amount of sediment accumulated in a given area in a known amount of time, yielding a rate of change. Therefore, net accumulation is commonly quantified in standardised mass units per unit area per unit time (e.g. g m^{-2} day^{-1}) (Table 1).

Standing stock measurements provide information on where and how much particulates accumulate (i.e. a time-averaged measure of accumulation), which can provide insights into how the reef functions (e.g. Goatley et al., 2016; Tebbett and Bellwood 2020; Tebbett et al., 2020b). As a variety of methods have been used to quantify the standing stock of algal turf sediments previously, we reviewed the literature to quantify the relative usage of different methods (details provided in Supplemental Text S1). Based on this literature review it is clear that underwater vacuum samplers (Fig. 1b and c) have been the most widely used equipment (Fig. 2), with airlift samplers representing the only other apparatus that is used to collect particulates in a manner that is easily standardised among studies (Fig. 2). Algal turf particulates have also been collected using manual hand tools (Fig. 2) including via the use of tweezers (Airoldi and Virgilio 1998), or by clearing areas using brushes (Kendrick 1991) and paint scrapers (Prathep et al., 2003). However, we do not elaborate on the use of manual hand tools herein as the time-consuming nature of this collection method limits widespread replication, it is difficult to ensure these methods are applied in a standardised manner among studies, and it is difficult to not disturb, resuspend and lose fine <63 μm sediment when using such methods. In addition, the standing stock of particulates has also been widely quantified based on sediment depth measurements in-situ on the reef (e.g. Clausing et al., 2014; Fong et al., 2018) and from photographs that examine relative sediment cover (e.g. Ceccarelli et al., 2005; Eurich et al., 2018) (Fig. 2). However, neither of these methods allow particulates from algal turfs to be collected and quantified, limiting the information that can be gleaned. Indeed, collected particulate material can be processed to quantify various properties (e.g. granulometry, organic content, silicate content; see Supplemental Text S5), which makes collection of particulates a far superior option for most applications to simple particulate depth measurements on the reef. As such, we elaborate on the use of vacuum and airlift samplers in more detail herein.

To fully understand the dynamics of algal turf particulates, the quantification of net accumulation rates is also necessary. This is because, standing stock measurements provide no indication of the timeframe over which particulates accumulate in turfs, making it exceedingly difficult to link such measurements to other processes such as sedimentation or other particulate reservoirs such as the water column or off-reef sediment aprons. Establishing such links is critical if we are to understand sediment budgets on reefs as well as how sediment mobilisation from human activities impact marine systems and their functioning (see Schlaefer et al., 2021). However, the quantification of particulate accumulation rates in algal turfs is exceedingly rare compared to standing stock measures (Schlaefer et al., 2021). Unfortunately, a previous study (Latrille et al., 2019) established that traditional

Table 1
Examples of representative studies on algal turf particulates/sediments using the three different methods.

Method	Type of measurement	Geographic location/s	Reported particulate/sediment loads (g m^{-2}) or accumulation rates (g m^{-2} day^{-1})	Reference
Vacuum sampling	Standing stock	Lizard Island, Australia	Average loads ranged from 127.5 to 4897.3 on the crest and flat, respectively	Purcell (2000)
	Standing stock	Coastal reefs on the Great Barrier Reef, Australia	Average loads ranged from 797.9 to 3681.8 among reefs.	Tebbett et al. (2018b)
	Net accumulation via clearing and re-sampling	Orpheus Island, Australia	Average rates varied from 41.3 to 56.9 for open and caged plots, respectively.	Latrille et al. (2019)
	Net accumulation via clearing and re-sampling	Palm Islands, Australia	Average rates varied from 19.3 to 187.6 among sites.	Chase et al. (2020)
Airlift sampling	Standing stock	Ningaloo Reef, Australia	Average loads ranged from 1980.7 to 4846.5 among sites.	Pessarrodona et al. (2022)
	Standing stock	Multiple geographic regions	Average loads ranged from 840 to 2420 among regions.	Pessarrodona et al. (2021)
TurfPods	Net accumulation	Orpheus Island, Australia	Average rates ranged from 17.1 to 28.2 depending on their length	Latrille et al. (2019)
	Net accumulation	Palau archipelago, Micronesia	Average rates ranged from 0.3 to 13.2 among sites.	Wakwella et al. (2020)

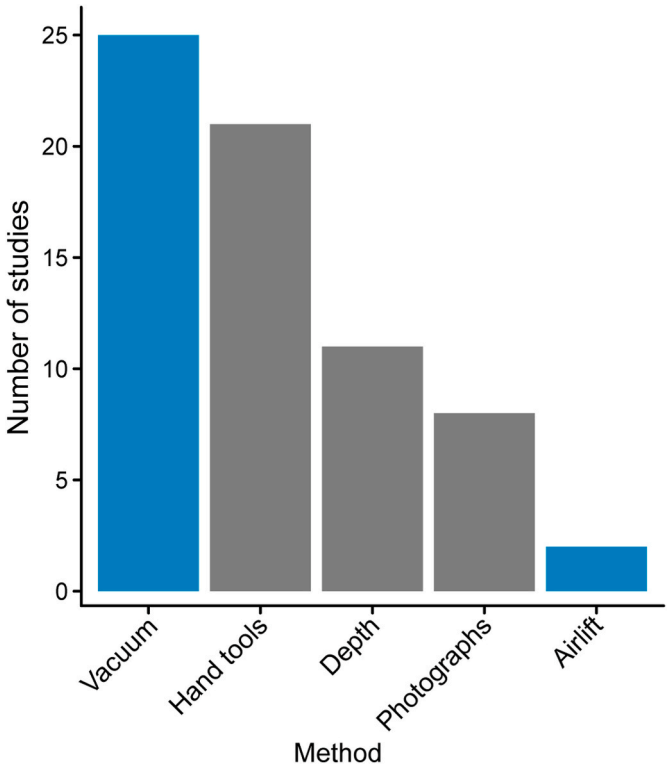

Fig. 2. The frequency by which different methods have been used to quantify the standing stock of algal turf sediments in marine systems. Details of how studies were sourced and quantified are provided in the supplemental material (Text S1). Note the 2 bars highlighted in blue represent the equipment that facilitates the collection of sediment in a standardised manner that are elaborated on herein. In this case, vacuum samplers generate suction via a water pump, while airlifts generate suction via rising air and the Venturi principle. Hand tools refer to manual hand tools such as scrapers or tweezers and depth refers to in-situ depth measurements of particulate on reefs.

ways of measuring sedimentation such as traps or SedPods (i.e. coral blocks designed to mimic a coral surface [Field et al., 2013]) are inaccurate proxies for algal turfs because they either do not account for resuspension or have a limited retention capability, respectively (Bothner et al., 2006; Storlazzi et al., 2011; Field et al., 2013). Sediment traps may nevertheless be useful as a complementary tool in areas where resuspension is low (such as less-exposed deeper reefs) (Max et al., 2013) or as a means of quantifying the gross amount of particulate material moving over reefs (Latrille et al., 2019). Measuring accumulation in natural turfs, by cleaning particulates from an area of turf using a vacuum and then remeasuring the same area a number of days later (e.g. Chase et al., 2020; Latrille et al., 2019), is time consuming and has the potential to be confounded by changes to herbivory (which increases when sediments are removed, see Bellwood and Fulton 2008; Goatley and Bellwood 2012; Akita et al., 2022) or caging effects (that facilitate sediment trapping see Rasher et al., 2012; Tebbett et al., 2018a; Akita et al., 2022). These issues have been overcome by the recent development of TurfPods (Latrille et al., 2019) which may allow accumulation of particulates in algal turfs to be estimated more widely. Indeed, TurfPods were specifically designed to mimic the trapping/retention capability of turfs and therefore act as a proxy for accumulation of particulates in natural turfs (Latrille et al., 2019). As TurfPods represent the major method by which accumulation of particulates in algal turfs may be quantified going forward, we focus on this method as the primary method for quantifying accumulation herein.

2.1. Vacuum sampling

2.1.1. Overview and use

Small electronic, self-contained vacuum samplers have been used to collect particulates, sediments and algae, as well as other benthic organisms and material for over two decades in shallow-water marine systems (e.g. Purcell 1996; Kramer et al., 2012; Max et al., 2013). While designs have been developed for quantification of coarser material (e.g. Taylor et al., 1995; Þorbjörnsson et al., 2018), only the design of Purcell (1996) (Fig. 3a) was specifically developed to quantify algal turf particulates and collect all material <2 mm. However, as this design was developed more than two decades ago, the initial version was bulky (predominantly due to the size of early batteries) (Fig. 3a). As batteries have become smaller, the design has been modified accordingly and is now a fraction of the size, facilitating use and transport (Fig. 3a and b). It is important to note that inorganic sediment loads collected using the new version fully encompass the loads sampled using the initial version (Fig. 3c), suggesting that both designs are comparable with a marked ability to collect sediments from algal turfs (Fig. 1e and f).

Vacuum samplers specifically consist of a small in-line water pump (often a small bilge pump) to create suction, an in-line filter to prevent coarse sediment from damaging the pump's impeller and a plastic collection bag at the end of the unit that ensures all the fine particulates are retained (Fig. 4a). A waterproof housing (constructed from PVC pipe) contains a battery to power the water pump and an on/off switch to control the unit (Figs. 3b and 4a). The separate components of the vacuum are all connected with clear silicone tubing (Fig. 4a). Such units can be readily constructed, and a full overview of the necessary equipment and construction steps is provided in the supplemental material (Text S2; Figs. S1 and S2).

These vacuum samplers are easy to use in most shallow-water aquatic ecosystems, and to date they have been used to a depth of ~15 m (although they are likely to be operational to greater depths) (Goatley and Bellwood 2012) (Fig. 1c and d). To operate the vacuum sampler efficiently, a two-person dive-team is required. Essentially, when underwater at the sampling location, the dive team assembles the sampler ensuring that there is no air trapped in the filter holder and tubing (opening/unscrewing the filter holder and holding it vertically will allow air to escape). The dive team then fit a filter to the tubing inside the filter holder using a rubber band (Fig. 4b). The collection bag is fitted at the very end of the silicone tubing using a rubber band (Fig. 4b). The separate components are then connected, and the unit is ready to use. The primary diver then locates a suitable sampling location and delineates it (often using a PVC ring) (Fig. 4a). Suitable sampling surfaces are generally considered to be flat, smooth, outside farming damselfish territories and free of sediment retaining pits (i.e. holes/concavities in the reef matrix in which sediment accumulates), large macroalgae and encrusting organisms (Purcell 2000; Tebbett et al., 2017b; Pessarrodona et al., 2021). Such surfaces are generally sampled as they allow particulate collection to be standardised, and because particulate dynamics can be heavily influenced by the slope of the surface (Whorff et al., 1995; Duran et al., 2018; Tebbett et al., 2020c) and the farming behaviour of territorial damselfishes (Tebbett et al., 2020a). Once a suitable sampling surface is located, the primary diver then signals to the secondary diver to switch the pump on and they can then suction out the particulates inside the ring (Fig. 4a). When this area is clear of sediment and particulates (Fig. 1e and f), the primary diver signals to the secondary diver to switch the sampler off. The primary diver then folds the clear tubing over, to prevent material from escaping out of the tube, unscrews the filter holder and removes the filter from the pipe (Fig. 4c). Simultaneously the secondary diver pulls the bag from the tubing (while keeping it sealed) and then the primary diver carefully pushes the filter into the bag and the bag is sealed tightly with a rubber band (Fig. 4d). This ensures the entire sample remains together (Fig. 4e).

If the research project calls for the algal turf to be collected as well (e.g. Purcell, 2000; Tebbett and Bellwood, 2020), a scraping tool can then

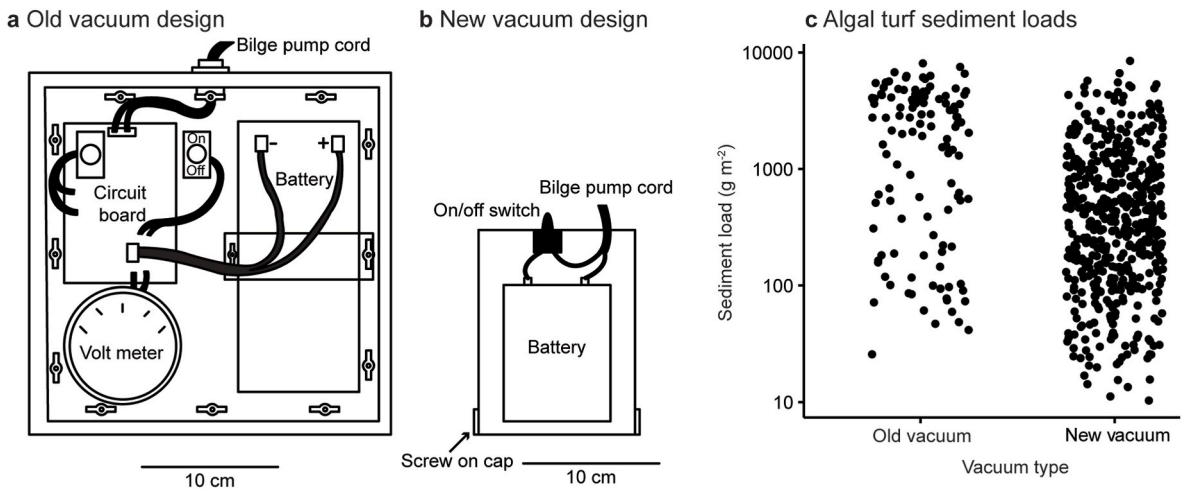

Fig. 3. The main battery housing of underwater vacuum samplers designed to collect particulates from algal turfs: a) the old design redrawn from Purcell (1996) and b) the new design for housing a smaller battery. c) Algal turf sediment loads from coral reefs that were quantified using the old vacuum and the new vacuum designs. Note that the range of algal turf sediment load data from the new design fully encompasses that from the old design. Algal turf sediment load data were sourced from Purcell (2000); Tebbett et al., (2017b), 2018b, 2020a; b; Tebbett and Bellwood (2020).

be fitted to the end of the unit and the unit assembled with a new filter but without a bag. The unit can be used as described above while scraping the reef surface to remove the algae. Upon finishing scraping, the filter can then be removed, as above, and stored in an additional bag.

2.1.2. Advantages

Collecting algal turf particulates with a vacuum sampler has several advantages (Table 2). Firstly, natural algal turfs are sampled (unlike TurfPods) and collecting the particulates with the vacuum causes little, if any, damage to the algal turf community (Fig. 1e and f). This makes it easy to sample the particulates and algal material separately (e.g. Purcell 2000; Tebbett and Bellwood 2020). Secondly, the sampling process (for particulates) does not remove any of the underlying reef matrix (Fig. 1e and f) so only lose particulates are collected covering the entire size spectrum of particulates (0–2 mm). Thirdly, the units are small and versatile, being easy to transport underwater and applied in a variety of scenarios. These advantages make the widespread use of vacuum sampling to quantify benthic particulates a clear possibility.

2.1.3. Disadvantages

The primary disadvantage of vacuum samplers is that they can be challenging to operate in high-energy locations or in rough seas because the divers must remain in very close proximity. In addition, when sampling high-sediment locations, the filter is prone to becoming clogged, so it is necessary to ensure the filter is large enough or modified filter holders and filters need to be developed (see supporting information – *Alternative filter holder design*). Furthermore, large shell fragments or rubble pieces can block or become stuck in the intake tube, making it necessary to avoid sucking up such material when sampling. Finally, although the unit itself is easy to transport, the samples are all contained in water-filled plastic bags that a) take up a lot of volume, b) are heavy, and c) have organic material. This makes it necessary to carefully consider the logistics of transporting samples back to a suitable processing area, how to preserve samples subsequently (e.g. ice, formaldehyde, etc – see Supplemental Text S5) as well as the extensive level of post-collection processing necessary to ready the samples for further transport (see Supplemental Text S5).

2.2. Airlift sampling

2.2.1. Overview and use

The use of airlift samplers, also known in the literature as air-lift, suction or Venturi samplers or pumps are commonly used in marine ecology (e.g. Barnett and Hardy 1967; Hiscock and Hoare 1973; Thiriet et al., 2016; Pessarrodona et al., 2021, 2022). Suction is induced by means of the Venturi principle: a rapid flow of air is introduced into a larger diameter PVC pipe creating a suction force at one end of the pipe, while a net or bag attached at the other end collects the material removed. The longer the pipe, faster the flow and deeper the location, the bigger the difference in pressure between the two ends of the sampler, and the larger the suction. While the principle is the same, different designs have been created to adapt these samplers to the material being collected (e.g. cryptic fish, mesofauna, sediment, algae) and conditions of use (e.g. rocky versus soft bottoms). Essentially, most designs consist of a hose connected to the low-pressure port of the first stage of a regulator and an air tank, a valve to regulate air flow, a PVC pipe and a series of collection bags with the desired mesh aperture (see Supplemental Text S3 and Fig. S5 for details on assembly and construction). For safety reasons the airlift should not be operated from the scuba tank used by the diver for breathing. The mesh aperture determines the finest size of material that can be reliably collected, although finer grain sizes often accumulate within the bag due to aggregation with coarser sediment particles.

A single diver can successfully operate the airlift sampler, but a team of two is recommended for ease of use (Fig. 5a). To begin sampling, a diver first ensures no material is present inside the PVC pipe (some material can settle inside during underwater transport to the sampling site). Blocking the sucking end of the pipe, the diver then secures a collection bag at the other end (e.g. using cable ties). The air supply is slowly turned on and regulated with the valve; subsequently, the diver checks whether there is satisfactory suction and that the air can flow freely out of the collection bag (too much air can cause the bag to detach). To begin suctioning, the diver unblocks the end of the pipe and positions it over the sampling surface (ca. 2 cm from the bottom) in an inclined or vertical position. The substratum can then be gently scraped with a paint scraper/putty knife to remove the particulates and algal filaments from the substratum, with care being taken not to scrape off pieces of substratum that may bias the sediment composition (Fig. 5b). A small metal brush can then be used to remove any remaining filaments. When the desired area has been sampled, we suggest the diver wait ca. 20 s before the air flow is turned off to enable all the remaining particulates and material to travel through the pipe. Upon doing so, the pipe is turned upside down, enabling all the remaining material to settle at the end of the bag. The bag is then carefully detached, ensuring no material escapes, and is tightly sealed by closing it with a knot and/or cable tie. The task of the second diver is to control the air supply, check

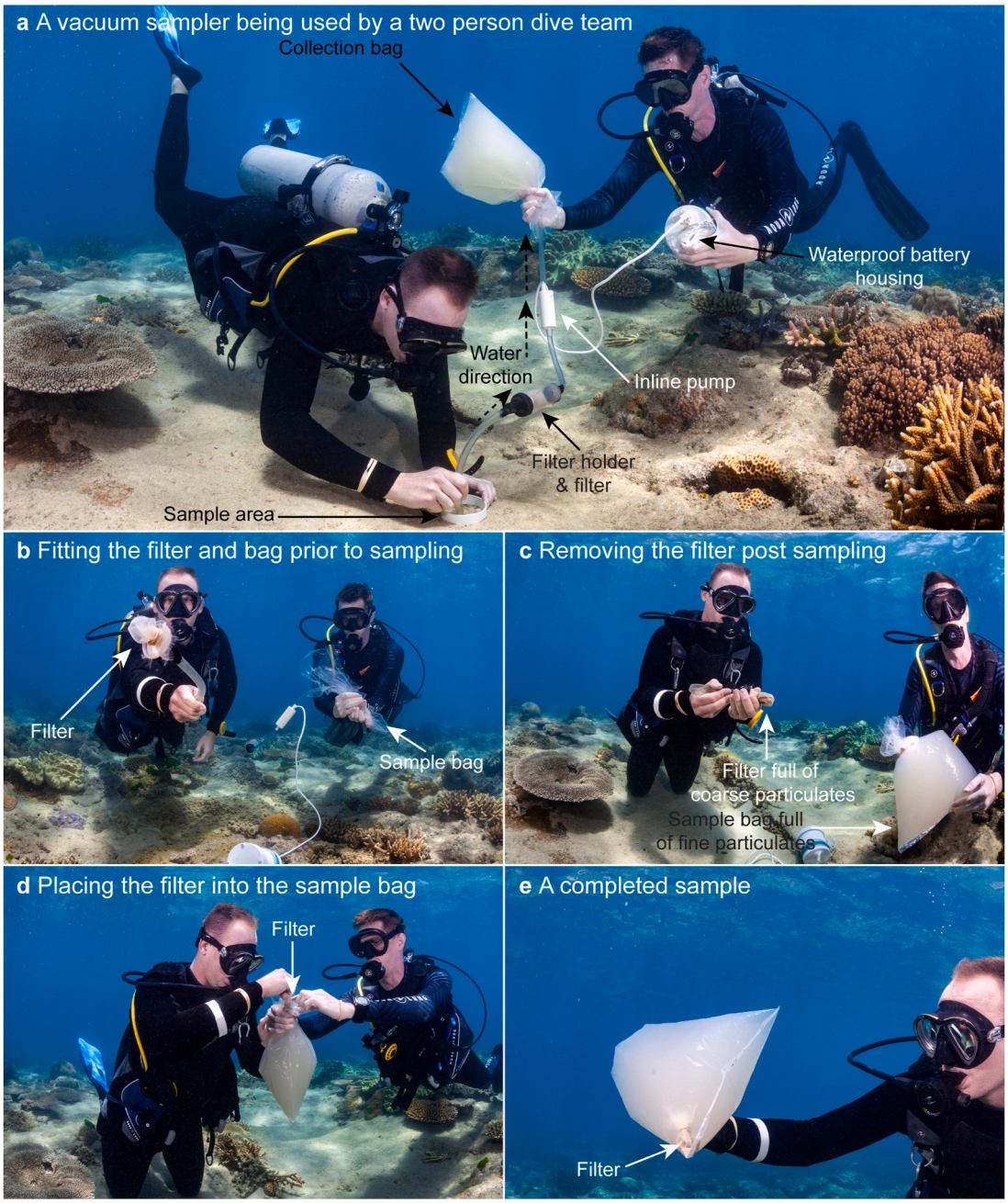

Fig. 4. a) A vacuum sampler being used on a coral reef to collect algal turf particulates, note one diver guides the sampler intake while the second diver controls the pump and the sample bag. The major steps involved (b–e) in setting up the vacuum sampler and collecting the particulate sample. b) Setting up the vacuum sampler at the sampling site, including fitting the filter and attaching the collection bag. c) Detaching the filter (note the folded over sampling tube) and collection bag post sampling and d) transferring the filter to the collection bag. e) A completed benthic particulate sample with the filter contained within the plastic bag. Refer to Supplemental Figs. S3 and S4 for enlarged versions of panels a–c. All photographs V. Huertas.

that air is flowing freely out of the collection bag and hold the air tank in a stable position, which is crucial in environments with high swell or hydrodynamic activity.

2.2.2. *Advantages*

The main advantage of the airlift sampling method is that large areas can be sampled in relatively short amount of time (Table 2). This is particularly important when turfs are heterogenous across space (e.g. different algal densities, heights, species composition from centimetre to seascape scales) (Harris et al., 2015; Pessarrodona et al., 2021) and a large amount of smaller replicates would be necessary to gain a representative, quantitative, sample of the turf assemblage. Furthermore, the airlift samplers are relatively powerful which can be advantageous in rough conditions or at great depths. In addition, the material collected is retained in a relatively small collection bag that is not filled with water. This means that no decanting steps are necessary (see Supplemental Text S5), thereby shortening the time needed for in-situ and ex-situ processing. It also means that the sample is small and compact which makes it a suitable method for use in areas where storage space is limited (e.g. boats or remote locations), or where transportation of water-filled plastic bags is not logistically feasible.

2.2.3. *Disadvantages*

The principal disadvantage of airlift samplers is that the finer

Table 2
Summary of the different methods used for algal turf sediment collection.

Method	Common type of measurement	Sediment size range sampled	Feasible sampling area and depth limits	Costs in USD	Major advantages	Major disadvantages
Vacuum sampling	Standing stock	0–2 mm	Area: <100 cm^2 Depth: 0–15 m (a greater maximum working depth is likely)	Per unit cost: ~$125-$175 Common number of units required: 1–3	Removes lose sediment (taking ~5 min per sample). Can collect different components of turfs separately. Small versatile units.	Logistical challenges following collection. Difficult to operate in high-energy conditions.
Airlift sampling	Standing stock	>63 μm	Area: 0–1000 cm^2 Depth: 0–15 m (a greater maximum working depth is likely as suction increases with depth)	Per unit cost: ~$20 excluding the first stage regulator Common number of units required: 1–2	Samples large areas relatively quickly (in ~5–10 min). Powerful and better in rough conditions. Less logistical challenges and the samples are easier to transport/process.	Unsuitable for quantifying organics and fine sediments. More difficult to collect different components of algal turfs separately.
TurfPods	Net accumulation	0–2 mm	Area: <100 cm^2 Depth: No depth limits	Per unit cost: ~$3-$5 Common number of units required: 10–100	Standardised replicate. Easily deployed and retrieved (within 1–2 min per unit). Cheap and very easy to make.	Not natural and raised. Less propensity to retain sediments than natural turfs. Logistical challenges following collection.

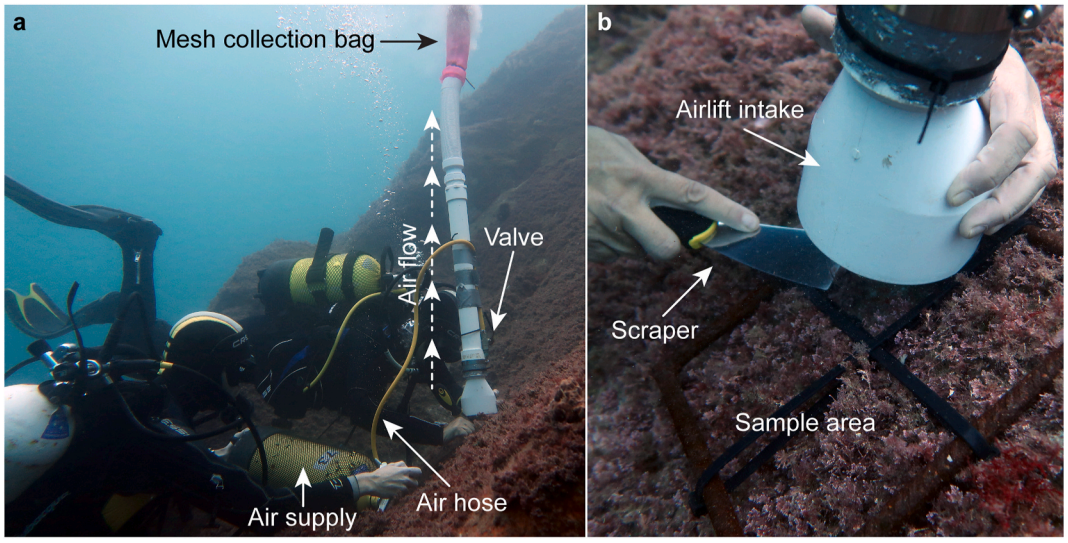

Fig. 5. a) A two-person dive team using the airlift sampler to collect algal turfs and the sediments they contain on a temperate reef, b) removing the algal turf community with a paint scraper for collection in the airlift sampler (Photographs: J. Boada).

sediment grain sizes (<63 μm) cannot be efficiently collected. The finest size of particles collected by this method is determined by the mesh size of the bag attached to the end of the airlift sampler. Very fine mesh sizes trap air bubbles and cause the bag to inflate rapidly and potentially detach from the airlift sampler. Bags with a mesh aperture of 63 μm have been found to be the finest that can be efficiently used; 125 μm bags are easier to work with. Given that the organic component of particulates is usually fine (<125 μm; Wilson and Bellwood 1997; Gordon et al., 2016), this method may not be suitable for studies aiming at quantifying the organic load of sediments. The sampling method may also miss a substantial fraction of the total sediment load if that is skewed towards the finest grain sizes, as is the case near sources of fine terrestrial siliceous material (e.g. river mouths) or in areas of low hydrodynamic activity (e.g. lagoons, back reefs or deep habitats) (Goatley et al., 2016; Gordon et al., 2016). Naturally, for a given sample area, the airlift method will always yield smaller loads than the vacuum (thus underestimating total particulate load). Therefore, if loads are compared between the two methods, the finest sediment size fraction (e.g. <63 μm) should also be excluded from the mass of samples collected via vacuum samplers to facilitate direct comparisons (e.g. Pessarrodona et al., 2022). However, the ability to sample larger areas with the airlift sampler may avoid overestimation as a result of sampling small areas of abnormally large loads.

2.3. TurfPods

2.3.1. Overview and use

TurfPods were designed as a proxy for algal turfs to quantify net particulate accumulation rates (Latrille et al., 2019). TurfPods are essentially modified SedPods (Field et al., 2013; i.e. small individual PVC units filled with concrete) with artificial grass/astro-turf attached to the concrete surfaces to mimic algal turfs (Fig. 6a) (see Supplemental Text S4 and Fig. S6 for construction details). As such, TurfPods represent a standardised surface and 3-dimensional structure with which to quantify particulate accumulation in turfs (provided that the turf length is homogenous across pods, as length is related to sediment trapping [Latrille et al., 2019]).

TurfPods can be securely deployed on the reef at any depth in a horizontal orientation (as surface slope can influence particulate trapping [Duran et al., 2018; Tebbett et al., 2020c] and vibration will also likely increase sediment loss). Rope, zip ties or rubber bands can be attached from the eyelet screws on the pods and to the reef to ensure that

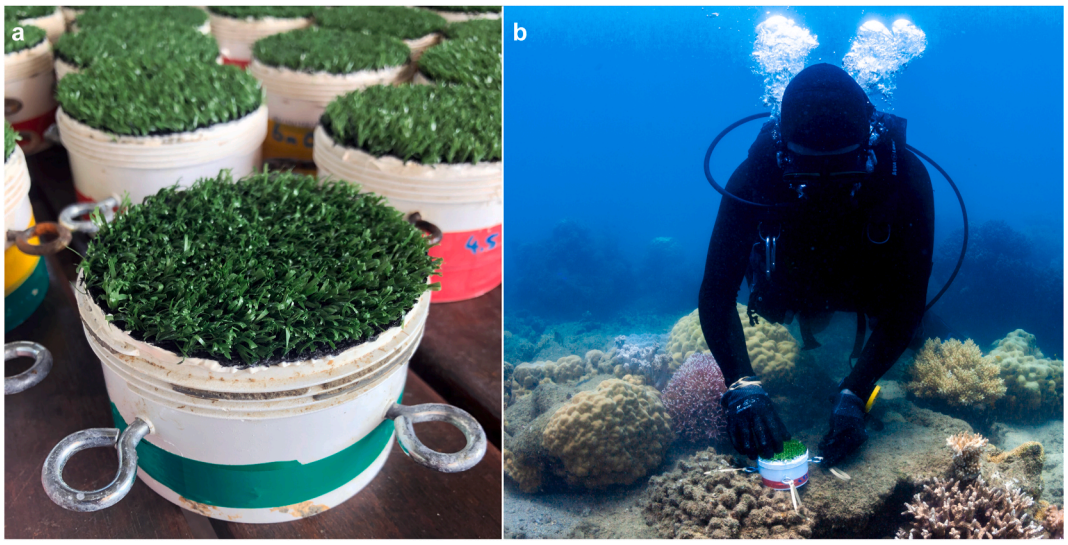

Fig. 6. a) A TurfPod, b) deploying a TurfPod on a coral reef (Photographs V. Huertas).

the TurfPods are secure (Fig. 6b). In addition, TurfPods can be deployed by wedging them into suitable holes or crevices in the reef matrix. After a given deployment length (typically 5–7 days), the TurfPods can be collected carefully by removing them from the reef and placing them inside a plastic bag (ensuring that there is no excess sediment trapped on the bottom or sides of the TurfPod) and sealing the plastic bag with a rubber band (Latrille et al., 2019). Therefore, TurfPods represent a quick and easy sampling method.

2.3.2. *Advantages*

The greatest advantage to TurfPods is that they offer a standardised sampling unit that can be easily replicated (Table 2). This means that they are particularly suitable for comparing relative rates of sediment accumulation among sites and across time. It is also likely that TurfPods will be less impacted by the grazing activity of fishes compared to natural algal turfs or via caging effects (if cages were used to prevent herbivorous fishes grazing). In addition, TurfPods are cheap to construct and easy to deploy on the reef. Furthermore, their development was based on SedPods which are now increasingly used to quantitatively estimate sediment accumulation rates on coral surfaces (Ennis et al., 2016; Duckworth et al., 2017; Whinney et al., 2017), which means their adoption into monitoring protocols may be easier than other methods. Indeed, from a logistical point of view, TurfPods are probably the easiest way to estimate particulate accumulation in algal turfs in aquatic ecosystems.

2.3.3. *Disadvantages*

The greatest disadvantage of TurfPods is that they are not a natural benthic surface and are raised off the substratum. This means they can be prone to 'edge-effects' and may not have the same propensity to trap particulates as algal turf communities on the substratum (Latrille et al., 2019; Tebbett and Bellwood 2021), especially compared to turf communities that contain substantial amounts of cyanobacteria which can help bind particulates together (Neumann et al., 1970; Stal, 2003; Latrille et al., 2019). In this respect, artificial turf mats nailed to the reef substratum may be better able to estimate sediment accumulation in turfs as they may capture both sediment deposition and horizontal movement (although deployment and collection of such mats may be more logistically challenging). Furthermore, TurfPods will also reach a saturation point whereby any additional particulates are unlikely to become trapped. Therefore, if TurfPods are deployed for too long in sediment-rich locations, they could underestimate the rate of sediment accumulation, making it necessary to carefully consider the length of the deployment period (as a rough guide we suggest 5–7 days). This saturation point is also dependent on the length of the artificial turf, and as a result, reporting the length of the turf used on the pods will help ensure reproducibility (based on the length of natural turfs we suggest a length of ~5 mm). In addition, using TurfPods in areas with large swell/high-energy can be difficult and may require adding an additional base to stay in place. Finally, as for vacuum sampling, the samples are all contained within water-filled plastic bags which makes it necessary to consider the logistics behind returning such samples to a suitable processing location.

3. Conclusion

Despite sediments being a major stressor in many marine ecosystems (Jones et al., 2015; Bainbridge et al., 2018; Magris and Ban 2019) and the fact that algal turfs are often the most abundant benthic covering in many temperate and tropical shallow-water marine ecosystems (Wernberg et al., 2013; Harris 2015; Filbee-Dexter et al., 2016; Smith et al., 2016), we lack baseline information on algal turf sediment standing stock and accumulation rates in nearly all geographic areas. This is particularly concerning considering the widespread impacts sediment-laden algal turfs can have on the functioning of marine systems, from the settlement of habitat-forming organisms (Alestra et al., 2014; Speare et al., 2019; Evans et al., 2020; Ricardo et al., 2021) to feeding by functionally important fishes (Bellwood and Fulton, 2008; Clausing et al., 2014; Tebbett et al., 2020b). Here, we provided an overview of easy and cheap to implement techniques to quantify algal turf particulates and sediments on both coral and temperate reefs.

From our review, it is clear that a variety of different methods have been used previously, however, we highlight the value in using vacuum samplers and airlifts samplers for the quantification of algal turf particulate standing stock, as they allow particulates to be collected in a standardised manner. Both methods have various advantages and disadvantages, and these need to be considered when addressing any given research question or implementing a monitoring program. Furthermore, we have highlighted that TurfPods represent the key method for quantifying particulate accumulation, with this method clearly having the potential to be widely used in monitoring programs. By endeavouring to make the methods for quantifying such particulates and sediments more accessible we hope this review will encourage other scientists and managers to incorporate algal turf particulate and sediment measurements into their field studies or monitoring.

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

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marenvres.2022.105673.

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