A snapshot of sediment dynamics on an inshore coral reef

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Abstract:

Sediments are ubiquitous on coral reefs. However, studies of reef sediments have largely focused on isolated reservoirs, or processes, and rarely consider hydrodynamic drivers. We therefore provide a quantitative snapshot of sediment dynamics on a coral reef. Across a depth profile, we simultaneously examined: suspended sediments, sediment deposition and accumulation, and hydrodynamic and biological movement processes. We reveal the marked potential for the water column to deliver sediments. Currents carried 12.6 t of sediment over the 2,314 m^2 study area in 6 days. Sediment traps suggested that a surprisingly high percentage of this sediment was potentially deposited (5.2%). Furthermore, wave-driven resuspension and reworking by parrotfishes separated a highly dynamic sediment regime on the shallow reef flat (3 m), from a more stagnant reef slope (4.5 m to 12 m). This study provides a comprehensive model of how hydrodynamic forces and on-reef processes may shape sediment dynamics on a coral reef.

Keywords:

Algal turf; Hydrodynamics; Parrotfish; Sediment resuspension; Sediment trap; Turbidity

1. Introduction

Sediments are found on, around, and above all coral reefs (Browne et al., 2013a; Hubbard, 1986; Macintyre et al., 1987; Roy and Smith, 1971). As a result, the organisms which inhabit reefs directly interact with sediments on a near continuous basis (e.g., Bessell-Browne et al., 2017; DeMartini et al., 2013; Moustaka et al., 2018; Rogers, 1990). Sediments are closely intertwined with a suite of key reef processes, such as reef building (Woolfe and Larcombe, 1999), nutrient transfer among trophic levels (Tebbett et al., 2018a; Wenger et al., 2012), and coral recruitment (Ricardo et al., 2017; Speare et al., 2019). This close association between sediments, reef organisms, and reef processes has led to growing concern that, by modifying reef sediment budgets, human activities could inflict a variety of sediment-mediated deleterious effects on coral reef ecosystem functioning. Indeed, a growing body of literature has documented a range of negative impacts of increased sediments on reef organisms and processes (reviewed in: Bainbridge et al., 2018; Erftemeijer et al., 2012; Fabricius, 2005; Jones et al., 2015b; Magris and Ban, 2019; Tebbett and Bellwood, 2019). However, the nature and extent of any such effects of sediments on reefs will depend on reef-scale sediment dynamics, our understanding of which is currently incomplete (Schlaefer et al., 2021).

On coral reefs, sediment dynamics involve the movement of sediments among and between three major reservoirs: the water column, the off-reef sediment apron, and on-reef substrata. Although these sediment reservoirs are believed to be closely linked, our quantitative understanding of such links is surprisingly limited (Schlaefer et al., 2021). This may be because of the physical complexity of sediment transport, and the related difficulties in studying sediments on coral reefs. The movement of sediment is determined by the properties of both the sediment and its bounding reservoir (e.g., the water column, algal turfs), and it is mediated by both biological (e.g., sediment reworking by parrotfishes; Bellwood, 1996) and hydrodynamic drivers (e.g., currents and waves; Browne et al., 2013b; Ogston et al., 2004; Presto et al., 2006; Storlazzi et al., 2004; Storlazzi and Jaffe, 2008). Historically, studies of reef sediments have not been able to capture this complexity and have often considered sediment reservoirs and linking processes in isolation. Indeed, a recent review highlighted that of 419 reefal sediment studies, the majority (67%) quantified a single sediment reservoir or linking process, with most studies focusing on suspended sediments and accumulation of sediments in traps (Schlaefer et al., 2021). By contrast, on-reef sediment reservoirs, such as those within algal turfs (reviewed in: Tebbett and Bellwood, 2019), or documented via the accumulation of sediments on proxy surfaces representing on-reef substrata (e.g., Field et al., 2013; Latrille et al., 2019) remain poorly studied. If we are to fully understand sediment dynamics on reefs, a quantitative overview of the potential linkages between these sediment reservoirs is needed.

The hydrodynamic environment is one of the primary factors governing the extent and strength of sediment linkages (Ogston et al., 2004; Storlazzi and Jaffe, 2008; Whinney et al., 2017). For example, currents can move sediments into, within, and out of reef systems (Brodie et al., 2010; Browne et al., 2013a; Draut et al., 2009), while waves can resuspend sediments to be entrained and deposited in new areas (Storlazzi et al., 2009). However, our comprehension of the quantities of sediment moved among and between reservoirs by hydrodynamic drivers is still relatively limited. As the review by Schlaefer et al. (2021) revealed, hydrodynamic drivers were only quantified in approximately 20% of sedimentary studies. Moreover, when a hydrodynamic driver was quantified, rarely was it quantified outside of a single reef habitat. This represents a substantial knowledge gap as currents and waves can vary markedly among habitats and along depth gradients on reefs, as they interact with the reef structure (Fulton and Bellwood, 2005; Pomeroy et al., 2018). This could, in turn, shape sediment dynamics across these gradients. As cross-habitat and cross-depth gradients are some of the strongest ecological gradients on coral reefs (Bellwood et al., 2018; Connolly et al., 2005; Done, 1983), identifying the role of hydrodynamic drivers in mediating sediment dynamics at this scale is likely to be important.

Establishing an in-depth understanding of reefal sediment dynamics is challenging as it requires the quantification of multiple components. To address this issue, the aim of this study was to comprehensively and simultaneously characterise numerous aspects of sediment dynamics in a snapshot of a sediment-impacted inshore reef, incorporating major reef habitat and depth gradients. Specifically, we quantified suspended sediments, sediment accumulation, sediment trapping rates, sediment reworking by parrotfishes, and multiple hydrodynamic processes, simultaneously, over a six-day period (with representative tides, and semi-regular winds) across two reef habitats (flat and slope), and at five different depths. In doing so, this study provides a detailed, if short-term, view of near-reef sedimentary processes operating at this location across biologically relevant spatial scales.

2. Materials and Methods

2.1. Site description and overview

This study was conducted at Orpheus Island in the central Great Barrier Reef (GBR), Australia (Figure 1). At this location, a study site was established on a section of reef off the south-west point of Pioneer Bay, on the sheltered, leeward side of the island. As Orpheus

Island is located approximately 15 km from the mainland, it sits within the inner-shelf sediment wedge of the GBR (Larcombe and Woolfe, 1999) and is potentially exposed to inputs of fine terrigenous sediment from the Herbert and Burdekin rivers on the mainland (Fabricius et al., 2013; Lewis et al., 2020).

The study took place over six sampling days from the 19th to the 25th of October 2020, within the local tradewind season (April to November). This period was directly after the spring tide following the new moon on 17th October 2020 (Figure S1a) and well outside of the local monsoon season (December to March). This ensured the focus remained on internal dynamics, rather than the effects of fresh sediment inputs into the reef system. The tides present during the study period were representative of the broader tidal regime at Orpheus Island. The tidal ranges during the study spanned from 0.4 to 2.6 m, which largely encompassed the tidal range predictions for 2020, lest the upper and lower extremes (Figure S1b). The winds during the study period were predominantly northerlies and north, north easterlies of weak to moderate strength (4.5 to 7.5 m s^{-1}; Figure S2c). Winds of these directions would probably direct more wave energy into Pioneer Bay compared to the southerlies and south easterlies that prevail in the trade wind season (Figure S2b), given the north-westward orientation of the bay mouth. Northerlies and north, north easterlies occur semi-regularly in both the trade wind (~ 10% of days) and monsoon (~ 16% of days) seasons, respectively (Figure S2ab).

For spatial coverage, a broad section of reef was sampled, partitioned by three transects (denoted bay-side, middle and channel-side), 25 m apart (Figure 1). The three transects were laid parallel to each other down the reef profile, from the outer reef flat at a maximum depth of 3 m (all cited depths hereafter refer to the maximum during the study period, unless otherwise specified) to 12 m on the reef slope. Five discrete depths were sampled along each transect: 3, 4.5, 6, 9 and 12 m. The study covered a total area of 2,314 m^2. The complementary components of the study were all collected within the same sample grid, to ensure the data were directly comparable. The whole study area bound by the sampling grid is termed the 'reef section' hereafter. The 'sediments' considered here include both inorganic and organic particulate material <2 mm in diameter (sands, silts and clays; ISO 14688-1:2017). We first focus on sediment dynamics at the 'reef section' scale, and then at the 'across-depth' scale within the reef section.

2.2. Total reef section sediment dynamics

At the reef section scale, we compared the potential supply of sediment from two major sources to the amount of sediment delivered to the benthos. Specifically, we simultaneously examined the potential supply from the water column reservoir, the potential supply from sediment reworking by parrotfishes, and observed benthic sediment accumulation rates. The estimated magnitudes of sediment supply and delivery were then put into perspective by comparing them to the standing reservoir of sediments within algal turfs, which was sourced from the literature (i.e., Gordon et al., 2016). This reference study was also conducted in Pioneer Bay at Orpheus Island, and found that sediment loads in the algal turfs at this location were temporally stable. Indeed, there is evidence to suggest that algal turf sediment loads have remained consistent at Orpheus Island since 2013 (Tebbett et al., 2021). Each of these four components is outlined below.

2.2.1. The water column reservoir

The potential water column supply was calculated as the mass of sediment suspended in the water column travelling through the reef section over the 6-day study period. This calculation combined an estimate of the volume of water travelling through the section with data on the average suspended sediment concentration during the study period. The volumetric flow rate was quantified via the analysis of depth stratified current data. An array of 27 Marrotte HS drag-tilt current meters was deployed at sites on the boundary of the sampling grid (i.e., the bay-side and channel-side transects, and the shallowest and deepest sites of the middle transect, Figure S5). The meters were deployed on the boundary so the water volume fluxes across the boundary could be calculated. Single current meters, held down by two dive weights, were deployed on the benthos at each of the 12 boundary sites (Figure 1). Additionally, at the boundary sites with depths of 6 m or greater (i.e., all sites greater than 6 m on the bay and channel side transects, and the middle 12 m site), the remaining 15 current meters were attached to taut rope lines to measure the currents in the water column (Figure 1). The lines were held taut through the combination of heavy concrete blocks on the bottom (3 x 10 kg) and the bouyant force from two spherical polystyrene sub-surface buoys (20 cm diameter and 15 cm diameter). The concrete blocks had an apparent mass of approximately 17 kg in seawater, and the buoys provided approximately 6 kg of buoyancy/tension. The taut lines were, therefore, a firm point to tether the drag-tilt current meters for accurate measurements (see supporting information section 1.2.; Figure S3, Figure S4). The meters were attached to the rope lines via horizontal 30 cm sections of PVC pipe, which held the meters off the lines so the rope could not interfere with the current measurements.

Meters were attached at 3 m depth intervals, starting from 3 m above the benthos, and ending 3 m below the surface. Therefore, 1, 2, and 3 currents meters were attached to the ropes at the 6, 9 and 12 m sites, respectively. The depth placement of both the bottom and on-line current meters, in combination with the 2.6 m tidal range during the study period, ensured all current meters were always submerged by at least 0.4 m of water. Setting this buffer between the current meters and the near-surface currents minimised the measurement interference from high-frequency orbital wave velocities, which are strongest in surface waters (Soulsby et al., 1993). The interference from orbital waves was further reduced by averaging the high-frequency raw current measurements (recorded at 1 measurement per second) to a lower frequency (10 min) in post-processing. Of the 27 current meters, one had to be excluded from the analysis following rigorous data quality control procedures (see supporting information section 1.2.; Figure S3, Figure S4).

Repeated water sampling was conducted to quantify the suspended sediment concentration. At least one water sample was collected per day during the study period and, where possible, a second sample was collected opportunely. In total, eight (n = 3 flood tide and n = 5 ebb tide) 25 – 50 L water samples were collected. Collections were done via either repeat drops of a 2.5 L Niskin bottle, or with an electronic vacuum sampler (following Latrille et al., 2019). In both methods, the sampling device was lowered to a consistent depth of 1 m above the benthos, so sample depths varied from ~ 2 – 3 m below the surface, depending on the tide. The mass of sediment in the water samples was determined following a decanting, sieving, drying, and weighing procedure following Purcell (1996). The mass together with the volume of water sampled gave the suspended sediment concentration for each sample. These concentrations were averaged for use in the water column sediment reservoir calculation. Therefore, the average suspended sediment concentration was used for all days, depths and tides, which necessitated the simplifying assumption that the suspended sediment concentration was constant with day, depth and tide. Importantly, the measured suspended sediment concentration varied little across days and tides (average 1.0085 ± 0.12 g m^{-3} SE), supporting the use of the average in the calculation. Additional turbidity profiling was conducted to further assess the validity of assuming a constant suspended sediment concentration, where the turbidity measurements were presumed to reflect the suspended sediment concentration (e.g., Gray et al., 2000; Whinney et al., 2017). In the profiling scheme, turbidity measurements were taken across days, depths and tides. The turbidity consistently remained low (below 1.6 Nephelometric Turbidity Units) across all days, depths and tides, further supporting the use of the average suspended sediment concentration in the water column reservoir calculation (for full details see supporting information section 1.3.1.; Figure S5, Figure S7).

The potential supply of water column-based sediments to the reef section was estimated by multiplying the volume of water that travelled through the reef section, as approximated from the current data, by the average suspended sediment concentration. For the calculation, the sites on the boundary formed the edges of the 11 vertical faces of the irregular prism framing the reef section. For each vertical prism face, the depth-stratified velocity components (m s^{-1}) oriented perpendicular to the face were calculated from the current measurements at the edge sites, and then linearly interpolated onto a fixed grid of 0.25 m resolution. The grid depth equalled the average depth of the deeper of the two edge sites, and length equalled the distance between edges. Multiplying the perpendicular speed components by the cell area (m^2) (giving the instantaneous volumetric flow rate (m^3 s^{-1}); e.g., Figure S6), the average suspended sediment concentration (g m^{-3}), and the time bin interval (10 min = 600 s) then gave the cell-wise through-flowing sediment mass over each time bin (g). The through-flowing masses were summed across cells and prism faces and balanced through time to provide an estimate of the total mass of sediment travelling through the reef section over the 6-day study period.

2.2.2. Sediment reworking by parrotfishes

Sediment reworking by parrotfishes was also investigated as a potential source of sediment. This line of investigation was followed because adult parrotfishes typically dominate biological sediment reworking on coral reefs (Bellwood, 1996; Bonaldo and Bellwood, 2008). To gauge the potential magnitude of their contribution, the mass of sediment which could be reworked at each depth stratum was calculated from a two-step, depth-stratified underwater visual census, combined with sediment reworking rate data from the literature. The visual census covered a strip of the whole reef section at each of the five study depths (i.e., 3, 4.5, 6, 9 and 12 m). Each strip followed a 50 m-long transect from the bay to the channel-side (or vice-versa, chosen haphazardly). Transects were, thus, parallel to one another. Consecutive transects were typically positioned >10 m from each other, minimising the probability of counting the same fish twice. First, all parrotfish individuals > 10cm total length (TL) within a 5 m strip along the transect were surveyed (parrotfishes were identified to species, counted, and their size estimated [to the nearest 2 cm for individuals < 30 cm or to the nearest 5 cm for individuals > 30 cm]). Then all individuals < 10 cm TL were surveyed along the same transect within a 1 m strip. Our census covered a total area of 5 x 250 m^2 = 1,250 m^2 or approximately 54% of the whole reef section.

Using the data from the census, we estimated sediment reworking following Hoey and Bellwood (2008) using the formula:

$$Rw_d = \sum_{i=1}^{n}(F_{id}L_{id}B_{id}S_d) \times \frac{1}{1000} \qquad (1)$$

where the depth-specific (d) reworking rate Rw_d (g m^{-2} day^{-1}) of the n individual parrotfishes was the summation of the products of their individual (i) feeding rates F_{id} (bites min^{-1}), feeding day lengths L_{id} (min) and bite areas B_{id} (in mm^2 bite^{-1}), multiplied by the depth-specific sediment loads S_d (g mm^{-2}). We sourced average values of each of these parameters from previous studies on Orpheus Island or the GBR. Feeding rates were obtained from Bellwood and Choat (1990) and were entered as species-level averages for each of the nine species in our study (*Chlorurus microrhinos*, *C. spilurus*, *Scarus chameleon*, *S. flavipectoralis*, *S. ghobban*, *S. niger*, *S. rivulatus*, *S. schlegeli* and *S. spinus*). Day length was considered to be the whole period between sunrise and sunset for the day the fishes were counted (20/10/2020) and was obtained from the package geosphere in R (Hijmans, 2019). Bite area was modelled separately for *Chlorurus microrhinos*, *C. spilurus* and *Scarus* spp. as a function of body length within a gamma distributed (log link) Generalised Linear Model. We used size and species-specific data from Bonaldo and Bellwood, (2008) and Hoey (2018) as inputs and linearly interpolated predictions for each counted individual. Finally, habitat-specific sediment loads matching our depth-related sampling were obtained from Gordon et al., (2016) as per below (section 2.2.4). Given the temporal stability of algal turf sediment loads at this location (Gordon et al., 2016; Tebbett et al., 2021) these previously measured sediment loads were very likely to be representative of the sediment loads present during the study period.

2.2.3. Sediment accumulation

The potential supply of sediments from the water column and from parrotfishes was compared to the realised delivery of sediments to the reef through the use of proxies for benthic sediment accumulation. Specifically, current meters deployed on the bottom at each location on the sampling grid (i.e., at each depth along each transect, see section 2.3.) denoted the centre of a 4 m^2 square whose corners were delimited by four TurfPods secured to the substratum (Figure 1). The TurfPods were concrete-filled PVC bases (height = 7 cm, diameter = 9 cm), with 7 mm long artificial plastic grass stuck to the concrete with silicone sealant following Latrille et al., (2019). Most TurfPods (75%) were on hard substrata, so they had a firm point of attachment. This location, the height of the TurfPods, and the sheltered nature of our study site meant there was limited potential for sediment redistributed by bed load transport to be delivered to the TurfPods. Furthermore, previous evidence suggests that this mechanism of sediment movement is of limited importance for turf-bound sediment dynamics at this location (Latrille et al., 2019).

TurfPods act as a proxy for natural algal turfs, a major benthic component on this reef and on most coral reefs globally (Emslie et al., 2019; Jouffray et al., 2019; Smith et al., 2016; Tebbett et al., 2021). As TurfPods allow for both sedimentation and some resuspension, they quantify net sediment accumulation rather than a gross 'trapping rate' (Latrille et al., 2019). However, we also quantified the 'trapping rate' using sediment traps (i.e. gross sediment deposition via gravitational settling from the water column). A single trap was deployed immediately adjacent to the 4 m^2 squares, at each site. The traps were constructed from 60 cm long, 9 cm diameter PVC pipes set into concrete bases. Traps do not allow for resuspension and, due to their elevation above the substratum, quantify the potential water column supply of sediments (Bothner et al., 2006; Storlazzi et al., 2011).

Furthermore, parrotfishes typically defecate close to the benthos, below the height of sediment trap openings but above the height of TurfPods (D. Bellwood, pers. obs.). Sediment reworking by parrotfishes, therefore, represents a potential source of sediment to TurfPods, but an unlikely source to sediment traps. The masses of sediments captured on the TurfPod surfaces and in the sediment traps were quantified through a decanting, sieving, drying and weighing procedure following Purcell (1996).

2.2.4. Sediment standing reservoir on the reef

The sediment accumulation measured over 6 days in this study was put into a broader context by comparing it to historic sediment loads in the natural algal turf reservoir at our study site. These data were sourced from Gordon et al. (2016), and included sediment standing reservoir data across two reef habitats: reef flat and reef slope. To match our sampling design (reef flat = 1 depth and reef slope = 4 depths, see section 2.3.), the total sediment reservoir for the studied reef section was the weighted average of reef flat and slope sediments, with weights equal to 0.2 and 0.8, respectively. Importantly, the data from Gordon et al., (2016) is broadly similar (in terms of accumulated algal turf sediment mass) to less spatially comprehensive sampling in more recent years (cf. Goatley et al., 2016; Latrille et al., 2019; Tebbett et al., 2021).

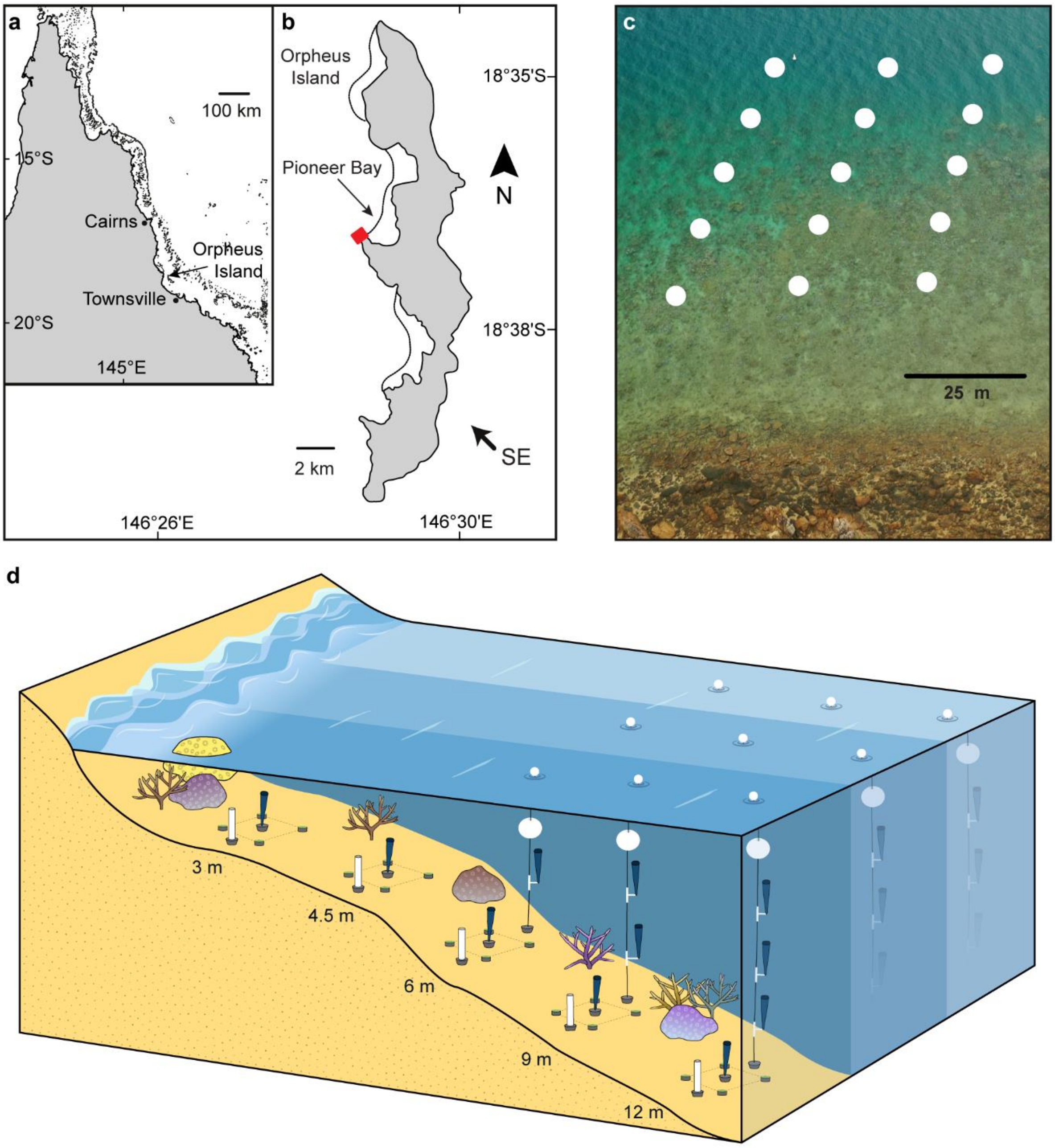

Figure 1 The sampling design. a) The location of Orpheus Island, North Queensland, Australia. b) The reef section (red square) off the south-west point of Pioneer Bay, Orpheus Island. c) Aerial view of the sampling grid (schematic). d) A diagrammatic representation of the grid for the simultaneous sampling of potential sediment sources, realized delivery, and hydrodynamic and biological drivers of sediment dynamics. Five depths (reef flat at 3 m, and reef slope at 4.5, 6, 9 and 12 m) were sampled across three transects (bay-side, middle, and

channel side). The diagram includes representations of the bottom-deployed and on-line current meters, and the sediment traps and TurfPods (Latrille et al., 2019). The equipment deployed on the bottom is only visualised for the bay-side transect. For clarity, the remaining components of the simultaneous sampling (i.e., the parrotfish census and the pressure sensors) are not represented.

2.3. Across depth sediment dynamics

Following the reef section examination, we then explored sediment dynamics at a smaller scale, along a depth gradient. Here, depth was the sampling level of interest, so sites sampled at the same depth across the three transects were retained as replicates. The sampled depths incorporated two distinct reef zones or habitats. The 3 m sites were located on the outer reef flat, and the sites from 4.5 m to 12 m were located on the reef slope. Sediment dynamics were investigated at this scale by concurrently collecting data on the near-bottom currents, the propensity for wave-driven sediment resuspension, sediment reworking by fishes, and benthic sediment accumulation.

The first component involved the examination of near-bottom, current-driven horizontal water movement. Current meters were deployed on the bottom at all internal sites in the sampling grid (middle transect at 4.5, 6 and 9 m), to accompany the previously described bottom current meters deployed at the boundary sites. The near-bottom currents were, therefore, measured at all 15 sites in the sampling grid. Currents can resuspend sediments by exerting shear stress on the bottom (Grant and Madsen, 1979; Soulsby et al., 1993), so current speed and directional differences in the shear stresses between sites were examined. For the direction component, more uniform currents were assumed to exert a greater sustained shear stress; however, there was no clear link between constancy in current direction and sediment dynamics (see supporting information sections 1.4 and 2.1; Figure S9, Figure S10).

Next, wave driven resuspension potential along the depth gradient was assessed through the comparison of data from 3 pressure sensors (RBRsolo3) mounted on hard substrata on the middle transect at 3, 6 and 12 m. The pressure sensors were programmed to take 16 measurements per second to capture the high frequency change in pressure exerted on the bottom by waves. However, the high-frequency wave-driven changes had to be isolated from the lower-frequency tide-driven changes. In a rolling analysis with a 5-minute time step, the wave-driven pressure change was calculated as the average absolute high-frequency pressure residual, around the linear regression line representing the low frequency change in pressure associated with the tide (Figure S8, python 3 package: statsmodel 0.12.2; Seabold and Perktold, 2010). This approach is akin to the calculation of the root mean square pressure fluctuation presented in Whinney et al. (2017). Notably, we analysed bottom pressure measurements i.e., measurements from the location of resuspension. We did not derive and analyse secondary products from the pressure data (e.g., near-bottom wave orbital velocity or bed shear stress) as it would have introduced additional complexities, assumptions, and uncertainties. Resuspension occurs when the stress exerted on the bottom by currents and waves exceeds a critical threshold (Jing and Ridd, 1996; Wilcock, 1993). Therefore, the range (rather than averages) of measured current speeds and wave-driven pressure changes are presented so the frequency of high-ranging measurements with the potential to resuspend sediment could be assessed.

In association with these components, the previously described calculation of sediment reworking by parrotfishes, and data on benthic accumulation from the sediment traps and TurfPods were re-analysed at the individual depth levels. Across-depth differences in the mass of sediment that accumulated in the sediment traps, and on the TurfPods were tested for statistical significance with generalised linear mixed effects models (GLMMs) (package: *glmmTMB* [Brooks et al. 2017]) (Tables S1-S2; R Core Team, 2020). In both cases the mass of sediment accumulated per day was treated as the response variable, depth was treated as a categorical fixed effect, and site was treated as a random effect (to account for the lack of spatial independence). In both cases the model was fitted using a Gamma distribution with a log-link function. Model fit and assumptions were assessed using simulation-based residual diagnostics, all of which were satisfactory. The substrata on which each TurfPod was secured was also examined by depth, to investigate if highly localised resuspension from the adjacent substrata could have represented an additional source of sediments to the pods surface.

3. Results

3.1. Total reef section sediment dynamics

During the study period the average (± SE) suspended sediment concentration was 1.0085 ± 0.12 g m^{-3}. Based on this sediment concentration, and the estimate of the total water volume that went through the study area during the study period (12,461,084 m^3), for the reef section we estimated that in total, 12.6 ± 1.5 t of sediment moved over the site in the water column during the 6-day study period. When partitioned by day and standardized by area, an average of 905 g day^{-1} of sediment travelled over each square meter of the reef section. Interestingly, this quantity of sediment that passed over the reef in a single day was broadly comparable to the standing reservoir of sediment bound in algal turfs on the reef (Figure 2). Given these numbers, the quantity of sediment moving over the reef in the water column clearly had the potential to be a major contributor to on-reef sediment dynamics.

The potential for water-column sediments to contribute to on-reef sediment dynamics was supported by the loads captured in sediment traps. Indeed, the 47 ± 11.7 g m^{-2} day^{-1} captured in traps represented 5.2% of the potential water column supply (Figure 2). Furthermore, 1.5 times more sediment was collected in the TurfPods (71 ± 10.9 g m^{-2} day^{-1}) than in the traps. This was interesting given the potential for resuspension of sediments from the TurfPod surface, versus no resuspension from traps, and suggests that there may be another source of sediments to these pods in addition to the deposition of sediments carried by currents. One potential additional source was the local parrotfish assemblage, which was estimated to rework 29 ± 10 g m^{-2} day^{-1} of sediment from algal turfs, and re-deposit it in the reef section, typically in close proximity to the benthos, i.e. below the height of the trap openings but above the height of the TurfPods. The 47 g m^{-2} day^{-1} from the water column, when combined with the 29 g m^{-2} day^{-1} from parrotfishes, makes a total of 76 g m^{-2} day^{-1}, which is remarkably close to the 71 g m^{-2} day^{-1} recorded from the TurfPods.

From a longer-term perspective, daily sediment accumulation on the TurfPods was 8.5% of the standing reservoir of sediments in algal turfs (i.e., 851 g m^{-2}) in the area (Figure 2). Thus, if the TurfPods represent an appropriate proxy for algal turfs, it would take roughly 12 days for entirely sediment-free turfs to accumulate sediment to their carrying capacity. Overall, the mass of sediment captured by the traps and TurfPods was surprisingly high compared to the available supply from the water column and parrotfish reworking. Thus, our data provides a quantification of the importance of water-borne pathways as a source of on-reef sediments.

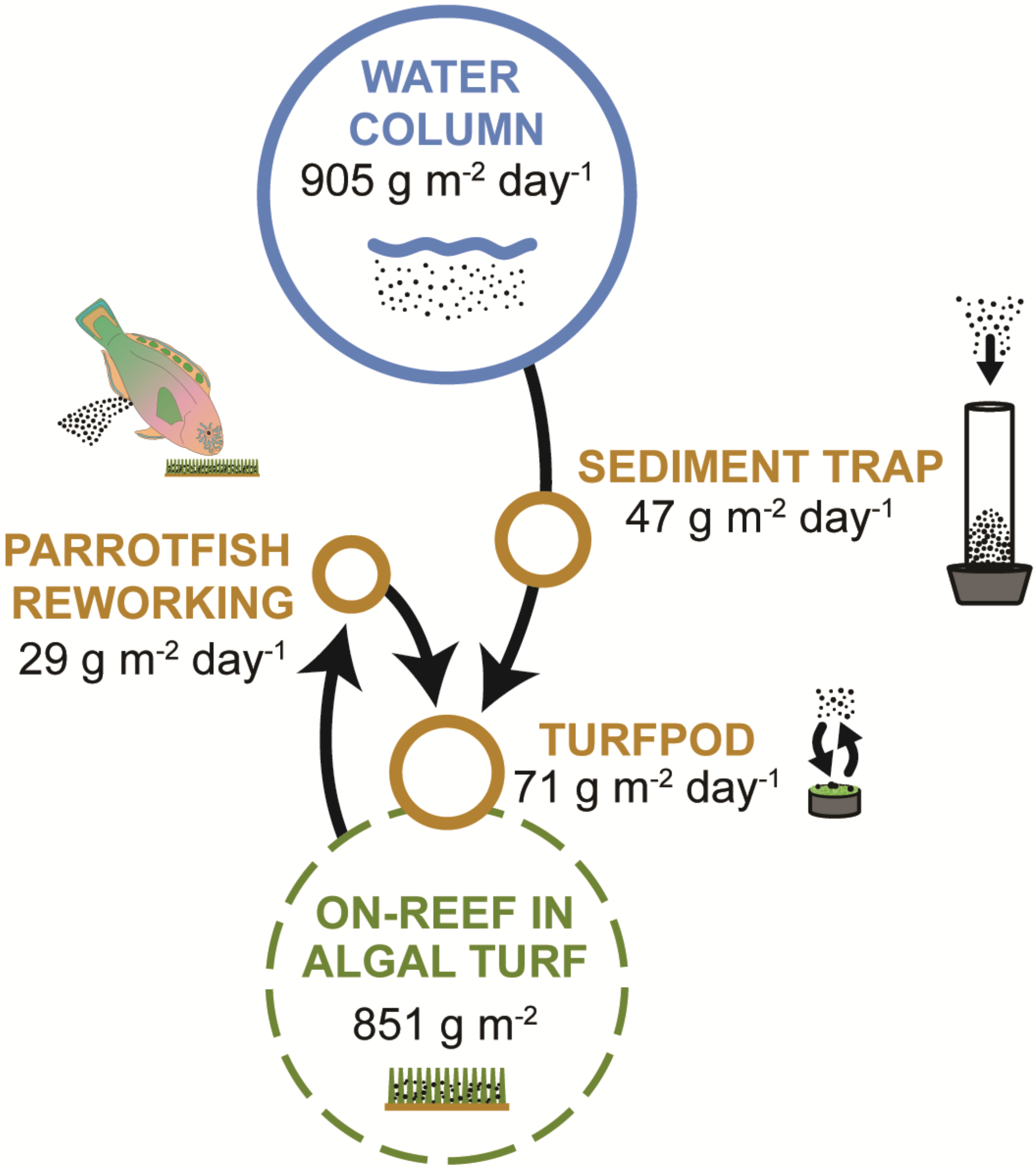

Figure 2 Total reef section sediment dynamics. The circles with the solid lines represent daily rates, and the circle with the dashed line represents a standing reservoir. The circles are scaled by the magnitude of the rate or standing reservoir. The black arrows indicate the

direction of movement of the sediment. Rates: water column = the mass of sediment suspended in the water column that moved through the array site. Sediment trap = accumulation in sediment traps. TurfPod = a proxy for on-reef sediment accumulation in algal turfs (Latrille et al., 2019). Parrotfish reworking = sediment reworking by parrotfishes. Standing reservoir: reservoir of sediment retained in algal turf in reef flat and slope habitats, extracted from Gordon et al., (2016).

3.2. Across depth sediment dynamics

By exploring sediment dynamics from an across-depth perspective we also revealed two distinctly different sediment regimes: a highly dynamic high sediment movement regime on the outer reef flat (3 m) and a less dynamic low sediment movement regime down the reef slope (4.5, 6, 9 and 12 m). Specifically, sediment traps on the highly dynamic flat (3 m) accumulated nearly four times more sediment compared to all other depths sampled on the slope (Figure 3a). This suggests that significantly more sediment was falling out of suspension and into the traps at 3 m compared to all other depths ($p < 0.05$ in all cases; Tables S1). Similarly, TurfPods accumulated three to five times more sediment at 3 m compared to the other depths (except at 9 m; Figure 3a). These differences were significant ($p < 0.05$; Table S2) in all cases except for 9 m ($p > 0.05$; Table S2).

Overall, the outer reef flat was a much more dynamic habitat compared to the slope, both physically and biologically. Physically, there was higher variability in the pressure transferred to the bottom by waves at the measured reef flat site, compared to the two measured slope sites, indicating a greater potential for wave-driven resuspension events (Figure 3c). The maximum pressure exerted from waves at the reef flat site was 1.6 to three times greater than the maximum pressures at the mid-depth and deep slope sites, respectively. In contrast, the across-depth uniformity in current speeds and directions suggests that the current shear stresses capable of resuspending benthic sediments would have been similar across the depths/habitats (Figure 3b, Figure S9 – S10). Therefore, the physical driver of the different sediment regimes in the flat and slope habitats was probably the variation in wave-driven resuspension, and not current shear stress.

The disparate regimes were also distinguished by biological differences, specifically in the relative role of parrotfishes in reworking sediments. The reef flat parrotfish assemblage had the capacity to rework and redistribute three times more sediment on average, compared to the reef slope (Figure 3d). Furthermore, the greater capacity for parrotfish sediment reworking at 9 m, compared to the adjoining 6 m and 12 m slope depths, could have contributed to the anomalous peak in sediment accumulation on the TurfPods at 9 m (Figure 3a). An additional contributor was probably the greater percentage of TurfPods sitting directly on sand at 9 m (58%) compared to the percentages on sand at the other sampled depths (17% for all other depths, Table S3). While it may not be desirable for comparability between depths, this higher cover of sand was unavoidable as it reflects the natural benthic cover on the reef at this location. However, this higher sand cover does mean that there would have been more coarse sediment available for mobilisation at this depth, potentially leading to high levels of resuspension and deposition on the TurfPods. The measured values reflect a natural, if localized, process at these depths in these locations. Overall, the highly dynamic sediment regime of the reef flat contrasted markedly with the less dynamic regime of the slope, and hydrodynamic and biological factors are both likely to have contributed to the disparity in sediment dynamics across habitats.

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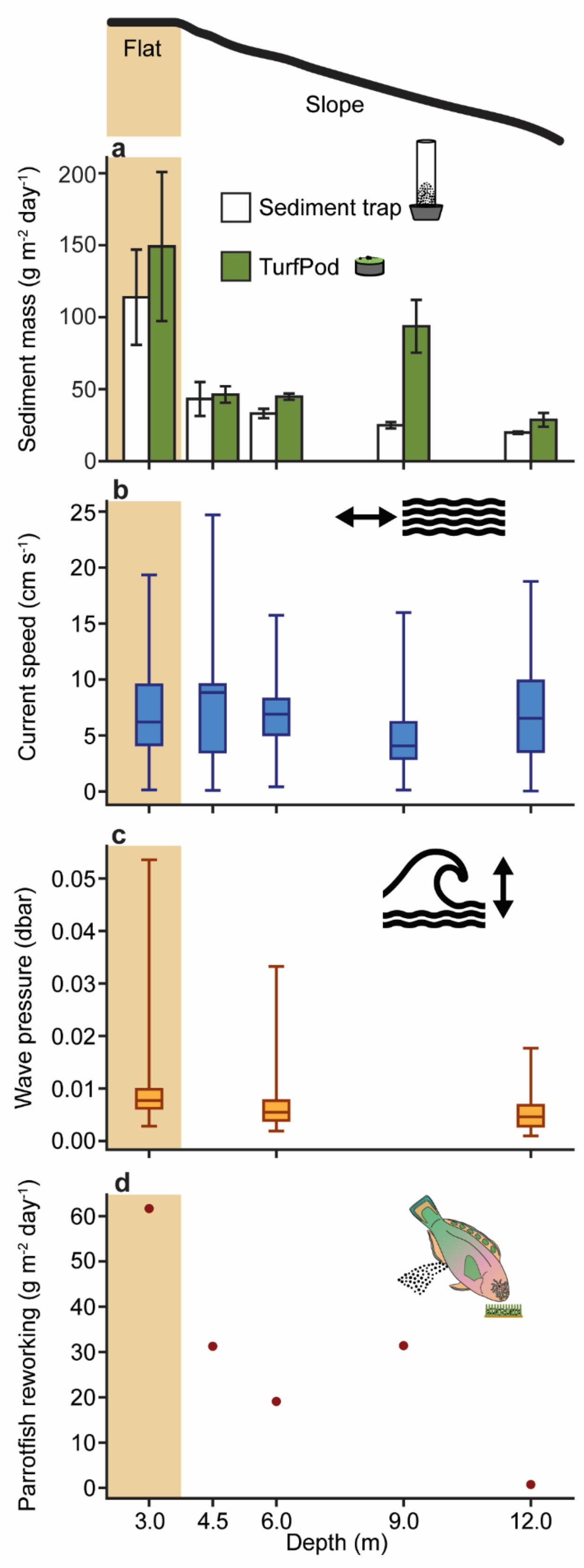

470 **Figure 3** Across depth/habitat sediment dynamics. a) Sediment delivery: the mean (±SE)

471 mass of sediment that accumulated in sediment traps (white) and on TurfPods (green). b)

and c) Potential hydrodynamic drivers: boxplots of the median and quantile ranges for b) near-bottom current speed, and c) change in pressure at the benthos, generated by wave energy. d) Potential biological drivers: the estimated sediment reworking rates by parrotfishes. Note the high levels of sediment accumulation on TurfPods at 9 m depth (a) was likely the result of a higher proportion of these TurfPods being located on sand compared to other depths (see Table S3 and discussion below).

4. Discussion

In this study we compiled a high-resolution, quantitative snapshot of sediment dynamics on an inshore coral reef. This quantitative method allowed us to simultaneously evaluate the relative role of key sediment movement processes and establish links between different sediment reservoirs. In doing so, the results highlight the marked capacity for water currents to transport sediments through our study site during the relatively short temporal period examined. Moreover, data from sediment traps suggested that a substantial proportion (5.2%) of the sediment moving through the water column may be deposited on the reef. By contrast, data from TurfPods suggested that algal turfs have the potential to accumulate more sediment, with potential sources being both the sediment passing through the water column and sediment reworking by parrotfishes. These observations are consistent with previous studies that suggeststrong links between the transitory water column sediment reservoir and the on-reef reservoir (i.e., between water column and benthic reservoirs) (e.g., Storlazzi et al., 2009; Whinney et al., 2017). Thus, our findings further highlight the need to consider both reservoirs in evaluations of sediment dynamics on reefs. In addition, we revealed that the rate at which sediment moved through the system differed markedly across habitats, with a highly dynamic high-sediment movement regime on the shallow reef flat, and a less dynamic lower-sediment movement regime on the reef slope. These cross-habitat differences related to variations in wave energy and the parrotfish assemblage, where both waves and parrotfishes had the capacity to redistribute more sediment in the reef flat habitat. Given that this cross-depth gradient represents one of the strongest ecological gradients across coral reefs (Bellwood et al., 2018; Connolly et al., 2005; Done, 1983), these differing sediment regimes may have important implications for our understanding of the functioning of these reef habitats. Applying our quantitative method across different systems and/or during different temporal periods, is likely to yield further key insights into sediment dynamics on reefs.

4.1. Total reef section sediment dynamics

The water column clearly represents an important vector of sediment transport over, around and onto reefs. By simultaneously quantifying the amount of sediment deposition into sediment traps, we highlight the potential for this suspended sediment to be deposited onto the reef. While the use of sediment traps to link suspended sediments to sediment deposition is common in coral reef sediment studies (reviewed in: Schlaefer et al., 2021), we took this approach a step further by quantifying the potential percentage of the available supply that was deposited. This way, we were able to quantify the potential strength of the link between the water column reservoir and on-reef sediment reservoirs over the course of our study.

There are multiple considerations when using sediment traps to infer on-reef deposition. The sediment traps deployed in this study were designed to have openings above the height of near-bottom remobilization of coarse benthic sediments by currents and waves (Ng et al., 2022; Pomeroy et al., 2021, 2015; van Rijn, 1993), and above the height of most parrotfish defecation (D. Bellwood, pers. obs.). Furthermore, the sediment deposited in traps is unlikely to be resuspended once trapped (Bothner et al., 2006; Storlazzi et al., 2011). The deposition into the traps, therefore, gave an indication of the water-column-specific component of the sediment supply to the substratum. However, sediment traps are known to collect sediments with properties different to the sediments in natural reservoirs, and they cannot capture the surface properties of reef substrata (Bothner et al., 2006; Latrille et al., 2019; Storlazzi et al., 2011). Consequently, while this study provides key insights into the link between the water column and on-reef sediment reservoirs, the physical complexity of the sediment deposition process was not fully captured.

Useful insights into these processes can be gained by comparing our results with those of studies that have quantified the link between suspended sediments and on-reef sediments with an accuracy beyond the application of sediment traps. For example, Whinney et al., (2017) deployed a self-cleaning deposition sensor with a measurement surface that simulated coral micro-topography and found that higher turbidity levels (i.e., the concentration of suspended sediment in the water column) corresponded to higher sediment deposition rates. Taken together, the deposition of a significant percentage of the available water column supply (present study), and the established relationship between increased turbidity and increased deposition (Whinney et al., 2017) suggests that increases in suspended sediment concentrations do have the potential to directly translate to higher levels of sediment deposition on coral reefs. This potential correlation has also been documented for pulse events such as flood plumes (Storlazzi et al., 2009), and dredging activity (Miller et al., 2016). However, our observations highlight the potential magnitude of these links, even during non-storm, non-flood periods.

Indeed, we quantified the strength of the link between water-borne sediments and on-reef sediments under conditions that are relatively commonplace at our study site in Pioneer Bay. The tides during the study were representative of the broader tidal regime. The winds did differ from the prevailing winds, where they tended to blow from the north rather than the prevailing south/south east of the tradewind season. However, northerly winds occur semi-regularly at our study site (10 – 16% of days depending on the season), so these do not represent rare conditions. The northerly winds probably directed more wave energy into Pioneer Bay compared to southerlies and south easterlies. Given the scarcity of data on the links between sediment reservoirs on coral reefs (Schlaefer et al. 2021), it is difficult to asses how the winds might have affected the strengths of the linkages that we inferred in the present study. More broadly, further quantification of the link between water column and on-reef sediments in different conditions, including prevailing and extreme (e.g., storms, floods and big tides) conditions, would help to elucidate the physical relationships underpinning this key component of sediment dynamics.

In addition to quantifying the potential magnitude of the water-column sediment supply to reef substrata, we explored the relative importance of alternate sources of sediments using TurfPods. TurfPods are proxies for algal turfs, the dominant benthic cover at this location as they covered an average (± SE) of 44.4 ± 1.8 % of the substratum in 2020 (Tebbett et al., 2021). Similarly high levels of algal turf cover (40-50%) of the benthos are also common on many other reefs globally (Emslie et al., 2019; Jouffray et al., 2019; Smith et al., 2016). The TurfPods accumulated 1.5 times more sediment than the sediment traps despite the potential for resuspension from the TurfPod surfaces, highlighting the propensity for turfs to accumulate sediments over and above the available water column supply. Based on the sediment accumulation rates from the TurfPods, it would take just 12 days to fully replace all sediments on the benthos. Notably, a previous study conducted at a smaller spatial scale experimentally demonstrated it would take a similar length of time (~14 days) for cleared natural algal turfs to regain initial sediment loads (Latrille et al., 2019). The disparity in sediment loads between the traps and TurfPods suggested alternative sources of sediment to the TurfPods in addition to the water column supply. One such source could be a greater input of sediments from the resuspension and subsequent deposition of bed load sediments compared to traps, due to the closer proximity of TurfPods to the substratum (also see Ng et al., 2022). In addition, sediment reworking by parrotfishes is another potential source. However, regardless of the exact source, the capacity for algal turfs to rapidly accumulate sediment suggests that this benthic cover should be considered more frequently in future studies of sediment movement on coral reefs.

Clearly, algal turfs are just one component of the diverse array of benthic components that typify coral reef communities. As a result, the relative contribution of algal turfs to sediment dynamics in any given location will be dependent on their benthic cover, as well as other factors such as the structural complexity of the reef , with lower complexity leading to higher sediment trapping (Duran et al., 2018; Tebbett et al., 2020b). Moreover, this contribution can change through time as benthic composition on reefs can be variable across temporal scales (de Bakker et al., 2017; Bruno and Selig, 2007; Koester et al., 2020). Despite this variability in the influence of algal turfs, our focus on algal turfs in the current study is based on a number of considerations. Firstly, algal turfs are often the most abundant component of coral reef communities (Emslie et al., 2019; Jouffray et al., 2019;

Smith et al., 2016). For example, in 2017-2019, algal turfs covered, on average, between 40-60% of the benthos on a GBR wide scale while hard corals generally covered just 10-30% (Emslie et al., 2019). Secondly, compared to other key coral reef organisms such as hard corals, algal turfs have a greater capacity to trap and retain sediments. For example, a previous study at our study location showed that natural algal turfs accumulated 5.7 times more sediment than proxies for hard coral surfaces (SedPods), highlighting the relative importance of algal turfs in sediment dynamics on reefs (Latrille et al., 2019). Thirdly, algal turfs are set to be a key component of future coral reef communities as a) their cover generally increases following disturbances such as bleaching (Gilmour et al., 2013; Koester et al., 2020; Tebbett et al., 2022), and b) they are a stress tolerant group of algae that appear to benefit from future climate change conditions (Harvey et al., 2021; Ober et al., 2016). Finally, algal turfs are central to how coral reefs function as they are highly productive primary producers (Klumpp and McKinnon, 1989) that are pivotal in supporting herbivorous and detritivorous trophic pathways on reefs (Choat and Clements, 1998; Kelly et al., 2017). Nevertheless, despite our focus on turfs, it is important to acknowledge that the cover of other benthic organisms such as corals (Duckworth et al., 2017) and macroalgae (Stamski and Field, 2006; Reeves et al., 2018) may also play influential roles in sediment dynamics. Therefore, quantifying, in detail, the role of other benthic organisms in sediment dynamics may be a fruitful avenue for future research. Similar quantitative frameworks to the one presented herein may be well suited.

The potential link between water column sediments and on-reef sediment deposition, and the capacity for algal turfs to accumulate sediment, have important ecological implications for sediment disturbances on coral reefs. Sediment disturbances on coral reefs are often acute events (e.g., dredging events and flood plumes) and are frequently monitored via turbidity measurements as indicators of suspended sediment concentrations (e.g., Fabricius et al., 2014; Luter et al., 2021; Wenger et al., 2016). The level of on-reef sediments is rarely quantified (reviewed in: Schlaefer et al., 2021; Tebbett and Bellwood, 2019). However, water column-based sediments clearly have the potential to be trapped on the reef. Notably, many processes on coral reefs that are directly linked to their resilience (e.g., herbivory [Duran et al., 2019; Goatley et al., 2016] and coral recruitment [Evans et al., 2020; Wakwella et al., 2020]) involve interactions with the benthos and, consequently, interactions with on-reef sediments. In the majority of cases, increased on-reef sediments have negative impacts on reef processes (reviewed in: Erftemeijer et al., 2012; Fabricius, 2005; Jones et al., 2015b; Magris and Ban, 2019; Tebbett and Bellwood, 2019). Thus, while suspended sediment concentrations may vary substantially (Browne et al., 2013b; Fabricius et al., 2013; Jones et al., 2015a; Storlazzi and Jaffe, 2008) and often represent an acute stressor, if these sediments are deposited onto the benthos they may become a chronic stressor (Gordon et al., 2016; Storlazzi et al., 2009) with substantial ecological ramifications. Although any ecological ramifications from sediment deposition and accumulation will invariably depend on the sediment type and composition (Clausing et al., 2014; Ricardo et al., 2021) as well as the context/background history of the reef in question (Browne et al., 2019; Zweifler et al., 2021).

It is important to acknowledge that the exact origins of the sediments in the reservoirs and processes explored in our study were unknown. We conducted our study in the dry season to reduce the confounding effects of fresh sediment inputs on internal dynamics (e.g., river runoff [Storlazzi et al., 2009; Wolanski et al., 2008]). It was, therefore, assumed that the sediments in the water column during our study period had been mobilised and redistributed from local benthic sediments on reef substrata and in off-reef sediment aprons (e.g., Ogston et al., 2004; Orpin and Ridd, 2012; Pomeroy et al., 2021). However, benthic sediments can be the reworked composites of past inputs from external sources and from internal process (e.g., Draut et al., 2009; Larcombe et al., 2001; Lewis et al., 2014; Storlazzi et al., 2009). Consequently, the exact source of the sediment in our study (including the suspended sediments and the sediments that accumulated in the sediment traps and on the TurfPods) and the timeframe of movement of these sediments from their given source, was unclear. Indeed, the sources and timeframes of movements of sediments on coral reefs are rarely identified (but see: Draut et al., 2009; Storlazzi et al., 2009), and this represents an interesting and important avenue for future research.

4.2. Across depth sediment dynamics

By exploring sediment dynamics, and their key drivers, across depth we found two markedly different sediment regimes: a highly dynamic, high sediment movement regime on the reef flat (3 m), and a less dynamic, low sediment movement regime on the slope (4.5 to 12 m, Figure 3). A reduction in the wave energy transferred to the benthos with depth (Figure 3c) and, thereby, a reduction in the resuspension potential with depth, appeared to be one of the factors driving the existence of the two regimes. The revealed importance of depth and habitat-dependent wave-driven resuspension in influencing sediment dynamics is congruent with previous studies, which have repeatedly highlighted the importance of waves in resuspending and facilitating the redistribution of sediments onto and around reefs (Larcombe et al., 1995; Ogston et al., 2004; Pomeroy et al., 2018; Storlazzi et al., 2004). Particularly notable is the divergence between sediment dynamics at 3 m (on the reef flat) and at 4.5 m (on the top of the reef slope). Under regular tides and semi-regular winds at our study site at Orpheus Island, this relatively small change in water depth appeared to represent a critical transition point, beyond which the wave energy exerted on the benthos infrequently exceeded the threshold necessary to resuspend sediments. As the northerly winds present during our study may have directed more wave energy to our study site compared to prevailing conditions, and without comparable data, it is difficult to ascertain if the distinct regimes persist across the same depth gradient under prevailing conditions.

In addition to wave energy, reductions in the sediment reworking capacity of the parrotfish assemblages with depth also appeared to distinguish the two regimes (Figure 3d). Parrotfishes are renowned for their capacity to create (Bellwood et al., 2003; Perry et al., 2015), and to rework and transport (Bellwood, 1995; Bruggemann et al., 1996) sediments on coral reefs. It is therefore unsurprising that they are seemingly a key determinant of across depth/habitat sediment dynamics. Notably, the high deposition of sediment from the near reef (< 50 cm) water column at 9 m, that was captured on the TurfPods but not in the traps (Figure 3a), appeared to be the result of a combination of parrotfish transport (Figure 3d), and the highly localised bed-load transport of sediments (Pomeroy et al., 2021, 2015; van Rijn, 1993) adjacent to the TurfPods (Table S3). These results highlight the potential for variability in sediment dynamics in near-bottom waters across a fine depth gradient, and the potential importance of parrotfishes and localised resuspension in driving these nuanced dynamics.

In contrast to wave-related hydrodynamics and reworking of sediments by parrotfishes, near-bottom currents appeared to play a limited role in driving cross-depth differences in sediment dynamics at our site. Specifically, our examination of current speeds (as well as variability in current direction) in near bottom waters (measured at approximately 30 cm above the bottom) showed no trends consistent with the measured differences in sediment accumulation across the depth gradient (Figure 3b, Figures S9-S10). This conclusion supports those of previous studies which have suggested that currents alone play a limited role in suspending sediments from the benthos (Harris et al., 2014; Larcombe et al., 1995; Pomeroy et al., 2021; Vila-Concejo et al., 2014); although, the interaction between currents and wave energy can be critical in generating sufficient stresses on the bottom to remobilise sediment (Grant and Madsen, 1979; Ogston et al., 2004; Pomeroy et al., 2018; Soulsby et al., 1993; Storlazzi et al., 2009). Therefore, while near-bottom currents are clearly important for distributing sediments around reefs (e.g., Hoitink and Hoekstra, 2003; Pomeroy et al., 2021; Storlazzi and Jaffe, 2008) they appear to be less important, at least in this specific case, and potentially in other sheltered locations, in driving differences in sediment dynamics at the cross-depth scale.

The recognition of the two distinct sediment movement regimes furthers our understanding of sediment dynamics on coral reefs. The high-dynamic sediment regime observed on the reef flat was characterised by substantial sediment movement, meaning that sediment deposited on the flat was likely to be resuspended and redistributed. In their investigation of sediment transport across a reef flat and into an adjoining lagoon, Rosenberger et al., (2020) similarly found a high rate of sediment turnover on the reef flat. By contrast, the less-dynamic regime that occurred deeper, on the reef slope, was characterised by a low level of sediment movement. Here, 1) sediment deposition rates were far lower and, 2) sediments had a far lower chance of being resuspended and transported away. Further support for these different regimes may have been gleaned from examination of sediment particle size distributions, especially via the use of a laser particle analyser. While such data was not collected in the current study, it is interesting to consider our results along with those of Gordon et al., (2016) who did analyse the particle size and composition of sediments accumulated within algal turfs on the flat and slope at our study location. This past study found that sediments on the flat were largely composed of coarser grain carbonate sediments, while fine-grained siliceous sediments made a substantial contribution to the sediments on the slope. Taken together, our results, along with those of Gordon et al., (2016), suggest that finer sediments may be getting resuspended and moved out of highly dynamic reef flat habitats at this location and accumulating in less dynamic reef slope habitats. Given the contrasting rates of sediment movement, increased sediment inputs into this system may thus disproportionately affect the less dynamic reef slope through the slow accumulation of fine sediments, which can be particularly deleterious to ecological processes (Storlazzi et al., 2015). However, the identified regimes were only a snapshot of sediment dynamics in calm weather and over a relatively short period, and so open questions remain about the relevance of these dynamics to the determination of on-reef standing stock reservoir sediment levels over longer time scales.

The establishment of on-reef reservoirs is likely to be a complex depth-dependent process involving bio-physical interactions. Depth-specific interacting factors would include: sediment and substratum properties and factors shaping differential resuspension thresholds (e.g., sediment grain size and cohesive properties [Debnath et al., 2007; Neill, 1968; Wilcock, 1993]; benthic composition and reef complexity [Pomeroy et al., 2017; Tebbett et al., 2020b]; algal turf length [Pessarrodona et al. 2022; Tebbett and Bellwood, 2019]; algal mucus/biofilms [Stal, 2003]); the frequency of hydrodynamic events energetic enough to resuspend sediments at the different depths (e.g., storms [Bothner et al., 2006; Storlazzi and Jaffe, 2008]); and the direction of sediment transport following re-mobilization (e.g., down or across the depth gradient [Ogston et al., 2004; Pomeroy et al., 2018; Presto et al., 2006]). Indeed, this complexity could explain the counterintuitive among-habitat algal turf standing stock reservoir levels previously measured at our study site by Gordon et al., (2016) who recorded higher sediment loads on the more dynamic flat, compared to the less dynamic slope. Nonetheless, irrespective of the standing reservoir of sediment, our data shows that fundamentally different rates in key sedimentary processes were operating across the measured depth/habitat gradient. Consequently, regimes of sediment movement, in addition to static sediment loads, may be a critical factor to consider when assessing the risks of sediments to reefs.

The different sediment movement regimes on the reef flat and slope closely mirror the distribution of reef organisms and processes across this same gradient. For example, herbivorous fish populations sizes (Bellwood et al., 2018; Oakley-Cogan et al., 2020), herbivory rates (Lewis and Wainwright, 1985) and benthic productivity (Klumpp and McKinnon, 1989; Russ, 2003) on reefs are all generally higher in the shallow-water outer-flat habitats corresponding to the highly-dynamic sediment movement regime, compared to the less-dynamic slope. While the distribution of these organisms/processes may be interconnected and related to other correlates, benthic sediments have been shown to have the potential to shape both biological distributions and processes (Bellwood and Fulton, 2008; Clausing et al., 2014; Ng et al., 2021; Tebbett et al., 2018a, 2020a). Furthermore, while our study quantified the sediment dynamics on the reef flat (3 m) and upper reef slope (4.5 m), we missed the reef crest, which represents the transition point between the flat and slope habitats. Interestingly, the standing reservoir of sediments is frequently minimised on the reef crest (Goatley and Bellwood, 2012; Gordon et al., 2016; Purcell, 2000), and the crest frequently also corresponds to peaks in numerous biological processes (e.g., herbivory and benthic productivity [Bellwood et al., 2018; Russ, 2003]). The specific conditions in this habitat, especially the interaction between reef structure and wave energy (Duce et al., 2022; Storlazzi et al., 2004) and how this pertains to sediment movement, could therefore represent an ecological 'sweet spot' of sediment dynamics and other environmental parameters. In the future, exploring the potential for varying sediment regimes across habitats to shape ecological processes is likely to yield interesting insights into how reefs may operate now and in the future.

4.3. Study site context and future application of our quantitative method

Our study was on the leeward side of Orpheus Island, one of the most sheltered locations on the GBR and one with the potential for relatively high sediment inputs compared to reefs further offshore or in more exposed locations (Fabricius et al., 2014; Tebbett et al., 2021). Given the prominence of sediments on inner-shelf reefs of the GBR (Browne et al., 2013b; Fabricius et al., 2014; Tebbett et al., 2018b), reefs such as those in Pioneer Bay, Orpheus Island, offer a particularly interesting study system in which to examine sediment dynamics. Nevertheless, coral reefs are inherently variable in terms of their proximity to new terrigenous sediment inputs (Álvarez-Romero et al., 2013; Brodie et al., 2010), geomorphology (Browne et al., 2012; Duce et al., 2020, 2016; Hopley et al., 2007), hydrodynamics (Lowe and Falter, 2015; Monismith, 2007), organismal assemblages (Aued et al., 2018; Cleary et al., 2016; Moustaka et al., 2018; Samoilys et al., 2019) and, consequently, in their sediment budgets (Browne et al., 2013b; Calhoun et al., 2002; Mallela and Perry, 2007; Wolanski et al., 2005). This variability means that it is difficult to place our results within a broader context and determine how applicable our results are to other reef systems. Indeed, our capacity to determine if the relative strength of the connections between different reservoirs is particularly high or low, is limited. This is because simultaneously quantifying different sediment reservoirs and movement processes, such as in the current study, is rare on coral reefs (reviewed in Schlaefer et al., 2021).

It should be noted that while our method produced valuable quantitative data on various sediment dynamics and movement processes there are several reasons why data of this nature is lacking in the literature. Firstly, data of this nature is logistically challenging to collect and requires an extensive number of people in the field to ensure equipment deployment and data collection can occur simultaneously within time constraints. Secondly, the equipment used (i.e., replicated current meters, pressure sensors) can require a substantial financial outlay. Finally, due to the various components and interactions quantified that span different disciplines including biology, geomorphology, sedimentology and physical oceanography, collection of these data requires extensive collaboration across different areas of expertise. Nevertheless, overcoming these difficulties is necessary if we are to gain a comprehensive understanding of sediment dynamics on coral reefs. In this respect, the method presented in this study provides valuable opportunities to examine sediment dynamics on reefs moving forward.

Replicating our quantitative approach to sediment dynamics at other reef locations, or at other time periods, and comparing the results with those of the present study could provide interesting and valuable insights into sediment dynamics on reefs. Replication of this method in a fundamentally different context, such as on a reef further offshore where there is more hydrodynamic exposure and less terrigenous input would be particularly valuable (e.g., Fabricius et al., 2014; Tebbett et al., 2018b; Woolfe and Larcombe, 1999). Furthermore, replication of our method at Orpheus Island during a different temporal period may be insightful. The current sampling was conducted during a moderately calm period when the winds blew from the north, opposed to the prevailing south/south easterly wind direction. It would be useful to establish if the sediment dynamics measured during the northerly winds persist under the prevailing conditions. Conversely, it would be similarly useful to investigate dynamics under more extreme conditions, as in storms or other high-energy weather events, the mechanisms and magnitudes of sediment movement at Orpheus Island are likely to vary widely (e.g., Bothner et al., 2006; Storlazzi and Jaffe, 2008). Therefore, replication of this quantitative method would represent an important next step on the path towards a comprehensive understanding of sediment movements on, around and above coral reefs at biologically relevant scales.

4.4. Conclusions

Overall, in this study we present a high-resolution snapshot of sediment dynamics on a sheltered inner-shelf GBR reef. We simultaneously and quantitatively considered a range of sediment reservoirs and linking processes including: the current-driven transient water column reservoir, wave-driven resuspension, sediment deposition in traps and algal turf proxies, and sediment reworking by parrotfishes. Our findings begin to tease apart the contributions of the water column sediment supply and of localised sediment turnover (e.g., resuspension and biological reworking) to on-reef sediment accumulation. We show that, each day, the currents flowing over the reef carry an amount of sediment equal to that already present on the reef in algal turfs. The moderate percentage of this water column supply that is deposited, in combination with the supply of turned-over sediment from parrotfish reworking, is sufficient to "refill" hypothetically emptied algal turfs within only 12 days. Clearly, the transient water column and parrotfish reworking both have the potential to be major sources of on-reef sediments. Beyond this supply versus delivery of sediment at the reef-section scale, we show that reef zones differ markedly in their sediment dynamics. The reef flat was characterised by a highly dynamic high sediment movement regime, driven by wave energy and parrotfishes. Just 1.5 m deeper, however, and extending to 12 m depth, sediments appear to be more stagnant. Our study provides a new, comprehensive survey of sediment dynamics on an inshore coral reef for a snapshot in time.

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