

# Effect of the surgeonfish *Ctenochaetus striatus* (Acanthuridae) on the processes of sediment transport and deposition on a coral reef in the Red Sea

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**Abstract** Excessive sedimentation is a major threat to coral reefs. It can damage or kill reef-building corals and can prevent the successful settlement of their planktonic larvae. The surgeonfish *Ctenochaetus striatus* feeds on rocky surfaces by sweeping loose material into its mouth with its flexible, broom-like teeth. In addition, it grasps and removes hard substrates with the aid of its special palate structure. It then transports sediment matter off the reef by defecating the ingested material outside the rocky zone of the reef. We analyzed 150 feces samples of six individuals, differentiating between (1) ingested by sweeping and (2) ingested by scraping, and compared their content with inorganic land-derived and marine sediments trapped at the feeding area. Projections based on fish densities, defecation rates, and quantities as well as composition of sediments collected by traps on the same reef site suggest that *C. striatus* removes at least 18% of the inorganic sediment sinking onto the reef crest. The eroded share in the exported matter is about 13%. This finding points to a hitherto not verified role of *C. striatus* as a reef sweeper and reef scraper, whereby the first function is by far dominating.

**Keywords** Coral reefs · Red Sea · Sedimentation · Feeding and defecation behavior · Reef sweeper

## Introduction

Sediment fluxes are one of the major forces influencing the growth of coral reefs (Gilmour 1999). Hard substrates covered by sediments are less attractive to the settlement of coral larvae than bare ones (e.g., Hodgson 1990; Rogers 1990; Babcock and Davies 1991). Crustose coralline algae, which bind the reef framework and thus may enhance conditions for the settlement of coral larvae (Harrington et al. 2004), are also endangered by excessive sedimentation (Fabricius 2005).

Carbonate sands and silts permanently produced (and shifted) in the reef system itself constitute the endogenous sediments; terrigenous sediments may be added by rivers and wind. The removal of sediments off the reef previously deposited on the reef surface is considered to result primarily from abiotic factors like wave action and currents (Hubbard 1990; Fabricius 2005). If reefs occur in protected bays with low hydrodynamic conditions, these factors alone may probably not be sufficient to prevent the over-accumulation of sediments, which in turn would result in the damage or even death of reefs. The idea that certain biological components of the reef can act as a kind of “cleaning agent” is obvious, and becomes more and more interesting in the light of increasing sediment stress and simultaneous over-exploitation of reef fish populations.

We studied the feeding behavior of the Lined bristle-tooth surgeonfish *Ctenochaetus striatus* (Krone et al. 2006, 2008, Fig. 1 and SOM), known as a common detritivorous species throughout Indo-Pacific reefs (Choat 1991; Randall and Clements 2001). With its feeding habits, it also

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**Fig. 1** Adult specimen of *C. striatus*, at a fringing reef, northern Red Sea (photo P. Kanstinger)

removes loose sediment matter from the rocky reef substratum (Purcell and Bellwood 1993; Fouda and El-Sayed 1994).

Our field observations and laboratory studies had recently shown that these fish also act as bio-eroders (Schuhmacher et al. 2008) by grasping knobs of hard substrate and removing them with the aid of a special palate structure (Krone et al. 2006). The fish were observed picking the surface of reef rock throughout the day, hereby ingesting sediments trapped in the thin algal turfs colonizing the reefal substrate (Montgomery et al. 1989). Erosive grasping bites were less frequently recorded.

Additionally, our extensive field observations confirmed the unique defecation behavior already mentioned by Bellwood (1995): the fish exclusively feed on rocky surfaces, and defecate only on a distinct small spot located on a sandy area outside the reef (Krone et al. 2008).

This peculiar behavior prompted us to try to answer the following questions on sediment export: (1) what is the amount of material exported off the reef crest through the distinct defecation pattern, and (2) how large is the possible export in relation to the sedimentation there?

To tackle the latter question, we had to distinguish between inorganic material generated by the erosive feeding action and that by intake of loose particles from the reef surface. For this purpose, we differentiated between carbonate and non-carbonate (siliceous) matter. The latter is considered allochthonous (land-derived) material, previously

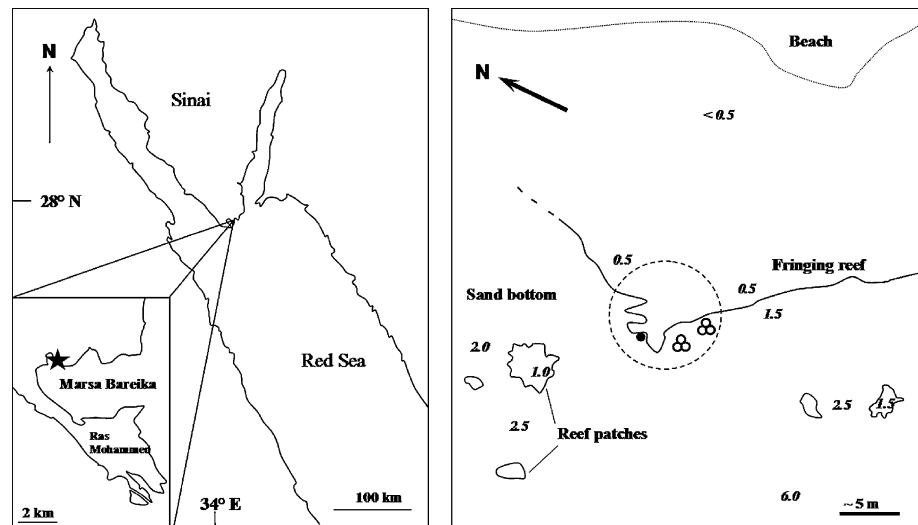
deposited on the reef and as such a tracer of ingestion by browsing. Comparisons with concurrent sediment samples at that site allowed estimating the extent of the fish's peculiar behavior on the sediment regime of its territory.

## Materials and methods

### Study area

The investigation site Kashaba Bay is located in Marsa Bareika in the Ras Mohammed National Park, Egypt, at the southern tip of the Sinai Peninsula (Fig. 2). At this site, a 150-m-wide “wadi” (a river valley that is dry except in the event of rare heavy rain falls) enters the sea and continues as a submarine canyon. A shallow fringing reef has developed at depths of approx. 0.2–2 m, 25 m off the shoreline. Some isolated patch reefs of different sizes are located in front of the fringing reef. The fringing reef crest has a live coral coverage between 5 and 50% (Krone et al. 2008). The opposite tongue of land, which separates the bay from the open Red Sea, keeps the height of the waves below 50 cm, even during occasionally strong onshore winds. Tides range between 30 and 50 cm. Typical winds are diurnal land-/sea-breezes with an average speed of 3–4 Bft (checked with a cup anemometer and a vane throughout the entire investigation time). Slow currents, causing detritus particles and

**Fig. 2** Research location in the northern Red Sea. *Right*: details of the study site in Marsa Bareika. The *dotted line* shows the approximate home range of six observed *C. striatus* specimens. The *black dot* marks the sampled defecation site. Fish censuses were performed on the fringing reef. Six sediment tube traps beside the reef (*triple rings*). (Water depth = numbers in *italics*). Modified from Krone et al. 2008



small pieces of algae drifting less than  $10 \text{ cm s}^{-1}$ , were observed along the shore, dominantly from east to west.

#### Fish feces sampling

The feeding and defecation behavior of *C. striatus* is described in detail by Krone et al. (2008). Defecation sites can be identified as accumulations of approx. 2-cm-long, 0.5-cm-wide drop-shaped pellets on the sand. These feces pellets stay compact for at least 20 min. Fecal samples were collected in order to analyze their mineral content. They were sampled at a defecation site next to the above-mentioned fringing reef (Fig. 2) between the 4th and 18th of November, 2005. This defecation site was frequented by six individuals (standard length 12–14 cm). The fish were observed to be most actively feeding and defecating between 11:00 and 16:00 (see also Montgomery et al. 1989). The fecal pellets were transferred into small plastic bags by hand. Special care was taken to avoid collecting other sediments. In the laboratory, the feces–water mixture was processed through a sieve (50- $\mu\text{m}$ -mesh diameter) and dried for conservation. Over a period of 15 days, we randomly collected ten pellets per day during the main defecation time. The pellets of 1 day were pooled for further analysis.

#### Mineral content of feces and sediment

To quantify the low masses of carbonate and non-carbonate fractions in the feces, the following analyses were performed: (a) X-ray diffractometric analyses were carried out on the feces samples to quantitatively distinguish carbonates (aragonite, calcite, and magnesium calcite), silicates (quartz, feldspar, and plagioclase), and halite as the main components; (b) The desalted and dried (60 h,  $60^\circ\text{C}$ ) samples were homogenized with a mortar. They were weighed

to the nearest 0.0001 g dry weight. Subsamples  $<0.06 \text{ g}$  were taken and solubilized for 3 h in a 10% HCl solution. Ca and Mg concentrations were identified by means of inductively coupled plasma atomic-emission spectroscopy (ICP/AES). The respective carbonate masses were calculated according to the 1-to-1 ratio of Ca to  $\text{CO}_3$  and Mg to  $\text{CO}_3$  of the carbonates; (c) Total N and C contents were determined with gas chromatography in order to obtain the solely organic portion of C in the samples, and previously identified C shares from the carbonates were subtracted. The total mass of organic C and N together was considered as the organic dry matter of the sample; (d) The non-carbonate mineral portion was obtained by subtracting the organic and carbonate masses from the sample mass. Organic matter was measured as well, but it is of no relevance in this context.

#### Sediments

At the Marsa Bareika study site, we examined the sedimentation rate by placing six tube traps (diameter 9.0 cm, height 11.0 cm) alongside the vertical level of the fringing reef edge, at a distance of 1 m (Fig. 2). In order to minimize any possible resuspension and disturbance caused by fish, we installed a baffling grid at the mouth of the trap (height 1.5 cm, mesh size 1 cm, according to English et al. 1997). The traps were emptied every other day. We chose a 2-day interval to be able to collect detectable sediment masses.

#### Statistical treatments

The portions of carbonate and non-carbonate inorganic fecal matter and the trapped particles were compared using the *t* test. Average masses of sediments and feces contents are displayed with standard deviation ( $\pm$ ).

## Fish census and calculations

In order to determine the abundance of adult *C. striatus* on the fringing reef in the Marsa Bareika, six 50-m belt transects (on six different days) with a width of 5 m (English et al. 1997) were laid out and observed between 11:00 and 16:00, during the same time of day the feces were sampled. At this time, the fish are very active. Only adult specimens (12–14 cm of standard length) were counted.

The transect lines were laid out on the reef crest of the fringing reef at a distance of 2.5 m to the reef edge, in the same reef section where the traps were deployed and the feces were sampled. To estimate the effect of *C. striatus* on the reef's sediments, the average mineral masses per fecal pellet sampled at the fringing reef were multiplied by the number of fish per  $\text{m}^2$  and the minimal daily defecation rate per individual.

## Results

The fish started feeding on the reef patches and crest soon after sunrise, and started defecating usually after 10:00 or 11:00 am in the morning. Throughout the observations, individual fish hurried approx. every 10–15 min from its actual feeding area to its “toilet”—a distinct spot outside the reef on sandy ground. Several fish may share the same defecation area; no defecation on hard ground was observed as already shown by Krone et al. (2008).

### Mineral contents of feces and material export from the reef

Single fecal pellets contained, on average,  $290 \pm 80$  mg of inorganic matter, composed of  $150 \pm 40$  mg non-carbonates and  $140 \pm 40$  mg carbonates.

The portion of carbonates, amounting to 48%, within the inorganic content of feces differ significantly (*t* test,  $p < 0.0001$ ) from the 35% carbonates within the trapped sediments. Repeated counts of the fresh fecal pellets and

video recordings of the defecation site showed that at least 45 pellets per individual per day were transported away from the reef's hard substrate zone. Thus, one individual fish in the studied size-range removed about  $195,750 \pm 54,000$  mg inorganic material from the reef within a period of 15 days—extrapolated to 1 year this amounts to about  $4.76 \pm 1.31$  kg ( $290 \times 45 \times 365 \times 10^{-6}$ ) of inorganic matter ( $2.46 \pm 0.66$  kg terrestrial siliceous sediment such as feldspar and quartz, and  $2.30 \pm 0.66$  kg marine carbonates) from the reef rock.

The fish census yielded the density of  $0.12 \pm 0.04$  *C. striatus* individuals  $\text{m}^{-2}$  reef crest. Within the transect, only fish sized comparable to those specimens visiting the defecation site (12–14 cm SL) were observed. Juveniles usually stay hidden. Combining fish density, feces content, and defecation rate, the calculated bulk transport of mineral sediment during the period of observation was about  $1,566$  ( $290 \times 45 \times 0.12$ )  $\text{mg m}^{-2} \text{day}^{-1} \pm 432$   $\text{mg m}^{-2} \text{day}^{-1}$ .

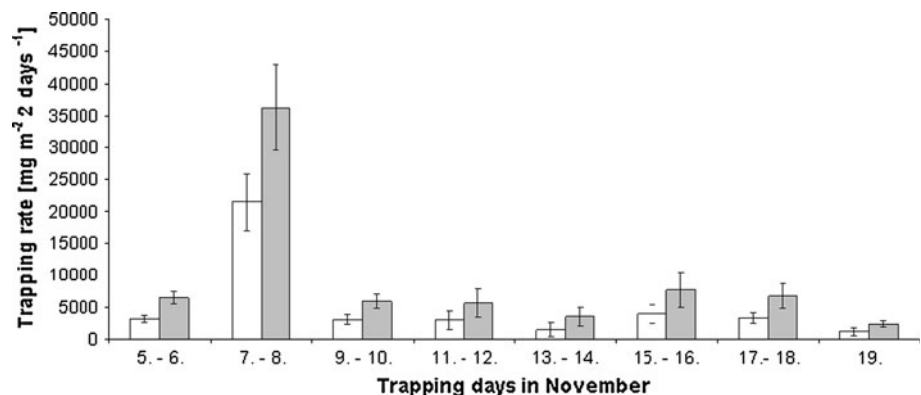
### Sedimentation

The trapping rates are given in Fig. 3—on average  $7,698 \pm 8,114$   $\text{mg m}^{-2} \text{day}^{-1}$ . The measurements per day varied by the factor 11 ( $2,551$   $\text{mg m}^{-2} \text{day}^{-1}$  and max.  $28,855$   $\text{mg m}^{-2} \text{day}^{-1}$ ). Both silicates and carbonates were found in every single sample: on average 64.7% non-carbonates =  $4,981 \pm 5,044$   $\text{mg m}^{-2} \text{day}^{-1}$  and 35.3% carbonates =  $2,717 \pm 3,069$   $\text{mg m}^{-2} \text{day}^{-1}$ ). The 7th/8th November collection experienced a strong northerly wind (i.e., from land). In total, a sediment load of  $115,480$   $\text{mg m}^{-2} \pm 28,876$  was trapped within 15 days.

## Discussion

The sediment budget of a coral reef is controlled by several factors: hydrodynamic regime, terrigenous inputs, activity of inhabiting fish, and invertebrates. At the Marsa Bareika, fine autochthonous sediments are produced by shell-secreting

**Fig. 3** Sedimentation masses measured between November 5th and 19th, 2005, on the observed reef (sediment traps  $n = 6$  were collected every 48 h, respectively, the last day after 24 h, carbonates are in white; non-carbonates are in grey). The high rate measured between November 7th and 8th occurred during strong off-shore winds





organisms (e.g., some calcareous algae, foraminifers, tiny molluscs) and bio-eroders (e.g., boring sponges, scraping sea urchins, parrotfish). Allochthonous material is blown in by the wind. From time to time, both kinds of sediment may be suspended in the water column. The tube traps collected both fractions of sediments. In contrast to the open reef surface, these fractions were hardly resuspended once trapped. Hence, the trapping data represent the gross amount (import) of loose material settling down from the water column.

The export by *C. striatus* also comprises both autochthonous and allochthonous material. The carbonate portion of feces contains loose material that was swept in with the bristle-like teeth—e.g., tiny shell fragments of shells, sea urchins, foraminiferans (Fouda and El-Sayed 1994) as well as small solid rock edges bitten off the reef surface (Krone et al. 2006; Schuhmacher et al. 2008) and further processed during digestion (Nelson and Wilkins 1988). The siliceous portion of the feces is undoubtedly sediment material that had settled down on the reef. Hence, the siliceous fraction can be considered as a “tracer” of loose particles, deposited on the reef, consumed, and subsequently exported from the reef.

The fact that both the *C. striatus*' feces and the collected sediments contain non-carbonate minerals in relatively high quantities shows that the investigated reef receives considerable amounts of terrigenous sediments. Eisinger (2005) measured  $37\text{--}50,000\text{ mg m}^{-2}\text{ 15 days}^{-1}$  during Dec–Feb 1999/2000 at the same site in 5-m depth.

To give a quick overview on the export efficiency of *C. striatus*, we found that with an estimated sediment removal rate of  $1,367\text{ mg m}^{-2}\text{ day}^{-1}$ , and ignoring the small resuspension possibility at the sheltered site, *C. striatus* exported approx. 18% of particulate matter off the reef, as was found accumulated in traps during the study period of 15 days, and 87% of the exported material was loose sediments and 13% was eroded matter.

In detail, this means that in order to figure out the sedimentary share (apart from the eroded one) in the fecal carbonate fraction, traces of the non-carbonate material were followed. To do this, we compared the percentage of non-carbonate particles in sediment traps and feces. The average quantity of trapped sediment amounts to  $7,698\text{ mg m}^{-2}\text{ day}^{-1}$ ; 64.7% of this amount is non-carbonate matter, totaling  $4,981\text{ mg m}^{-2}\text{ day}^{-1}$ . The mineral content of feces transported off the reef surface totals  $1,566\text{ mg m}^{-2}\text{ day}^{-1}$ , of which 52%—equalling  $814\text{ mg m}^{-2}\text{ day}^{-1}$ —are non-carbonates. This amount corresponds to 64.7% of non-carbonates in the sediment traps; hence, the remaining 35.3% carbonate share equals  $553\text{ mg m}^{-2}\text{ day}^{-1}$ .

Judging from these observations, we can conclude that *C. striatus* ingested and exported  $1,367\text{ mg m}^{-2}\text{ day}^{-1}$  (= 17.76%) of the total examined sediment amount of

$7,698\text{ mg m}^{-2}\text{ day}^{-1}$  from the reef, which is the sum of the above stated figures of  $814\text{ mg m}^{-2}\text{ day}^{-1}$  non-carbonates and  $553\text{ mg m}^{-2}\text{ day}^{-1}$  carbonates. By deducting the amount of settled sediment exported by *C. striatus* from the total amount of fecal mineral content transported off the reef ( $1,566\text{ mg m}^{-2}\text{ day}^{-1} - 1,367\text{ mg m}^{-2}\text{ day}^{-1} = 199\text{ mg m}^{-2}\text{ day}^{-1}$ ), we conclude that this remaining portion—approx. 13% of the exported material—can be attributed to fish erosion. This conclusion does not, however, account for benthic organisms such as foraminifers, bryozoans, and others that live attached to turf algae and are not captured by the traps.

Our analysis principally elucidates the role of *C. striatus* as questioned in the introduction. *C. striatus* is a reef sweeper, i.e., it cleans the reef surface by collecting and exporting parts of the sedimentary cover. It is also a bio-eroder. Earlier gut analyses (Choat 1991; Fouda and El-Sayed 1994) had identified considerable amounts of carbonate matter, however, without information on its origin. The intake of carbonate matter varies during the year with minima during summer and autumn and maxima during spring (Fouda and El-Sayed 1994); hence our data gathered in November can be considered as conservative when extrapolated to an annual mean. The experimentally collected data of eroded carbonate matter (Schuhmacher et al. 2008)— $449\text{ g ind.}^{-1}\text{ year}^{-1}$ —are definitely conservative, since they were obtained from subadult fishes scraping on coral plates not yet weakened by endolithic borers. Nevertheless, the erosive impact is low compared to that of some parrotfishes close to our study area: Alwany et al. (2009) measured  $42.3\text{ kg year}^{-1}$  for *Chlorurus sordidus* and even  $290.3\text{ kg year}^{-1}$  for *C. gibbus*.

Even though this study is based on a limited time span and number of fish, some theoretical approximations of the fish's role in the sediment dynamics of the studied coral reef can be done. The reef in the sheltered Kashaba Bay is very rarely exposed to strong water movement. The current velocity, usually below  $20\text{ cm s}^{-1}$ , does not significantly resuspend settled sediments (Ogston et al. 2004). However, terrestrial carbonate and non-carbonate dust is blown in from the hills and fossil reefs surrounding the bay. This situation is different from localities where the dynamics of sedimentation and resuspension as well as transport on and off the reef were studied (e.g., Bothner et al. 2006; Ogston et al. 2004; Gibbs 2001). Hard substrates covered by sediments are less attractive to coral larvae than bare ones. Experiments have shown that a 50% sediment cover (only inorganic particles) reduces larvae settlement on glass by a factor 6 (Hodgson 1990). Babcock and Davies (1991) tested the influence of different sedimentation regimes on coral larvae (*Acropora millepora*). Even their lowest sediment treatment of approx.  $31,000\text{ mg m}^{-2}\text{ day}^{-1}$  was found to significantly reduce the number of larvae settling on the

upper sides of settlement plates (from ~30 to 5). The average trapping rate of carbonates and non-carbonates found in the Marsa Bareika ( $7,698 \text{ mg m}^{-2} \text{ day}^{-1}$ ) probably do not present a critical sediment load for coral recruitment, but during calm weather periods with low resuspension by currents (Hubbard 1990; Chazottes et al. 2008), sediments could accumulate beyond a critical level. Hence, the export activity of *C. striatus* amounting to 18% sediment removal per day may play an important role in keeping the reef habitable for coral larvae. Cleaning the algal turf from sediments may also be beneficial to the co-occurring herbivorous species as *Acanthurus sohal* (Red Sea) and *Acanthurus lineatus* (Indo-West-Pacific). These fish defend their territory against other fish—except *C. striatus* (Choat 1991).

Values of sedimentation vary strongly between sites, depending on coastal topography and wind regimes (Wilson et al. 2003), wave action, and human impact. Nevertheless, our results not only corroborate the findings of sediment transport by fish (Bardach 1961; Bellwood 1995) but they also show that reef sweepers actively transport loose sediments away from the reef. They are distinguished from the reef scrapers (Steneck 1988)—e.g., the parrotfish *Chlorurus gibbus*—which export matter eroded mainly by themselves off the reef crest and disperse it on the sediment apron (Bellwood et al. 2003).

The assignment to the group of scrapers or sweepers depends on the percentage of loose sediment that is transported away from the hard reef surface. These proportions may vary depending on the site. In our case, *C. striatus* clearly has to be classified as a reef sweeper, and only to a much lower degree as a reef scraper. It might be intriguing to investigate the variations within the sweeper/scraper ratio at different reefs in the vast distribution area of *C. striatus*.

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