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Future seagrass beds: Can increased productivity lead to increased carbon storage?

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ABSTRACT

While carbon capture and storage (CCS) is increasingly recognised as technologically possible, recent evidence from deep-sea CCS activities suggests that leakage from reservoirs may result in highly CO_2 impacted biological communities. In contrast, shallow marine waters have higher primary productivity which may partially mitigate this leakage. We used natural CO_2 seeps in shallow marine waters to assess if increased benthic primary productivity could capture and store CO_2 leakage in areas targeted for CCS. We found that the productivity of seagrass communities (*in situ*, using natural CO_2 seeps) and two individual species (*ex situ*, *Cymodocea serrulata* and *Halophila ovalis*) increased with CO_2 concentration, but only species with dense belowground biomass increased in abundance (e.g. *C. serrulata*). Importantly, the ratio of below:above ground biomass of seagrass communities increased fivefold, making seagrass good candidates to partially mitigate CO_2 leakage from sub-seabed reservoirs, since they form carbon sinks that can be buried for millennia.

1. Introduction

Global emissions of CO_2 are predicted to accelerate over the coming decades (Meehl et al., 2007). As ~30% of these emissions are absorbed into the world's marine waters (Feely et al., 2004; Doney, 2010), there is increasing recognition that CO_2 is a marine pollutant, defined by the United Nations Convention on the Law of the Seas (UNCLOSs) as "the introduction by man, directly or indirectly, of substances or energy into the marine environment, including estuaries, which results or is likely to result in such deleterious effects as harm to living resources and marine life etc." (UNCLOS, 1982). Indeed, there is clear evidence that marine ecosystems face three combined pressures due to CO_2 emissions, those of warming, oxygen loss and ocean acidification (Connell and Russell, 2010; Rodolfo-Metalpa et al., 2011). This recognition has focussed urgent attention on mitigation strategies to reduce the impact of increasing concentrations of carbon dioxide. One such strategy is carbon capture and storage (CCS).

Once carbon dioxide has been captured from either the atmosphere or, more likely, as it is being emitted by industrial point sources (such as coal-fired power stations), one of the strategies already in use and with planned expansion is injection of the captured carbon into geological formations. Indeed, storage for millennia is one of the criteria for categorising a carbon storage technique as being deemed "successful". One of the potential problems with this geological injection is that a percentage of the injected CO_2 could seep from storage reservoirs back into the environment, yet estimates of potential leakage are difficult because of the number of factors involved (e.g. location of fractures in the rock bed). Seabed leakage of CO_2 could lead to two potential problems; (1) overestimation of the mitigation effectiveness because this carbon is released back into the environment, and (2) adverse impacts on benthic ecosystems (as demonstrated in coral reef and temperate coastal systems; Hall-Spencer et al., 2008; Fabricius et al., 2011). In some locations and cases, however, photosynthetic organisms may be able to capture some of this leakage, not only reducing the overestimation of CO_2 mitigation but also limiting the extent of further biological impacts of escaping sequestered CO_2 (e.g. the Blue Carbon Strategy; Herr et al., 2012).

Subtidal vegetation is receiving increasing attention as possible natural CCS ecosystems in shallow waters. Seagrass habitats are able to store carbon as some species have root mats which are buried for centuries to millennia (Romero et al., 1994; Mateo et al., 1997). While their slow growth under current environmental conditions means that seagrasses will have a relatively small effect on mitigating global CO_2 emissions (e.g. they may only capture ~0.1% of emissions globally; Irving et al., 2011), they may complement geological CCS activities by capturing a proportion of seabed leaks as well as absorbing carbon that enters surface waters from the atmosphere. This role would, however, be contingent on both their ability to survive highly carbonised conditions and become

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increasingly productive in the presence of elevated CO_2 at leakage sites (e.g. Vizzini et al., 2010).

Seagrass are generally considered to be CO_2 limited and photosynthetically inefficient in seawater (Beer and Koch, 1996; Beardall et al., 1998; Palacios and Zimmerman, 2007) because they are inefficient in utilising bicarbonate (HCO_3), which forms the majority of dissolved inorganic carbon, for photosynthesis. As a result, many species will increase their use of CO_2 when it is available (Beer and Koch, 1996) and are predicted to increase growth rates and biomass under future CO_2 conditions (Palacios and Zimmerman, 2007; Hall-Spencer et al., 2008; Martin et al., 2008). Indeed, it seems that they could be one of the true "winners", as has been seen in locations of elevated CO_2 conditions (Hall-Spencer et al., 2008; Martin et al., 2008; Fabricius et al., 2011). In this study, we used three separate tropical volcanic CO_2 seeps in Papua New Guinea as natural "laboratories" to assess whether seagrass productivity and biomass increase in response to localised elevation of CO_2 concentrations as a proxy for what may occur near locations of CCS activities. These seeps have recently been used to test hypotheses about the structure of marine communities under future conditions, but they also provide a valuable opportunity to test how changes in productivity of these systems may enhance carbon capture at geographically localised extreme pH (e.g. <7). To understand whether biological capture of CO_2 may provide a solution to CO_2 emissions, we tested the hypothesis that seagrass productivity and biomass increase in response to localised elevation of CO_2 concentrations at volcanic seeps in Papua New Guinea. This provides the most accurate mimic for the conditions occurring at CCS leakage sites, and thus paints an ecologically realistic picture of the ecosystem response specifically to CCS leakage.

2. Materials and methods

2.1. Study sites

Seagrass was sampled along the shallow (0.1–2.0 m, below lowest astronomic tide) shore of three sites, separated by >7 km, in Milne Bay Province, Papua New Guinea (9°45′ S, 150°50′ E): Dobu on the northern coast of Dobu Island, Esa'Ala and Upa-Upasina along the north-eastern and north-western coast of Normanby Island, respectively (see maps in Fabricius et al., 2011), in April 2011. Tidal range in the region is <1 m. Volcanic CO_2 seeps acidify the seawater and increase its DIC availability, with seeping being most intense near the shore at <0.5 m depth. Two sampling stations of intermediate to low mean pH were selected at both Esa'Ala and Upa-Upasina and extremely low pH at Dobu and Esa'Ala. Reference stations with normal, relatively stable pH were chosen several hundred meters away from the seeps at comparable geophysical settings.

At all sites 20 quadrats (50 cm × 50 cm) were placed haphazardly within 15 × 3 m survey zones at each station along the CO_2 gradients. Within each quadrat the seagrass shoot density was recorded. Above-ground biomass of *Cymodocea serrulata* was cut from four quadrats per site. Samples were placed in individual bags, sun-dried for 48 h and then oven dried at 60 °C for a further 48 h immediately on returning to the laboratory.

In addition, on a previous trip (6–15 August 2010) to Esa'Ala, both above and below ground biomass of all seagrass species present in 15 quadrats was quantified in 15 plots consisting of both haphazardly placed 20 cm × 20 cm quadrats and 15.5 cm diameter cylindrical incubation chambers. Photosynthesis and respiration were measured on August 15 at ~1:00 pm using replicate underwater incubation chambers to assess oxygen evolution over four plots of mixed seagrass communities, both in and outside of a high CO_2 area. Winkler titrations on before and after water samples were used to measure photosynthesis by oxygen evolution. Chambers deployed were exposed to normal sunlight (mean 327 $\mu E\ m^{-2}\ s^{-1}$) for ~30 min between the hours of 1:00 and 2:00 pm at a depth of 1–1.5 m. Circulation was continuously provided by 75 ml bulbs pumped every 3 s to provide water movement within the chambers. Tests performed with dye showed that water was circulated within the chamber within 30 s. Plots were then harvested to quantify the amount of epibionts, the shoot density and the above and below-ground biomass of all species present. All quadrats and chamber contents were collected and returned to the boat to allow for detailed quantification. Shoots were counted prior to drying for 24 h in the boat engine room and then shipped back to the lab. Below-ground biomass from high CO_2 sites at Esa'Ala was extremely dense, forming large mats of interwoven live and dead rhizomes. For these samples, additional rinsing was performed in the field and in the lab on dried and separated samples which allowed for the dried below-ground biomass to stay on the surface of the rinse water and the sinking of any remaining sediment in the sample. Final drying was performed in a drying oven at 65 °C until a steady mass was obtained.

2.2. Carbonate chemistry measurements

A calibrated pH metre was used to measure pH (NBS scale) at each sampling station (Hach or Oakton, two-point calibration, with readings cross-checked against a Tris buffer seawater standard, A.G. Dickson, Scripps Institute of Oceanography, Dixon, Batch 5). Temperature and salinity were also measured alongside each pH reading. Mean pH (calculated via back-transformed hydrogen ion concentrations) were calculated for each station (25th and 29th April 2011, $n = 6–9$). Total alkalinity data for Papua New Guinea used in calculations of the carbon system parameters were taken from Fabricius et al., (2011). Carbon chemistry parameters were derived using the CO2SYS package (Lewis and Wallace, 1998).

2.3. Seagrass productivity and respiration incubations

Productivity and respiration incubations were carried out onboard the research vessel for both *C. serrulata* and *Halophila ovalis* at Upa-Upasina in April 2011. Incubations were done using 2 cm sections of leaf for *C. serrulata* and entire leaves for *H. ovalis*. Leaves were cut from their stems and placed in mesh bags at their collection station overnight to ensure that respiration was not over-estimated due to stress responses. Leaves were then collected and placed in sealed 20 ml glass vials which contained water from either reference or high pCO_2 water from the collection stations ($n = 6$ leaves per species per station for both productivity and respiration). An additional six vials for each treatment were filled with seawater only as blank controls for both respiration and productivity incubations. Prior to sealing vials, concentration of dissolved oxygen was measured using a luminescent dissolved oxygen optode (HQ10-HQ20 Meters HACH, Hydrolab oxygenmeter, USA). This was repeated at the end of the incubations. Respiration was calculated by subtracting final from initial oxygen concentration. Oxygen production was calculated by subtracting both average oxygen concentration following the respiration incubation and changes in final blank values from each final oxygen reading. All respiration and productivity was standardised to g dry mass of the seagrass leaves. To maintain stable water temperatures (30 °C), vials were placed in 40 L tubs with constant seawater flow-through for the duration of incubations. The water flow in the tubs ensured continual movement and rotation of the experimental vials so that leaves moved inside the vials, stirring the water inside the vials. Respiration incubations were done in blackened tubs, productivity in open tubs, for approximately 2 h between 11:0 am and 3:00 pm. It is important to note that