Algal turf sediments on coral reefs: what's known and what's next

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Abstract

Algal turfs are likely to rise in prominence on coral reefs in the Anthropocene. In these ecosystems the sediments bound within algal turfs will shape ecosystem functions and the services humanity can obtain from reefs. However, while interest is growing in the role of algal turf sediments, studies remain limited. In this review we provide an overview of our knowledge to-date concerning algal turf sediments on coral reefs. Specifically, we highlight what algal turf sediments are, their role in key ecosystem processes, the potential importance of algal turf sediments on Anthropocene reefs, and key knowledge gaps for future research. The evidence suggests that the management of algal turf sediments will be critically important if we are to sustain key functions and services on highly-altered, Anthropocene coral reef configurations.

Keywords:

Anthropocene Coral Reefs; Epilithic Algal Matrix; Ecosystem Function; Herbivory; Productivity; Sediment

1. Introduction

In the wake of increasing anthropogenic disturbances, marine ecosystems have changed profoundly (Hughes et al., 2017; Vergés et al., 2019; Wernberg et al., 2015). In many cases these disturbances have driven a loss of canopy forming foundation organisms (Airoldi and Beck, 2007; Hughes et al., 2018b; O'Brien and Scheibling, 2018; Wernberg et al., 2015; Wismer et al., 2019), and a rise in the coverage of algal turfs (Feehan et al., 2019; Filbee-Dexter and Wernberg, 2018; Goatley and Bellwood, 2011; Jouffray et al., 2015) (Fig. 1). This has been epitomised on the world's coral reefs which have now undergone three global-scale coral bleaching events (Bruno et al., 2019; Hughes et al., 2018a). Indeed, the effects of climate change are now interacting with a myriad of other stressors, including terrestrial inputs (Bainbridge et al., 2018; Ban et al., 2014; Fabricius, 2005) and overfishing (Graham et al., 2017; Jackson et al., 2001), on coral reef ecosystems. Many coral reefs now exist in a coral depauperate state (Fig. 1c-f), with some punctuated by periods of apparent recovery or by transitions to alternative states (Bruno et al., 2019; Gilmour et al., 2019; Mellin et al., 2019; Wilson et al., 2019).

Following the trajectory outlined above, herein we posit that 'Anthropocene' (i.e. human modified) coral reefs will be characterised by lower coral cover, lower topographic complexity, and an increasing abundance of algal turfs (following Bellwood et al., 2019a, b) (Fig. 1c-f). On these Anthropocene coral reefs the relative importance of ecosystem processes are in a state of flux (Bellwood et al., 2019b; Hughes et al., 2017). In particular, the increasing prevalence of algal turfs has brought to the fore the capacity of sediments, when interacting with algal turfs, to shape reef processes such as herbivory and coral settlement (Birrell et al., 2005; Duran et al., 2018; Fong et al., 2018; Goatley et al., 2016; Tebbett et al., 2018a). This is because, after climate change, increasing sediment inputs/declining water quality is one of the most pervasive stressors faced by coral reefs (Bainbridge et al., 2012;

Erftemeijer et al., 2012; Jones et al., 2019; McCulloch et al., 2003), with more than 50% of the world's reefs at risk (Burke et al., 2011). Importantly, algal turfs readily trap and accumulate these sediments (Gordon et al., 2016b; Tebbett et al., 2019a), and can represent the major reservoir of sediments on coral reefs (the off-reef sediment apron notwithstanding) (Latrille et al., 2019). As such, algal turfs represent a critical interface where sediments can impact reef organisms and reef processes.

However, while sediment impacts on coral reefs have been the focus of a substantial body of literature (reviewed in Bainbridge et al., 2018; Erftemeijer et al., 2012; Fabricius 2005; Jones et al., 2015; Rogers, 1990; Wenger et al., 2017), this has largely focused on turbidity and water quality. By contrast, our understanding of algal turf sediments on coral reefs is still in its infancy but it appears to be a burgeoning research field. To engender further growth, this review will focus on providing an overview of our knowledge concerning algal turf sediments on coral reefs to-date. In doing so, we will highlight what algal turf sediments are, their roles in ecosystem processes, their importance on Anthropocene coral reefs, and key knowledge gaps for further research.

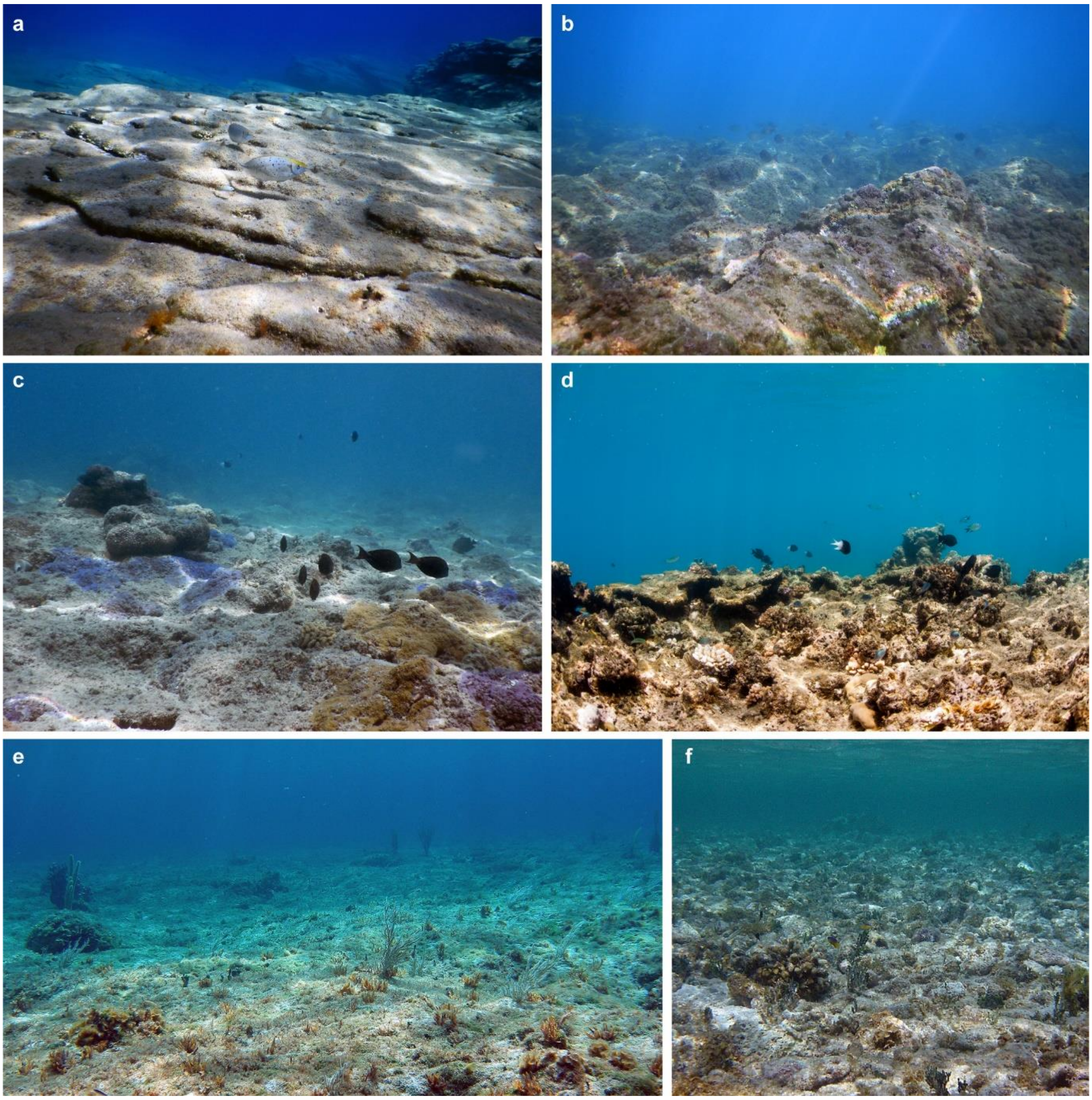

Figure 1 Low-complexity algal turf-covered a), b) subtropical rocky reefs off Crete in the Mediterranean, c), d) coral reefs around Lizard Island on the Great Barrier Reef, and e), f) coral reefs in the Caribbean off e) Little Cayman Island, and f) Carrie Bow Cay. Photographs were taken in a-d) 2018, e), 2005, and f) 2004. Photographs by a), e), f) D.R. Bellwood, b), c) S.B. Tebbett, d) V. Huertas.

2. Defining algal turf sediments

2.1. What are algal turfs?

Herein, we consider algal turfs to be the short (<2 cm), multispecies assemblage of generally filamentous macroscopic algae that cover the hard substratum on coral reefs (for further detail see Connell et al., 2014; Fong and Paul, 2011; Steneck and Dethier, 1994). It should be noted that past studies have included non-algal taxa (i.e. cyanobacteria) in their definition of algal turfs (e.g. Larkum et al., 1988; Borowitzka et al., 1978), however, for clarity cyanobacteria are considered separately. Algal turfs are often the most abundant benthic covering on coral reefs (Arias-González et al., 2017; Jouffray et al., 2015; Smith et al., 2016; Vroom et al., 2006; Wismer et al., 2009), especially following disturbances when their coverage under coral canopies is revealed (Goatley and Bellwood, 2011) and early successional forms readily colonise dead coral skeletons following primary colonisation by cyanobacteria (which colonise within days) (Arthur et al., 2005; Diaz-Pulido and McCook, 2002; Houk et al., 2010). Furthermore, algal turfs are remarkably productive (Carpenter, 1985; Hatcher, 1988; Klumpp and McKinnon, 1992; Steneck, 1997; Wanders, 1977) and can support key trophic pathways on reefs, e.g. energy flows up the food chain through herbivorous fishes (Bellwood et al., 2018; Kelly et al., 2017; Russ, 2003). However, they are also heterogeneous across multiple spatial (Harris et al., 2015; Scott and Russ, 1987) and temporal scales (Diaz-Pulido and McCook, 2002), and have been referred to under a number of different terms in the coral reef literature (see Connell et al., 2014).

During the 1980s-90s the term ‘epilithic algal community’ (EAC) was frequently used when describing algal turfs on coral reefs, to recognise that these were far more than a homogenous benthic covering and were a diverse community (e.g. Hatcher and Larkum, 1983; Klumpp and McKinnon, 1989; Purcell, 1996; Russ, 1987). This term morphed into the ‘eplithic algal matrix’ (EAM) in the late 90s (Wilson and Bellwood, 1997) and has been used frequently in the literature since (e.g. Heenan et al., 2016; McAndrews et al., 2019; Rasher et al., 2013; Tebbett et al., 2017a; Wilson et al., 2003). The term EAM was coined to recognise the importance of other non-algal turf constituents within the matrix including organic detritus, inorganic sediments, microalgae and microbes [inc. cyanobacteria] (Wilson and Bellwood, 1997). Similarly, the term ‘turf algal sediment mats’ (TAS mats) has been used in reference to reefs in the Atlantic to recognise the condition of algal turfs when they become laden with sediments (e.g. Lacey et al., 2013; Rodríguez-Martínez et al., 2011; Roy, 2004; Shantz et al., 2015). Also in the Caribbean, the term ‘hardpan’ has been used to describe a coral reef state typified by a covering of sediment-laden algal turfs (Bellwood and Fulton, 2008). More recently, the terms ‘short productive algal turfs’ (SPATs: ~ <5 mm and relatively sediment-free algal turfs) and ‘long sediment-laden algal turfs’ (LSATs: ~ >5 mm algal turfs that are laden with sediments) were coined to explicitly recognise a fundamental division in the nature of algal turfs, separating those with low sediment loads from those with high sediment loads (Goatley et al., 2016) (Fig. 2). The evolution of these definitions highlights the increasing importance placed on sediments contained within the algal turfs.

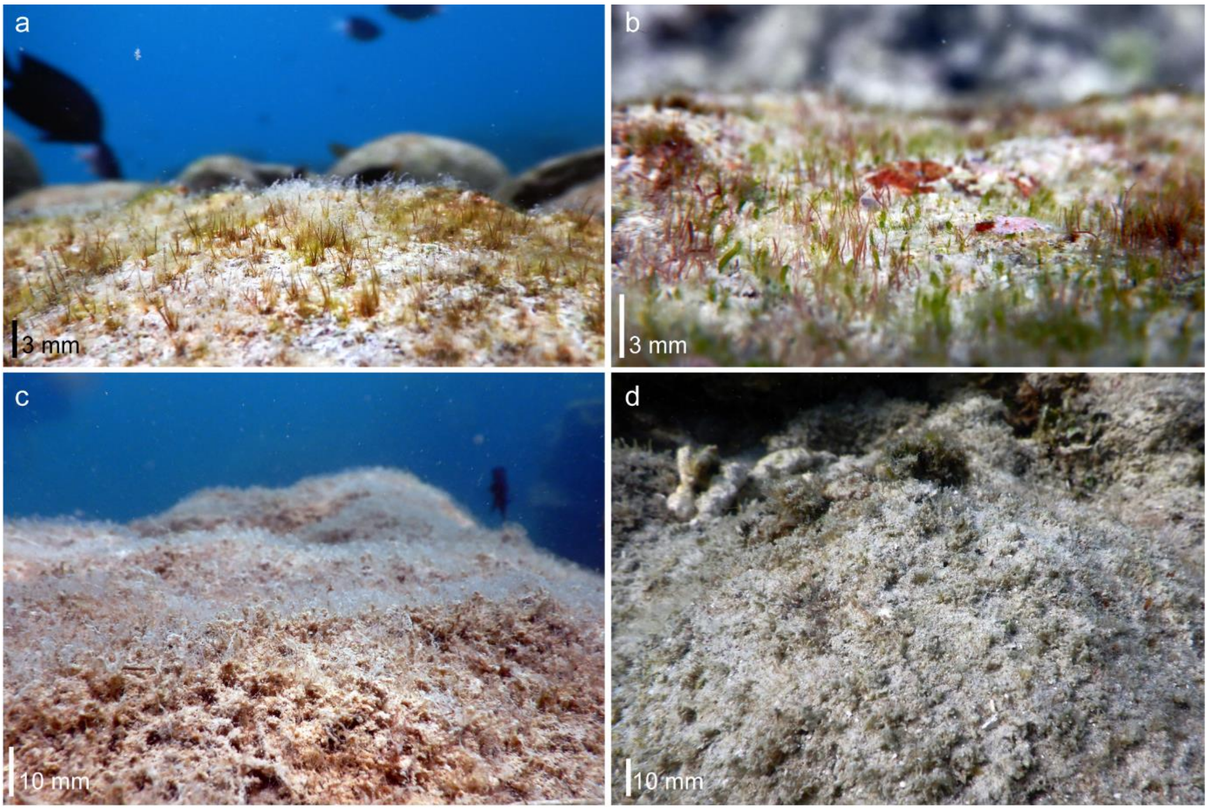

Figure 2 a, b) Short productive algal turfs (SPATs), note the lack of sediment (photographs R.P. Streit). c, d) Long sediment-laden algal turfs (LSATs) (S.B. Tebbett). Scale bars are approximate.

2.2. What are algal turf sediments?

Algal turf sediments are inorganic particulate material <2 mm (sands, silts and clays; ISO 14688-1:200) bound within algal turfs on coral reefs (Goatley, 2013; Tebbett et al., 2017a). However, the term 'sediments', when used in reference to algal turfs, has also been applied to all inorganic material in algal turfs including pieces >2 mm (e.g. Bellwood and Fulton, 2008; Goatley et al., 2012; Goatley and Bellwood, 2012; Purcell, 2000), as well as both inorganic and organic particulate material combined, especially when only sediment depth is recorded (e.g. Clausing et al., 2014; Duran et al., 2018; Eurich et al., 2018; Fong et al., 2018; Goatley and Bellwood, 2013). It should also be noted that the working definition of 'inorganic sediments' includes living organisms such as endolithic, microboring organisms that can be contained within inorganic calcareous sediments (e.g. Perry, 1998). The organic particulate component of the benthic particulate mix within the EAM is defined more broadly as 'detritus', with a commonly used working definition of detritus being: non-living organic particulate material that is also likely to contain life in the form of microbes (for a comprehensive review of coral reef detritus see Wilson et al., 2003). The term 'benthic particulates' has been applied to both the organic and inorganic components when summed together, recognising this amalgamation (Tebbett et al., 2018b, 2017b). Clarity of terms and distinction amongst inorganic sediments and organic components of the particulate mixture is necessary to assess: a) the different effects of each component on ecosystem processes (Birrell et al., 2005; Gordon et al., 2016a; Tebbett et al., 2017b), and b) how organisms can utilise components. For example, the organic detrital and microbial component can represent a critical nutritional resource that is specifically targeted by a wide range of fishes (Choat et al., 2002; Crossman et al., 2001; Max et al., 2013; Robertson and Gaines, 1986; Wilson et al., 2003).

Furthermore, algal turf sediments *sensu stricto* can be composed of both carbonates and silicates (Gordon et al., 2016b; Latrille et al., 2019; Tebbett et al., 2018b). The carbonate component is largely derived from the on-reef production of sediments via mechanisms such as bioerosion (Bellwood, 1996; Hutchings, 1986; Yarlett et al., 2018) and the physical breakdown of skeletal remains of calcifying organisms (Fujita et al., 2009; Scoffin, 1992). By contrast, the siliceous component is largely derived from terrestrial sources (Goatley et al., 2016; Gordon et al., 2016b), and can be composed of 'new' sediments (i.e. recently deposited sediments from terrestrial runoff and river plumes) or 'old' sediment (i.e. settled sediments that have been resuspended and transported to reefs) (Bainbridge et al., 2018; Fabricius et al., 2014; Lewis et al., 2014; Orpin and Ridd, 2012; Wolanski et al., 2008). In general, the different types of sediment have different characteristics including their density, association with organic material, size and ability to adsorb nutrients (Bainbridge et al., 2018; Gordon et al., 2016b; Lutgens and Tarbuck, 2006). With the composition and amount of sediments being trapped in algal turfs depending on a range of factors including local sediment inputs (Browne et al., 2013; Tebbett et al., 2018b), reef geomorphology (Hopley et al., 2007; Tebbett et al., 2017a), hydrodynamics (Bodde et al., 2014; Carpenter and Williams, 1993; Purcell, 2000) and the feeding activity of fishes (Goatley and Bellwood, 2010; Hoey and Bellwood, 2008; Krone et al., 2011). While algal turf sediments can be disparate in terms of their composition, they can all generally be defined as inorganic particulate material <2 mm that reside within algal turfs.

2.3. How do sediments become algal turf sediments?

The diffusive boundary layer formed by the complex structure of algal turfs can slow water movement and is the predominant mechanism that facilitates the deposition and accumulation of sediments in algal turfs (Carpenter and Williams, 1993; Latrille et al., 2019). In addition, this process is likely to be supplemented by other factors, such as the secretion of mucilaginous sheaths by filamentous cyanobacteria within the EAM which can bind sand particles together (Stal, 2003). As such the EAM as a whole, and algal turfs in particular, appear to have a particularly remarkable propensity to accumulate and retain sediments. For example, algal turf sediments can accumulate to reach ambient levels following clearing in a matter of days (Tebbett et al., 2018a), and once trapped these levels can remain remarkably stable over long (6 month) temporal scales (Gordon et al., 2016b). Moreover, Latrille et al., (2019) highlighted that over a week-long period, algal turfs accumulated far more sediment than artificial sediment traps, which have previously been criticised for their excessive trapping abilities (Storlazzi et al., 2011). Unfortunately, while we know algal turfs can readily accumulate sediments and are likely to play a key role in sediment dynamics, our understanding of the links between suspended sediments, sediment input rates and algal turf sediment accumulation are relatively limited.

Recently, Latrille et al., (2019) began to place algal turf sediments into the context of suspended sediments and sedimentation. Latrille et al., (2019) highlighted that lateral accumulation of sediments was limited, and accumulation appeared to be driven primarily by direct deposition by parrotfishes and deposition of suspended sediments (including local resuspension from nearby 'sediment-saturated' algal turfs). Furthermore, Whinney et al., (2017) revealed that sedimentation rates were higher following turbidity peaks, however, the nature of the relationship was complex and varied across temporal scales due to factors such as wind speed and tidal phase. However, apart from these two studies, our understanding of links between algal turf sediments, sedimentation, and suspended sediments remains limited.

3. Quantification and distribution of algal turf sediments

3.1. How do we quantify algal turf sediment characteristics?

Algal turf sediments can be quantified directly in several ways including by depth (Adam et al., 2018; Clausing et al., 2014; Goatley and Bellwood, 2013), coverage (Ceccarelli et al., 2005; Duran et al., 2018; Eurich et al., 2018) and mass (Gordon et al., 2016b; Purcell, 2000; Rasher et al., 2012; Tebbett et al., 2017a). The exact method employed depends on the nature of the question being addressed and the level of detail required. As the properties of algal turf sediments can differ markedly depending on their composition and size (Gordon et al., 2016b; Latrille et al., 2019), the different methods vary markedly in their ability to quantify different aspects. The two most frequently used methods in the literature are depth measurements and underwater vacuum sampling for collection and mass analysis. Sediment traps are not included as they have a limited capacity to quantify algal turf sediments (Latrille et al., 2019). Each is outlined in detail below.

In-situ sediment depth and algal turf length measurements are non-destructive, fast and inexpensive to perform. Such measurements can indicate the nature of the algal turfs and the quantity of sediments they contain (i.e. SPATs vs LSATs; sensu Goatley et al., 2016), and can be readily employed in experimental scenarios to monitor changes in algal turf length (Fong et al., 2018; Goatley and Bellwood, 2013; Tebbett et al., 2017c). For example, sediment depth and/or algal turf length can be measured using the depth probe of vernier callipers, which yields the same distance as between the tips of the callipers (Fig. 3a, b, e). This distance is then recorded by pressing the tips of the callipers into saltwater-resistant pressure-sensitive poster adhesive (blu tack) (Fig. 3c, f), which can then be measured more accurately in the laboratory using digital callipers. However, while fast and non-destructive, depth measurements only provide limited information on the sediments with no detail on the composition or size. Furthermore, as sediments can have different depths depending on their size and density (e.g. Gordon et al., 2016b; Latrille et al., 2019), depth and mass estimates are not necessarily comparable. If more detailed measures are required, depth measurements can be combined with sediment collection.

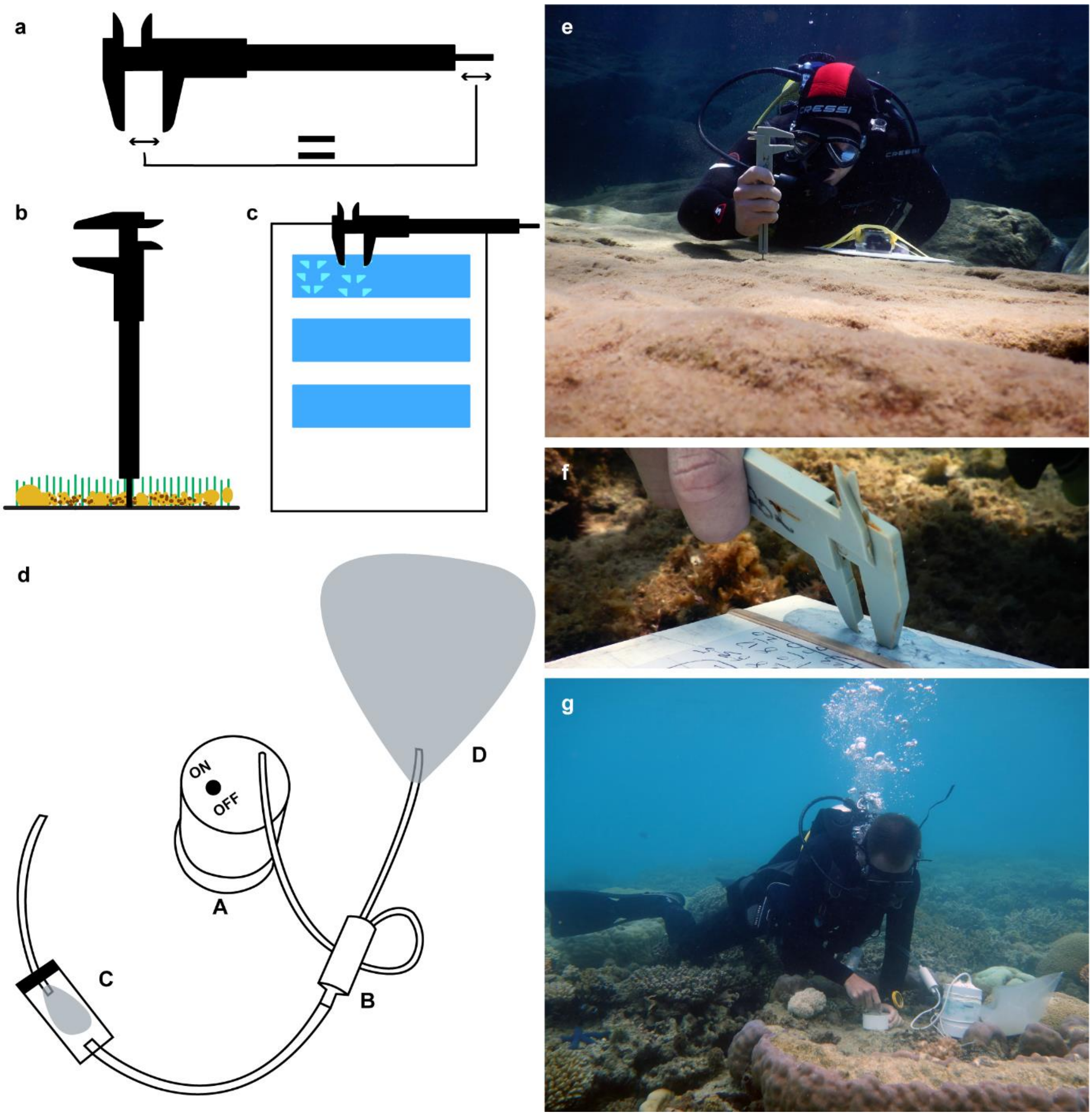

Figure 3 A schematic diagram showing the tools that can be used to quantify algal turf sediments. a) The depth probe of callipers is the same as the length between the tips, b) this depth probe can be used to examine algal turf filament length and/or sediment depth, and c) these measurements can be quickly recorded underwater in ‘blu tack’ for later quantification in the lab. d) a small handheld underwater vacuum sampler is composed of: A – a waterproof housing containing the battery, controlled by a toggle switch to provide power to B – a small inline water pump. The impellor in the water pump is protected by C – a container that holds a filter (~250 µm plankton mesh) that traps coarse sediments which are retained. Finer

sediments pass through the filter and are retained in D – a plastic bag (~5 L). B, C and D are all connected with clear vinyl tubing. e), f) S.B. Tebbett measuring algal turf length using the methods described above, and g) sampling algal turf sediments using an electronic vacuum sampler (photographs e), f): D.R. Bellwood, g): R.P. Streit).

Small underwater vacuum samplers (Fig. 3d, g), are frequently used for collecting sediments, organic detritus, and algal material from the substratum on coral reefs (e.g. Crossman et al., 2001; Kelly et al., 2017; Kramer et al., 2012; Max et al., 2013; Purcell, 1996; Tebbett et al., 2017a). These samplers can remove all particulate material from the algal turfs for more detailed processing and scraping tools can be fitted to remove the algal turfs themselves (for detailed methods see Purcell, 1996). The collected particulates can then be processed to yield information including depth, mass, inorganic vs organic ratios, silicate vs carbonate content, grain size distributions (using sieves or laser diffraction analysis) and nitrogen fractionation (Gordon et al., 2016b; Judy et al., 2018; Latrille et al., 2019; Purcell, 2000; Weber et al., 2006). These indices can then be related to other properties of algal turfs such as length and biomass (Purcell, 2000; Purcell and Bellwood, 2001), yielding insights into local algal turf sediment dynamics (Goatley et al., 2016; Gordon et al., 2016b; Latrille et al., 2019).

It should be noted that attempts have been made to quantify algal turf sediments through more indirect methods such as sediment traps (for an overview see Storlazzi et al., 2011), SedPods (for an overview see Field et al., 2013), and TurfPods (for an overview see Latrille et al., 2019). However, preliminary evidence suggests that such methods provide only a partial, and in some cases, unrepresentative insight into the nature of algal turf sediments (for a detailed comparison of all methods see Latrille et al., 2019). Such methods are designed to quantify other aspects of sediment dynamics on coral reef, rather than algal turf sediments. If working on algal turf sediments, the most accurate method is probably to quantify them directly.

3.2. Quantities and distribution of algal turf sediments

Algal turfs can represent the major reservoir of sediments on coral reefs (not including the off-reef sediment aprons) (Latrille et al., 2019). This is because algal turfs can contain far higher sediment levels than those accumulated on corals or suspended in the water column (Latrille et al., 2019). However, algal turf sediment loads can vary markedly, ranging from 10s of g m^{-2} to 1000s of g m^{-2} and from <1 mm to ~20 mm depth (Bellwood and Fulton, 2008; Clausing et al., 2014; Purcell, 2000; Tebbett et al., 2018b) (Fig. 4). This variability is exemplified across the continental shelf of Australia's Great Barrier Reef (GBR) with coastal reef crests containing average sediment loads up to 3681.8 ± 713.7 g m^{-2}, while sediment-depauperate mid-shelf reef crests can maintain average loads as low as 63.8 ± 19.4 g m^{-2} (Fig. 4a). The composition of sediments also varies across large scales. Reefs closer to shore generally have higher levels of siliceous sediments and, as expected, levels decrease with distance from the coast (Gordon et al., 2016b; Tebbett et al., 2018b).

At smaller, within-reef scales, algal turf sediment loads vary consistently among habitats (Fig. 4b). Low sediment loads occur on high-energy reef crests, while higher sediment loads accumulate in lower-energy reef slope and flat habitats (Gordon et al., 2016b; Purcell, 2000) (Fig. 4b). Indeed, average sediment levels over 8000 g m^{-2} have been reported from the reef flat at Lizard Island, Australia (Goatley and Bellwood, 2012). In addition to the amount of sediment, other metrics such as the grain size distribution (finer sediments occur in lower-energy habitats) and relative detrital levels (higher proportions of detritus are found on the reef crest) differ markedly among habitats (Gordon et al., 2016b; Purcell and Bellwood, 2001; Tebbett et al., 2017a). Within reef habitats algal turf sediment loads can also be heterogenous due to fine scale factors such as fish feeding patterns (Goatley and Bellwood, 2010) or structural complexity (Duran et al., 2018; Tebbett et al., 2019a). Clearly algal turf sediments vary at multiple spatial scales, but often in a predictable manner (i.e. regardless of the reef they generally decrease with distance from shore and are lowest on high-energy reef crests [Fig. 4]).

The predictable gradients in algal turf sediment loads may underpin other important ecological gradients on coral reefs especially in organisms that associate closely with algal turfs, e.g. herbivorous fishes and scleractinian corals. In the case of herbivorous fishes for example, species abundance, biomass and richness are frequently correlated with water quality gradients (e.g. Cheal et al., 2013; Moustaka et al., 2018). However, these correlations are more likely to be explained by gradients in algal turf sediment loads, which have a marked propensity to alter herbivorous fish feeding behaviour and potentially, therefore, their long-term persistence (outlined in detail in section 4.3). As such, while water quality gradients might be correlative, algal turf sediment gradients might offer a more plausible mechanistic basis for some observed ecological gradients.

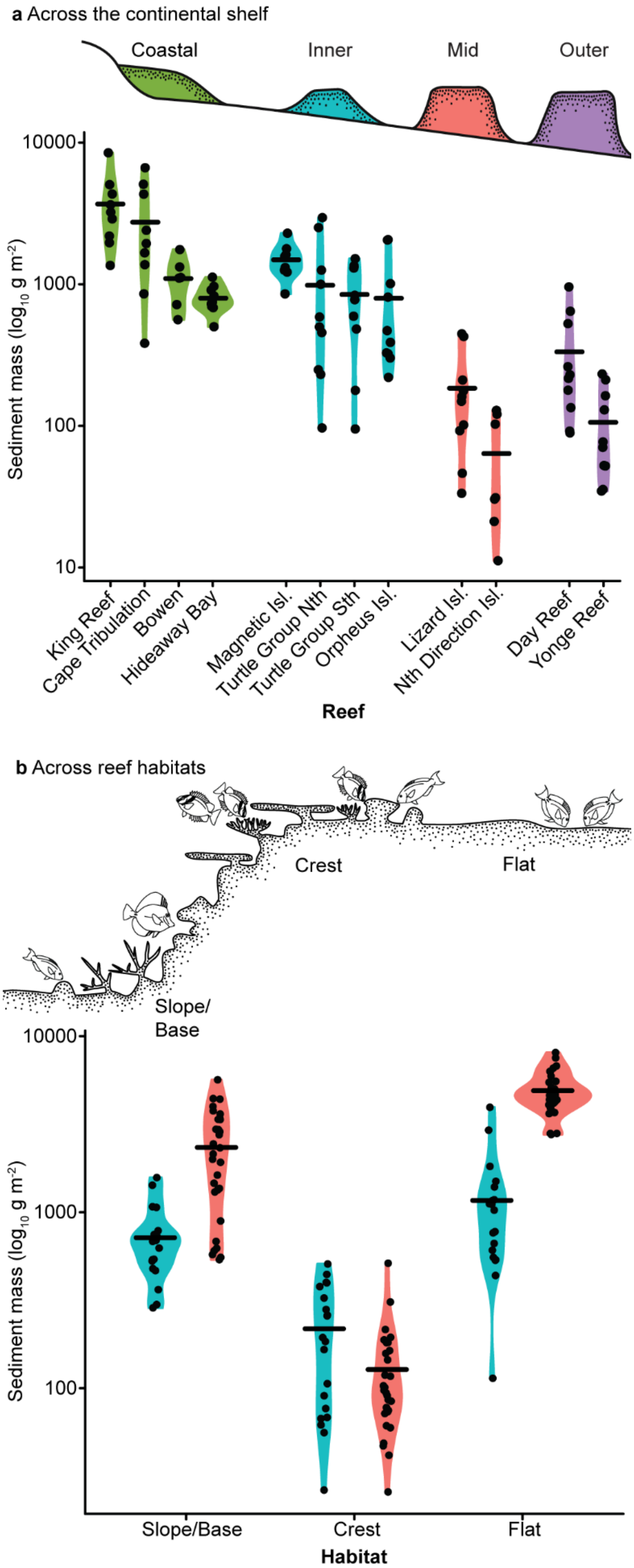

Figure 4 Sediment loads in algal turfs at different spatial scales a) on reef crests across the continental shelf of the Great Barrier Reef, Australia, and b) across different reef habitats on

an inner-shelf (Orpheus Island [turquoise]) and a mid-shelf (Lizard Island [orange]) reef, from the Great Barrier Reef. Note the consistent patterns of algal turf sediment loads among a) different reefs in the same shelf positions, or b) habitats between different reefs. Also note that the y-axis is logged in both cases. Cross-bars indicate the means. Data were sourced from (Goatley et al., 2016; Gordon et al., 2016b; Purcell, 2000; Tebbett et al., 2018b, 2017a). Isl. = Island.

4. Sediment effects on coral reef organisms

4.1 Overview

Intuitively, algal turf sediments appear to primarily affect coral reef taxa that closely associate with the benthos, e.g. algae, nominally herbivorous fishes, and corals. Indeed, these three broad taxonomic groups have been the basis of most research to-date concerning algal turf sediments on coral reefs and will be the focus of this section. However, preliminary results have highlighted that algal turf sediments can influence the distribution patterns, and/or feeding behaviour of a suite of reef taxa including crytofauna (Kramer et al., 2012; Logan et al., 2008), invertebrate grazers (Sangil and Guzman, 2016; Tebbett et al., 2018a), turtles (Goatley et al., 2012), and probably even microbes within algal turfs (Bourne et al., 2016; Meirelles et al., 2018; Zaneveld et al., 2016).

The primary mechanism underpinning the effects of algal turf sediments on coral reef organisms appears to be the positive association between algal turfs and algal turf sediments (Fig. 5). Algal turf sediments can release algal turfs from intense grazing pressure, with a positive relationship occurring between algal turf length and algal turf sediment load on coral reefs (Bonaldo and Bellwood, 2011; Gordon et al., 2016b; Purcell, 2000; Purcell and Bellwood, 2001) (Fig. 5b). This correlation is due to either a) longer algal turfs developing first and trapping more sediment (Latrille et al., 2019), or b) algal turf sediments initially accumulating more sediments leading to less herbivory resulting in longer algal turfs and further sediment trapping (Goatley and Bellwood, 2013; Goatley et al., 2016), or both. LSATs therefore develop as a result of a positive feedback as the increase in sediments leads to a decrease in herbivory, with resulting increases in algal turf length further increasing sediment trapping and decreasing herbivory. It is these long sediment-laden algal turfs (LSATs) that appear to have the largest effect on coral reef taxa (see below).

4.2. How do algal turf sediments affect algae?

Coral reef algae are frequently grouped together in three broad functional groups (crustose coralline algae [CCA], macroalgae and algal turfs) (see Steneck and Dethier, 1994). As these functional groups are united based on morphological similarities, they are affected by algal turf sediments to various extents and in different ways. This was initially conceptualised by Steneck (1997) who highlighted the success of algal turfs, over other algal functional groups, when algal turf sediments are abundant (Fig. 5a). By contrast, CCA and macroalgae are more prolific in conditions where algal turf sediments are not as high (Steneck, 1997) (Fig. 5a). This functional group approach is maintained herein to highlight the key effects of algal turf sediments on each group separately.

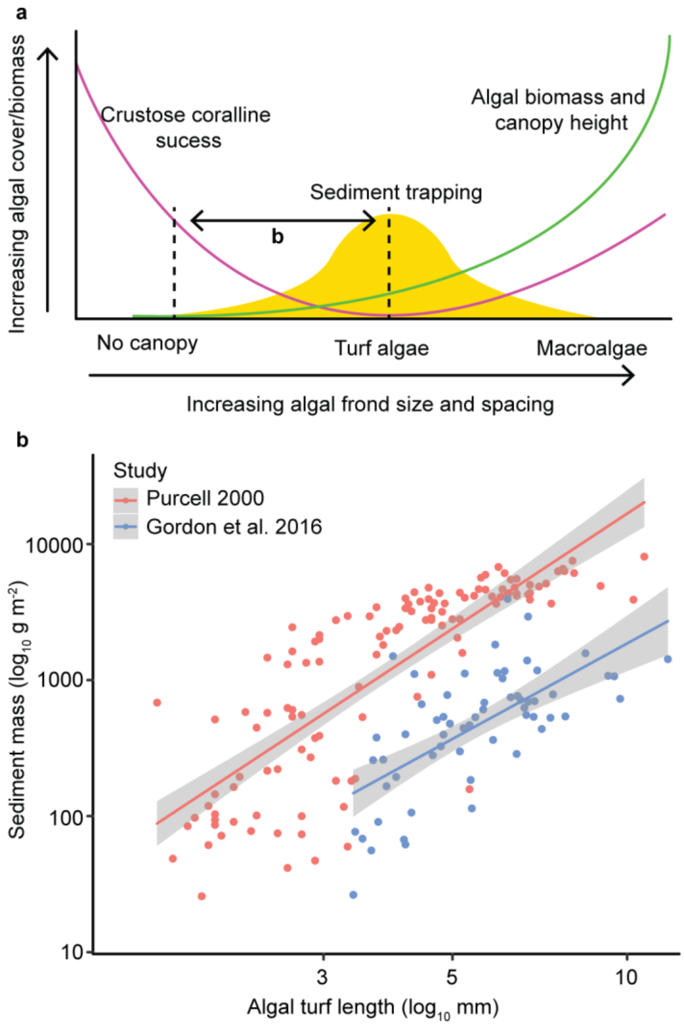

Figure 5 a) A conceptual model (modified after Steneck, 1997) for the coexistence of three algal functional groups (crustose coralline algae, turf algae, and macroalgae) and the propensity for the assemblage to trap sediments. Note that when sediment trapping is maximised algal turfs dominate. The box delineated by dashed black vertical lines and arrows indicate the relationship described in further detail in panel b) i.e. the relationship between algal turf length and algal turf sediment mass at Orpheus Island (blue) (Gordon et al., 2016b) and Lizard Island (orange) (Purcell, 2000), on the Great Barrier Reef, Australia. The coloured lines and grey shaded areas show the predicted fit of linear models and their 95% confidence intervals.

4.2.1 Algal turfs

While algal turf length is generally positively associated with increasing algal turf sediment load (Fig. 5), it is certain that a threshold exists, whereby, once too much sediment is trapped, conditions can become unfavourable even for algal turfs. For example, Tebbett et al. 2018a experimentally demonstrated that higher algal turf sediment loads reduced algal turf biomass accrual, supported by similar results from subtropical rocky reef algal turfs (Airoldi and Virgilio, 1998). One of the main factors underpinning such results may be the development of unsuitable conditions in deeper layers of algal turf sediments. Indeed, Clausing et al., (2014) found that at depths of 4 mm algal turf sediments can suppress the growth of algal turfs through the formation of hydrogen sulphide (H_2S). This formation of anoxic conditions is likely to be particularly prevalent if high loads of fine algal turf sediments get trapped in habitats with limited hydrodynamic activity. Although algal turfs appear to be a particularly stress-tolerant functional group of algae (Hay 1981), extreme accumulation of algal turf sediments appears to influence even these resistant algae.

4.2.2 Crustose coralline algae

CCA play a major role in reef building through calcification and cementation of the reef substratum, as well as promoting coral settlement (Adey, 1998; Harrington et al., 2004). CCA are well suited to shallow, high-energy coral reef environments and are particularly resistant to the grazing pressure of herbivores, unlike other algal functional forms (Steneck, 1983a). Indeed, for CCA to persist, it appears that high herbivory rates are crucial to control the growth and expansion of algal turfs (Steneck, 1997, 1983a). However, while experimental evidence assessing the impacts of algal turf sediments on CCA is limited, evidence examining the influence of sediments alone suggests that CCA are likely to be highly susceptible to algal turf sediment impacts (Fabricius, 2005; McClanahan, 1997; Steneck, 1997). For example, the cover of CCA is frequently negatively correlated with sedimentation rates (Albert et al., 2008; Fabricius and De'ath, 2001; Fabricius and McCorry, 2006) and burial of CCA by fine sediments has been experimentally demonstrated to decrease photosynthesis and compromise survival (Fabricius, 2005; Harrington et al., 2005). Therefore, under such conditions, accumulated sediments are likely to foster the competitive ability of algal turfs, which can successfully compete with and overgrow CCA (Steneck, 1997) (Fig. 5).

4.2.3 Macroalgae

Steneck (1997) suggested that macroalgae, like CCA, are sensitive to increased sediment loads. This notion was supported by Umar et al., (1998), who demonstrated that increased algal turf sediment loads can significantly reduce recruitment, growth, survival and vegetative regeneration in one species of tropical *Sargassum.* Unfortunately, beyond the study of Umar et al., (1998) our understanding of the effects of algal turf sediments on coral reef macroalgae is limited. However, these effects have been studied in far more detail in subtropical and temperate rocky reef macroalgae assemblages (reviewed in Airoldi, 2003; O'Brien and Scheibling, 2018). Indeed, several subtropical/temperate studies have found similar results to Umar et al., (1998) in that algal turf sediments significantly impede the settlement and survival of canopy forming macroalgae (e.g. Airoldi, 1998; Alestra et al., 2014; Gorman and Connell, 2009; Isæus et al., 2004). The evidence gleaned to-date from other systems suggests that the ability of algal turf sediments to impair the settlement abilities and survival of macroalgae may be widespread. As such, coral reef systems that have transitioned to LSAT-covered states may resist further transitions to macroalgae covered states, as suggested in Goatley et al., (2016).

4.3 How do algal turf sediments affect fishes?

There are two primary mechanisms by which algal turf sediments can affect fishes: a) by directly mediating feeding rates and behaviour (Bellwood and Fulton, 2008; Goatley and Bellwood, 2012; Gordon et al., 2016a), and b) by reducing the quality and productivity of nutritional resources in the epilithic algal matrix with the potential for bottom-up effects on fish productivity (Gordon et al., 2016b; Purcell and Bellwood, 2001; Tebbett et al., 2018a). These two mechanisms are discussed in more detail below.

4.3.1 Feeding rates and behaviour

Based on observations, Randall, (1955) suggested that surgeonfish feeding behaviour was mediated by algal turf sediments, as sediments controlled how fishes removed algal material and when sediments were removed by fishes they were often rejected. Initial experimental studies supported these observations, as removal of algal turf sediments on coral reefs led to marked increases in herbivorous fish feeding rates (Bellwood and Fulton, 2008; Goatley and Bellwood, 2012). Furthermore, Duran et al. (2019) highlighted that in the Caribbean, surgeonfishes, especially smaller size classes, selectively fed on SPATs compared to LSATs. Interestingly, these results are supported by findings from freshwater systems including the African Rift Lakes and South American streams that found: a) many grazing fishes avoided feeding on algae laden with sediments (Genner et al., 1999), b) feeding rates increased when algal sediments were removed (Rusuwa et al., 2006) and c) size-dependent selectivity for sediment-cleared grazing areas (Power, 1984). Taken together, these studies highlight the pervasive nature of algal turf sediments in controlling herbivorous fish feeding rates and behaviour in aquatic systems.

Studies on nominally herbivorous coral reef fishes have now also begun to tease apart the mechanisms underpinning the interaction between fish feeding behaviour and algal turf sediments. This was achieved by exploring the effects of sediment size, source, mass and particulate organic content on the feeding behaviour of morphologically and functionally different fishes (Gordon et al., 2016a; Tebbett et al., 2017d, 2017b). For example, the ‘brushing’ surgeonfish *Ctenochaetus striatus*, must interact closely with algal turf sediments when targeting detritus using its long brush-like teeth (Tebbett et al., 2018c, 2017c), and appears to be highly sensitive to small increases in algal turf sediment mass (as little as 75 g m^{-2}) (Tebbett et al., 2017b) (Fig. 6a). By contrast, ‘croppers’ such as the surgeonfish *Acanthurus nigrofuscus*, appear to be more resilient to sediment increases as they can use their multidenticulate teeth to ‘crop’ off the tips of algal filaments protruding through the algal turf sediment layer (Tebbett et al., 2017b) (Fig. 6b). Finally, coarser algal turf sediments deter feeding by the scraping parrotfish *Scarus rivulatus* more than finer sediments (Gordon et al., 2016a). This appears to be a result of their morphology, specifically their beak-like teeth, which mean that scraping parrotfish must remove the entire EAM when feeding on the substratum (Bellwood and Choat, 1990) (Fig. 6c). As such, scraping parrotfishes must either sort and reject, or ingest the algal turf sediments within the EAM. In this case coarser sediments are likely represent a less nutritional resource (fine sediments are likely to contain more organic particulates) and are likely to be more energetically costly to process (Gordon et al., 2016). These distinctions highlight how functionally different fishes interact with algal turf sediments in markedly different ways and offer insights into the mechanisms underpinning the effects of sediments on feeding behaviour. However, ultimately, in all cases, algal turf sediments appear to drive increased algal turf length by either a) reducing feeding rates (Goatley et al., 2016; Gordon et al., 2016a; Tebbett et al., 2017d) or b) limiting feeding to the ‘above-sediment’ portion of algal filaments (Adam et al., 2018; Tebbett et al., 2017b).

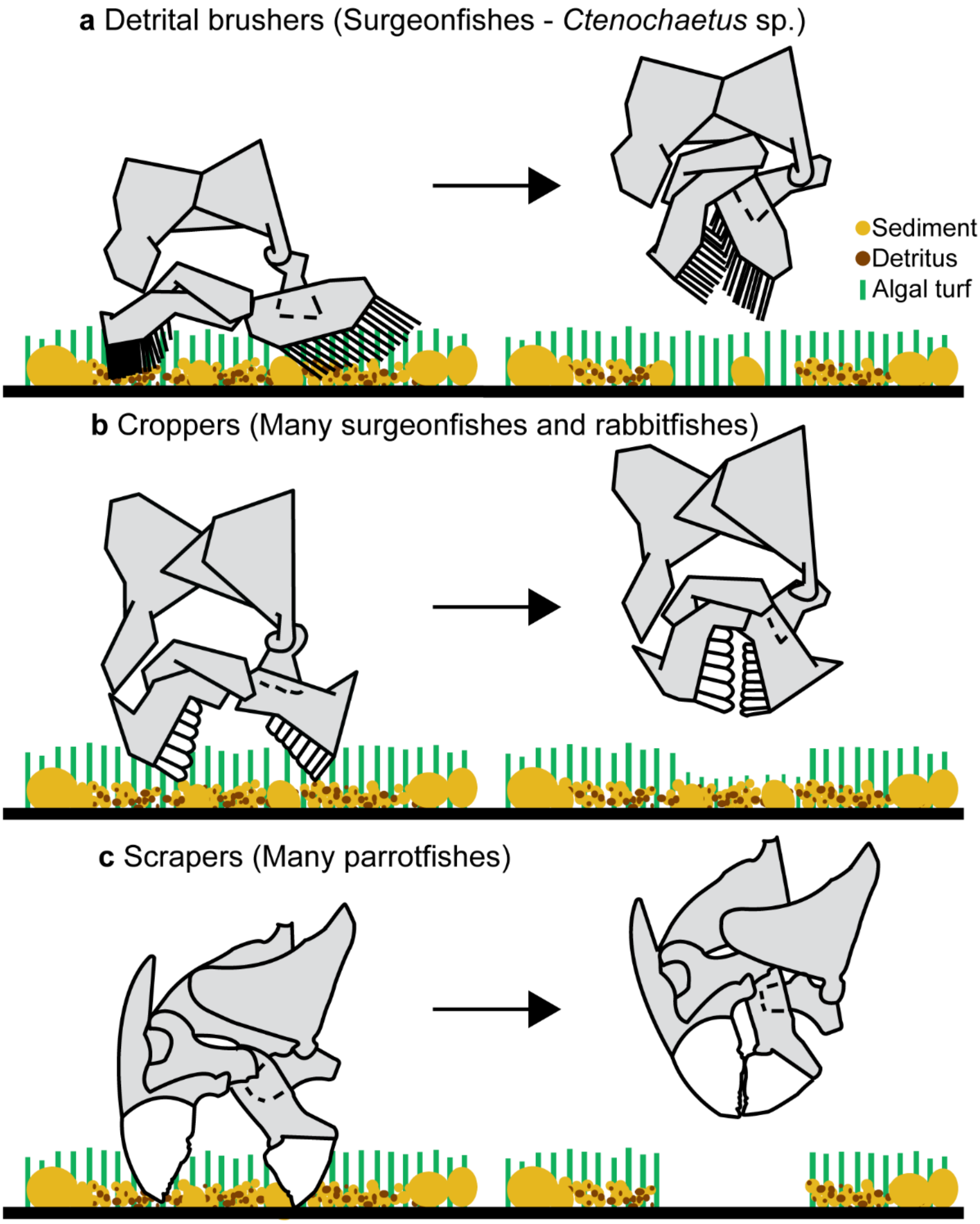

Figure 6 A schematic diagram showing how three functionally distinct herbivorous/detritivorous fishes interact with algal turfs, detritus and sediment. a) the lined bristletooth surgeonfish, *Ctenochaetus striatus*, selectively feeds on detritus (particulates) removing fine organic and inorganic particulates, b) the brown surgeonfish, *Acanthurus nigrofuscus*, crops algal turfs above the layer of particulates and c) the surf parrotfish, *Scarus rivulatus*, scrapes the substratum removing the entire algal turf, sediment and detritus mixture (i.e. the complete epilithic algal matrix (EAM) including cyanobacteria, other microbes and

microalgae etc). These functional differences may underpin the effect of sediments on fishes. *C. striatus* and *A. nigrofuscus* jaws redrawn from (Purcell and Bellwood, 1993; Tebbett et al., 2017b). It should be noted that this diagram does not necessarily highlight the nutritional resources targeted, or assimilated by these fishes, as biomarker data suggests there are further differences between these fishes after assimilation (see Clements et al., 2017). Our diagram highlights the different components of the EAM removed by fishes when feeding on coral reefs.

4.3.2 Nutritional consequences for fishes

In addition to directly mediating the feeding behaviour of fishes, algal turf sediments can impact the ability of nominally herbivorous fishes to extract suitable nutritional resources from the EAM. Indeed, Choat (1991) suggested that sediments trapped in algal turfs could reduce the nutritional return per feeding event. This is because algal turf sediments on coral reefs can directly: a) reduce the productivity of the algal turfs (Tebbett et al., 2018a), b) 'water-down' the relative level of organic material within the algal turfs (Gordon et al., 2016a; Purcell and Bellwood, 2001), and/or c) lead to the formation of LSATs which are likely to reduce the abundance of euendolithic cyanobacteria available for exploitation by parrotfishes (Clements et al., 2017; Hutchings et al., 2005). Indeed, a recent study revealed that sediment additions led to a 2000% and 3300% decrease in the potential yield of algal turf biomass and nitrogen to herbivorous fishes, respectively, relative to algal turfs containing ambient or reduced sediment loads (Tebbett et al., 2018a). Intuitively, such decreases in the productivity/nutritional value of the algal turfs could have significant bottom-up effects on the herbivorous fish community through reduced growth and/or altered distribution patterns.

Support for bottom-up effects of algal turf sediments on the populations of herbivorous fishes can be gleaned from the freshwater literature (reviewed in Vadeboncoeur and Power, 2017). For example, Munubi et al., (2018) found that sediment mass associated with benthic algae/biofilms was the strongest predictor of among-site variation in the density of a herbivorous cichlid in Lake Tanganyika. Furthermore, Takeuchi et al., (2010) posited that a decrease in the abundance of herbivorous cichlids in Lake Tanganyika over 20 years could be due to increased accumulation of sediments associated with algae/biofilms. While Power, (1984) demonstrated that deposited benthic sediments imposed energetic costs on a South American armoured catfish. Taken together, these studies suggest sediments deposited on the benthos, particularly when associated with algae (i.e. algal turf sediments in the coral reef realm), may impose bottom-up effects on the fishes that interact with these sediments. In terms of coral reefs, it has been repeatedly suggested that the abundance of herbivorous and detritivorous fishes is heavily influenced by bottom-up forces (e.g. Bellwood et al., 2018; Clements et al., 2017; Purcell and Bellwood, 2001 Russ, 2003; Russ et al., 2015), suggesting that algal turf sediments may limit nutritional resources with direct consequences for herbivorous fish populations. Furthermore, as nominally herbivorous fishes can make up a large proportion of artisanal fisheries catches (Edwards et al., 2014; Robinson et al., 2019; Russ et al., 2015) bottom-up effects may manifest themselves as less productive fisheries yields to humanity (Bellwood et al., 2018; Morais and Bellwood, 2019; Tebbett et al., 2018a).

4.4 How do algal turf sediments affect corals?

There are two chief mechanisms by which algal turf sediments can impact corals: a) by reducing coral recruitment (Birrell et al., 2005; Speare et al., 2019) and b) by enhancing the competitive abilities of algal turfs when interacting with corals (reviewed in O’Brien and Scheibling 2018). Each is addressed separately below.

4.4.1 Coral recruitment

Coral recruitment is a critical ecosystem process on coral reefs that facilitates recovery after disturbances (Elmhirst et al., 2009; Hughes et al., 2019; Ritson-Williams et al., 2010). However, corals require suitable surfaces and cues to settle, especially microtopographic refuges (Brandl and Bellwood, 2016; Nozawa, 2012) and crustose coralline algae (Harrington et al., 2004; Ritson-Williams et al., 2010). As such, the suppression of CCA development by algal turf sediments (see section 4.2.2) may suppress key cues. Similarly, as the microbe community on the benthos can influence coral settlement (Sharp et al., 2015), if algal turf sediments influenced the microbiome within algal turfs (Bourne et al., 2016; Meirelles et al., 2018), this may also supress coral settlement rates.

When it comes to direct effects of algal turf sediments most studies have focused on the effects of sediments in isolation on coral recruitment. These studies have repeatedly highlighted that settlement on bare surfaces (e.g. glass, tiles, settlement plates) is heavily impacted by sediments (e.g. Babcock and Smith, 2000; Hodgson, 1990; Moeller et al., 2017; Perez III et al., 2014; Ricardo et al., 2017; but see Trapon et al., 2013). By contrast, studies that have considered the effects of algal turfs in isolation on coral settlement have found more mixed results, revealing either limited changes (Diaz-Pulido et al., 2010; Speare et al., 2019) or significant decreases (Arnold et al., 2010) in settlement depending on the algal community (reviewed in Birrell et al., 2008). Surprisingly, studies considering both algal turfs and sediments together are limited to just three (Birrell et al., 2005; Leong et al., 2018; Speare et al., 2019). In these studies, algal turf sediments led to significant declines in coral settlement on reefs in both the Indo-Pacific (Birrell et al., 2005; Leong et al., 2018) and the Caribbean (Speare et al., 2019). Considering the paucity of studies examining the effects of algal turf sediments on coral settlement, and the clear potential for profound impacts, this research topic offers fertile grounds for further investigation.

4.4.2 Competitive interactions

Algal turf sediments also play a role in coral-algal turf competitive interactions. Coral-algal turf interactions have received a substantial degree of attention on coral reefs (e.g. Gowan et al., 2014; Liao et al., 2019; McCook, 2001; Nugues and Roberts, 2003; Vermeij et al., 2010; Wild et al., 2014). However, the findings are far from clear and appear to be highly context and taxon specific, with results ranging on a spectrum from competitive dominance by corals to competitive dominance by algal turfs (reviewed in McCook et al., 2001; O'Brien and Scheibling 2018). In certain contexts, algal turf sediments appear to enhance the competitive abilities of algal turfs, as the they foster the growth and/or increased canopy height of algal turfs (Gowan et al., 2014; Liao et al., 2019) and probably alter the microbial community within algal turfs (Barott and Rohwer, 2012; Brown et al., 2019; Roach et al., 2017). However, in other cases sediment accumulation on corals can lead to partial mortality, with subsequent expansions and development of algal turfs (Nugues and Roberts, 2003). In the latter case, algal turfs are not directly competing with corals but instead are simply occupying new space, and as such, algal turf sediments are not involved in this interaction. Unfortunately, it can be difficult to determine whether algal turf expansion is a result of the former or latter scenario (McCook et al., 2001), with other factors such as hydrodynamics (Gowan et al., 2014) and nutrients (Vermeij et al., 2010) likely to influence the nature of these interactions. Furthermore, studies examining competitive interactions rarely quantify the amount and nature of sediments trapped in the algal turfs (but see Liao et al., 2019). Without specifically investigating the nature of the algal turf sediments, our understanding of their role in competitive interactions, and the mechanistic basis underpinning competition, remains limited.

5. Algal turf sediments on Anthropocene coral reefs

5.1. Will algal turf sediments be important on Anthropocene coral reefs?

Yes. Following the global reconfiguring of coral reefs after repetitive bleaching events and other disturbances, algal turf sediments are poised to play an increasingly important role in structuring ecosystem processes such as coral settlement, herbivory, and benthic productivity (Bellwood et al., 2019a; Bruno et al., 2019; Hughes et al., 2018a). Indeed, it is becoming increasingly apparent that many, if not most, coral reefs, will simply emerge as lower-complexity systems covered in algal turfs (Bellwood and Fulton, 2008; Bellwood et al., 2019a; Brown et al., 2017; Jouffray et al., 2015; Smith et al., 2016). Other configurations including an increased abundance of stress-tolerant coral taxa (e.g. *Porites*) (Loya et al., 2001; Marshall and Baird, 2000), weedy fast-recovering coral taxa (e.g. *Acropora*, *Pocillopora*) (Berumen and Pratchett, 2006; Johns et al., 2014; Torda et al., 2018), other sessile invertebrates (Norström et al., 2009; Tebbett et al., 2019b), or fleshy macroalgae (Graham et al., 2006; Hughes, 1994) are also possible in certain circumstances. However, even in such cases, algal turfs are likely to be abundant following disturbances and during regenerative phases. This is because algal turfs can be: a) ‘uncovered’ when coral canopies are lost (Goatley and Bellwood, 2011), b) occupy recently dead coral skeletons rapidly following primary colonisation by cyanobacteria (Arthur et al., 2005; Diaz-Pulido and McCook, 2002), c) are a particularly stress-tolerant functional group of algae (Hay, 1981; Steneck and Dethier, 1994) and d) even appear to benefit physiologically from future climate change conditions (Bender et al., 2015; Johnson et al., 2017; Ober et al., 2016). This combination of traits sets the scene for a rise in algal turf cover on Anthropocene reefs.

Algal turf-covered reef configurations may continue to provide key services to humanity, such as fishable biomass production (Bellwood et al., 2018; Morais and Bellwood, 2019; Robinson et al., 2019). However, the functions provided by organisms in these systems, and in-turn the services reefs provide to humanity, are heavily dependent on the nature and amount of algal turf sediments (see section 4). Unfortunately, sediment-laden algal turfs are likely to proliferate on algal turf-covered reefs, especially close to shore, as sediment inputs are increasing from coastal development and dredging (Erftemeijer et al., 2012; Wolanski et al., 2009) and increased terrestrial runoff (Bainbridge et al., 2012; McCulloch et al., 2003). For example, even on the highly-regulated GBR, Hughes et al. (2015) noted that "in the past 10 years, more than 25 million cubic meters of dredge spoil from ports has been dumped at sea in the GBR WHA [World Heritage Area]…an amount that roughly equals the total volume of sediment historically delivered from all 35 rivers draining into the GBR each decade, prior to land-clearing".

Algal turf sediments appear likely to underpin the functionality of many Anthropocene coral reefs. Their role is likely to be further increased through the loss of topographic complexity (Alvarez-Filip et al., 2009; Graham et al., 2006), which further promotes sediment trapping in algal turfs (Duran et al., 2018; Tebbett et al., 2019a), as well as through the overexploitation of nominally herbivorous fish communities which play a central role in algal turf sediment dynamics and potentially in the maintenance of SPATs (Goatley and Bellwood, 2010; Krone et al., 2011; McAndrews et al., 2019). As such, algal turf sediments represent a multifaceted stressor that interacts with climate change, overfishing and human development (Bellwood et al., 2018; Tebbett et al., 2018a). The study of algal turf sediments therefore transcends marine/terrestrial boundaries and encompasses extensive social-ecological linkages. Unfortunately, like scraping parrotfish (sensu Steneck, 1983b) – we are still just scratching the surface when it comes to understanding algal turf sediments on coral reefs.

5.2 What do we need to know about algal turf sediments?

Studies assessing the dynamics and ecological ramifications of algal turf sediments are still in their infancy. However, work on the GBR (Goatley and Bellwood, 2012; Gordon et al., 2016b; Purcell, 2000; Tebbett et al., 2018a), Pacific Islands (Clausing et al., 2014; Fong et al., 2018; McAndrews et al., 2019) and Caribbean (Adam et al., 2018; Duran et al., 2019; Speare et al., 2019; Steneck, 1997), suggests that this is a burgeoning research field with clear opportunity for collaborations to enhance our understanding of algal turf sediments across biogeographic boundaries. Furthermore, advances are being made in understanding how algal turf sediments on coral reefs affect key ecosystem process (e.g. Duran et al., 2019; Speare et al., 2019), are mediated by fishes (e.g. Fong et al., 2018; McAndrews et al., 2019), and accumulate in algal turfs (e.g. Latrille et al., 2019; Tebbett et al., 2019a). Yet, while considerable progress is being made, we still lack the answers to many basic questions.

In many coral reef regions we simply do not know how much sediment is in the algal turfs, or how these algal turf sediments are linked to suspended sediment levels and sedimentation. Furthermore, monitoring of coral reef algal turf sediment levels before, during and after exceptional sedimentation events, such as dredging activities, would provide valuable insights into how such events impact the deposition and accumulation of algal turf sediments. Indeed, there is remarkably little long-term data on sedimentation rates and algal turf sediment loads in coral reef systems. For example, examination of temporal dynamics in algal turf sediments loads (>6 months) is limited to just two studies (Goatley et al., 2016; Gordon et al., 2016) from a single island on the GBR. However, while it is often assumed sediment loads are increasing on other reefs globally, as a result of increasing inputs (Burke et al., 2011), there is little quantitative evidence to support this.

To achieve a comprehensive understanding of algal turf sediment dynamics this will require linking research on algal turf sediments with the vast and growing literature surrounding general sediment dynamics on coral reefs. For example, clear progress has been made in terms of understanding ridge-to-reef sediment transport (e.g. Bainbridge et al., 2018; Bartley et al., 2014; Comeros-Raynal et al., 2019; Fabricius et al., 2014), dredge plume dynamics and deposition (e.g. Fisher et al., 2015; Jones et al., 2019), within reef sediment transport mechanisms (e.g. Ogston et al., 2004; Orpin and Ridd, 2012; Pomeroy et al., 2017), and links between turbidity and sediment deposition (e.g. Whinney et al., 2017). However, apart from the study by Latrille et al., (2019) which began to place algal turf sediments into this context, our understanding of the links between algal turf sediments and other sediment dynamics remains exceedingly limited. Addressing these unknown links represents a critical knowledge gap on ecological time scales.

Furthermore, on geological time scales, there has been significant progress in our understanding of reef growth and development in sediment-rich habitats (e.g. Browne et al., 2013; Perry et al., 2012; Roff et al., 2015; Ryan et al., 2018). This is becoming increasingly topical as sea-level rise becomes an inevitability, along with the associated notion of 'drowned reefs' (Perry et al., 2018; van Woesik et al., 2015). However, while Bellwood and Fulton (2008) posited that algal turf sediments may be a key factor underpinning reef drowning, algal turf sediments have received little attention within this context. As such, a multidisciplinary approach linking algal turf sediments with other reef processes and sediment dynamics may offer insights into the survival of coral reefs in both ecological and geological time scales.

In terms of furthering our understanding of the direct ecological effects of algal turf sediments there are several key research gaps across multiple spatial scales. For example, at small spatial scales, further examination of the interaction between algal turf sediments, ‘crevice cleaning’ fishes, and coral recruitment in microtopographic refuges is particularly important for understanding coral recruitment dynamics and potential recovery of reefs following disturbances (Brandl and Bellwood, 2016; Ricardo et al., 2017). In conjunction with this line of research, furthering our understanding of the microbiome within algal turfs is necessary. As stressors such as overfishing and nutrient enrichment may affect the algal turf microbiome (e.g. Meirelles et al., 2018; Zaneveld et al., 2016), with potential effects on coral settlement (Bourne et al., 2016; Meirelles et al., 2018), examining the influence of algal turf sediments on these microbes could offer interesting insights into coral settlement dynamics.

Also, at small spatial scales, there have been calls for a more nuanced understanding of nutritional resources within the EAM, especially the role of cyanobacteria (Clements et al., 2017). Cyanobacteria are important early colonisers of dead coral reef substrata (Diaz-Pulido and McCook, 2002) and are likely to play an important role in accumulating and binding algal turf sediments (Stal, 2003). However, our understanding of the relationships between algal turf sediments and both epilithic and euendolithic cyanobacteria, is limited. These relationships warrant further investigation, especially considering that these cyanobacteria appear to be a key nutritional resource targeted by parrotfishes (Clements et al., 2017). Furthermore, as algal turf communities are composed of diverse algal taxa and morphological forms (Harris et al., 2015; Scott and Russ 1987), different algal turf communities are likely to: a) be influenced by algal turf sediments differently and/or b) trap and retain algal turf sediments at different rates. While there has been some attention paid to these factors in the subtropical/temperate rocky reef literature (Airoldi et al., 1995; Stewart, 1983), our understanding of the relationships between algal turf taxonomy/form/composition and algal turf sediments is currently limited on coral reefs. Resolving these relationships with more precision will enhance our ability to predict the effects of algal turf sediments on algal turf communities, and the organisms that associate with, or use, algal turfs.

At larger reef-wide scales, understanding how SPATs are maintained is vital. For example, a comprehensive understanding of algal turf sediment removal, transport and maintenance by fishes, and the relative importance of different taxa is necessary (Bellwood, 1995; Goatley and Bellwood, 2010; Krone et al., 2011). At even larger regional spatial scales, understanding how to maintain key services such as fisheries productivity from algal turf-covered reefs is key. This is particularly important in 'telecoupled' (Liu et al., 2016) reef-land systems, where land-use and overfishing practices are linked (see Comeros-Raynal et al., 2019) which could potentially facilitate transitions to LSAT states in a synergistic nature. This represents a complex socio-ecological challenge, transcending ecosystem boundaries and requiring a multidisciplinary approach.

Clearly, there is a broad swath of questions to address in relation to algal turf sediments on coral reefs. These range from basic descriptive studies to more complex, multifaceted, socio-ecological investigations. Progress will require forward-looking studies that identify key functional interactions in algal turf-covered coral reef systems. This endeavour will help us to embrace change and address the major overarching goal of managing reefs in a manner that sustains the key functions and services coral reefs provide (Hughes et al., 2017).

6. Conclusion

In many cases coral reef ecosystems now exist as highly-altered configurations, and in this context the importance of once-critical ecosystem functions and functional groups are changing (Bellwood et al., 2019b; Hughes et al., 2017). Specifically, the importance of algal turf sediments in mediating the functionality of these altered ecosystems is set to increase. However, despite evidence highlighting the importance of these sediments, our understanding remains limited. Herein, we have endeavoured to provide a brief overview of our knowledge to-date and hope that this will act as a 'spring-board' to encourage further scientific investigation within this field. On Anthropocene, low-coral cover reefs, there will be no shortage of algal turfs and the sediments they contain.

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Competing Interests Statement

On behalf of all authors, the corresponding author states that there is no competing interests.

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