Predicting the role of Enhanced Rock Weathering relative to future carbon emissions for the Great Barrier Reef.

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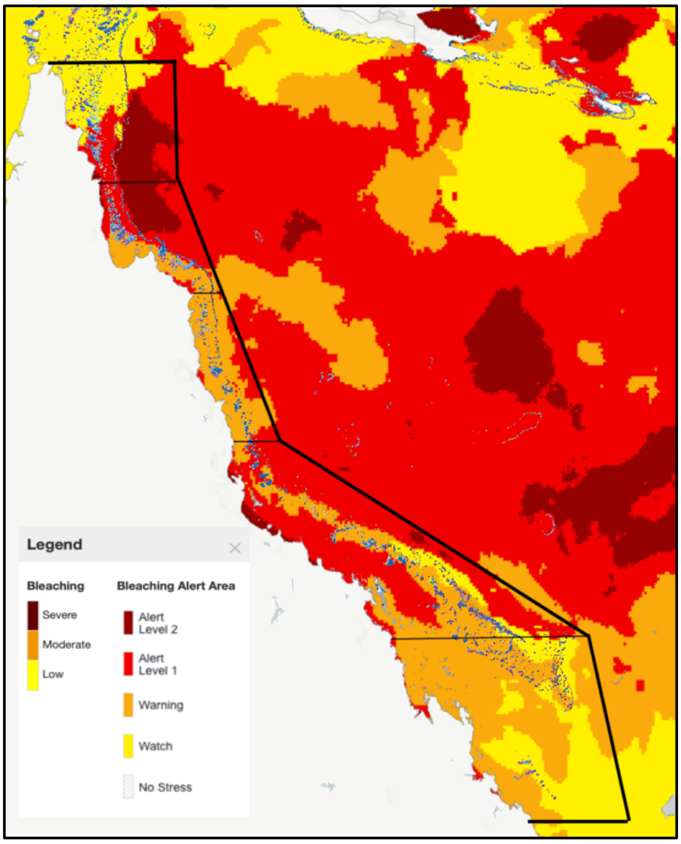
Coral reefs cover less than 0.2% of the ocean seafloor but house 25% of all marine species with estimated annual earnings of $38.7 billion worldwide (Souter, 2020). The rise in greenhouse gas emissions, leading to ocean acidification, puts coral reefs at risk of extinction. Carbon capture methods like the use of terrestrial enhanced rock weathering (ERW) on croplands may reduce the impact of this key threat. Estimates of coral reef ecosystem calcification (G_{net}), productivity (NEP), and aragonite saturation state (Ω_{arag}) provide a means of representing the health and functionality of coral reefs communities and how they will respond to these stressors. By coupling the Grid ENabled Integrated Earth system (cGENIE) Ocean Biochemistry (BIOGEM) model and R's *seacarb* carbonate chemistry model, I simulated changes in seawater chemistry for the Great Barrier Reef (GBR) from the year 2000 to 2200 utilizing the IPCC A6 Representative Concentration Pathway (RCP) scenarios. The model results highlighted that RCP 2.6 was the only scenario to create oceanic conditions that can support the GBR by the end of the century. Under the RCP 2.6 scenario, the inclusion of ERW significantly increases the opportunity of meeting this requirement as Ω_{arag} and NEP increased by 7% and 433% (2200) respectively. The middle of the Great Barrier Reef (GBR3) is predicted to benefit the most from the inclusion of ERW with a 6% increase in Ω_{arag} before the end of the century, while the vertical extremes of the reef would experience the smallest changes (Ω_{arag} = + 0.09). Large extents of ERW will reduce the effects of global warming, but this study highlights the importance of meeting the Paris 2°C warming target by 2100 under the conditions of the RCP 2.6 scenario in order to save the GBR.

Introduction

The Great Barrier Reef (GBR) supports approximately 39,000 jobs and houses over 1,700 species of marine animals with an estimated economic, social and icon value of $56 billion, making it a focal site for oceanic studies (O'Mahoney, 2017). The rise in greenhouse gas emissions has significantly impacted the health of coral reefs across the globe as the oceans absorb approximately ¼ of the anthropogenic carbon dioxide released into the atmosphere each year (Albright, 2016; Le Ouréré, 2015).

This process, known as ocean acidification, causes a decline in ocean pH, carbonate ion concentrations [CO_3^{2-}], and carbonate mineral saturation states (Ω_{arag}). Since the industrial revolution, the Earth's oceans have absorbed approximately 39% of the industrial-age fossil carbon emissions (McKinley, 2020). Although this has helped regulate the rise in atmospheric CO_2, it has put the coral reefs at risk of transitioning from a state of net accretion to one of net erosion (Andersson, 2013).

The main consequence of ocean acidification is the reduced ability of coral reefs to produce calcium carbonate ($CaCO_3$), while rates of bioerosion and $CaCO_3$ dissolution increase. Coral calcification is an important indicator of the health of coral reef ecosystems due to the numerous species that rely on the structural complexity that the corals provide (De'ath, 2009). The combination of these various stressors causes coral bleaching, a process where corals expel the zooxanthellae that live within their tissue, leaving a white skeleton behind. **Figure 1.** shows the Bleaching Alert Area heat stress levels as defined by NOAA's



Alert Level	Level Definition	Effect
No Stress	HotSpot ≤ 0.0	No thermal stress
Bleaching Watch	Watch 0.0 < HotSpot < 1.0	Low-level thermal stress
Bleaching Warning	1.0 ≤ HotSpot and 0.0 < DHW < 4.0	Coral bleaching possible
Bleaching Alert Level 1	1.0 ≤ HotSpot and 4.0 ≤ DHW < 8.0	Coral bleaching likely
Bleaching Alert Level 2	1.0 ≤ HotSpot and 8.0 ≤ DHW	Coral mortality likely

Figure 1. [Top] Map of the Great Barrier Reef showing coral bleaching thermal stress levels (Allen Coral Atlas, 2022). **Figure 2.** [Bottom] Coral bleaching thermal stress levels based on the NOAA Coral Reef Watch 5-km Coral Bleaching HotSpots and DHW products (NOAA Coral Reef Watch, 2020).

established Coral Reef Watch program for the GBR (Allen Coral Atlas, 2022). The Bleaching Alert Area measures SST anomalies that are warmer than the Monthly Maximum Mean and estimates how likely it is to cause coral bleaching (**Figure 2**.) (NOAA Coral Reef Watch, 2020; INCOIS, 2011).

The GBR is founded on reef-building coral species which rely on aragonite (soluble mineral form of calcium carbonate) to build their exoskeletons (Mongin, 2016). As the ocean's aragonite saturation state declines, it becomes much more difficult for corals to extract calcium and bicarbonate ions from the surrounding seawater to form their skeletons (Zheng, 2014). One possible solution for reversing these effects is the introduction of Enhanced Rock Weathering (ERW). ERW is based on the idea of distributing large amounts of crushed basalts (ex. Olivine) over agricultural areas to induce and accelerate natural rock weathering (Zheng, 2014). By increasing the erosion and dissolution of the basalt minerals there is a shift in the carbonate chemistry equilibrium (**Equation 1**) towards HCO_3^- and CO_3^{2-} (Bach, 2019).

$$(1)\quad CO_2(atm) \leftrightarrow CO_2(aq) + H_2O \leftrightarrow H_2CO_3 \leftrightarrow HCO_3^- + H^+ \leftrightarrow {CO_3}^{2-} + 2H^+$$

This equilibration allows H^+ ions to be taken up by the basalt minerals via replacement of their positively charged ions (**Equation 2**) (Bach, 2019)

$$(2)\ \textit{Olivine}\qquad Mg_2SiO_4 + 4H^+ = 2Mg^{2+} + H_2SiO_4$$

The release of these remaining positively charged ions (Mg^{2+}) drives the shift from CO_2 to HCO^{3-} and CO_3^{2-} as they must be balanced due to the constraint of electroneutrality (Wolf-Gladrow, 2007). By shifting the ocean's carbonate chemistry equilibrium, it allows additional CO_2 from the atmosphere to be absorbed and permanently stored in the oceans.

With atmospheric CO_2 emissions continuously rising, the 2007 IPCC's Fourth Assessment Report predicted that doubling the atmospheric CO_2 would reduce calcification rates within corals by 20-60% (Fischlin, 2007). Since the reversal of global surface warming lags the decrease in atmospheric CO_2 concentrations by a few years, Enhanced Rock Weathering (ERW) can provide a possible solution to avoid breaching the 2°C warming under the Paris Agreement RCP 2.6 climate target (IPCC, 2021). Previous global ERW simulations have shown that an ERW deployment delivering a net removal of 2 GT CO_2/year approximately doubles the probability of meeting the Paris 1.5°C target from 23% to 42% under the RCP 2.6 scenario (Vakilifard, 2021). For this study we will be using a coupled cGENIE and R code model simulation to quantify the effects that ERW will have on the future of the oceans' carbon chemistry and the health of coral reef ecosystems.

Unlike previous reports, this study bases its predictions on the relations between atmospheric CO_2 concentrations, calcification, and Ω_{arag} from model simulations rather than field studies (Schoepf, 2015). While these studies have been done on a local scale in Brazil and at One Tree Island, GBR, this study focuses on the whole GBR ecosystem (Davis, 2019; Longhini, 2015).

Methods

GENIE model simulations

We ran two GENIE simulations across all four RCP mitigation scenarios [RCP 2.6, 4.5, 6.0, 8.5]. The first simulation acted as a 'Control' where no ERW was added, and the second simulation functioned as a 'Capture' scenario with ERW removing 10 GT CO_2/yr on top of an emissions trajectory. Enhanced rock weathering (ERW) was modelled as a reduction in anthropogenic CO_2 emission through ground capture and storage, rather than the effects of increased ocean alkalinity from ocean alkalinity enhancement.

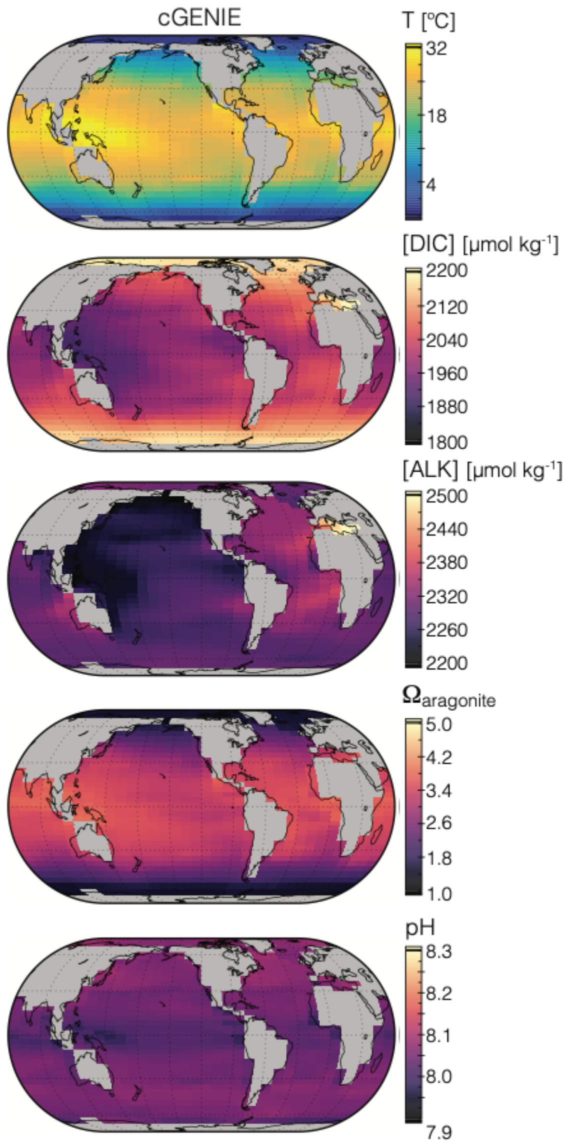


Figure 2. Global distribution of current oceanic surface temperature (T), dissolved inorganic carbo (DIC), total alkalinity (ALK) aragonite saturation state (Ω_{arag}), and pH from the GENIE simulations.

The ‘Capture’ scenario assumes that crushed basalt is added throughout the world’s agricultural systems and transferred to the ocean through the global river systems resulting in 10 GT of atmospheric CO_2 being removed annually. Under this model, it was assumed that alkalinity entering the oceans as a result of ERW is equally spread throughout the river systems based on similar discharge rates. cGENIE-16 version 2.7.7 includes seven main modules to study the Earth’s system dynamics and make long term future predictions (Vakilifard, 2021). For this study we used the ocean biochemistry module, (BIOGEM), which includes the physical climate system (at 12 x 18 grid-cells horizontal resolution with 16 ocean vertical levels) (Ridgewell, 2007). The cGENIE-16 model was selected for this study over other global carbon cycle models as it features a reduced frictional geostrophic 3-D ocean circulation model which is coupled with a 2-D energy-moisture balance model (EMBM) of the atmosphere and a dynamic-thermodynamic sea-ice model (Cao, 2009). The ocean biochemistry module includes marine carbon cycling that accounts for biogenically induced geochemical fluxes based on a phosphate control of biological productivity. The module is calibrated against historical observational datasets of ocean geochemistry (Ridgewell, 2007; Cao, 2009).

Both simulation experiments for the model were run with the four IPCC AR6 climate Representative Concentration Pathway (RCP) trajectories. Each RCP scenario [2.6, 4.5, 6.0, 8.5] represents the radiative forcing in Wm^{-2} in the year 2100 relative to 1750 (Vakilifard, 2021). The model plotted decadal-scale climate variations for the GBR between 2000 and 2200, with the enhanced rock weathering ‘Capture’ runs starting from 2050.

For this model, the GBR was broken down into 5 sections ranging from the northern tip of the reef (10°40’55”S, 145°00’04”E) to the most southern point of the reef (24°29’55”S, 154°00’04’E) (GBRMPA). **Figure 3.** shows the breakdown of the GBR into the five sections that were assessed. The sections are labelled GBR1-GBR5 running from north to south. The average depth of the GBR is 35m within the inshore waters so I only focused on data values from the model within the upper 40m of the ocean. I extracted data values for the ocean surface pH, Dissolved Inorganic Carbon (DIC), CO_2 Flux (F), and Aragonite saturation state (Ω_{arag}) for both the Capture/Control scenario, across all five locations, and all four RCP scenarios.

Seawater Carbonate Simulation

I used the R package *seacarb* to process the GENIE simulation outputs. Specifically, I used *seacarb’s* ‘*carb’* function to calculate all 6 components of the marine carbonic acid system, making the common assumption of thermodynamic equilibrium within the system (e.g., Smith, 1978). Within the package, pH and DIC were

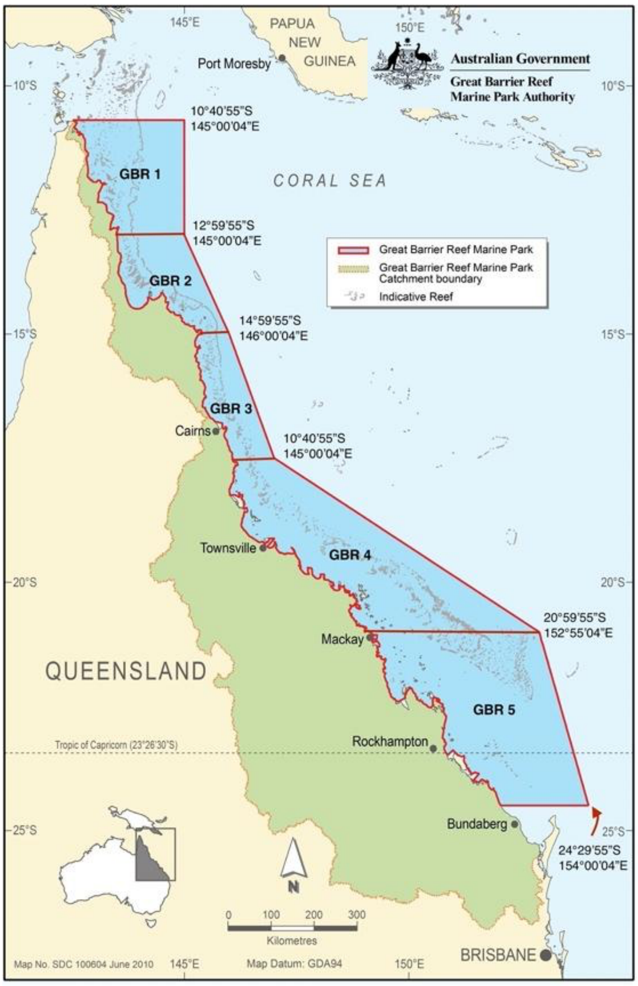


Figure 3. Map of the Great Barrier Reef broken down into the 5 studied sections (GBRMPA, 2022).

used as known variables (flag 9) to calculate the biological responses to the predicted elevated atmospheric CO_2 concentrations. The package output provided Alkalinity and Aragonite Saturation State values which were used alongside the GENIE outputs (e.g., temperature) to calculate the rate of $CaCO_3$ precipitation/dissolution (G_{net}), CO_2 Flux (F), and Net Ecosystem Production (NEP).

Calculations

Two chemical equations were used from Davis (2019), Longhini (2015) to estimate decadal rates of G_{net} and NEP. The rate of $CaCO_3$ precipitation/dissolution was estimated using Smith ad Kinsey’s (1978) alkalinity anomaly technique:

$$G_{net} = \frac{-0.5\Delta TAz\rho}{\Delta t}$$

A positive G_{net} represents a state of net ecosystem calcification and a negative G_{net} implies net dissolution ($mmolm^{-2} h^{-1}$). ΔTA is the change of salinity normalized (S=36) total alkalinity ($mmolkg^{-1}$). The change in TA is multiplied by -0.5 to account for two mols of TA being taken up to produce one mol of $CaCO_3$. z refers to the mean water depth (m), ρ represents the water density as a function of temperature and salinity (Kgm^{-3}), and Δt is the time interval (hr).

The NEP was estimated from the changes in total inorganic carbon concentrations excluding total alkalinity variations due to precipitation/dissolution of $CaCO_3$ using:

$$NEP = \frac{\Delta DICz\rho}{\Delta t} - G_{net} - F$$

A positive NEP value denotes a net production, and a negative value describes a state of net respiration ($mmolm^{-2}h^{-1}$). ΔDIC represents the salinity-normalized concentration of dissolved inorganic carbon ($mmolkg^{-1}$). G_{net} is the precipitation/dissolution of carbonate and F is the carbon dioxide flux across the atmosphere-water interface. G_{net} is subtracted to account for changes in DIC due to the inorganic precipitation of CO_3^{2-}.

The carbon dioxide flux across the atmosphere-water interface (F) was directly taken from the GENIE model outputs [variable: fseaair_pCO_2: net sea → air gas exchange flux] ($mmolm^{-2}h^{-1}$). A positive flux denotes a net transfer of CO_2 out of the ocean to the atmosphere, resembling a carbon source rather than sink.

Results

Enhanced Rock Weathering

The cGENIE earth system simulations combined with *seacarb* carbonate chemistry models revealed that the application of ERW reduces the uptake of atmospheric CO_2 by the oceans, benefiting the growth of corals. Following the RCP 2.6 model pathway, ERW slowed down the atmospheric CO_2 growth rate and lowered the peak atmospheric CO_2 concentration by approximately 10.2%. These results agree with Vakilifard's 2021 study which saw a ~40 ppm atmospheric CO_2 reduction by the end of the century with the addition of ERW.

Aragonite Saturation State

The aragonite saturation threshold required to sustain the growth of coral reef ecosystems is still heavily debated because of the confounding effects of other environmental factors. Open ocean aragonite saturation states relative to the preindustrial distribution can provide some insight on this critical limit. Prior studies have proposed a minimum oversaturation threshold $\Omega_{arag} > 3.3$ for the coral species within the GBR reef (Kleypas, 1999). With enhanced mineral weathering, aragonite saturation state of the GBR is predicted to decline at least to the middle of the century, followed by a steady increase. The timing and rate of this turn between a declining Ω_{arag} and an increasing Ω_{arag} is determined by the radiative forcing of the RCP scenarios. **Figure 4.** shows the average projected Ω_{arag} saturation state for the whole GBR relative to all four RCP scenarios. Without ERW, RCP 2.6 was the only scenario to generate ocean waters with $\Omega_{arag} > 3.3$ by the end of the century. The three other RCP scenarios revealed that Ω_{arag} will drop below this supersaturation threshold prior to the middle of the century. The

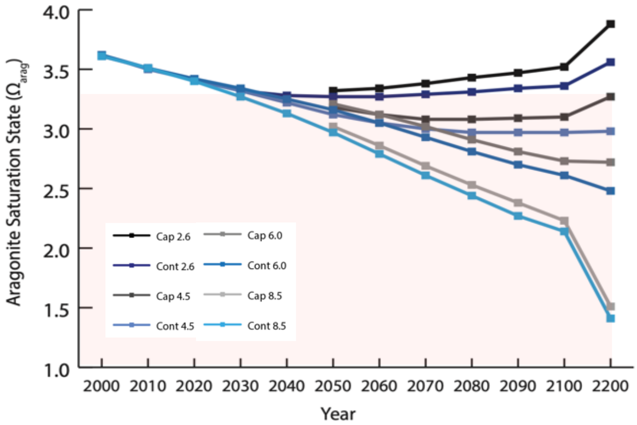


Figure 4. Aragonite Saturation state (Ω) across the whole GBR following the conditions set by IPCC A6 RCP scenarios.

addition of ERW slowed the decline of aragonite saturation state across all four RCP scenarios. All projections had a higher minimum Ω_{arag} value and a steeper increase in Ω_{arag} across future centuries. Aside from RCP 2.6, RCP 4.5 was the only scenario to reach the minimum saturation threshold by the year 2200 with the inclusion of ERW.

Generally, the lowest emissions scenario (RCP 2.6) resulted in the greatest increase in the Ω_{arag} value between 2050 and 2200 with the inclusion of ERW. **Table 1.** shows the increase in Ω_{arag} across all five locations when comparing the increase in aragonite saturation state between the 'Capture' and 'Control' scenarios. The RCP 2.6 scenario indicates a mean increase of $\Omega_{arag} = 0.1$ (σ=0.008) between 2050-2100 and Ω_{arag}=0.19 (σ=0.006) between 2100-2200 across the entire GBR.

	RCP 2.6		RCP 4.5		RCP 6.0		RCP 8.5	
Year	2100	2200	2100	2200	2100	2200	2100	2200
GB1	0.16	0.35	0.13	0.29	0.11	0.23	0.08	0.10
GB2	0.16	0.35	0.14	0.30	0.12	0.24	0.09	0.10
GB3	0.20	0.39	0.12	0.27	0.16	0.28	0.13	0.13
GB4	0.14	0.32	0.12	0.27	0.10	0.22	0.07	0.08
GB5	0.13	0.33	0.13	0.28	0.11	0.22	0.08	0.09

Table 1. Differences in Aragonite Saturation state (Ω) when ERW is included across thee 5 GBR locations and 4 RCP scenarios.

A breakdown of the percentage increase due to ERW in aragonite saturation across all five locations (**Figure 5.**) revealed that GBR3 (middle of the reef) will see the greatest increase in Ω_{arag}. The aragonite saturation state of GBR 3 experienced an average increase of 5.55% by 2100 and 10.13% by 2200 across all four RCP scenarios. A breakdown of the individual RCP scenarios highlighted that for GBR3 the greatest change in Ω_{arag} occurred under RCP 6.0 (6.14% by 2100, 11.28% by 2200). GBR4 experienced the smallest increase in Ω_{arag} for both 2100 (3.95%) and 2200 (8.43%) amongst the five locations. These variations in the rate of Ω_{arag} increases across locations may be attributed to differences in the coral reef size and positions, distinct site-specific baseline oceanic conditions, and alterations in site-specific seawater carbonate chemistry (influx of TA or DIC through groundwater seepage) (Davis, 2019).

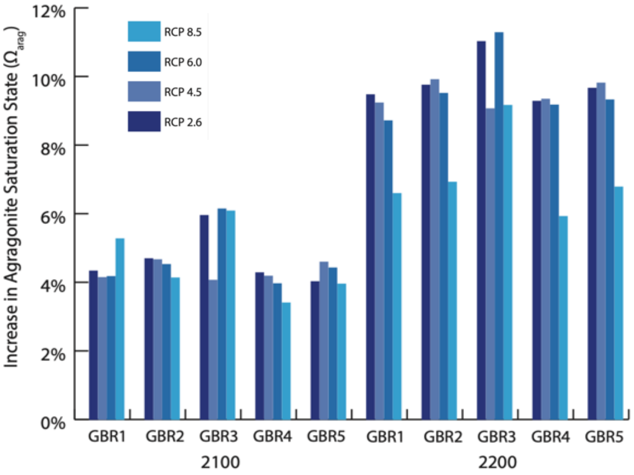


Figure 5. Percentage increase in Aragonite saturation state (Ω_{arag}) when ERW is included across 5 GBR locations and 4 RCP scenarios.

Net Ecosystem Production (NEP)

Under all RCP scenarios, our simulation showed an initial rise in NEP before experiencing a stronger decline resulting in low positive and even negative NEP values (**Figure 6**.). Without ERW, the maximum positive NEP value achieved was under the highest mitigation scenario (RCP 2.6), where NEP peaked in 2060 (0.01 mmolm^{-2}h^{-1}). RCP 8.5 was the only scenario to reach a negative NEP rate before the end of the century, suggesting the GBR will turn from a carbon sink to source by 2056.

Under the 'Capture' scenario, where ERW is added from the year 2050, all four RCP scenarios showed a higher NEP value and a slower decline into the future. The greatest difference in NEP due to the inclusion of ERW was seen in 2200 where under the RCP 2.6 scenario NEP increased by 0.0039 mmolm^{-2}h^{-1} (433.6%). Although the inclusion of ERW delays the point at which the GBR becomes a carbon sink under the RCP 8.5 scenario (~12 years), it doesn't ultimately prevent the NEP becoming negative.

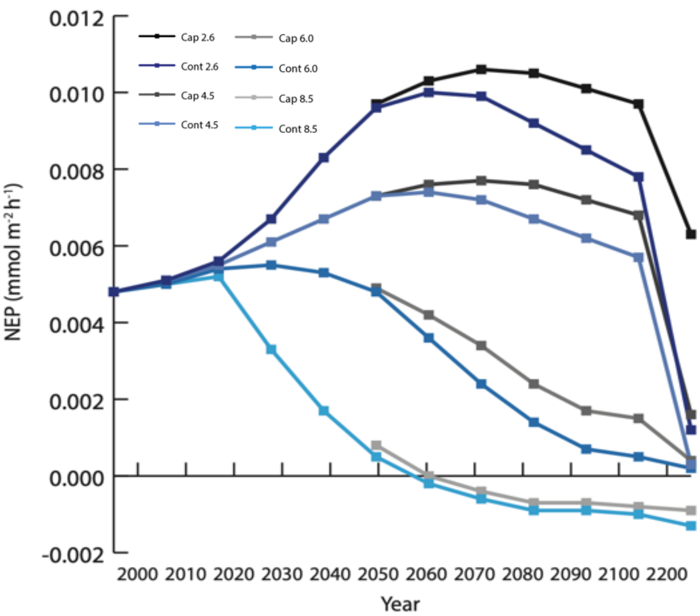


Figure 6. Net Ecosystem Production (NEP) across the whole GBR following the conditions set by IPCC A6 RCP scenarios.

Even though only the lowest mitigation scenario (RCP 8.5) reached an overall state of negative NEP by 2200 it does not suggest that this state cannot be reached under the other RCP scenarios. Under both the RCP 4.5 and 6.0 scenarios, NEP drops to 0.0012 and 0.0003 mmolm^{-2}h^{-1} by 2200 following a negative slope trajectory. This suggests that although these scenarios will delay the NEP becoming negative, they are not sufficient enough to prevent the GBR from becoming a carbon source in the future.

Calcification (G) and CO_2 fluxes (F)

Figure 7. illustrates the ecosystem's overall rate of calcification and dissolution for the entire GBR. Currently the GBR is in a state of positive net calcification as positive values of G_{net} denote a carbon sink state where atmospheric carbon dioxide is taken up by ocean. As atmospheric carbon emissions increase under all RCP scenarios the GBR's calcification rate follows a steady decline towards a state of net dissolution. The rate of calcification decline was dependent on the RCP scenario with RCP 8.5 having the strongest decline in calcification rates towards the end of the century. The highest mitigation scenario, RCP 2.6 was the only pathway that resulted in positive calcification rates for the GBR by 2200. The addition of ERW resulted in a stabilization of calcification rates and mitigated the decline as atmospheric emissions increased. While the use of ERW may not increase the rates of calcification they can prevent the GBR from turning into a state of net dissolution. ERW stabilized the decline in calcification rates across all four RCP scenarios, however it was most effective under the RCP 2.6 pathway. The 2.6 track showed the greatest delta between the control and capture scenario and was the only scenario to generate calcification rates similar to modern times.

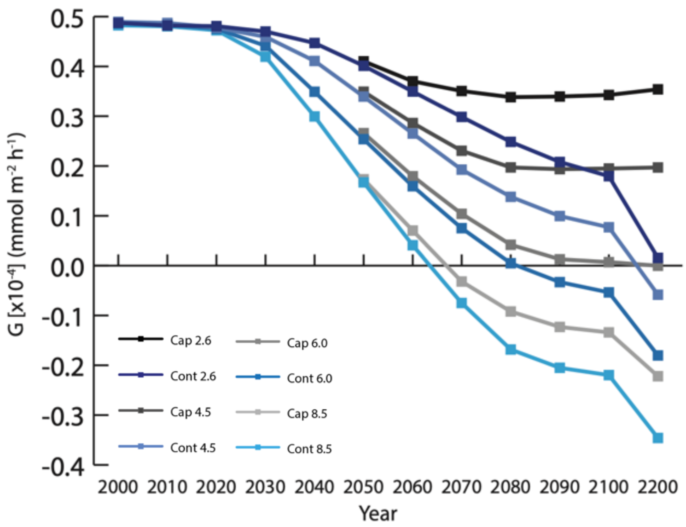


Figure 7. Net Ecosystem Calcification (+) and Dissolution (-) rates for the GBR following the RCP scenarios.

Currently the GBR acts as a carbon sink, intaking atmospheric carbon dioxide, creating a negative CO_2 flux from sea to air. Under all RCP scenarios the rate of CO_2 intake diminishes towards the end of the century and 2200. The RCP 2.6 scenario was the only one to generate a state of carbon capture without the inclusion of ERW by 2200. In relation to the ecosystem's calcification rates, the addition of ERW stabilizes the rate of CO_2 flux and prevents the gradual decline as atmospheric emissions increase. ERW was most effective under the RCP 2.6 scenario and saw CO_2 flux rates similar to modern times compared to the control scenario which saw flux rates converge towards 0 $mmolm^{-2}h^{-1}$ (**Figure 8.**)

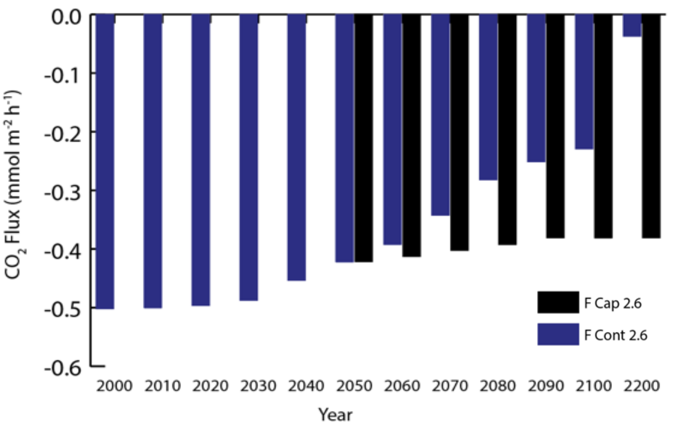


Figure 8. Rate of CO_2 flux across the whole GBR under the RCP 2.6 scenario.

Discussion

Aragonite saturation state (Ω_{arag}) and calcification rates (G_{net}) have been used as metrics of ocean acidification to predict the threat of increased atmospheric CO_2 concentrations to the health of coral reefs. Previous field and simulation experiments suggest that for the majority of coral species that inhabit the GBR require a minimum $\Omega_{arag} = 3.3$ in order to maintain their carbonate skeletons (Zheng, 2014; Kleypas, 1999; van Hooidonk, 2014). According to our coupled GENIE ocean biochemistry and *seacarb* ocean chemistry simulation models the only scenario that meets this requirement by 2100 and 2200 is RCP 2.6. However, under the RCP 2.6 scenario, the GBR is still expected to reach a state of undersaturation between 2037 and 2074.

The removal of atmospheric CO_2 via the additional alkalinity of ERW is not a 1:1 ratio because the ocean CO_2 outgassing offsets the artificial drawdown (Vakilifard, 2021; Hansen, 2013; Taylor, 2016). Nonetheless, the inclusion of ERW increases the Ω under every RCP scenario, with the smallest difference seen under the RCP 2.6 scenario (4.3%). However, it remains the only scenario where by 2200 the ocean is sufficiently saturated to support the coral reef ecosystem. The outputs for the RCP 8.5 scenario agreed with previously reported results, where the inclusion of ERW still failed to reduce atmospheric CO_2 concentrations to the target of 350 ppm by 2100 and generate oceanic conditions that are sufficient to sustain the growth of coral reefs (Taylor, 2016; Ricke, 2013).

Breaking down the GBR into five sections revealed that the central part of the reef would experience the largest increase in Ω_{arag} whilst the vertical edges of the reef would experience equal but smaller increases in Ω_{arag}. Looking at historical trends, studies that have monitored temporal trends in coral cover across the GBR have shown that between 1985-2012, the middle and southern third of the GBR experienced severe coral cover loss, -12.5% and - 29.5% respectively, whilst the northern third of the reef experienced no decline in coral cover (De'ath, 2012).

However, the record-breaking marine heatwave in 2016 saw the worst damage occurring in the northern half of the GBR, with decreases in coral cover ranging from 20-60% (Hughes, 2018). Our model revealed that based on future carbon trajectories the southern part of the GBR (GBR5) will be most at risk to ocean acidification and coral bleaching. GBR 5 had the lowest Ω_{arag} values across all RCP scenarios, even with the inclusion of ERW.

In contrast to the 2016 bleaching event, the northern part of the GBR (GBR 1) is least likely to be affected by the reduction in Ω_{arag} (Prideaux, 2018). This suggests that either the 2016 bleaching event was an anomaly or that as coral mortality increases, there will be fewer corals and therefore fewer bleaching events. The 2017 and 2020 bleaching events, which affected the middle and southern parts of the GBR respectively, supports the long-term results from our model which predicted that the southern part of the GBR will experience the greatest coral cover loss due to bleaching by the end of the century (Prideaux, 2018). However, our model's timescale is only accurate to decadal intervals which presents long-term trends but conceals the effects of individual anomaly bleaching events due to varying climate patterns.

The importance of NEP is seen in the records of severe bleaching events. As bleaching events begin to occur annually, many of the goods and services that the coral reefs provide begin to diminish and can be entirely wiped (Moberg,1999). Declines in the abundance of coral colonies reduces the productivity of the entire reef ecosystem, and fisheries, both directly as a food source but also indirectly through the loss of the structural complexity that provide a habitat for other animals. Our model showed that the greatest NEP values for the GBR were achieved under the conditions of the RCP 2.6 scenario. This scenario revealed a NEP that was 3.8 times greater by 2100 compared to the RCP 4.5 scenario. Inducing ERW increased the peak NEP value by 14.2% under the RCP 2.6 scenario. Even if we fail to meet the conditions of the highest emission scenario, the NEP rates of the RCP 2.6 scenario can be met under the RCP 4.5 scenario if ERW is included.

While our model aims to predict future trends based on historical records, coral reefs are extremely complex ecosystems with numerous marine and atmospheric factors contributing to their productivity, making them highly unpredictable. This emphasizes that while predictions can be made, there are factors that are impossible to forecast, and so hypothetical trends may not accurately reflect what we will actually see in the future. Nonetheless, as other studies have shown, by quantifying the net calcification response of the coral reefs to the enriched CO_2 and alkalinity conditions, our results highlight that when the ocean chemistry is restored closer to pre-industrial conditions the net community calcification increases (Andersson, 2013).

Our results emphasize that increased atmospheric CO_2 concentrations, which gives rise to ocean acidification, will put the GBR at risk of becoming in a state of net dissolution. As previously reported, the increasing rate of ocean acidification has shown to cause greater rates of $CaCO_3$ dissolution within the carbonate framework of coral reefs (Yates, 2006; Manzello, 2008). Historic calcification records calculated from core samples of *Porites* colonies within the GBR have indicated that calcification rates have been gradually declining since the 1980s (De'ath, 2009). Our model suggests that this decrease in calcification rates will continue and get stronger from 2040 onwards under all the RCP scenarios.

The greatest rate of calcification decrease occurs under the lowest mitigation scenario (RCP 8.5) where calcification rates are expected to halve before 2050. Under the RCP 2.6 scenario, this was only predicted to occur after the end of the century. By 2200, there is a 104.5% increase in calcification rates under RCP 2.6 compared to RCP 8.5 without the inclusion of ERW. Following the RCP 2.6 scenario, the addition of ERW led to a 29.6% decrease in calcification rates by the turn of the century. However, when comparing the differences between the control and capture scenario, the exclusion of ERW saw calcification rates decrease by 63.2% by 2100. It is also important to highlight that after the turn of the century calcifications rates were relatively stable until 2200 with the ERW but continued to steadily decline without it. While the removal of 10 GT of CO_2 on a yearly basis will not return calcification rates to modern and historic proportions, it will prevent the continual decline and limit the amount of coral bleaching that occurs.

Overall, the patterns observed for changes in CO_2 flux were comparable to the patterns observed for net ecosystem calcification (G_{net}). The absorption of atmospheric carbon emissions by the ocean is predicted to gradually decline towards the end of the century. Our model predicts that this decline will begin around 2050 and continuously grow as we approach the end of the century. Global ocean acidification simulations have observed similar patterns with carbon intake decreasing after the middle of the century, with the rate of decline being dependent on which RCP pathway is followed.

The GBR is forecasted to eventually become a carbon source rather than a carbon sink under all the RCP pathways except for RCP 2.6. Our model predicts that while absorption rates are due to decline, they will remain negative in 2200, implying the GBR will still be able to absorb atmospheric CO_2. The incorporation of ERW will see absorption rates be 66.5% and 923.1% higher in 2100 and 2200 respectively, under the RCP 2.6 pathway. Even though CO_2 absorption rates are predicted to be lower than modern times, they are significantly greater than the anticipated rates under the control scenario.

Variability in the ecosystem's calcification rate and CO_2 flux is controlled by numerous factors such as oceanic mixing of the surface water, submarine groundwater discharge, and variability in coral species' responses (Cyronak, 2013; Silervman, 2012). Overall, diurnal and seasonal variability in both calcification and CO_2 flux rates have been observed from individual field studies across the GBR (Shaw, 2015). However, the absolute value of G_{net} and rate of changes with respect to Ω_{arag} have not been comparable between studies due to the differences in physical, chemical, and biological properties amongst community compositions (Shaw, 2015).

Conclusions

Although there has been an increase in the number of surveys across the GBR in response to disturbance events, particularly after the back-to-back mass bleaching events in 2016 and 2017, only 12% of the GBR has been surveyed in major global coral reef datasets (Abdo, 2020). While our model equations capture what is currently known about coral carbonate chemistry as a function of aragonite saturation, net ecosystem production, calcification rates, its results correlate satisfactorily with observations from previous studies (Andersson, 2013; Bach, 2019; Davis, 2019). The 2016 bleaching event saw the reef colonies within the northern third of the GBR experience the most severe bleaching with an estimated 30% decline in coral cover. Our results showed that this region of the GBR is most vulnerable to declines in aragonite saturation state even with the addition of ERW.

Our model also has underlying assumptions that may not directly correlate with the observed patterns of the GBR. By breaking down the GBR into five sections, there is a large grouping of different parts of the coral reef which may experience differential rates of decline for net ecosystem calcification and production. Within each section of the GBR, our model only generates predictions for the entire section as an average value, but in reality, there is a wide variability in the values observed amongst individual coral colonies and bay areas. Variability in biotic and abiotic factors amongst each section, as well as differences in individual species' tolerances will see individual colonies degrade at different rates depending on the topography, ocean currents, and ecosystem diversity.

The model additionally ran under the assumption that alkalinity from ERW was equally distributed amongst global rivers based on a constant discharge. Achieving a uniform global alkalinity distribution will be difficult to accurately accomplish due to numerous global environmental, social, and economic factors. Failing to reach this uniform alkalinity distribution would result in stronger degrading impacts on the GBR.

One of the major concerns for the future is that even the most optimistic emission trajectories under RCP 2.6 fail to remain within the carbon budget requirements for a 2°C warming limit through decarbonization alone (Peters, 2016). Improvements to the condition of the coral reef ecosystems can be achieved in the next 25-30 years, but only if restoration interventions are deployed concurrently with atmospheric CO_2 emission reduction methods (Abdo, 2020) As a minimum requirement, there must be an immediate reduction in carbon emission by 1-10% per year as the techno-economic assessments of the RCP 2.6 scenario suggests (Bach, 2019; Taylor, 2016; Rogeli, 2016).

While our model has suggested that ERW may provide a partial solution for ocean acidification further testing and verification in future experimental and observational studies is required. As the global environmental conditions change rapidly and abruptly, simulation models are only able to provide a snapshot prediction based on previous results. With growing global concerns about reaching a 2°C warming limit under the Paris RCP 2.6 agreement, the only way to accurately control and predict the health of coral reef ecosystems is through continuous and recurring monitoring amongst the entire biological system.

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