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Optimising reef-scale CO₂ removal by seaweed to buffer ocean acidification

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Abstract

The equilibration of rising atmospheric CO_2 with the ocean is lowering pH in tropical waters by about 0.01 every decade. Coral reefs and the ecosystems they support are regarded as one of the most vulnerable ecosystems to ocean acidification, threatening their long-term viability. In response to this threat, different strategies for buffering the impact of ocean acidification have been proposed. As the pH experienced by individual corals on a natural reef system depends on many processes over different time scales, the efficacy of these buffering strategies remains largely unknown. Here we assess the feasibility and potential efficacy of a reef-scale (a few kilometers) carbon removal strategy, through the addition of seaweed (fleshy multicellular algae) farms within the Great Barrier Reef at the Heron Island reef. First, using diagnostic time-dependent age tracers in a hydrodynamic model, we determine the optimal location and size of the seaweed farm. Secondly, we analytically calculate the optimal density of the seaweed and harvesting strategy, finding, for the seaweed growth parameters used, a biomass of 42 g N m⁻² with a harvesting rate of up 3.2 g N m⁻² d⁻¹ maximises the carbon sequestration and removal. Numerical experiments show that an optimally located 1.9 km² farm and optimally harvested seaweed (removing biomass above 42 g N m⁻² every 7 d) increased aragonite saturation by 0.1 over 24 km² of the Heron Island reef. Thus, the most effective seaweed farm can only delay the impacts of global ocean acidification at the reef scale by 7–21 years, depending on future global carbon emissions. Our results highlight that only a kilometer-scale farm can partially mitigate global ocean acidification for a particular reef.

1. Introduction

The ocean is becoming more acidic as anthropogenic carbon dioxide (CO_2) is taken up and sequestered by the ocean. The pH of the surface oceans has decreased by approximately 0.1 pH units over the last century, equivalent to a 25% decrease in hydrogen ion concentration (Pörtner 2014). Under a doubling of atmospheric CO_2 concentration, coral calcification rates are projected to decline by more than 30%.

As atmospheric CO_2 concentrations continue to rise at their current rate, long-term viability of coral reefs, the habitats they support and ecosystem services they provide will be impacted (Fabricius *et al* 2011).

One of the consequences of ocean acidification is a decrease in dissolved carbonate ion concentration,

 $[CO_3^{2-}]$. Calcifying organisms utilise CO_3^{2-} ions in conjunction with dissolved calcium ions, Ca^{2+} , to produce calcium carbonate (CaCO₃) skeletal materials and shells.

Aragonite is a metastable form of CaCO₃, and the predominant form used by reef building corals (Stanley and Hardie 1998). The aragonite saturation state, Ω_a , is commonly used to describe the ability of corals to calcify (Mucci 1983), and is given by:

$$\Omega_{\rm a} = \frac{[{\rm CO}_3^{2^-}][{\rm Ca}^{2^+}]}{K_{\rm sp}},\tag{1}$$

where K_{sp} is the solubility product constant.

Coral reef ecosystems have the ability to significantly alter the carbon chemistry of the overlying waters (Anthony *et al* 2011, Kleypas *et al* 2011). The





direction of the change (increase or decrease of Ω_a) depends on the benthic community structure, the balance of biogeochemical processes, and the residence time of the water (Anthony *et al* 2013).

Diurnal changes in Ω_a on reefs can be larger than the century-scale shifts predicted for open ocean waters under climate change scenarios (Shaw *et al* 2012, Albright *et al* 2013). This demonstrates the impact that local biogeochemical processes have on the Ω_a experienced by individual corals. Manipulation of these natural processes may provide powerful tools to mitigate the effects of global ocean acidification at the scale of the reef.

Under favourable growing conditions, seaweed build up their biomass by taking up dissolved inorganic carbon $(C_{\rm T})$ during photosynthesis, releasing a smaller fraction through respiration (Duarte et al 2005b), effectively storing carbon. A seaweed community that is grown (net carbon uptake), and harvested (carbon removed from the site), in a farm infrastructure upstream of a reef, will potentially result in a net reduction in the $C_{\rm T}$ of water flowing over the reef, thereby increasing pH and Ω_a (Unsworth et al 2012, Jiang et al 2013). Natural seaweed communities can remove in excess of $3000 \,\mathrm{g \, C \, m^{-2} \, yr^{-1}}$ through net production (Duarte et al 2005a). A parcel of water 1m thick residing for 1 h over such a seaweed community would remove 342 mg C m⁻³, leading to an increase in Ω_a of approximately 0.25. Exisiting seaweed farms have been reported to produce up to $4500 \,\mathrm{g}\,\mathrm{C}\,\mathrm{m}^{-2}$ over a 7 month period (Gao and Mckinley 1994).

As suggested by Unsworth *et al* (2012) (using a natural seagrass habitat) and McLeod *et al* (2013), and verified *in situ* in Florida by Manzello *et al* (2012), the presence of seaweed /seagrass beds upstream of a coral patch could be a viable ocean acidification mitigation strategy. While the concept is appealing in a conceptual framework (Unsworth *et al* 2012), the question of its efficacy when upscaled to a real reef system remains partially unanswered.

Artificially enhancing fleshy macroalgae growth, combined with continuous harvest of the algal biomass could be used in a farm environment for CO_2 sequestration, locally buffering ocean acidification.

In this study, the term seaweed refers to different species of macroscopic, multicellular, marine algae (macroalgae) that live near the seabed (more specifically the two phyla *Chlorophyta* and *Phaeophyta*), and can be farmed. In the case of farming, seagrasses are not as good a candidate, as they must grow in sediment.

The viability of a seaweed farm used as a buffering platform depends on the local circulation that transports and dilutes reduced $C_{\rm T}$ water from the farm across the reef. Furthermore the air–sea exchange of CO₂ acts to reverse the $C_{\rm T}$ perturbation generated by the farm. Thus, the feasibility of seaweed farm mitigation can only be fully assessed using a coupled hydrodynamic, carbon chemistry, seaweed model that captures the interacting physical, chemical and biological processes.

The objective of this study is to determine the optimal location and plant density of a seaweed farm, for the purposes of mitigating the impact of global ocean acidification at the reef-scale, and quantify the effectiveness of the optimally designed farms.

2. Methods

2.1. Design of a seaweed farm for the Heron Island reef

Heron Island reef is located in the southern Great Barrier Reef (GBR), approximatively 10 km long and 2–4 km wide (figure 1). The reef habitat is composed of a mixture of coral and sand. The reef is composed of different zones, the outer reef or forereef with high cover of branching coral, the inner reef flat and sandy zone with low coral cover, and the central lagoon with patchy bommie colonies.

The Heron Island reef was chosen because it has the suitable characteristics, both in term of water flushing rate (from hours to days) and morphology (a lagoon surrounded by a large reef flat), to accommodate a seaweed farm. Additionally, Heron Island reef is the most studied reef on the GBR, with enough local observations to constrain a high resolution hydrodynamic model (Mongin and Baird 2014).

The water circulation is characterised by semidiurnal tides with an average neap-spring tidal range of 1.09–2.28 m. Tidal oscillations fill up and empty the reef flat and lagoon regularly. Wind plays a large role in enhancing water flushing on the reef, reducing in some cases the residence time of the water on the reef to 16 h (Mongin and Baird 2014). At low tide, water depth over a large proportion of the reef flat is 0.3–1 m, the deepest part in the lagoon is 3.5 m.

To be effective, the seaweed farm needs to be located in areas where the water originating from the farm flows onto, and resides on, the reef for a reasonable duration. Additionally, the farm cannot be located on the reef itself, due to damage to the reef and reduced light availability for coral growth. The farm also needed to be located in an area deep enough so that the seaweed are always submerged. The size of the farm should be optimised, to maximise its carbon removal rate inside the reef and minimise its impacts elsewhere.

2.2. Hydrodynamic and carbon chemistry models and set-up

We use the hydrodynamic and chemistry model of Mongin and Baird (2014) that has been calibrated to simulate water movement around Heron Island reef (figure 1). The model has a horizontal resolution of 167 m, a vertical *z*-coordinate scheme with 24 fixed *z*levels, and includes meteorological, tidal and open ocean forcing. A 1 km resolution three-dimensional (3D) hydrodynamic model of the whole GBR region is used for oceanic boundary conditions (Schiller *et al* 2014). Heron Island reef's biogeography can be divided into four types of coral communities, whose distribution has been obtained from Roelfsema *et al* (2002) (figure 1). We define the coral reef ecosystems as the area covered by these communities.

The model is initialised with a total alkalinity $A_{\rm T} = 2320 \ \mu \text{mol kg}^{-1}$, $C_{\rm T} = 23800 \ \mu \text{g C kg}^{-1}$, and forced with a constant atmospheric *p*CO2 concentration of 380.6 ppmv. We use the Ocean Carbon Cycle Model Intercomparison Project numerical methods (see supplementary materials for more details) to



quantify air–sea carbon fluxes and carbon dioxide system equilibria (Aumont and Orr 1999).

The model ran from 19 March through to 28 June 2013. In the Coral Sea, autumn is a period of high weather variability with variable wind regimes. This period was chosen to allows us simulate a wide range of water circulation patterns.

2.3. Diagnostic age tracer

In order to optimise the location and size of the seaweed farm, a diagnostic 'age' tracer is used (Monsen *et al* 2002, Macdonald *et al* 2009). Generally, 'age' quantifies the spatially resolved residence time of water in different regions. Age tracer (τ) is advected and diffused by the hydrodynamic model, using the same numerical schemes as other tracers such as salinity. When inside the region of interest, the age increases at the rate of 1 d d⁻¹. When the age tracer is outside the region of interest, its age decays (or anti-ages) with a rate constant Φ d⁻¹. Thus, the local rate of change over the whole domain due to non-advective and non-diffusive processes is given by:

$$\frac{\partial \tau}{\partial t} = 1 - \Phi \tau$$
 in ageing region, (2)

$$\frac{\partial \tau}{\partial t} = -\Phi \tau \text{ outside ageing region.}$$
(3)

Two 'ageing' regions are considered. The first region is the entire 3D water field above the reef, for which the age is referred to as 'reef age'. The second region is the submerged layer (0.7 m thick between 2.3 and 3.0 m deep, below the lowest low tide of the simulated period) in which the seaweed farm resides, which is referred to as 'farm age'.

To calculate reef age, the hydrodynamic model is run and the 3D velocities (u, v, w) and diffusion coefficients (K) are saved every 15 min. The velocities and time directions are then reversed, to allow the age tracer to be advected backwards in space and time. This time and space reversal allows us to find the origin of water that spends the most time on the reef.

A semi-Lagrangian scheme calculates the transport of the age tracer given the reversed velocities and time. The resulting distribution provides age throughout the model domain. Those windward forereef regions with the highest 'reef age' are the locations where water is about to flow onto the reef and spend the most time on the reef, and are therefore considered to be the optimal locations for the farm. Thus, the farm is sited within contours of high reef age. For the reef age calculations, we have chosen an anti-ageing rate of $\Phi = 0.1$ d⁻¹ to approximate non-advective processes that neutralise the effect of being on the reef, such as air–sea exchange or planktonic processes.

2.4. Seaweed and optical models

Seaweed is quantified as a biomass per unit area, or as an areal biomass. At low biomass, the horizontal area covered by the seaweed community is a linear function





0.5

of biomass. As the total frond area approaches, and exceeds the projected area of the community, the projected area becomes independent of biomass, this is represented using:

$$A_{\rm eff} = 1 - \exp\left(-\omega_B B\right),\tag{4}$$

where A_{eff} is the effective projected area fraction of the seaweed community (m² m⁻²), *B* is the biomass of the seaweed, and ω_B is the nitrogen-specific frond area coefficient (m² g N⁻¹) (figure 2). The parameter ω_B is critical: it provides a means of converting between biomass and fractions of the project area covered, and is also used in calculating the absorption cross-section of the frond (Baird *et al* 2016). Simply, the thicker the frond, the smaller ω_B .

In the biogeochemical model, the seaweed biomass is quantified in $g N m^{-2}$ with a constant, non-Redfield stoichiometry (C:N:P = 550:30:1, defined as the Atkinson ratio Atkinson and Smith 1983).

The spectrally resolved optical model considers the processes of absorption and scattering by pure seawater and the submerged seaweed farm, and the azimuth angle of the incident radiation, and is described in full in the CSIRO Environmental Modelling Suite Technical Description (CSIRO 2014). Here we will consider just the optical properties of the seaweed farm and the overlying water.

The downwelling irradiance at wavelength λ after passing through the seaweed, $E_{d,below,\lambda}$, is given by:

$$E_{d,below,\lambda} = E_{d,above,\lambda} e^{-A_{\lambda}\omega_B B},$$
(5)

where $E_{d,above,\lambda}$ is the downwelling irradiance just above the seaweed, A_{λ} is the absorbance of the frond, ω_B is the nitrogen specific frond area, and *B* is the frond nitrogen biomass.

With the location of the farm optimised, a second goal is to operate the farm with a density of seaweed that maximises growth. To simplify the calculation of optimal density, we use the PAR-integrated light, E_{PAR} , although the exact calculation in the model is integrated over the visible spectrum using 23 individual wavelengths. Furthermore, we assume that the seaweed farm is nutrient replete (see discussion).

The rate of change of seaweed biomass as a function of growth, respiration and harvesting is given by:

$$\frac{\partial B}{\partial t} = 0.0302 E_{\text{PAR}} (1 - \exp(-A_{L,\lambda} \omega_B B)) - \phi B - H, \qquad (6)$$

where *H* is the harvest rate of biomass (g N m⁻² d⁻¹), E_{PAR} is the solar irradiance reaching the surface of the farm (W m⁻²), and ϕ is the respiration rate (d⁻¹). A conversion factor 0.0302 = 86400 $\frac{30}{5500}$ 14 $\frac{2.77 \times 10^{18}}{A_V}$ is used, where the factor 2.77 × 10¹⁸ quanta s⁻¹ W⁻¹ converts light in the PAR range to an accuracy of a few percent (Morel and Smith 1974), seconds are converted to days, 86 400 s d⁻¹, A_V = 6.023 × 10²³ mol⁻¹ is the Avogadro constant, and 30/5500 mol N mol quanta⁻¹ and 14 g mol⁻¹ are stochiometric conversions for seaweed (equation (4)).

Equating equation (6) to zero gives the steady-state harvesting rate:

$$H = 0.0302E_{\text{PAR}}(1 - \exp(-A_{L,\lambda}\omega_B B)) - \phi B.$$
(7)

At low biomass, too much light passes through the farm, and harvest is sub-optimal. At high biomass, too much of the growth is lost to respiration. In general, the rate of change of harvest with biomass given by:

$$\frac{\partial H}{\partial B} = 0.0302 A_L E_{\text{PAR}} \omega_B \exp\left(-A_{L,\lambda} \omega_B B\right) - \phi. \quad (8)$$

Equating this derivative to zero and solving for B gives the biomass for the optimal harvesting rate, B_{opt} :





$$B_{\rm opt} = -\frac{1}{\omega_B A_{L,\lambda}} \log \left[\frac{\phi}{0.0302 \omega_B A_L E_{\rm PAR}} \right].$$
(9)

Thus, using the generic seaweed parameters (CSIRO 2014), with $E_{PAR} = 200 \text{ W m}^{-2}$ (mean over a day), $\phi = 0.01 \text{ d}^{-1}$ and $\omega_B = 0.1 \text{ (g N m}^{-2})^{-1}$ (assume a relatively thick frond, $B_{opt} = 53.5 \text{ g N m}^{-2}$ is the seaweed biomass for which harvest is greatest. Substituting, B_{opt} into equation (7) gives an optimal harvest of $H_{opt} = 1.35 \text{ g N m}^{-2} \text{ d}^{-1}$.

In practice we set the initial biomass of the seaweed farm to 42 g N m⁻² and aim to keep biomass at this level to maximise carbon uptake. Every 7 d the farm is harvested by returning its biomass to 42 g N m⁻². In the simulation reported later, during a 7 d period biomass increases to a maximum of ~67.5 g N m⁻², equivalent to 3.2 g N m⁻² d⁻¹, depending on temperature (that affects ϕ) and solar radiation.

3. Results

3.1. Hydrodynamic simulation

Figure 3 shows a map of simulated mean current, a time series of current velocities at three locations, and corresponding surface wind stress. The mean surface flows show an anti-clockwise circulation with water moving around the reef edge. There is a strong gradient in the mean current velocities as water moves inside the reef. Currents are generally strongest to the

north of the reef and slowest inside the reef. Current velocities are partially correlated with the wind strength, especially inside the reef. In summary, tidal currents are strongly steered by the reef topography. Mean currents across the reef are westward, driven by the prevailing wind. The model showed that elevated mean sea level inside the lagoon, relative to that outside, drives a barotropic circulation, expelling water from the lagoon.

3.2. Optimised farm location

In order to determine the optimised location of the farm, we calculate reef age. The velocities and time direction from the 100 d simulation are reversed and used to drive a transport model that simulated reef age. Figure 4 shows the average reef age. As expected, the water in the middle of the reef has an older reef age than waters outside the reef. The spatially averaged residence time of the water inside the reef (delimited by the green contour line) varies between 1.0 and 1.8 d. The magenta contour shows the 1.0 d isoline (inside the contour the water spent more than 1 d on the reef).

We decided to place the farm outside the reef to minimise non-carbon-chemistry impacts on the reef. The white contour in figure 4 encloses the areas within the 1 d reef age contour that lie in water depths >5 m. We define this area as the optimum location for the





farm, covering an area of 1.9 $\rm km^2$ in three separate sites.

Most of the farm area is to the south of the reef, a consequence of the trade winds blowing from the southeast (MacKellar *et al* 2013) pushing water onto the reef from the south. Additionally, tides exchange water between the reef and offshore. Localised re-circulation due to bathymetric features is responsible for the smaller optimised area in the lee of the reef in the northern sector.

In order to assess our novel approach of optimising the farm location using an age tracer with velocity and time directions reversed, we restored the velocity and time to the forward direction, and followed an age tracer that aged only within the farm region, referred to as farm age (figure 4). Note that because the farm has only a small volume (1.9 km^2 area $\times 0.7$ m thick layer), water resides in the farm only briefly. Furthermore, since the farm is at depth (just below the lowest low tide mark, at 2 m), the farm age at the surface has already undergone considerable dilution due to vertical mixing. Thus, the maximum farm age is only \sim 40 min. The destination of this water determines the effectiveness of the farm.

The water originating from the farm spreads inside the reef, spending the most time (i.e. those areas with the highest mean farm age) in reef areas in the southwest (for the southern farm) and northwest (for the northern farm). The areas most affected by the farm waters are areas of low to medium coral density, representing a reef flat system with a combination of sand rubble and coral (figure 1). The bommies benthic community that lies in the deeper section of the reef, and the sections of reef around the island toward the east are the least impacted. Most importantly, areas outside the reef show very low values of farm age, a result of water flowing from the farm area moving quickly onto the reef rather than remaining off the reef. Thus, given the ocean currents simulated by the hydrodynamic model, the reef age diagnostic successfully optimised the farm location, maximising the time the water that originated from the farm spends on the reef.





3.3. Change in Ω_a due to the seaweed farm

In order to estimate the impact of the farm on the Ω_a inside the reef, we ran two model simulations, one with and one without the optimised farm. Coral and algae processes inside the reef have not being included as they produce large diurnal variability in C_T and A_T (Shaw *et al* 2012, Mongin and Baird 2014) that masks the seaweed farm effect. Without any biogenic fluxes of C_T and A_T (no seaweed farm), the background value of Ω_a in the control run is around 3.9 (range 3.7–4.1) (red lines in figure 5).

On average, throughout the simulation period and when the seaweed farm is active, Ω_a is increased by 0–0.5 (figure 5), with the footprint of the farm extending across large areas of the reef. Changes in Ω_a of greater than 0.2 occur as far as 1 km downstream of the farms.

The red contour in figure 5 shows the +0.1 change in Ω_a due to the farms. As expected from the distribution of farm age (figure 5), the areas best buffered are located just within the reef, and slightly downstream of the farms, with a mean change in Ω_a of ~0.3. The areas south of the lagoon and the one near the island are not as well buffered as the central areas. Similarly the branching corals, to the north of the reef are not well buffered.

Time-series of Ω_a and farm age in the southern farm, on the reef flat, and in the lagoon, illustrate the scale and variability of the change in Ω_a due to the farms (figure 6). Within the largest farm, Ω_a variability increases during the day, while the low night time values remain unchanged (between 3.63 and 3.67). Short-lived spikes in Ω_a occur intermittently, being frequent and regular inside the farm (figure 6) and less frequent and of a lower magnitude towards the middle of the reef. These spikes are the result of streams of high Ω_a waters, generated during the slack flow periods while in the farm.

During the simulation period, Ω_a is higher than 4.5 multiple times: 18 times at the site in the southern farm, seven times at the reef flat site, and only four times at the lagoon site. The average Ω_a is increased by 0.23, 0.20 and 0.17 above the southern farm, on the reef flat and in the lagoon, respectively.

The time period when Ω_a is higher should correspond to periods with the greater farm age. While there is indeed a relationship between the spikes in Ω_a and farm age inside the farm, change in Ω_a is less well correlated with change in age on the reef. Downstream of the farm, air–sea exchange and mixing of water that has passed through the farm at different solar intensities, act to uncorrelate the two variables. Further, loss of seaweed to organic matter that decays downstream of the farm will decrease Ω_a . This demonstrates the complexity of the interactions between circulation and carbon chemistry, and the difficulties to explain the impact of the farm at one given location.

The entire reef ecosystem as defined in figure 1 covers an area of 35.2 km². The total area where the change in Ω_a is greater than 0.1 is 29.11 km² (red contour in figure 6). The region where the change in Ω_a is greater than 0.1 that resides within the reef ecosystem



Figure 6. Time series of Ω_a with and without buffering effect from the hydrodynamic seaweed farm (blue and red respectively) and farm age (black) at three different sites (see figure 4 for the location of the time series).

covers 23.92 km² or 82.1% of the whole reef. Overall 84.2% of the sand and rubble on the reef flat, 46.0% of the Coral on the slope, 74.6% of the Bommies and 87% of the reef flat have a buffering effect equal or greater than 0.1.

Figure 6 shows a section across the reef of the mean change in Ω_a due to the farm. The 0.1 envelope of change in Ω_a extends to the bottom of the water column on the reef slope in the southern part (near the southern farm) and two thirds of the water column on the northern slope. Thus vertical mixing and recirculation processes transport the high farm age water around the reef and down the reef slope where much of the reef calcification occurs.

The frequency distribution of the mean change in Ω_a for the entire reef ecosystem is presented in figure S1. Ω_a changes by 0.025–0.075, 0.075–0.125 and 0.125–0.175 for 15%, 40% and 25% of the entire reef area respectively. Changes greater than 0.2 accounts for less than 10% of the area.

4. Discussion

For a reef-scale ocean-acidification buffering project to proceed, many environmental, social and economic considerations will need to be met. Before these more complicated issues should even be considered we must investigate at what scale and how efficiently ocean acidification can be locally mitigated. The numerical experiments presented in this study determine the optimal farm design given the environmental constraints due to meteorological forcing, reef topography and seaweed physiology for Heron Island reef. Thus, the numerical experiments undertaken here represent the absolute upper limit of a seaweed farm efficacy. With the possible exception of lifting seaweeds above the waterline during dark respiration, no other type of farms are likely to be more effective at buffering ocean acidification than the designs presented here. A constructed farm is more likely to be much less efficient, due to designs constraints related to cost limitations and environmental risks.

Letters

In our simulation of seaweed growth, we assumed that nutrient limitation could be alleviated. Artificial fertilisation techniques such as: deep water nutrient rich pumping (Lovelock and Rapley 2007) (although this introduces carbon rich water as well); mariculture or integrated aquaculture with an associated fish farm (Neori *et al* 2004); or fertilisation with exogenous fertiliser (Gao and Mckinley 1994), (Tseng and Fei 1987) could be used. Determining which method should be used is beyond the scope of this study, which only aimed to showcase the feasibility and efficacy of buffering ocean acidification with natural processes.

Without undertaking similar studies on a broad range of reefs, it is difficult to assess whether Heron Island reef is the best location for building a seaweed farm. Nonetheless, the dominance of wind-generated circulation that drives a generally westerward flow across the shallow reef, allows for a relatively effective and contained seaweed farm placement. Reefs dominated by tidal excursions across the reef flat would be expected to have less effective farms. Further, as the reef increases in size, its perimeter to surface area ratio decreases, reducing the ability of offshore farms to mitigate ocean acidification throughout a reef lagoon. Our optimal seaweed biomass of 42 g N m^{-2} is equivalent to 6.6 tC ha⁻¹, which is comparable to an existing farm in South Korea (Chung *et al* 2013) (not in a reef environment) that operates with a seaweed biomass of 2.1–5 tC ha⁻¹. The South Korean farm is designed with forty-nine 100 m long lines spaced 2 m apart, with 430 mg C m⁻¹ of rope. The average net $C_{\rm T}$ uptake of our simulated farm is 37.0 tC ha⁻¹ yr⁻¹, compared to the 15.8 tC ha⁻¹ yr⁻¹ for natural seaweed benthic communities (Duarte *et al* 2005a). The South Korea pilot farm of Chung *et al* (2013) sequesters as much as 16 tC ha⁻¹ yr⁻¹.

The size of the farm (1.9 km^2) was determined by a reef age contour of 1 d. We choose 1 d to approximate tidal, diurnal and air–sea exchange time scales. A reef age contour less than 1 d would outline a larger, but less efficient per m², seaweed farm. Nonetheless 2 km² is at the lower end of size required to have a significant impact on the Ω_a of Heron Island reef, while being at the upper end of present globally installed seaweed farm ventures.

It is important to put these results in the context of projected changes in ocean acidification (e.g. Gattuso et al 2015). A 0.1 decrease in Ω_a represents 7 years of increased atmospheric carbon dioxide concentrations under the highest IPCC RCP 8.5 (Intergovernmental Panel on Climate Change) emissions scenario, 8 years under RCP 4.5 (medium emission) and 21 years under the strong reduction emission scenario RCP 2.6 (low emissions). Therefore, despite considerable cost, the 1.9 km² farm only has the ability to buffer the majority of the Heron Island reef from ocean acidification for a period of 7-21 years (up to 40 years, in small localised areas downstream of the farm). This highlights the importance of mitigation of anthropogenic carbon emissions to reduce the impacts of ocean acidification on the marine ecosystem.

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