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

Authors:

Sterling B. Tebbett[1]*, M. Paula Sgarlatta[2], Albert Pessarrodona[3], Adriana Vergés[2,4], Thomas Wernberg[3,5], David R. Bellwood[1]

Addresses:

[1] Research Hub for Coral Reef Ecosystem Functions, College of Science and Engineering and ARC Centre of Excellence for Coral Reef Studies, James Cook University, Townsville, Queensland 4811, Australia

[2] Centre for Marine Science & Innovation and Evolution & Ecology Research Centre, School of Biological, Earth and Environmental Sciences, UNSW Australia, Sydney, New South Wales, Australia

[3] UWA Oceans Institute and School of Biological Sciences, University of Western Australia, Crawley, Western Australia 6009, Australia

[4] Sydney Institute of Marine Science, Mosman, New South Wales, Australia

[5] Norwegian Institute of Marine Research, His, Norway.

***Corresponding Author:**

Email: sterling.tebbett@my.jcu.edu.au

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.

Key words:

Airlift; Benthic; Ecosystem monitoring; Epilithic algal matrix; Reef; TurfPod; Vacuum Sampler

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) (Figure 1a, 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; 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 2011). 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 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 very 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.

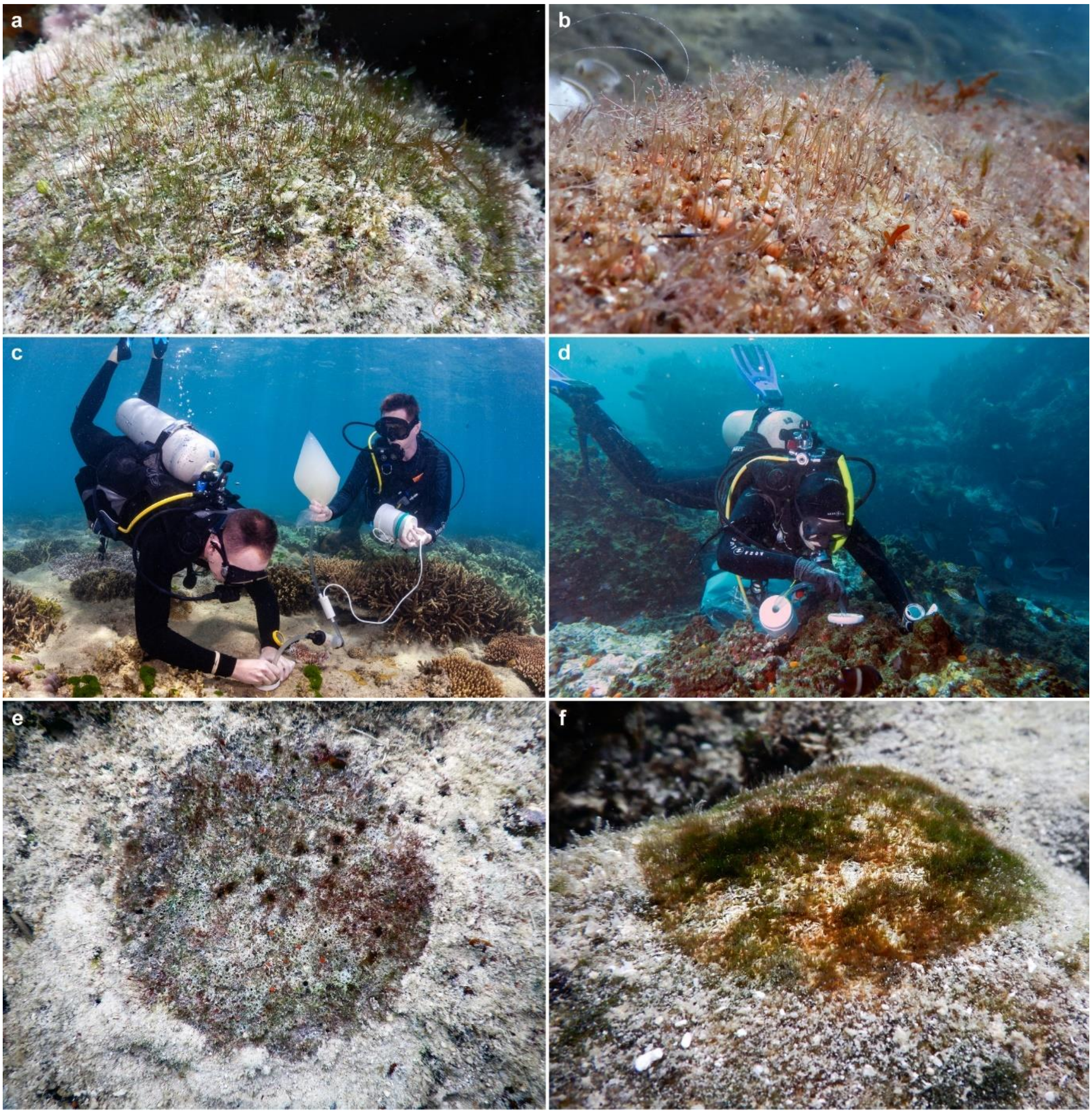

Figure 1 Algal turf communities on a) a coral reef at Lizard Island, Australia and b) a temperate rocky reef in the Mediterranean, off Tossa de Mar, Spain. Sampling benthic particulates from algal turfs with vacuum samplers on c) a coral reef at Fantome Island, Australia and d) a subtropical rocky reef 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).

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 (Figure 1b, c) have been the most widely used equipment (Figure 2), with airlift samplers representing the only other apparatus that is used to collect particulates in a manner that is easily standardised among studies (Figure 2). Algal turf particulates have also been collected using manual hand tools (Figure 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) (Figure 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.

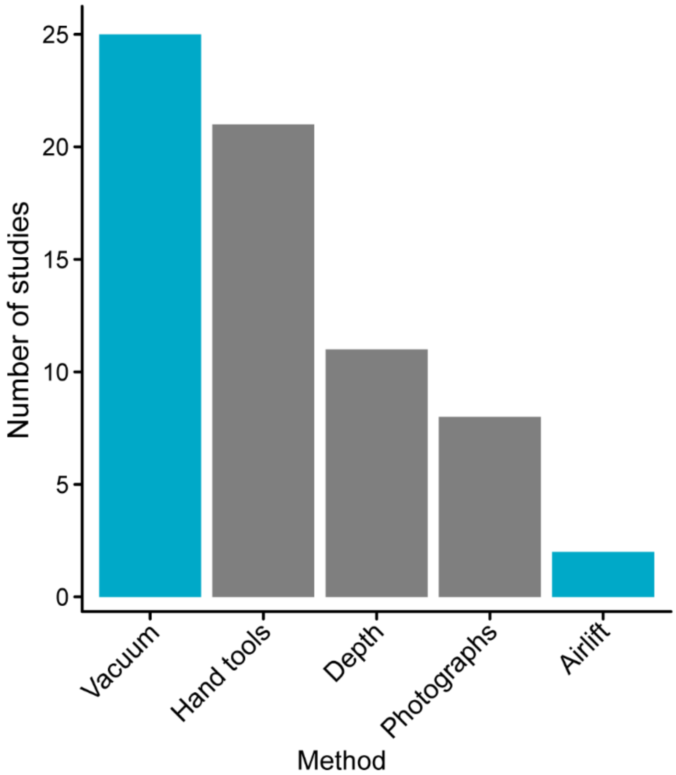

Figure 2 The frequency by which different methods have been used to quantify the standing stock of algal turf sediments in marine systems. Details of how studies were sourced and quantified are provided in the supplemental material (Text S1). Note the two bars highlighted in blue represent the equipment 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.

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 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) (Figure 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) (Figure 3a). As batteries have become smaller, the design has been modified accordingly and is now a fraction of the size, facilitating use and transport (Figure 3a, b). It is important to note that inorganic sediment loads collected using the new version fully encompass the loads sampled using the initial version (Figure 3c), suggesting that both designs are comparable with a marked ability to collect sediments from algal turfs (Figure 1e, f).

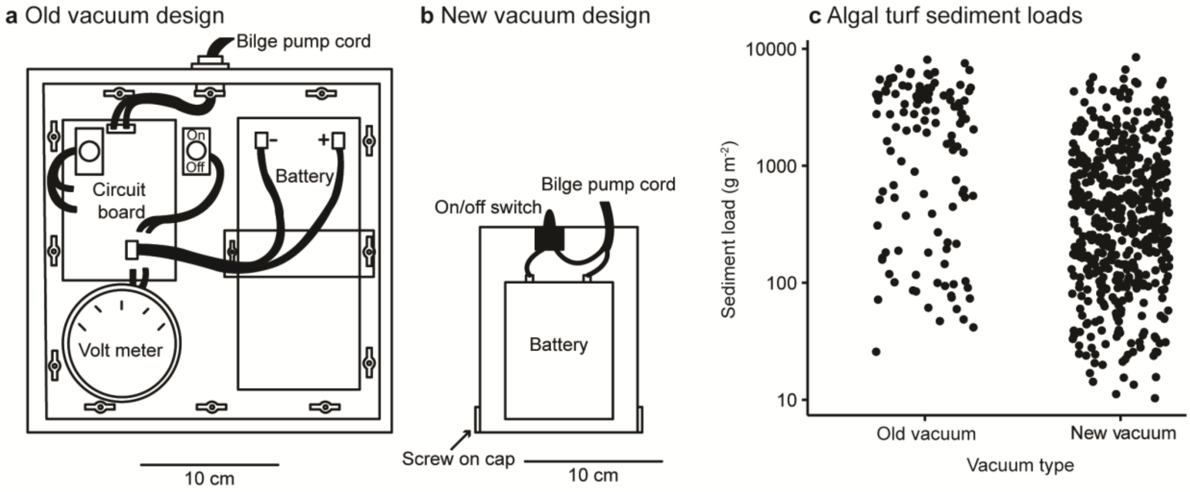

Figure 3 The main battery housing of underwater vacuum samplers designed to collect particulates from algal turfs: a) the old design redrawn from Purcell (1996) and b) the new design for housing a smaller battery. c) Algal turf sediment loads from coral reefs that were quantified using the old vacuum 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.

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 (Figure 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 (Figures 3b, 4a). The separate components of the vacuum are all connected with clear silicone tubing (Figure 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; Figures S1, 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) (Figure 1c, 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 (Figure 4b). The collection bag is fitted at the very end of the silicone tubing using a rubber band (Figure 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) (Figure 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 (Figure 4a). When this area is clear of sediment and particulates (Figure 1e, 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 (Figure 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 (Figure 4d). This ensures the entire sample remains together (Figure 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 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.

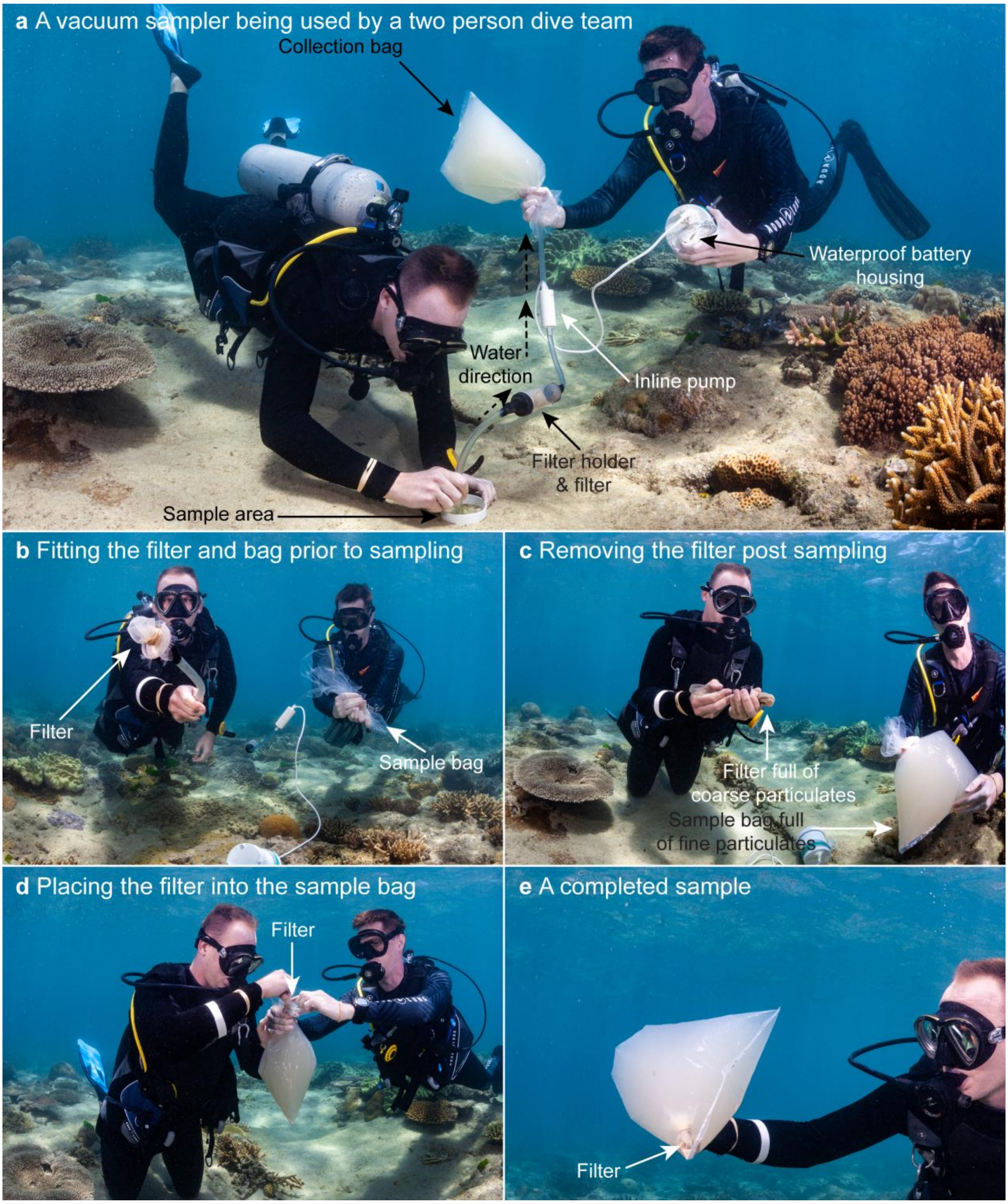

Figure 4 a) A vacuum sampler being used on a coral reef to collect algal turf particulates, note one diver guides the sampler intake while the second diver controls the pump and the sample bag. The major steps involved (b-e) in setting up the vacuum sampler and collecting the particulate sample. b) Setting 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 Figures S3 and S4 for enlarged versions of panels a-c. All photographs V. Huertas.

2.1.2. Advantages

Collecting algal turf particulates with a vacuum sampler has several advantages (Table 2). Firstly, natural algal turf are sampled (unlike Turfpods) and collecting the particulates with the vacuum causes little, if any, damage to the algal turf community (Figure 1e, 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 does not remove any of the underlying reef matrix (Figure 1e, 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 Figure 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 (Figure 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 (Figure 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 seconds 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 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 sampler is that the finer 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.

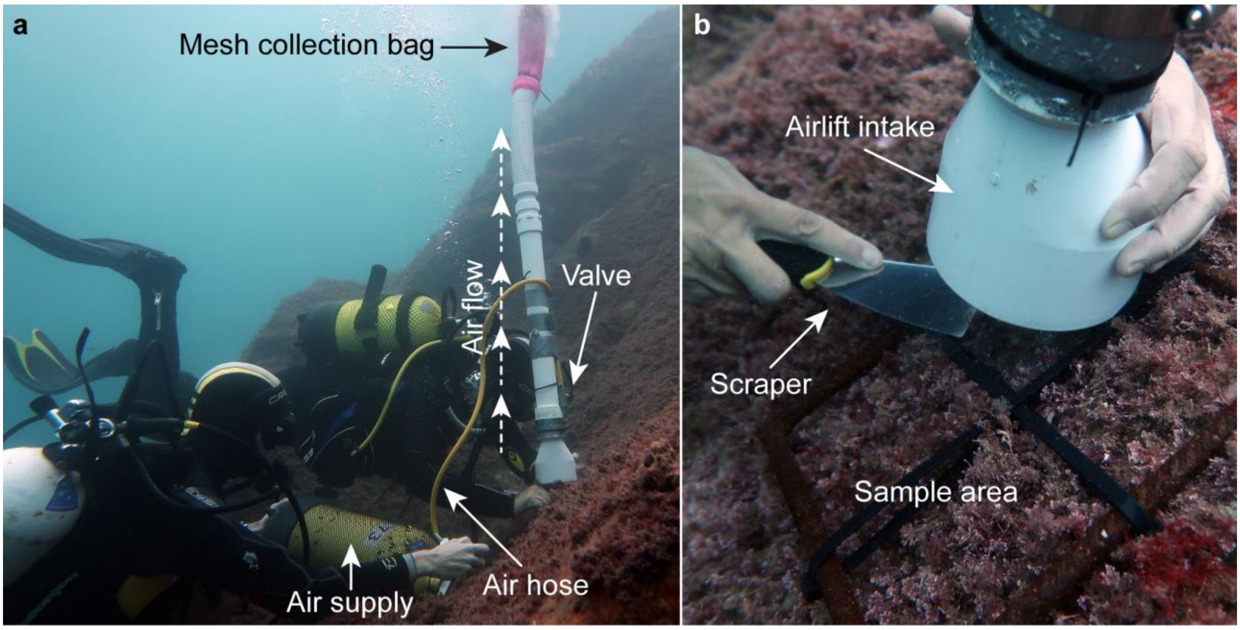

Figure 5 a) A two-person dive team using the airlift sampler to collect algal turfs and the sediments they contain on a temperate reef, b) removing the algal turf community with a paint scraper for collection in the airlift sampler (Photographs: J. Boada).

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 (Figure 6a) (see Supplemental Text S4 and Figure 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 the TurfPods are secure (Figure 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). As such, TurfPods represent a quick and easy sampling method.

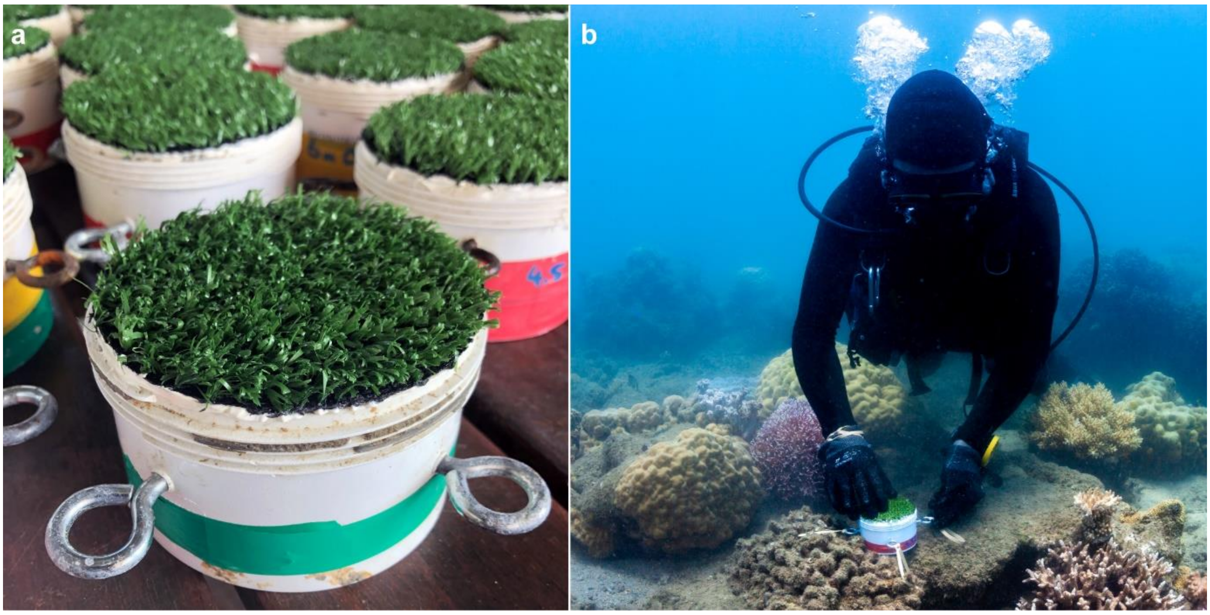

Figure 6 a) A TurfPod, b) deploying a TurfPod on a coral reef (Photographs V. Huertas).

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 2011; 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 such, 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.

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 – 28.2 depending on their length	Latrille et al. 2019
	Net accumulation	Palau archipelago, Micronesia	Average rates ranged from 0.3 – 13.2 among sites.	Wakwella et al. 2020

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 minutes 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 minutes). 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	Per unit cost:	Standardised replicate.	Not natural and raised.

	Depth: No depth limits	~$3-$5 Common number of units required: 10-100	Easily deployed and retrieved (within 1-2 minutes per unit). Cheap and very easy to make.	Less propensity to retain sediments than natural turfs. Logistical challenges following collection.

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) 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.

Acknowledgements

We thank V. Huertas and J. Boada for supplying photographs; M.J. Kramer and C.H.R. Goatley for assistance with vacuum sampler design and use; C.R. Hemingson and Orpheus Island Research Station staff for field support; two anonymous reviewers for constructive comments; the Australian Research Council (Grant numbers: DRB CE140100020 and FL190100062; AV DP190102030; TW DP190100058), the New South Wales Environmental Trust, an Endeavour Postgraduate Scholarship (MPS) and an Australian Government Research Training Program Scholarship (SBT, AP) for financial support.

References

Airoldi L (2003) The effects of sedimentation on rocky coast assemblages. Oceanogr Mar Biol An Annu Rev 41:161–236

Airoldi L, Virgilio M (1998) Responses of turf-forming algae to spatial variations in the deposition of sediments. Mar Ecol Prog Ser 165:271–282

Akita Y, Kurihara T, Uehara M, Shiwa T, Iwai K (2022) Impacts of overfishing and sedimentation on the feeding behavior and ecological function of herbivorous fishes in coral reefs. Mar Ecol Prog Ser 686:141–157

Alestra T, Tait LW, Schiel DR (2014) Effects of algal turfs and sediment accumulation on replenishment and primary productivity of fucoid assemblages. Mar Ecol Prog Ser 511:59–70

Andrello M, Darling ES, Wenger A, Suárez-Castro AF, Gelfand S, Ahmadia GN (2022) A global map of human pressures on tropical coral reefs. Conserv Lett 15:e12858

Bainbridge Z, Lewis S, Bartley R, Fabricius K, Collier C, Waterhouse J, Garzon-Garcia A, Robson B, Burton J, Wenger A, Brodie J (2018) Fine sediment and particulate organic matter: a review and case study on ridge-to-reef transport, transformations, fates, and impacts on marine ecosystems. Mar Pollut Bull 135:1205–1220

Barnett PRO, Hardy BLS (1967) A diver-operated quantitative bottom sampler for sand macrofaunas. Helgoländer Wissenschaftliche Meeresuntersuchungen 15:390–398

Bellwood DR, Fulton CJ (2008) Sediment-mediated suppression of herbivory on coral reefs: decreasing resilience to rising sea-levels and climate change? Limnol Oceanogr 53:2695–2701

Bellwood DR, Pratchett MS, Morrison TH, Gurney GG, Hughes TP, Álvarez-Romero JG, Day JC, Grantham R, Grech A, Hoey AS, Jones GP, Pandolfi JM, Tebbett SB, Techera E, Weeks R, Cumming GS (2019) Coral reef conservation in the Anthropocene: confronting spatial mismatches and prioritizing functions. Biol Conserv 236:604–615

Bennett S, Wernberg T, Harvey ES, Santana-Garcon J, Saunders BJ (2015) Tropical herbivores provide resilience to a climate-mediated phase shift on temperate reefs. Ecol

Lett 18:714–723

Birrell CL, McCook LJ, Willis BL (2005) Effects of algal turfs and sediment on coral settlement. Mar Pollut Bull 51:408–414

Bothner MH, Reynolds RL, Casso MA, Storlazzi CD, Field ME (2006) Quantity, composition, and source of sediment collected in sediment traps along the fringing coral reef off Molokai, Hawaii. Mar Pollut Bull 52:1034–1047

Bowden CL, Streit RP, Bellwood DR, Tebbett SB (2022) A 3D perspective on sediment turnover and feeding selectivity in blennies. Mar Pollut Bull doi: 10.1016/j.marpolbul.2022.113799

Burek KE, O'Brien JM, Scheibling RE (2018) Wasted effort: recruitment and persistence of kelp on algal turf. Mar Ecol Prog Ser 600:3–19

Carpenter RC (1986) Partitioning herbivory and its effects on coral reef algal communities. Ecol Monogr 56:345–364

Carpenter RC, Williams SL (1993) Effects of algal turf canopy height and microscale substratum topography on profiles of flow speed in a coral forereef environment. Limnol Oceanogr 38:687–694

Ceccarelli DM, Jones GP, McCook LJ (2005) Effects of territorial damselfish on an algal-dominated coastal coral reef. Coral Reefs 24:606–620

Chase TJ, Pratchett MS, Mcwilliam MJ, Hein MY, Tebbett SB, Hoogenboom MO (2020) Damselfishes alleviate the impacts of sediments on host corals. R Soc Open Sci 7:192074

Clausing RJ, Annunziata C, Baker G, Lee C, Bittick SJ, Fong P (2014) Effects of sediment depth on algal turf height are mediated by interactions with fish herbivory on a fringing reef. Mar Ecol Prog Ser 517:121–129

Connell SD, Foster MS, Airoldi L (2014) What are algal turfs? Towards a better description of turfs. Mar Ecol Prog Ser 495:299–307

Connell SD, Russell BD (2010) The direct effects of increasing CO2 and temperature on non-calcifying organisms: increasing the potential for phase shifts in kelp forests. Proc R Soc B Biol Sci 277:1409–1415

Copertino M, Connell SD, Cheshire A (2005) The prevalence and production of turf-forming algae on a temperate subtidal coast. Phycologia 44:241–248

Duckworth A, Giofre N, Jones R (2017) Coral morphology and sedimentation. Mar Pollut Bull 125:289–300

Duran A, Adam TC, Palma L, Moreno S, Collado-Vides L, Burkepile DE (2019) Feeding behavior in Caribbean surgeonfishes varies across fish size, algal abundance, and habitat characteristics. Mar Ecol 40:e12561

Duran A, Collado-Vides L, Palma L, Burkepile DE (2018) Interactive effects of herbivory and substrate orientation on algal community dynamics on a coral reef. Mar Biol 165:156

Ennis RS, Brandt ME, Grimes KRW, Smith TB (2016) Coral reef health response to chronic and acute changes in water quality in St. Thomas, United States Virgin Islands. Mar Pollut Bull 111:418–427

Eurich JG, Shomaker SM, Mccormick MI, Jones P (2018) Experimental evaluation of the effect of a territorial damselfish on foraging behaviour of roving herbivores on coral reefs. J Exp Mar Bio Ecol 506:155–162

Evans RD, Wilson SK, Fisher R, Ryan NM, Babcock R, Blakeway D, Bond T, Dorji P, Dufois F, Fearns P, Lowe RJ, Stoddart J, Thomson DP (2020) Early recovery dynamics of turbid coral reefs after recurring bleaching events. J Environ Manage 268:110666

Falkenberg LJ, Connell SD, Coffee OI, Ghedini G, Russell BD (2015) Species interactions can maintain resistance of subtidal algal habitats to an increasingly modified world. Glob Ecol Conserv 4:549–558

Feehan CJ, Grace SP, Narvaez CA (2019) Ecological feedbacks stabilize a turf-dominated ecosystem at the southern extent of kelp forests in the Northwest Atlantic. Sci Rep 9:7078

Field ME, Chezar H, Storlazzi CD (2013) SedPods: a low-cost coral proxy for measuring net sedimentation. Coral Reefs 32:155–159

Filbee-Dexter K, Feehan CJ, Scheibling RE (2016) Large-scale degradation of a kelp ecosystem in an ocean warming hotspot. Mar Ecol Prog Ser 543:141–152

Filbee-Dexter K, Wernberg T (2018) Rise of turfs: a new battlefront for globally declining kelp forests. Bioscience 68:64–76

Fong CR, Bittick SJ, Fong P (2018) Simultaneous synergist, antagonistic, and additive interactions between multiple local stressors all degrade algal turf communities on coral reefs. J Ecol 106:1390–1400

Ford AK, Eich A, McAndrews RS, Mangubhai S, Nugues MM, Bejarano S, Moore BR, Rico C, Wild C, Ferse SCA (2018) Evaluation of coral reef management effectiveness using conventional versus resilience-based metrics. Ecol Indic 85:308–317

Gao X, Lee JR, Park SK, Kim NG, Choi HG (2019) Detrimental effects of sediment on attachment, survival and growth of the brown alga *Sargassum thunbergii* in early life stages. Phycol Res 67:77–81

Goatley CHR, Bellwood DR (2011) The roles of dimensionality, canopies and complexity in ecosystem monitoring. PLoS One 6:e27307

Goatley CHR, Bellwood DR (2012) Sediment suppresses herbivory across a coral reef depth gradient. Biol Lett 8:1016–1018

Goatley CHR, Bonaldo RM, Fox RJ, Bellwood DR (2016) Sediments and herbivory as sensitive indicators of coral reef degradation. Ecol Soc 21:29

Gordon SE, Goatley CHR, Bellwood DR (2016) Composition and temporal stability of turf sediments on inner-shelf coral reefs. Mar Pollut Bull 111:178–183

Gorgula SK, Connell SD (2004) Expansive covers of turf-forming algae on human-dominated coast: the relative effects of increasing nutrient and sediment loads. Mar Biol 145:613–619

Gorman D, Horta P, Flores AA V, Turra A, Augusto de Souza Berchez F, Batista MB, Lopes Filho ES, Melo MS, Ignacio BL, Carneiro IM, Villaça RC, Széchy MTM (2020) Decadal losses of canopy-forming algae along the warm temperate coastline of Brazil. Glob Chang Biol 26:1446–1457

Harris J (2015) The ecology of turf algae on coral reefs. PhD Thesis, University of California

Harris JL, Lewis LS, Smith JE (2015) Quantifying scales of spatial variability in algal turf assemblages on coral reefs. Mar Ecol Prog Ser 532:41–57

Hay ME (1981) The functional morphology of turf-forming seaweeds: persistence in stressful marine habitats. Ecology 62:739–750

Hayes HG, Kalhori PS, Weiss M, Grier SR, Fong P, Fong CR (2021) Storms may disrupt top-down control of algal turf on fringing reefs. Coral Reefs 40:269–273

Hiscock K, Hoare R (1973) A portable suction sampler for rock epibiota. Helgoländer Wissenschaftliche Meeresuntersuchungen 25:35–38

Holbrook SJ, Schmitt RJ, Adam TC, Brooks AJ (2016) Coral reef resilience, tipping points and the strength of herbivory. Sci Rep 6:35817

Irving AD, Connell SD (2006) Physical disturbance by kelp abrades erect algae from the understorey. Mar Ecol Prog Ser 324:127–137

Jones R, Ricardo GF, Negri AP (2015) Effects of sediments on the reproductive cycle of corals. Mar Pollut Bull 100:13–33

Jouffray J-B, Nyström M, Norstrom AV, Williams ID, Wedding LM, Kittinger JN, Williams GJ (2015) Identifying multiple coral reef regimes and their drivers across the Hawaiian archipelago. Philos Trans R Soc B Biol Sci 370:20130268

Kendrick GA (1991) Recruitment of coralline crusts and filamentous turf algae in the Galapagos archipelago: effect of simulated scour, erosion and accretion. J Exp Mar Bio Ecol 147:47–63

Kennedy EV, Vercelloni J, Neal BP, Ambariyanto, Bryant DEP, Ganase A, Gartrell P, Brown K, Kim CJS, Hudatwi M, Hadi A, Prabowo A, Prihatinningsih P, Haryanta S, Markey K, Green S, Dalton P, Lopez-Marcano S, Rodriguez-Ramirez A, Gonzalez-Rivero M, Hoegh-Guldberg O (2020) Coral reef community changes in Karimunjawa National Park, Indonesia: assessing the efficacy of management in the face of local and global stressors. J Mar Sci Eng 8:760

Kennelly SJ (1987) Inhibition of kelp recruitment by turfing algae and consequences for an Australian kelp community. J Exp Mar Bio Ecol 112:49–60

Klumpp DW, McKinnon AD (1989) Temporal and spatial patterns in primary production of a coral-reef epilithic algal community. J Exp Mar Biol Ecol 131:1–22

Kramer MJ, Bellwood DR, Bellwood O (2012) Cryptofauna of the epilithic algal matrix on an inshore coral reef, Great Barrier Reef. Coral Reefs 31:1007–1015

Latrille FX, Tebbett SB, Bellwood DR (2019) Quantifying sediment dynamics on an inshore coral reef: putting algal turfs in perspective. Mar Pollut Bull 141:404–415

Layton C, Cameron MJ, Shelamoff V, Fernández PA, Britton D, Hurd CL, Wright JT, Johnson CR (2019) Chemical microenvironments within macroalgal assemblages: Implications for the inhibition of kelp recruitment by turf algae. Limnol Oceanogr 64:1600–1613

Liao Z, Yu K, Wang Y, Huang X, Xu L (2019) Coral-algal interactions at Weizhou Island in the northern South China Sea: variations by taxa and the exacerbating impact of sediments trapped in turf algae. PeerJ 7:e6590

Magris RA, Ban NC (2019) A meta-analysis reveals global patterns of sediment effects on marine biodiversity. Glob Ecol Biogeogr 28:1879–1898

Max LM, Hamilton SL, Gaines SD, Warner RR (2013) Benthic processes and overlying fish assemblages drive the composition of benthic detritus on a central Pacific coral reef. Mar Ecol Prog Ser 482:181–195

McAndrews RS, Eich A, Ford AK, Bejarano S, Lal RR, Ferse SCA (2019) Algae sediment dynamics are mediated by herbivorous fishes on a nearshore coral reef. Coral Reefs 38:431–441

McCulloch M, Fallon S, Wyndham T, Hendy E, Lough J, Barnes D (2003) Coral record of increased sediment flux to the inner Great Barrier Reef since European settlement. Nature 421:727–730

Moy FE, Christie H (2012) Large-scale shift from sugar kelp (*Saccharina latissima*) to ephemeral algae along the south and west coast of Norway. Mar Biol Res 8:309–321

Neumann AC, Gebelein CD, Scoffin TP (1970) The composition, structure and erodability of subtidal mats, Abaco, Bahamas. J Sediment Petrol 40:274–297

Ng D, Taira D, Heery EC, Todd PA (2021) Antagonistic effects of seawalls and urban sedimentation on epilithic algal matrix (EAM)-feeding fishes. Mar Pollut Bull 173:113098

O’Brien JM, Scheibling RE (2018) Turf wars: competition between foundation and turf-forming species on temperate and tropical reefs and its role in regime shifts. Mar Ecol Prog Ser 590:1–17

Pessarrodona A, Filbee-Dexter K, Alcoverro T, Boada J, Feehan CJ, Fredriksen S, Grace SP, Nakamura Y, Narvaez CA, Norderhaug KM, Wernberg T (2021) Homogenization and miniaturization of habitat structure in temperate marine forests. Glob Chang Biol 27:5262–5275

Pessarrodona A, Tebbett SB, Bosch NE, Bellwood DR, Wernberg T (2022) High herbivory despite high sediment loads on a fringing coral reef. Coral Reefs 41:161–173

Prathep A, Marrs RH, Norton TA (2003) Spatial and temporal variations in sediment accumulation in an algal turf and their impact on associated fauna. Mar Biol 142:381–390

Purcell SW (1996) A direct method for assessing sediment load in epilithic algal communities. Coral Reefs 15:211–213

Purcell SW (2000) Association of epilithic algae with sediment distribution on a windward reef in the northern Great Barrier Reef, Australia. Bull Mar Sci 66:199–214

Purcell SW, Bellwood DR (2001) Spatial patterns of epilithic algal and detrital resources on a windward coral reef. Coral Reefs 20:117–125.

Rasher DB, Engel S, Bonito V, Fraser GJ, Montoya JP, Hay ME (2012) Effects of herbivory, nutrients, and reef protection on algal proliferation and coral growth on a tropical reef. Oecologia 169:187–198

Ricardo GF, Jones RJ, Nordborg M, Negri AP (2017) Settlement patterns of the coral *Acropora millepora* on sediment-laden surfaces. Sci Total Environ 609:277–288

Schlaefer JA, Tebbett SB, Bellwood DR (2021) The study of sediments on coral reefs: a hydrodynamic perspective. Mar Pollut Bull 169:112580

Smith JE, Brainard R, Carter A, Grillo S, Edwards C, Harris J, Lewis L, Obura D, Rohwer F, Sala E, Vroom PS, Sandin S (2016) Re-evaluating the health of coral reef communities: baselines and evidence for human impacts across the central Pacific. Proc R Soc B Biol Sci 283:20151985

Speare KE, Duran A, Miller MW, Burkepile DE (2019) Sediment associated with algal turfs inhibits the settlement of two endangered coral species. Mar Pollut Bull 144:189–195

Stal LJ (2003) Microphytobenthos, their extracellular polymeric substances, and the morphogenesis of intertidal sediments. Geomicrobiol J 20:463–478

Storlazzi CD, Field ME, Bothner MH (2011) The use (and misuse) of sediment traps in coral reef environments: theory, observations, and suggested protocols. Coral Reefs 30:23–38

Taylor RB, Blackburn RI, Evans JH (1995) A portable battery-powered suction device for the quantitative sampling of small benthic invertebrates. J Exp Mar Bio Ecol 194:1–7

Tebbett SB, Bellwood DR (2019) Algal turf sediments on coral reefs: what's known and what's next. Mar Pollut Bull 149:110542

Tebbett SB, Bellwood DR (2020) Sediments ratchet-down coral reef algal turf productivity. Sci Total Environ 713:136709

Tebbett SB, Bellwood DR (2021) Algal turf productivity on coral reefs: a meta-analysis. Mar Environ Res 168:105311

Tebbett SB, Bellwood DR, Purcell SW (2018a) Sediment addition drives declines in algal turf yield to herbivorous coral reef fishes: implications for reefs and reef fisheries. Coral Reefs 37:929–937

Tebbett SB, Chase TJ, Bellwood DR (2020a) Farming damselfishes shape algal turf sediment dynamics on coral reefs. Mar Environ Res 160:104988

Tebbett SB, Goatley CHR, Bellwood DR (2017a) The effects of algal turf sediments and organic loads on feeding by coral reef surgeonfishes. PLoS One 12:e0169479

Tebbett SB, Goatley CHR, Bellwood DR (2017b) Algal turf sediments and sediment production by parrotfishes across the continental shelf of the northern Great Barrier Reef. PLoS One 12:e0170854

Tebbett SB, Goatley CHR, Bellwood DR (2018b) Algal turf sediments across the Great

Barrier Reef: putting coastal reefs in perspective. Mar Pollut Bull 137:518–525

Tebbett SB, Goatley CHR, Streit RP, Bellwood DR (2020b) Algal turf sediments limit the spatial extent of function delivery on coral reefs. Sci Total Environ 734:139422

Tebbett SB, Streit RP, Bellwood DR (2020c) A 3D perspective on sediment accumulation in algal turfs: implications of coral reef flattening. J Ecol 108:70–80

Thiriet PD, Di Franco A, Cheminée A, Guidetti P, Bianchimani O, Basthard-Bogain S, Cottalorda JM, Arceo H, Moranta J, Lejeune P, Francour P, Mangialajo L (2016) Abundance and diversity of crypto- and necto-benthic coastal fish are higher in marine forests than in structurally less complex macroalgal assemblages. PLoS One 11:e0164121

Umar MJ, McCook LJ, Price IR (1998) Effects of sediment deposition on the seaweed *Sargassum* on a fringing coral reef. Coral Reefs 17:169–177

Vergés A, Doropoulos C, Malcolm HA, Skye M, Garcia-Pizá M, Marzinelli EM, Campbell AH, Ballesteros E, Hoey AS, Vila-Concejo A, Bozec YM, Steinberg PD (2016) Long-term empirical evidence of ocean warming leading to tropicalization of fish communities, increased herbivory, and loss of kelp. Proc Natl Acad Sci U S A 113:13791–13796

Vergés A, McCosker E, Mayer-Pinto M, Coleman MA, Wernberg T, Ainsworth T, Steinberg PD (2019) Tropicalisation of temperate reefs: implications for ecosystem functions and management actions. Funct Ecol 33:1000–1013

Vermeij MJA, van Moorselaar I, Engelhard S, Hörnlein C, Vonk SM, Visser PM (2010) The effects of nutrient enrichment and herbivore abundance on the ability of turf algae to overgrow coral in the Caribbean. PLoS One 5:e14312

Wakwella A, Mumby PJ, Roff G (2020) Sedimentation and overfishing drive changes in early succession and coral recruitment. Proc R Soc B Biol Sci 287:20202575

Wernberg T, Bennett S, Babcock RC, Bettignies T De, Cure K, Depczynski M, Dufois F, Fromont J, Fulton CJ, Hovey RK, Harvey ES, Holmes TH, Kendrick GA, Radford B, Santana-Garcon J, Saunders BJ, Smale DA, Thomsen MS, Tuckett CA, Tuya F, Vanderklift MA, Wilson S (2016) Climate-driven regime shift of a temperate marine ecosystem. Science 353:169–172

Wernberg T, Kendrick GA, Toohey BD (2005) Modification of the physical environment by an *Ecklonia radiata* (Laminariales) canopy and implications for associated foliose algae. Aquat Ecol 39:419–430

Wernberg T, Smale DA, Tuya F, Thomsen MS, Langlois TJ, de Bettignies T, Bennett S, Rousseaux CS (2013) An extreme climatic event alters marine ecosystem structure in a global biodiversity hotspot. Nat Clim Chang 3:78–82

Whinney J, Jones R, Duckworth A, Ridd P (2017) Continuous in situ monitoring of sediment deposition in shallow benthic environments. Coral Reefs 36:521–533

Whorff JS, Whorff LL, Sweet MH (1995) Spatial variation in an algal turf community with respect to substratum slope and wave height. J Mar Biol Assoc United Kingdom 75:429–444

Wilson SK, Bellwood DR (1997) Cryptic dietary components of territorial damselfishes (Pomacentridae, Labroidei). Mar Ecol Prog Ser 153:299–310

Þorbjörnsson JG, Ólafsdóttir JH, Kristjánsson BK (2018) Diver-operated manual suction pump sampler: a reliable method for sampling benthos on rock substrates. Aquat Biol 27:87-92