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Impact of ocean acidification on the carbonate sediment budget of a temperate mixed beach

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Abstract

The production of sediments by carbonate factories is an important input for beach sediment budgets in coastal areas where no terrigenous input occurs. Calcifying organisms living in carbonate factories are a major source of bioclastic carbonate sediment for coastal systems. Increased levels of CO_2 in the atmosphere are leading to an increase in the partial pressure of CO_2 on ocean seawater, causing ocean acidification (OA), with direct consequences for the pH of ocean waters. Most studies of OA focus on its impact on marine ecosystems. The impact of OA on calcifying algae could be to reduce the amount of sediments produced by carbonate factories and supplied to temperate coastal systems. The aim of this study was to quantify the effect of the predicted OA on the long-term sediment budget of a temperate Mediterranean mixed carbonate beach and dune system. Based on projections of OA we estimated a fall of about 20% in the present bioclastic carbonate sediment deposition rate, with the biggest decreases seen in the Dunes (-36%) and the Subaerial beach (-40%). In the long term, OA could play a primary role in the response of these systems to sea level rise. Indeed the reduction in the quantity of carbonate sediments provided to the system may affect the speed with which the system is able to adapt to sea-level rise, which, by increasing wave run-up, may promote erosion of dunes and subaerial beaches.

Keywords: Calcifying algae, Posidonia oceanica, Mediterranean beaches, global change, Sea level rise

1. Introduction

In coastal areas, where little or no sediment is delivered by rivers from the land to the inner shelf, marine sources of sediment are key to the maintenance of the coastal system and beaches become progressively more calcareous (Bird 2008). Biogenic carbonate beaches and dunes are widely distributed in both tropical and temperate environments (Short 2000; De Falco et al. 2008; Short 2010; Gomez Pujol et al. 2013; Tecchiato et al. 2015; De Falco et al. 2017). Along shores bordered by barrier reef or atolls, sources of carbonates for beaches include coral reef ecosystems such as barrier reefs and lagoons (Yamano et al. 2002). In temperate areas, marine biogenic carbonate sediments are often produced inside the seagrass meadows that colonise nearshore areas (Short 2010, Mazarrasa et al. 2015).

Posidonia oceanica seagrass meadows cover about 1.5% of the Mediterranean Sea bed (Vacchi et al. 2017) and represent the main carbonate factory for nearshore areas. High levels of biogenic carbonate, produced by calcifying organisms, are usually detected inside the sediments of these meadows (Vacchi et al. 2017). Coralline algae, foraminifers, gastropods, bivalves, serpulid polychaetes, bryozoans, and echinoids are the most important calcifying organisms associated with *P. oceanica* meadows (Fornós and Ahr 1997). The production of carbonate sediments by the biota inside P. *oceanica* meadows has been recognised as the most important sediment input for beach sediment budgets in coastal areas where no terrigenous input occurs (Gomez-Pujol et al. 2013; De Falco et al. 2017).

Recently, De Falco et al. (2017) quantified the contribution of biogenic sediments, mainly produced in *P. oceanica* seagrass meadows and secondarily in photophilic algal communities, to the long term sediment budget of a beach-dune system over a time span of ~4000 years. The study shows that about 28% of the carbonate sediment produced inside the carbonate factories was transported to the adjacent beach-dune system and led to a positive sediment budget (De Falco et al. 2017). However, the decline of the coastal ecosystem, caused by local impacts and by global climate change (Duarte et al. 2013; Mazarrasa et al. 2015), can alter the carbonate sediment budget.

One of the main forcing agents of global climate change is the rising concentration of atmospheric carbon dioxide (CO_2) (Gattuso et al. 2015). Rising CO_2 levels increase the partial pressure of CO_2 on ocean seawater (Orr et al. 2005; Gattuso et al. 2015). This in turn results in the phenomenon known as ocean acidification (OA) (Orr et al. 2005), which has a direct consequence on the pH of ocean waters. The present pH of ocean water (pH = 8.1) is ~0.1 lower than the preindustrial age. Current models predict the pH of the surface water will drop further, by 0.14 to 0.4, by the end of the century (Basso 2012 and references therein; Gattuso et al. 2015). The decreasing pH of seawater is a critical driver of the solubility of calcium carbonate shells and skeletons (Gattuso et al. 2015). Furthermore, such conditions impact calcification on the part of calcifying organisms (Fabry et al. 2008). Specifically, calcareous algae are sensitive to decreasing seawater pH, which leads to unfavourable conditions for calcification (Hall Spencer et al. 2008; Martin et al. 2008; Basso et al. 2012).

The impact of OA on calcifying algae could be to reduce the amount of sediments produced inside carbonate factories and consequently the supply of carbonate sediments to temperate coastal systems (e.g. the Mediterranean Sea and South Australia) (Bianchi et al. 2012). The reduced supply of sediments to coastal systems has always been neglected in studies of OA, and information on its potential impact on the long-term sediment budgets of temperate carbonate beaches is thus lacking.

This is the first study seeking to quantify the effect of the predicted OA on the long-term sediment budget of a temperate mixed carbonate beach-dune system. The investigated beach-dune system was in the western Mediterranean Sea (San Giovanni bay, western Sardinia). The effect of OA on the sediment budget was calculated by assessing the fall in marine bioclastic sediment supply arising from the projected reduction in the pH of marine water. Specifically, the estimated fall in the sediment budget took account of the decreased activity on the part of calcifying algae. The novelty of the study is that our computation of the budget of a temperate beach-dune system includes the variable of sedimentation decrease due to the declining abundance of calcifying algae. The proposed model concerning the future evolution of the system was also considered in relation to the adaptation of the beach-dune system to future sea-level rise. The data come from previously published research by De Falco et al. (2017), including a set of geophysical, petrographic and sedimentological data used to estimate the sediment volume, sediment composition and long-term sediment budget of the beach-dune system as a whole.

2. Impact of ocean acidification on calcifying algae

The majority of studies on OA focus on its impact on marine ecosystems (Byrne et al., 2011, Koch et al., 2013). OA poses a risk to marine species worldwide, and forecasting the ecological impacts of acidification is a high priority.

Indeed, the argument is widely debated, and although responses to OA may vary among taxonomic groups depending on their sensitivity (Duarte et al. 2013;; Hendrix et al. 2015), the scientific community agrees that calcifying organisms may be the most severely impacted taxonomic group (Gattuso et al., 2015).

Weakening of calcified structures and reduced calcification are expected and have been documented (Orr et al. 2005; Basso 2012; Gattuso et al. 2015; Zunino et al. 2017). Several studies (Hall Spencer et al. 2008; Martin et al. 2008; Basso 2012; Donnarumma et al. 2015; Cox et al. 2015) have demonstrated the negative impact of OA on calcifying algae. Many of these studies have sought to simulate the effects of OA on the epiphytic assemblages of *P. oceanica* leaves. Some have simulated the effect of OA by using natural gradients of pH values in the vicinity of CO_2 vents (Hall Spencer et al. 2008; Donnarumma et al. 2015), while others have involved controlled laboratory environments (Cox et al. 2015). In both cases, a fall in pH from the current value (pH 8.1) to an acidified value (pH 7.6-7.7) was found to result in a drastic reduction (more than 50%) in the leaf coverage of calcifying epiphytes, and encrusting calcareous algae in particular. Table 1 shows the state of the art concerning evidence of the impact of OA on calcifying algae described in peer-reviewed studies conducted in the field in the Mediterranean Sea or in acidified aquaria along decreasing pH gradients. The results of those studies show that acidification has a major impact on the epiphytic compartment of *P. oceanica* meadows and on rocky algal communities. Within those communities, calcareous algae are the most severely impacted. Declines ranging from 20% to 100% of the initial abundance were observed for both *P. oceanica* epiphytes and shallow rocky algal communities. Recently, the effect of acidification on Mediterranean benthic organisms was estimated by a meta analysis of 41 published papers carried out by Zunino et al. (2017). The study considered a sequence of experiments, in situ and in the laboratory, to investigate the impact of OA on Mediterranean benthic organisms. A decrease of about 79%, in terms of the abundance of calcifying algae, was found to result from a reduction of pH to 7.7.

3. Study Site

The study area is located in the bay of San Giovanni, on the Sinis Peninsula, western Sardinia (western Mediterranean). Situated between Cape Seu and Cape San Marco, the bay is about 4 km wide (Fig. 1).

San Giovanni Bay has been studied since the early 2000s in order to determine trends in the shoreline and beach morphology, the distribution of biogenic carbonate and siliciclastic sediments and the morphodynamic state of the beach (De Falco et al., 2017 and references cited therein) This system can be seen as a model for mixed and carbonate temperate beaches because it is far from any inland sources of terrigenous sediments and the major sources of sediment are carbonate factories (*P. oceanica* meadows and shallow rocky outcrops covered by photophilic algae) located on the inner continental shelf (De Falco et al. 2017).

De Falco et al. (2017) subdivided the system into three compartments: dunes, subaerial beach and coastal wedge (Fig. 1). Bioclastic sands predominate in the dunes and coastal wedge sediments ($CaCO_3$ 75±12% and 67±11% respectively), whereas the subaerial beach sediments are mixed ($CaCO_3$ 44±18%) (De Falco et al. 2017).

The same authors estimated the volume, mass and deposition rate of Modern Bioclastic Grains (MBGs) in each compartment of the system. MBGs originate from the carbonate factory of the infralittoral zone. The grains are slightly abraded, light grey to buff-coloured skeletal particles. Some of them show (i) lack of brightness, (ii) rounding of skeletal edges and (iii) lack of well-defined fine-scale skeletal surface structures. Some of the grains are also bioclasts that show little or no sign of alteration or reworking (from De Falco et al. 2017).

The various datasets are available from De Falco et al. (2017) and the supplementary materials (see http://sk.oristano.iamc.cnr.it/maps/285).

Table 2 quantifies the sediment mass and MBGs (as a percentage of the total and mass) in the San Giovanni beach-dune system. Furthermore, the deposition rate of MBGs was calculated as the total mass deposited on the system over the time span of sediment deposition.

The most abundant taxonomic groups in the MBGs are molluscs and calcifying algae, followed by bryozoans, benthic foraminifera, echinoids and brachiopods The sedimentation deposition rate of MBGs was ~7,000±1000 tons $cent^{-1}$ on dunes, ~300 ± 100 tons $cent^{-1}$ on the subaerial beach and ~38,000 ± 5000 tons $cent^{-1}$ on the coastal wedge (De Falco et al., 2017).

4. Methods

Modern Bioclastic Grains are made up of calcite and micrite particles derived from six taxonomic groups: molluscs (bivalves and gastropods), calcareous algae (rhodophytes), benthic foraminifers, echinoids, bryozoans and brachiopods (Supplementary Materials S2 in De Falco et al. 2017). Six distribution maps for each taxonomic group were drawn.

All contour maps were obtained with the “Surfer” Surface Mapping System supplied by Golden Software©. The interpolation algorithm used was Point Kriging, which estimates the values of the points at the grid nodes.

4.1 MBG sediment budget model and impact of OA

The distribution of MBGs in each compartment was calculated, together with the mass of sediment produced by each taxonomic group for each compartment:

$M_{tax.group} = \%_{tax.group}\ M_{comp}$

where $M_{tax.group}$ is the MBG mass (tons) composed of six taxonomic groups in each compartment

M_{comp} is the MBG mass (tons) in each compartment and

$\%_{tax.group}$ is the percentage of each compartment accounted for by each taxonomic group.

Therefore we estimated the sediment deposition rate for each taxonomic group in each compartment:

$Dr_{tax.group} = M_{taxgroup}/T_{dep}$

where $Dr_{tax.group}$ is the deposition rate (tons $cent^{-1}$) for each taxonomic group in each compartment and

T_{dep} is the Time of deposition (43 centuries).

This allowed us to establish the total MBG deposition rate as:

$Tot\ Dr = Dr_{molluscs} + Dr_{Calcifying\ Algae} + Dr_{Benthic\ Foraminifera} + Dr_{Echinoids} + Dr_{Brachiopods} + Dr_{Bryozoans}$

The impact of OA on the sediment budget of the San Giovanni system was then simulated. We assumed that in carbonate factories, OA mainly affects the abundance of calcifying algae. Consequently we estimated the decrease in the contribution of calcifying algae to MBGs in relation to the OA envisaged for the Mediterranean Sea, considering that the projected decrease in the abundance of calcifying algae calculated by Zunino et al. (2017) for the Mediterranean Sea is 79%. Consequently, we evaluated an equivalent reduction in the deposition rate of the sediment produced by calcifying algae in an acidified scenario, assuming a decrease of 79% in the present deposition rate. Thus:

$Dr_{Calcifying\ Algae\ (acid)} = 0.21 Dr_{Calcifying\ Algae}$

$Tot\ Dr_{acid} = Dr_{molluscs} + Dr_{Calcifying\ Algae\ acid} + Dr_{Benthic\ Foraminifera} + Dr_{Echinoids} + Dr_{Brachiopods} + Dr_{Bryozoans}$

where $Tot\ Dr_{acid}$ is the total deposition rate in the acidified scenario (pH from 8.1 to 7.7).

5. Results

5.1 Distribution of MBGs in system compartments

The mass of sediment produced by each taxonomic group for each compartment is shown in Table 3.

Generally speaking, molluscs and calcifying algae were the most important taxonomic groups contributing to MBGs as a whole (673,000 tons and 519,000 tons respectively). In the dunes, calcifying algae were the most abundant group (130,000 tons), followed by molluscs (55,000 tons). On the other hand, the contribution of molluscs to the coastal wedge sediment mass was about double the contribution of calcifying algae (615,000 tons and 382,000 tons respectively). In the same compartment, the other taxonomic groups showed lower abundances: 250,000 tons for bryozoans, 200,000 tons for benthic foraminifera, 116,000 for echinoids and 100,000 tons for brachiopods.

Spatial distribution maps of the percentages accounted for by the various taxonomic groups were drawn in order to assess the importance of each group to the sediment budget of each compartment (Fig. 2).

In each compartment, the MBGs were mainly composed of molluscs and calcifying algae. Molluscs were most abundant in the coastal wedge, where this taxonomic group accounted for more than ≥40% of MBGs in some cases. In the dunes and the subaerial beach, molluscs were less abundant and calcifying algae more so (≥40%). Indeed, calcifying algae were the most abundant taxonomic group in the dunes and subaerial beach. Among the other taxonomic groups, benthic foraminifera, echinoids and brachiopods reached their maximum percentages (~20%) in the coastal wedge; while the maximum percentage of bryozoans (~30%) was recorded in the subaerial beach and dunes.

5.2 Effects of OA on the carbonate sediment budget

Table 4 shows the deposition rate (tons $cent^{-1}$) of carbonate derived from each taxonomic group in each compartment. The projected deposition rate for calcifying algae in acidified seawater conditions is also shown. This value (2535 tons $cent^{-1}$) is equivalent to 21% of the present rate (12,070 tons $cent^{-1}$), following the estimate reported by Zunino et al. (2017).

The overall reduction in the deposition rate did not follow the same pattern in each compartment. A decrease of about 36% (from 6,628 to 4,240 tons $cent^{-1}$) was estimated for the dunes and about 40% for the subaerial beach (from 326 to 197 tons $cent^{-1}$). On the other hand, on the coastal wedge the deposition rate of calcifying algae was estimated to fall by about 19% (from 38,674 to 31,093 tons $cent^{-1}$). The different reductions in deposition rates among compartments was related to their initial sediment composition. Indeed in the dunes and subaerial beach, bioclasts produced by calcifying algae were more abundant than the other taxonomic groups (see Fig. 2a-e).

6. Discussion

The majority of studies on the effects of OA have sought to evaluate and determine the impact of this phenomenon on marine ecosystems (Kroeker et al. 2010; Byrne et al. 2011; Harvey et al. 2013). This is because the pH of sea water is expected to fall by about 0.1-0.4 by the end of this century (Gattuso et al. 2015). This process is likely to affect calcifying organisms and calcifying algae in particular (Orr et al. 2005; Fabry et al. 2008; Koch et al. 2013; Zunino et al. 2017).

In our study we attempt, for the first time, to evaluate the effect of OA on the sediment budget of a temperate mixed carbonate-based beach-dune system. The impact of OA on the carbonate sediment budget was estimated with reference to the falling sediment deposition rates resulting from the projected decrease in calcifying algae abundance caused by OA. In the Mediterranean Sea, significant fractions of the carbonate sediments provided by marine ecosystems to the coastal area originate from calcifying algae. This taxonomic group represents a significant proportion of the epiphytes of *P. oceanica* leaves and widely colonises shallow rocky outcrops in the upper shoreface (Canals and Ballesteros 1997, Cebrian et al. 2000, Asnaghi et al. 2015, Piazzi et al. 2016). Several experiments have demonstrated that a reduction in pH from 8.1 to 7.7 produces a drastic reduction in calcifying algae abundance (Hall Spencer et al. 2008; Asnaghi et al. 2013; Cox et al. 2015). Recently this reduction was estimated to be about 79% (Zunino et al. 2017). We assumed that such a decline in the taxonomic group would be reflected equally in the sediment deposition rate, although our approach could be considered conservative. Indeed, when estimating the total deposition rate of MBGs in an acidified scenario we did not consider the negative impact that OA could have on the abundance, survival or calcification of several other taxonomic groups, such as molluscs, bryozoans and echinoids (Lombardi et al. 2011; Zunino et al. 2017).

In the San Giovanni beach-dunes system, the present total deposition rate of MBGs is about 46,000 tons cent^{-1} (calculated for a time span of 43 centuries): ~7000 tons cent^{-1} on the dunes; ~ 300 tons cent^{-1} on the subaerial beach and ~39,000 tons cent^{-1} on the coastal wedge. Taking account of the acidified scenario proposed by Zunino et al. (2017), the total deposition rate may decrease by ~20% (from 45,628 to 36,093 tons cent^{-1}): ~36% on the dunes (from 6,628 to 4,240 tons cent^{-1}), ~40% on the subaerial beach (from 326 to 197 tons cent^{-1}) and ~19% on the coastal wedge (from 38,674 to 31,656 tons cent^{-1}). The different percentages reflect the different distribution of bioclastic fragments produced by calcifying algae on the dunes, subaerial beach and coastal wedge (Fig. 2b).

In the Mediterranean Sea, the material produced in carbonate factories is of primary importance for the beach and dune sediment budget (Gomez-Pujol et al. 2013; De Falco et al. 2014; De Falco et al. 2017). The San Giovanni beach-dune system is one such system and can be considered as a model for the simulation of the impact of OA on carbonate sediment budgets.

In this environment, the reduction in bioclastic sediment may affect the sediment budgets of the beach and dunes as well as their morphodynamic behaviours. In the San Giovanni system this reduction will particularly affect the subaerial beach and the dunes. Furthermore, the decreasing quantity of sediment delivered to the coastal system by carbonate factories could be amplified by local and global anthropogenic impacts. The shrinking of *P. oceanica* meadows has been described for several coastal areas of the Mediterranean Sea and is related to anthropogenic impacts (Vacchi et al., 2017). The decrease in sediment supply can also affect the adaptation of these systems to sea level rise (SLR). Indeed, the rate of sediment supply is one of the main factors that determine the response of beach-dune systems to SLR (Short et al. 1999). Figure 3 shows a schematic model of the response of a beach-dune system under the combined effects of OA (reduction of the sediment deposition rate) and SLR (shoreline retreat and a higher run-up).

The reduction of bioclastic sediment input (from 45,628 tons cent^{-1} to 36,093 tons cent^{-1}) due to OA can weaken the system, because a smaller quantity of sediment will be delivered from the carbonate factory to each compartment (Fig 3a,b). Specifically, the biggest falls are seen in the subaerial beach (~40%) and the dunes (~36%) (Fig. 3b). The reduction in sediment supply could amplify the effects of the expected SLR. In our study area, SLR was estimated to be 0.5 m - 1.3 m by the end of this century (De Falco et al. 2015; Antonioli et al. 2017). This may entail shoreline retreat and a higher maximum wave run-up that will promote massive dune and beach erosion (Fig 3c). At present, during the most intense storms, the maximum run-up in the San Giovanni system ranges between 3 and 4 m. This causes marked dune and beach erosion, with a beach recovery time of about one year (Simeone et al., 2014). Hence, taking account of SLR, the higher maximum run-up will cause more severe erosion of the dunes and subaerial beach, leading to a transfer of sediment from the beach-dune system towards the coastal wedge (Fig. 3c).

In the long term, OA could play a primary role in controlling the response of this system to SLR in terms of the availability of sediment. Indeed, the dwindling supply of carbonate sediments to the system may affect the time required by the system to adapt to SLR more heavily than a coastal system where sediment supply is mainly composed of terrigenous sediment provided by rivers or other terrigenous sediment sources.

7. Conclusions

The main considerations regarding the effects of ocean acidification on shallow coastal sites to emerge from this preliminary study are the following:

1. In our study we attempt to evaluate the effect of OA on the sediment budget of a temperate mixed beach-dune system for the first time. The previous literature on the effect of OA mainly sought to evaluate and determine the impact of the phenomenon on the marine ecosystems.

2. OA can affect the production of MBGs by carbonate factories. We estimated a decrease in the supply of sediment to the beach-dune system (the MGB deposition rate) of ~20% (from 45,628 to 36,093 tons cent^{-1}).
3. The sediment budget was assessed by means of a conservative approach. Indeed, the reduction in the MBG deposition rate was calculated by simulating the effects of OA on calcifying algae alone, without considering other taxonomic groups in the San Giovanni beach-dune system. The lower deposition rate arising from the decrease in calcifying algae has a particularly strong effect on the dunes (from 6,628 to 4,240 tons cent^{-1}, a ~36% loss) and the subaerial beach (from 326 to 197 tons cent^{-1}, a ~40% loss). In the coastal wedge the decrease in sediment supply (from 38,674 to 31,656 tons cent^{-1}) was ~19%.
4. The decrease in sediment supply, as well as the shrinking of the carbonate factories caused by local and global anthropogenic impact, can affect the speed with which this system adapts to SLR, leading to an increase in wave run-up and possibly intensifying dune and beach erosion and shoreline retreat.

Figure captions

Fig 1 Geomorphological map of the study area. Location of sampling points along the Sinis Peninsula in the Bay of San Giovanni and distribution of *Posidonia oceanica* meadows growing on hard ground and sedimentary substrates.

Fig 2 Spatial distribution of taxonomic groups in the San Giovanni system, showing their percentage of the total. a) Molluscs; b) Calcifying Algae; c) Benthic Foraminifera; d) Echinoids; e) Brachiopods; f) Bryozoans; green line: coastal wedge limit.

Fig 3 Evolutionary model of the San Giovanni beach dune system from the present to 2100. a) current conditions: light blue arrow: maximum run-up; b) effect of acidification on the carbonate sediment budget. The values in brackets are the estimated falls in deposition rates; c) SLR and effect of acidification combined. Light blue arrow: maximum run-up under current conditions, dark blue arrow: maximum run-up with the expected SLR.

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Figure1

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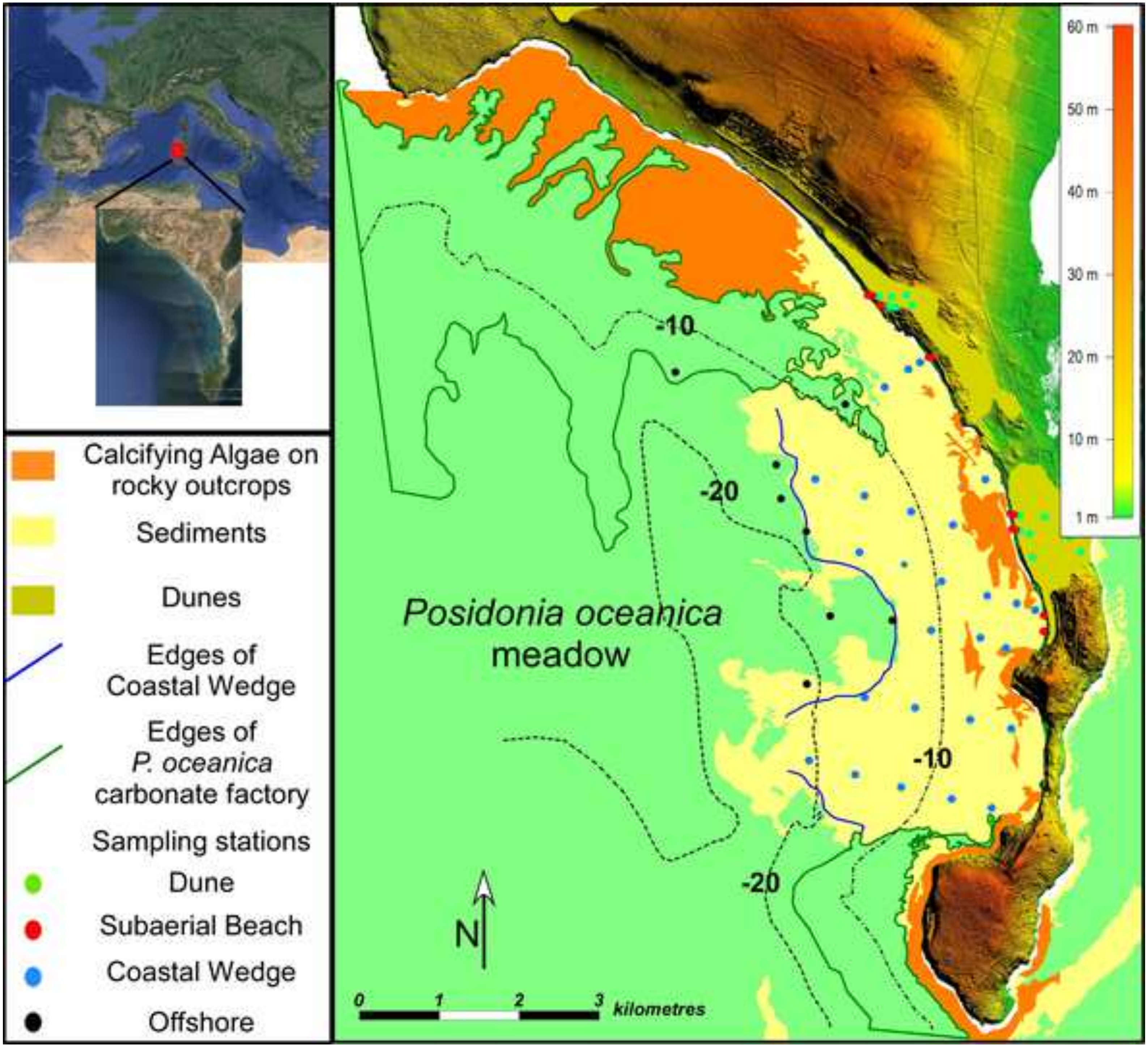

Figure2

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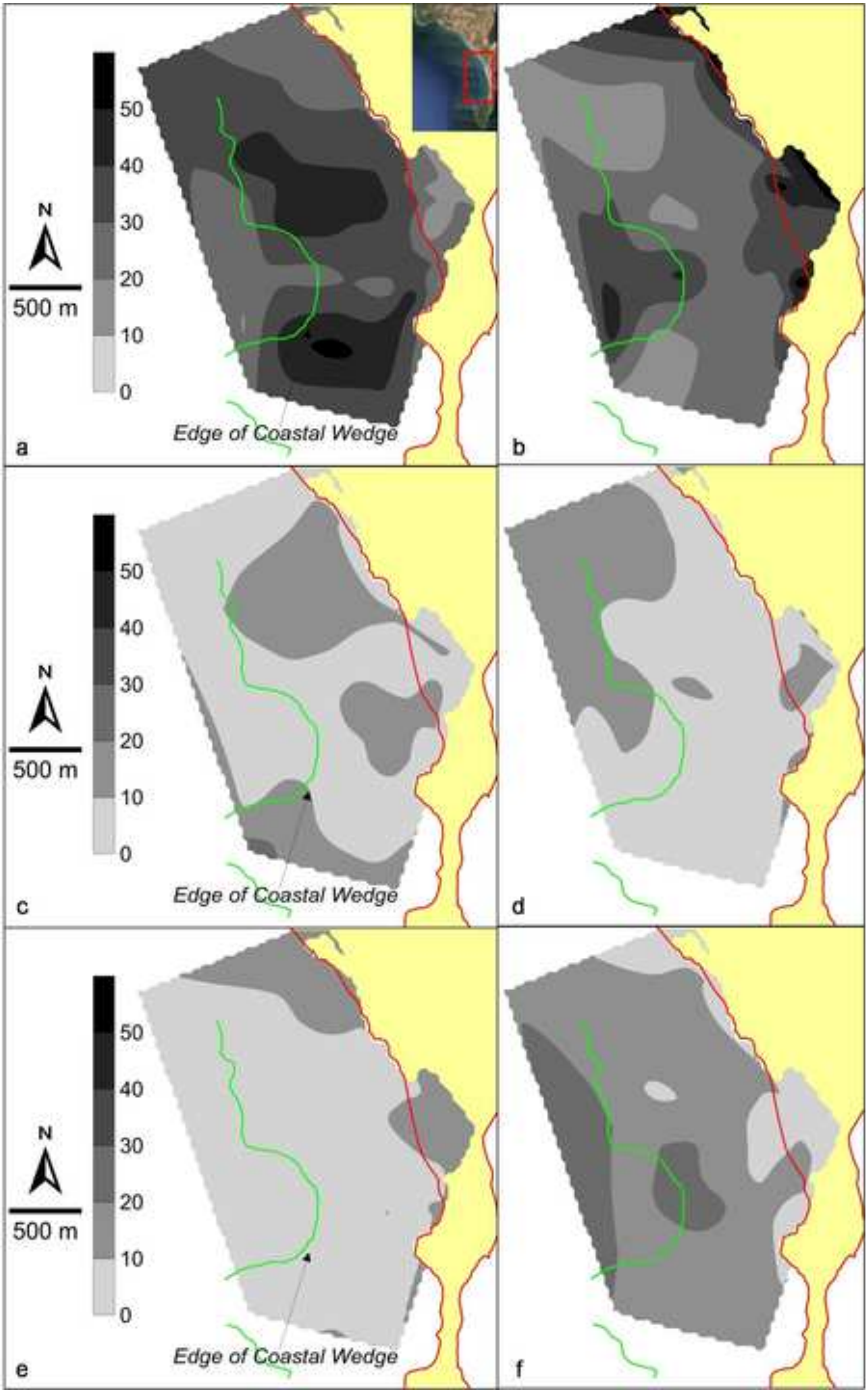

Figure3

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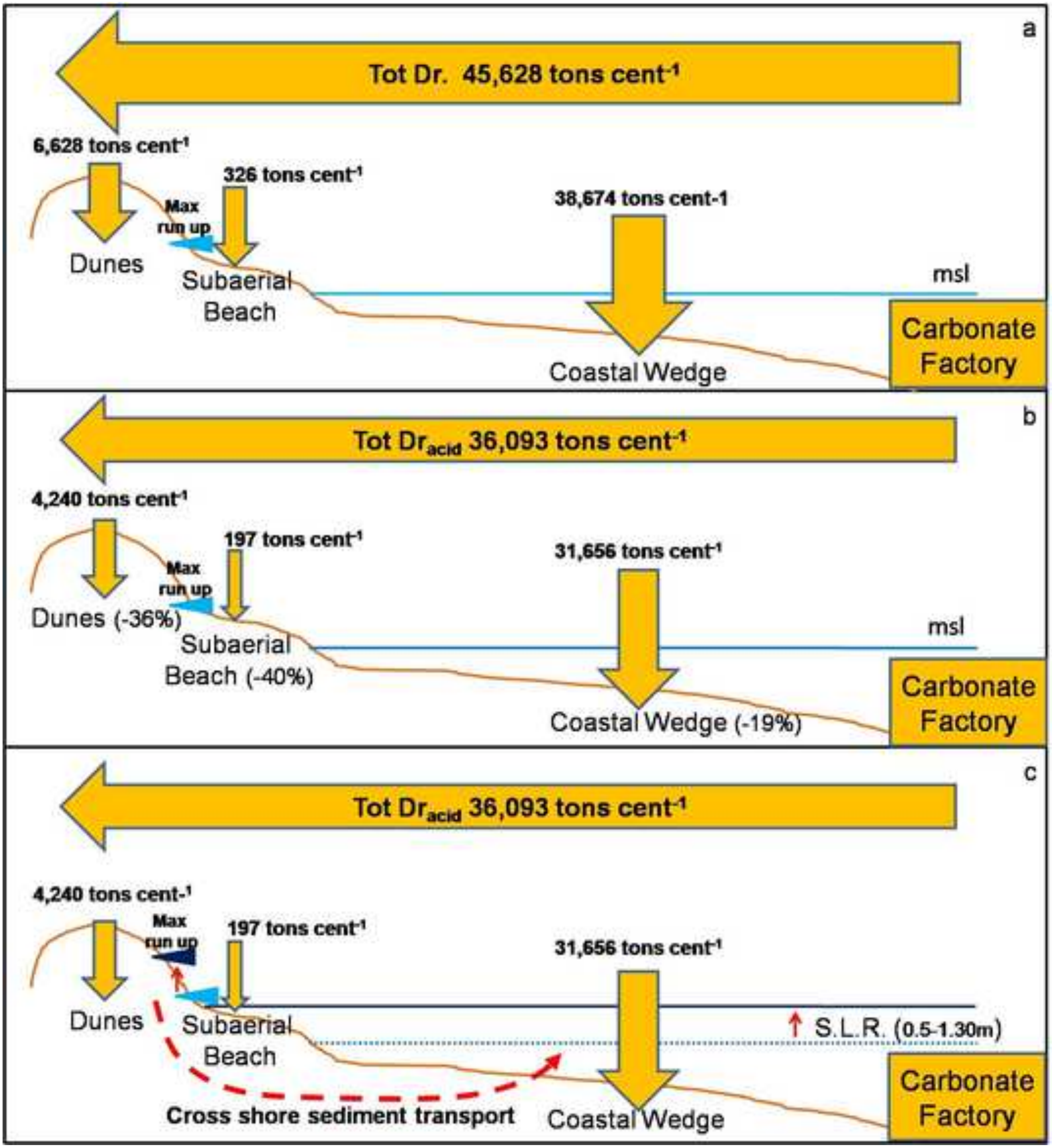

Table 1 List of studies of the impact of OA on calcifying algae and other marine organisms (modified from Basso 2012).

Reference	Manipulation	Site	Results
Hall Spencer et al. 2008	Naturally acidified seawater	Mediterranean Sea	Shift from dominant corallines to fleshy algae with pH 7.8. Reduction of about 60% in the amount of $CaCO_3$ produced by epiphytes of *P. oceanica*
Martin et al. 2008	Naturally acidified seawater	Mediterranean Sea	Reductions in $CaCO_3$ from 41 mg to 11 mg, and in corallines from 69% to 29%, at pH 8
Martin and Gattuso 2009	Acidified and warmed aquaria	Mediterranean Sea	Calcification increasing up to 660 ppm of CO_2 in the atmosphere and decreasing thereafter
Porzio et al. 2011	Naturally acidified seawater	Mediterranean Sea	Calcitic species significantly reduced (-25%) at pH 7.8
Asnaghi et al. 2013	Acidified and warmed aquaria	Mediterranean Sea	Significant reduction (about 50% weight loss) in calcifying algae at pH 7.8
Martin et al. 2013	Acidified and warmed aquaria	Mediterranean Sea	Calcification shows different responses depending on the season
Baggini et al. 2014	Naturally acidified seawater	Mediterranean Sea	Strong fall in abundance of calcifying algae in autumn at pH 7.7
Campbell et al. 2014	Acidified and enriched open water	Florida Keys	Reduction of about 20% in epiphytic communities (CCA)
Donnarumma et al. 2015	Naturally acidified seawater	Mediterranean Sea	Reduction of about 70% in CCA (all species) at low pH (7.2)
Cox et al. 2015	Acidified aquaria	Mediterranean Sea	Reduction of 50% in the carbonate content of epiphytes at low pH (7.3), reduction of about 50% in epiphyte coverage at pH 7.7, reduction in $CaCO_3$ of about 20% (non-significant) at pH 7.7.
Nogueria et al. 2017	Naturally acidified seawater	Mediterranean Sea	Decrease in calcareous epiphytes observed in only one of the impacted sites, not both.

Table2

Table 2 Total sediment mass in the three compartments. Mass of MBGs and percentage of total for each compartment. Total deposition rate of MBGs on the San Giovanni System (modified from De Falco et al. 2017).

Variable		**unit**	**value**	**Method**
Total sediment mass	Dunes	tons	619,000±88,000	
	Subaerial beach	tons	41,000±15,000	
	Coastal wedge	tons	3,137,000±301,000	
	Total	tons	3,797,000±404,000	
Modern Bioclastic sediments as a percentage of total sediments	Dunes	%	46	Petrographic analysis
	Subaerial beach	%	33	
	Coastal wedge	%	53	
Mass of Modern Bioclastic Grains	Dunes	tons	285,000±41,000	Petrographic analysis
	Subaerial beach	tons	14,000±5,000	
	Coastal wedge	tons	1,663,000±160,000	
	Total	tons	1,962,000±205,000	
Time span of sediment deposition		centuries	43	Calibrated ^{14}C dating
Deposition Rate		tons $century^{-1}$	45600±5000	

Table3

Table 3 Total mass of MBGs in each compartment and mass of sediment produced by each taxonomic group (modified from De Falco et al (2017).

Compartments	Total mass of MBGs (tons)	$M_{tax.group}$ (tons)					
		Molluscs	Calcifying Algae	Benthic Foraminifera	Echinoids	Brachiopods	Bryozoans
Dunes	285,000±41,000	55,000±7,000	130,000±18,200	21,000±3,000	27,000±3800	38,000±5200	14,000±2000
Subaerial beach	14,000±5,000	3,000 ±1,000	7,000±2,500	1,000±400	1,000±400	2,000±800	0
Coastal wedge	1,663,000±160,000	615,000±61,000	382,000±38,000	200,000±20,000	116,000±12,000	100,000±10,000	250,000±25,000
Total	**1,961,000±205,000**	**673,000±74,000**	**519,000±57,100**	**222,000±24,400**	**144,000±15,800**	**140,000±15,400**	**264,000±29,000**

Table4

Table 4 Sediment deposition rate of each taxonomic group in each compartment. In bold the predicted values for Calcifying Algae sediment deposition rates in response to a decrease in pH.

Compartments	Tot Dr MBGs (tons cent^{-1})	Tot Dr MBGs (at low pH) (tons cent^{-1})	$Dr_{tax.group}$ (tons cent^{-1})						
			Molluscs	Calcifying Algae	Calcifying Algae (at low pH)	Benthic Foraminifera	Echinoids	Brachiopods	Bryozoans
Dunes	6,628	4,240	1,279	3,023	**635**	488	628	884	326
Subaerial beach	326	197	70	163	**34**	23	23	47	0
Coastal wedge	38,674	31,656	14,302	8,884	**1,866**	4,651	2,698	2,326	5,814
Total	45,628	**36,093**	15,651	12,070	**2,535**	5,163	3,349	3,256	6,140