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Unifying framework for assessing sensitivity of marine calcifiers to ocean alkalinity enhancement identifies potential winners, losers and biological thresholds - importance of precautionary principle

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Abstract

Ocean alkalinity enhancement (OAE), one of the marine carbon dioxide removal strategies, is gaining importance in its role towards alleviating the consequences of climate change as well as mitigating against ocean acidification (OA). OAE is based on adding alkalinity to open-ocean and coastal marine systems through a variety of different approaches, which raises carbonate chemistry parameters (such as pH, total alkalinity, aragonite saturation state), and enhances the uptake of carbon dioxide (CO_2) from the atmosphere. There are large uncertainties in both short- and long-term outcomes related to potential environmental impacts, which would ultimately decide on the success of OAE as a climate strategy. This paper represents a synthesis effort, leveraging on the OA studies, data, observed patterns and generalizable responses. We propose a conceptual framework of categorized responses that are predicted under OAE implementation. The synthesis was done using raw experimental OA data based on 96 collected studies, capturing the responses of eleven biological groups (coralline algae, corals, dinoflagellates, mollusks, gastropods, pteropods, coccolithophores, annelids, crustacean, echinoderms, and foraminifera), using regression analyses to predict biological responses and thresholds to NaOH or Na_2CO_3 additions. Predicted responses were categorized into six different categories (linear positive and negative, threshold positive and negative, parabolic and neutral) to delineate species- and group-specific responders: 40% of species are predicted to respond positively (N=38), 20% of species negatively (N=20), and 40% (N=38) were found to demonstrate a neutral response upon alkalinity addition. For negatively impacted species, biological thresholds corresponding to 10 to 500 µmol/kg NaOH addition were found, occurring at much lower values than previously expected. Such lower threshold values represent realistic conditions related to OAE field deployments but contrast with the conditions where current OAE lab experiments are conducted. We thus explicitly emphasize the importance of including much lower additions of alkalinity in experimental trials to realistically evaluate *in situ* biological responses. Due to practicality and high correlation with $\Omega_{ar,}$ we propose using the TA:DIC ratio as a helpful proxy to explore regional applications and biological response to OAE. The ultimate goal of the study is to provide a framework that can serve as a tool for predicting biological responses and thresholds to delineate OAE risks, guide and prioritize future OAE biological research and regional OAE monitoring efforts. With 60% of species showing non-neutral response, a precautionary approach for OAE implementation is warranted, identifying the conditions where potential negative ecological outcomes could happen, which is key for scaling up while also avoiding potential risks.

https://doi.org/10.5194/egusphere-2024-947
Preprint. Discussion started: 17 April 2024

1. Introduction

Anthropogenic carbon dioxide (CO_2) emissions have increased at an unprecedented rate and have contributed to global climate change and negative ecological and biogeochemical impacts in the oceans (Feely et al., 2004; IPCC, 2021; Gattuso et al., 2018), to the extent of crossing six different planetary boundaries (Richardson et al., 2023). Oceans play a crucial role in attenuating the increase in atmospheric CO_2 through the absorption of the excess atmospheric CO_2 of roughly a quarter of anthropogenic carbon dioxide (CO_2) emissions, drawing down around 2–3 Pg C yr^{-1} in recent decades (Friedlingstein et al., 2022). However, without substantial CO_2 emissions abatement and CO_2 removal strategies, profound repercussions on climate, extreme weather events, and socioeconomic implications will follow. Ocean-based CO_2 removal and sequestration strategies (broadly referred to as marine CDRs) are among the proposed CDR approaches that remove CO_2 and store it for geologically relevant times (National Academies of Sciences, Engineering, and Medicine, 2021). mCDR approaches only complement CO_2 emission reductions and contribute to the portfolio of climate response strategies needed to meet the global goal of limiting warming to well below 2°C as established by the Paris Agreement (UNFCCC, 2015). Various mCDR approaches have unique benefits and costs but differ in their value depending on their state of implementation, and whether they act globally and/or locally (Oschlies et al., 2023).

Ocean alkalinity enhancement (OAE) has the potential to mitigate climate change through increasing ocean uptake of CO_2, while simultaneously reversing ocean acidification (OA), and improving marine habitats. Despite being in the concept stage, OAE is viewed with a high level of confidence as to its effectiveness, medium on environmental risk, but low on the underlying knowledge base (Gattuso et al., 2021; National Academies of Sciences, Engineering, and Medicine, 2021). The primary concerns for OAE are large uncertainties in both short- and long-term OAE outcomes related to potential environmental impacts of OAE (Kheshgi, 1995; Bach et al., 2019), especially if OAE were to induce novel conditions in the marine systems that are outside the range of the natural variability, exposing organisms to conditions not experienced in their evolutionary history. The outcome of OAE as a successful climate strategy depends on a thorough and advanced understanding, as yet absent, of the impacts of OAE implementation while avoiding negative biological effects. Unless OAE can be ensured not to show any serious negative impacts on marine organisms, OAE implementation could potentially be halted (Riebesell et al., 2023).

1.1 Leveraging ocean acidification research on marine calcifiers

Increased CO_2 uptake, which initially is absorbed by the ocean as dissolved CO_2, causes a decline in pH, shoaling of the saturation state horizon (Ω_{ar}) and reduced carbonate ion amount content in a process termed ocean acidification (OA) (Feely et al., 2004), causing negative consequences to marine biota, especially marine calcifiers, the structure and function of the vulnerable marine ecosystem, and alteration of the carbon cycle. On the other hand, chemical changes induced by OAE are inherently linked to reversing the OA process: increasing pH, shifting carbonate chemistry speciation towards lower aqueous carbon dioxide (pCO_2) and higher carbonate ion (CO_2^{3-}) amount contents, as well as higher aragonite saturation state (Ω_{ar}). Such changes could either be within the ranges of the variability of the natural systems to which species are

https://doi.org/10.5194/egusphere-2024-947
Preprint. Discussion started: 17 April 2024

acclimatized, or outside them, creating novel conditions for which species might not have developed suitable adaptation strategies. As such, the biological outcomes are, due to their complexity, highly unpredictable.

Scientific progress in over 20 years of OA research has brought substantial insights into the biological effects, with the most fundamental outcome being that calcifying organisms would be primarily affected (Riebesell and Gattuso, 2015), with the calcification process being one of the most susceptible pathways, underpinned by species differences in calcification mechanisms (Ries et al., 2009; 2011; Bach et al., 2013; 2015; Leung et al., 2022). However, OA focused heavily on investigating biological effects on the more acidic range of the carbonate chemistry conditions predicted under future scenarios and most of the studies focused on manipulating the level of pCO_2 rather than alkalinity. This resulted in poor understanding of the biological effects at the alkaline end of the carbon chemistry range (Renforth and Henderson, 2017). Some biological inferences can be made based on the understanding of the physiological mechanisms underlying the calcification mechanisms (Bach et al., 2019), but such insights do not provide sufficient understanding.

Despite the lack of biological data at the upper ranges of pH and Ω_{ar}, this study builds on the premise that previous OA studies could be leveraged to establish a framework of biological responses under OAE. Despite more nuanced species-specific responses, there are patterns of OA sensitivity that hold across the pathways as well as the functional groups (Ries et al., 2009; 2011). In addition, comparative experimental work, meta-analyses, and the threshold work (Kroeker et la., 2013; Leung et al., 2022; Bednaršek et al., 2019, 2020, 2021) have indicated that even very diverse responses can be grouped into categorical responses. This study aims at establishing a systematic framework for categorizing responses under OAE impact, specifically looking at the calcification rate responses.

1.2 Testable conceptual framework based on the existing OA studies

Based on Ries et al. (2009), calcification responses can be categorized into six categories (Fig. 1): linear positive or negative response; threshold positive or negative response (exponential fit); parabolic response; and neutral (no significant) response. We hypothesize that similar categories of responses, as delineated by Ries et al. (2009, 2011), could also be applicable to the OAE dosing. For this meta-analyses, we have undertaken three steps: first, synthetize carbonate chemistry data at regional and global scales to obtain TA, DIC and Ω_{ar} correlations; second, conduct a literature review and collect available data from OA literature related to the calcification rate responses across the species of eleven groups of marine calcifiers; and third, run regression analyses and determine the category of calcification rate response to TA:DIC, further extending it with addition of NaOH and Na_2CO_3. We propose to operate with the TA:DIC ratio because the TA:DIC ratio essentially controls the value of Ω_{ar} (Bach et al., 2019) even though alkalinity itself does not directly affect biological responses. Here, we demonstrate its relationship with biological outcomes and show the application for the TA:DIC thresholds beyond which the responses become negative. Ultimately, we synthesize which calcifying species or groups are predicted to benefit or lose to OAE, what constitutes a species-specific safe operating space related to the OAE and delineate what experiments are most urgently needed before massive OAE field implementation occurs.

2. Methodology

2.1 Extraction of the carbonate chemistry data from the GLODAP dataset

We extracted total alkalinity, dissolved inorganic carbon, Ω_{ar}, and pH from the Global Ocean Data Analysis Project GLODAPv2.2023 dataset (https://glodap.info). We used regression in MATLAB with a second-order polynomial equation to predict Ω_{ar} from the TA:DIC. The regression analysis was performed using data from various depth intervals (0–10m, 0–30m, 0–50m, 0–100m, 0–200m) regionally and globally. The regional analysis divided the global oceans into the following groupings: Arctic (north of 65°N), Southern (south of 40°S), North Pacific (north of 40°N), Central Pacific (40°S to 40°N), North Atlantic (North of 40°N), Central Atlantic (40°S to 40°N), and Indian Ocean (north of 40°S).

2.2 Literature review of ocean acidification data collection

To assess the impact of OAE on a range of marine calcifiers, we used existing studies on marine species calcification response that had aligned raw biological (calcification rate) data along with the carbonate chemistry. We searched within Scopus, Web of Science, and PubMed and then used the datasets that were archived in NCEI, OA-ICC and Pangea. Through personal correspondence, we have additionally contacted lead authors of the studies, whose data are not or are insufficiently archived, mostly to validate the predicted response. If we received data through this way, that was explicitly acknowledged in the dataset. These searches for the biological datasets related to calcification and corresponding carbonate chemistry were carried out until November 2023 and cover 96 existing studies, with the aim to cover a wide range of calcifying organisms across various functional groups and 82 species. This data was compiled, and units standardized where possible. The functional groups and categories of response were based on the typology of OA response as described by Ries et al. (2009) and Ries (2011).

The main issue when compiling data was the lack of standardization of the calcification rates. A variety of calcification rate units were used across different studies. Where possible, the units were converted to mmol of $CaCO_3$ g weight^{-1} hr^{-1}. However, the data required to do so was not always readily available. Other units used for calcification rate were mmol of $CaCO_3$ m^{-2} h^{-1} and mmol of $CaCO_3$ m^{-3} hr^{-1}, and there was also data used as an indication of calcification rate with units mmol/# h^{-1}, mmol h^{-1}, mmol/# h^{-1}, mmol cm^{-2}, % h^{-1}, where '#' indicates one individual. Growth rates were used as indicators of calcification rate for single-cell organisms. Data were analyzed on a species level. Where there were multiple studies available for the calcification rate of one species using the same rate units, the data were combined (see example for the coccolithophores). The final response for those species was chosen by the study with the most data points and lowest p-value.

2.3 Sorting species-specific responses into categories per calcification response

https://doi.org/10.5194/egusphere-2024-947
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As mentioned above, the categories of calcification rate responses were replicated based on Ries et al., (2009) the species' responses to Ω_{ar} were split into 6 categories (Fig. 1): linear positive and linear negative, parabolic, threshold positive and negative, and neutral, whatever was the best as determined by their respective regression models (using the ordinary least squares method in Statsmodels for Python, see Seabold et al. (2010)). The regression with the lowest mean squared error and highest goodness of fit (R^2) value was chosen as having the best fit. Where a linear regression having the best fit, we assigned a linear response, which could be either positive or negative based on the slope. The species with a significant exponential fit were categorized as threshold positive (+) or threshold negative (-) (Ries et al., 2009), which was distinguished from the parabolic response with the fitted parabolic curve.

The best fit regression was assigned to each species and plotted, but only if the p-value was considered significant, i.e. lower than 0.1. These regressions were plotted along with a 90% prediction interval, which accounts for the variability of the experimental data. The species with a p-value > 0.1 were categorized as having no correlation. The decision for greater than 0.05 p value was made because a lot of studies showed a strong trend in a response but were not significant at $p < 0.05$.

A more practical way of looking at the impacts of the OAE treatment is by using the changes in the TA:DIC ratio instead of using a single carbonate parameter because of the highly correlative relationship between them (Fig. 3). As such, regression models were also applied to TA:DIC vs calcification rate. Their best fit regressions and responses were the same as for Ω_{ar} vs calcification rate. See Fig. 1 for an overview of the responses of calcification rate to increasing Ω_{ar} and TA:DIC. For each regression, the Root Mean Square Error (RMSE) was computed.

The TA:DIC threshold was computed to indicate the point at which calcification rate is reduced by a half (linear negative and threshold negative), or as a point at which the calcification rate is predicted to change slope (see Supplementary Fig. 2, Tables 2, 3). Once the species' responses were determined, an attempt was made to group them based on functional groups. However, the wide range of species' responses per group meant the spread of data was often too large to see any meaningful overall response. Therefore, most of the analysis remained on the species level (Table 1).

https://doi.org/10.5194/egusphere-2024-947
Preprint. Discussion started: 17 April 2024

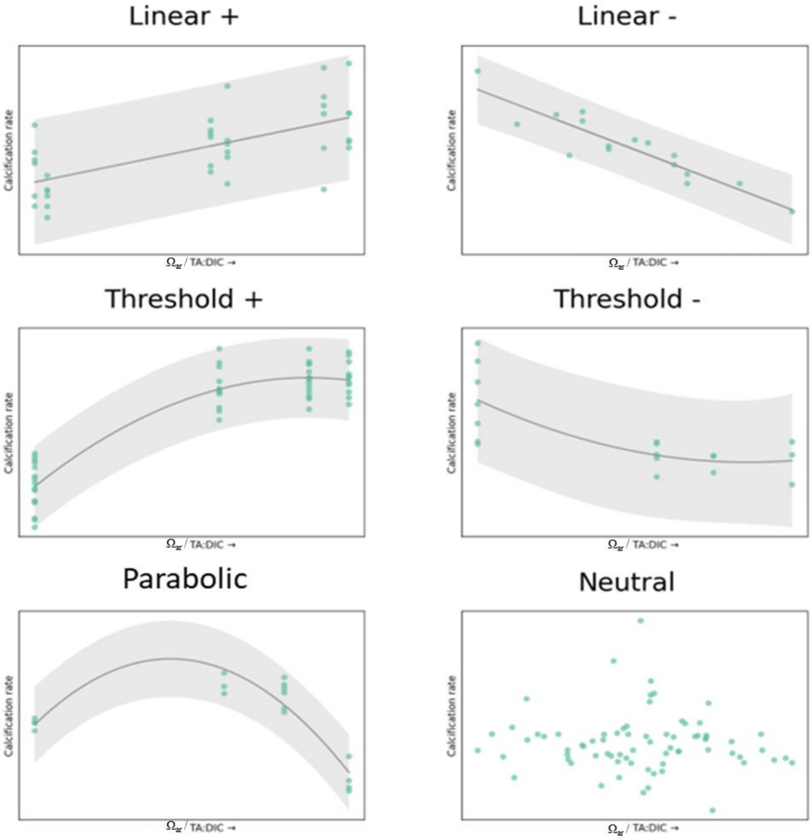


Figure 1: *Overview of the categories of responses between carbonate chemistry parameters (Ω_{ar} /TA:DIC) and calcification rate: linear positive (calcification increase at higher Ω_{ar}/TA:DIC), linear negative (calcification decrease at higher Ω_{ar}/TA:DIC), exponential for the threshold positive response (calcification increase with plateauing at higher Ω_{ar}/TA:DIC), exponential for the threshold negative response (calcification decline with plateauing at lower Ω_{ar}) and parabolic (calcification increase followed by a decrease at higher Ω_{ar}/TA:DIC). Responses were only considered significant when $p < 0.1$, otherwise they were categorized as neutral.*

2.4 Conceptual framework to evaluate increases in TA:DIC

The regression models applied to each species could be used to predict calcification rates at higher TA:DIC ratio. We added alkalinity at the average of the response form OA dataset, and this was computed for each functional group, representing a baseline for NaOH additions. From this baseline, TA was added in the form of both NaOH and Na_2CO_3. These two compounds were chosen as they differentially change the carbonate chemistry settings, with NaOH changing TA:DIC in the 1:1 ratio, while Na_2CO_3inducing 2:1 TA:DIC change. For example, 10 µmol/kg of NaOH addition will increase TA by 10 µmol/kg and not affect DIC. For Na_2CO_3, 10 µmol/kg

https://doi.org/10.5194/egusphere-2024-947
Preprint. Discussion started: 17 April 2024

addition will increase TA by 10 µmol/kg and increase DIC by 5 µmol/kg. The Deffeyes diagrams presented in Schulz et al. (2023) demonstrated the usefulness of this approach. For both NaOH and Na_2CO_3, 10 µmol/kg was conceptually added, and the carbonate system was recomputed. This was repeated for increments of 100 µmol/kg up until a total of 500 µmol/kg. The new TA:DIC ratios were estimated using the ratio of the new TA and DIC by adding the direct effect of ΔTA and ΔDIC due to chemical additions of NaOH (assume $\Delta DIC=0$) or Na_2CO_3 (assume $\Delta DIC=0.5*\Delta TA$). A maximum of 500 µmol/kg was chosen to have more realistic additions of TA that resemble those appropriate within the OAE field trials (e.g. Wang et al., 2023).

With the new TA:DIC ratios after TA addition, the species' regression models based on the fitted OA response data were used to compute respective calcification rates (note that added points with NaOH or Na_2CO_3 were not calculated as part of the regression). These data points were all plotted along with the experimental data, regression model and prediction intervals as shown in Fig. 2. The TA:DIC values at which the prediction interval exceeds four standard deviation were also calculated to indicate the limit of what TA:DIC we can accurately predict calcification rates.

2.5 Evaluation of the biological responses based on the OAE addition

The species with significant correlations were grouped visually based on their best-fit regression models and are classified into positive, negative, and neutral as the following:

1) *Positive responders*: species with predicted linear positive and threshold positive calcification rate response corresponding with increased TA addition.
2) *Negative responders*: species with predicted *linear negative, parabolic and threshold negative response* in calcification rate upon TA addition. For the parabolic and threshold negative response, a concentration of NaOH was determined that indicates the threshold in TA:DIC ratio beyond which the response becomes negative. Additionally, NaOH concentration was determined to reduce the calcification rate to a half, with the threshold at the corresponding TA:DIC.
3) *Neutral responders:* species with *no significant correlation* ($p < 0.05$) in calcification rate upon TA addition.

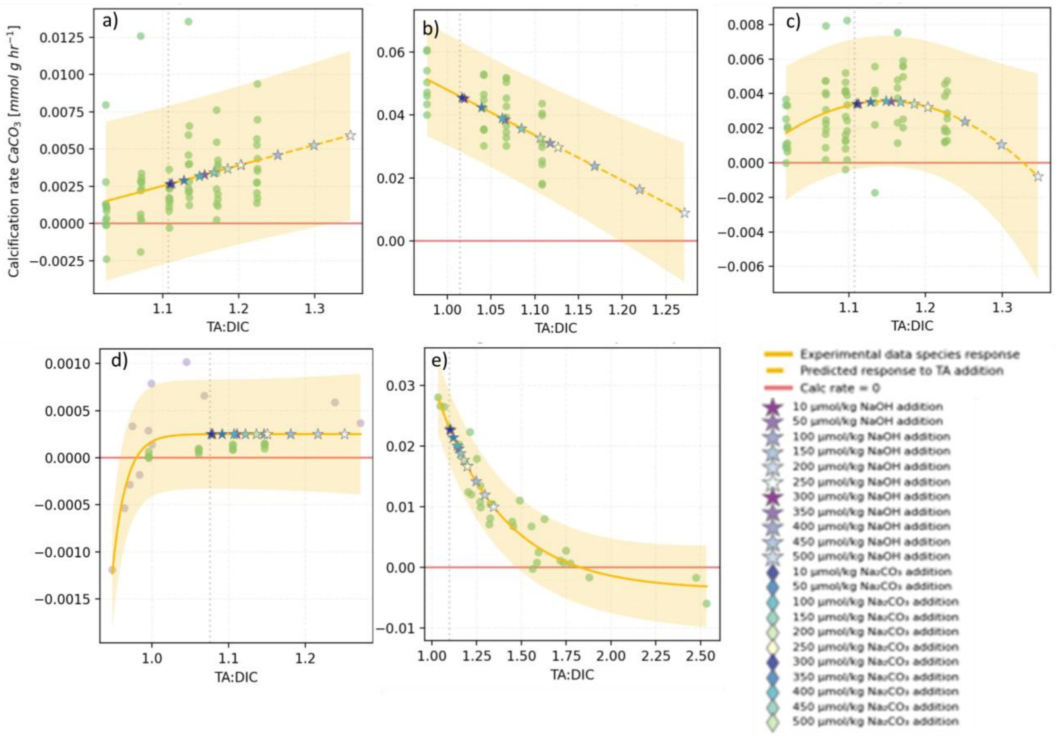


Figure 2: *Conceptual diagram to show how experimental data, predicted values at various additions of alkalinity, the regression line and prediction error margins are fitted for a) linear positive; b) linear negative; c) parabolic; d) exponential for with threshold positive; e) exponential for negative with threshold negative. The uncertainty interval indicates four standard deviations. Blue horizontal dotted line indicates reduction of calcification rate to half of its values, and the red line indicates zero net dissolution (calcification rate is equal to 0; dissolution rate = calcification rate).*

3. Results

3.1 Global and regional carbonate chemistry data coverage

The compilation of chemical observational data (pH, Ω_{ar}, TA, DIC) was done for the GLODAP data across the regional ocean and global scales to determine the range of Ω_{ar}, TA and DIC (as represented by the TA:DIC ratio) and TA:DIC vs Ω_{ar} correlation down to the depths averaged over 200 m. Here, we focus on showing the results ranging over the 0–50m because this covers most of the biological habitat for examined species and it is where the OAE enhancement would induce the greatest changes. Over the 0–50 m depth, Ω_{ar} ranges from 0.2 to 5 and TA:DIC ranges from 0.1 to 1.25 and both parameters are correlated across all the regions, as demonstrated by the fitted second-order polynomial regressions, with R^2 of 0.96 or higher, and all the correlations being significant (Fig. 3), with regional specific relationships not impacting the fit. All the correlation

https://doi.org/10.5194/egusphere-2024-947
Preprint. Discussion started: 17 April 2024

parameters are presented in Supplementary Table 1. Similar fits were found at different depths. The conditions in the higher latitude regions are located at the lower range of Ω_{ar} vs TA:DIC, while the conditions in the low latitudes and temperate regions are at the upper range, with the highest values present in the central Atlantic and Pacific region.

Such strong correlation as observed for Ω_{ar} vs TA:DIC does not exist with pH, regardless of the depth interval examined. While the correlations are still significant, they are broadly distributed and represented over a shorter TA:DIC range, with significantly lower goodness of fit (Supplementary Fig. 1), with the correlations being highly regionally dependent due to pH and temperature co-linearity. Because of this, all further biological analyses are only done using the Ω_{ar} vs TA:DIC ratio.

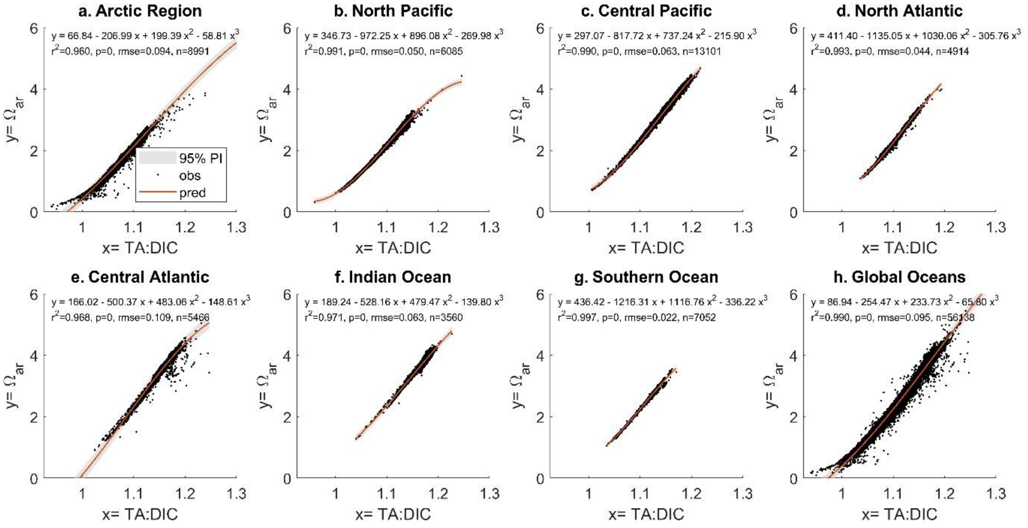


Figure 3: *The range of observed Ω_{ar} and DIC and TA values (as represented by the TA:DIC ratio) values and the relationship with the best fitted curve between Ω_{ar} vs TA:DIC across regional (a-g) and global (h) scales based on the observational GLODAP dataset averaged over 0-50 m depth.*

3.2 Biological experimental data from the OA studies

Biological data from the OA experimental studies was compiled to determine the range of Ω_{ar} experimental conditions used and their TA:DIC relationship (Fig. 4). Most studies covered pH conditions up to 8.5 and Ω_{ar} up to 5, with a few studies increasing pH up to 8.8 and Ω_{ar} of 15. This indicates the potential of leveraging such experimental studies as a baseline for predictive regression models of biological responses to a range of Ω_{ar} conditions, as expected under OAE studies. We also observed that experimental data ranges were not always consistent with natural conditions, for example, having a lower Ω_{ar} at a higher TA:DIC ratio.

In addition, plotting biological data from the OA datasets against the regional and global TA:DIC gradient (Fig. 8), it is obvious that various biological groups are clustered around specific TA:DIC ratios, for example, mollusks and corals are represented on the lower and higher TA:DIC gradients, respectively, while dinoflagellates are randomly scattered off the TA:DIC line. This indicates that there is a general lack of data distribution in the upper ranges of TA:DIC ratio, especially for the groups that are lying at the lower and mid end of the TA:DIC ratio spectra.

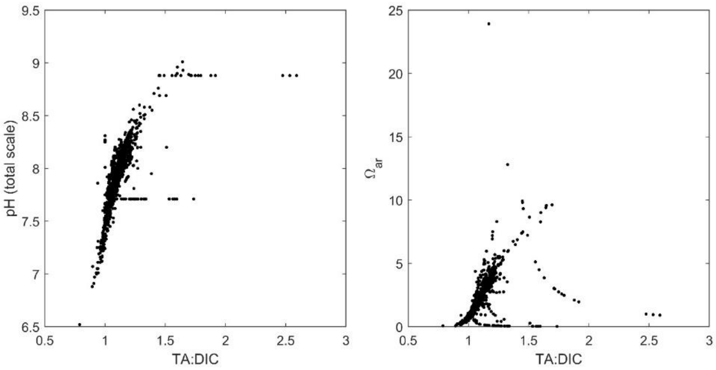


Figure 4: *Chemical data for TA:DIC vs Ω_{ar} used in the experimental OA treatments.*

3.3 Data collection for the calcification rate responses of different biological groups

We examined 96 datasets, which covered 82 different species that were divided into 9 different groups (Fig. 5). These functional groups were corals (26% of datasets), calcifying algae (15%), mollusks (16%), foraminifera (10%), dinoflagellates (10%), coccolithophores (6%), gastropods (5%), crustaceans (5%), echinoderms (4%), pteropods (1%), and annelids (1%). In the mollusks group, we have separated out the gastropod and pteropod because there of a higher number of studies that explicitly cover for these two groups. The group of gastropods refers to all gastropods that are not pteropods. If all three groups were combined (mollusks, gastropods, pteropods), this group would be the second most representative.

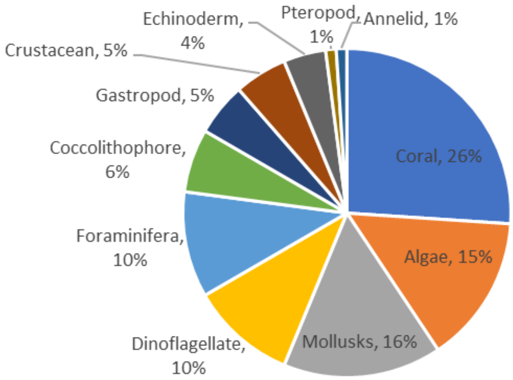


Figure 5: *Percent of studies for multiple groups (N=11) with available data for the calcification rate responses as part of data compilation of 98 studies).*

3.4 Species-specific responses to NaOH/Na_2CO_3 addition

Calcification rate responses of species from different groups were correlated to Ω_{ar} vs TA:DIC and summarized to obtain calcification rate response (Figs. 1, 2; Table 1). The calcification rate responses encompassed linear (positive and negative), exponential (positive and negative), parabolic, and neutral responses, with the slope and the intercept of the response determining the type and the magnitude of the response. We present fitted responses of calcification rate per TA:DIC ratio for each examined species (Table 1, Supplementary Fig. 2). When possible, we fitted a regression to multiple datasets of the same species that used the same units. We also present the response with the additions of NaOH and Na_2CO_3 on a species level (Supplementary Fig. 2) and their biological TA:DIC thresholds (Table 2). The uncertainty of the responses was evaluated as the prediction interval where four standard deviation intervals are exceeded, which indicated the maximum ratio that allows for accurate prediction of the calcification rate.

Within each of the 11 groups, several categories of calcification response occur within each functional group, with the most varied being the group of coralline algae, dinoflagellates, foramenifera and mollusks, with each of them showing 4 or 5 different categories of calcification responses (Fig. 6). Of the six types of responses of calcification rate vs TA:DIC, 28% were linear positive (N=27), 10% linear negative (N=10), 12% threshold positive (N=11), 3% threshold negative (N=3), 7% parabolic (N=10) and 40% neutral (N=38).

Table 1: *This table includes all the studies OA data was collected, the name of the species and group it belongs to, and the accompanying calcification rate unit. The most significant regressions (with at least $p < 0.1$) per species and rate unit are shown, the p-value, goodness of fit (R^2) and Root Mean Square Error (RMSE). The type of regression (linear positive or negative, threshold positive or negative, parabolic, and neutral (not significant) as well as an overall response (positive, negative, neutral) is indicated.*

Studies	# Datapoints	Group	*Species*	Rate unit	Response	Type of response	p-value	R2	rmse
Camp et al. (2017)	2	Coral	*Acropora formosa*	[mmol/m-2/hr]	neutral	Neutral			
Meyer et al. (2016)	24	Coral	*Acropora millepora*	[mmol/m-2/hr]	neutral	Neutral			
Camp et al. (2017), Comeau et al. (2013)	74	Coral	*Acropora pulchra*	[mmol/m-2/hr]	exponential +	Positive	0	0.29	1.330E+03
Agostini et al. (2021)		Coral	*Acropora solitaryensis*	[mmol/m-2/hr]	neutral	Neutral			
Comeau et al. (2018), Comeau et al. (2019)	81	Coral	*Acropora yongei*	[mmol/m-2/hr]	linear +	Positive	0	0.29	1.945E+04
Tatters et al. (2013)	45	Dinoflagellate	*Alexandrium sp.*	[1/hr]	neutral	Neutral			
Keul et al. (2013)	205	Foraminifera	*Ammonia sp.*	[mmol/m-3/hr]	linear -	Negative	0.028	0.02	2.16E+10
Pansch et al. (2014)	36	Crustacean	*Amphibalanus*	[mmol/g/hr]	linear +	Positive	0	0.43	4.444E-04
Vasquez-Elizondo et al. (2015)	4	Algae	*Amphiroa tribulus*	[mmol/m**2/hr]	neutral	Neutral			
Prazeres et al. (2015)	32	Foraminifera	*Amphistegina lessonii*	[%/hr]	parabolic	Negative	0.001	0.39	1.038E-03
Ries et al. (2009)	17	Echinoderm	*Arbacia punctulata*	[mmol/g/hr]	parabolic	Negative	0	0.89	3.114E-04
Ries et al. (2009)	18	Mollusks	*Argopecten irradians*	[mmol/g/hr]	linear +	Positive	0.01	0.35	1.692E-04
Ramajo et al. (2016)	6	Mollusks	*Argopecten purpuratus*	[mmol/g/hr]	linear -	Negative	0.075	0.59	1.22E+10
Zhang et al. (2011)	5	Mollusks	*Azumapecten farreri*	[mmol/g/hr]	linear +	Positive	0.011	0.92	6.81E+10
Fiorini et al. (2011), Langer et al. (2011)	8	Coccolithophore	*Calcidiscus leptoporus*	[mmol/#/hr]	neutral	Neutral			
Langer et al. (2006)	6	Coccolithophore	*Calcidiscus leptoporus*	[mmol/m-3/hr]	neutral	Neutral			
Ries et al. (2009)	36	Crustacean	*Callinectes sapidus*	[mmol/g/hr]	linear -	Negative	0	0.4	8.195E-03
Hansen et al. (2007)	19	Dinoflagellate	*Caratium lineatum*	[#/hr]	exponential -	Negative	0	0.69	4.156E-03
Ong et al. (2017)	24	Mollusks	*Cerastoderma edule*	[mmol/g/hr]	neutral	Neutral			
Sordo et al. (2021)	27	Mollusks	*Chamelea gallina*	[mmol/g/hr]	neutral	Neutral			
Langer et al. (2006)	3	Coccolithophore	*Coccolithus pelagicus*	[mmol/h]	neutral	Neutral			
Camp et al. (2017)	2	Coral	*Coelastrea aspera*	[mmolm-2/hr]	neutral	Neutral			
Manriquez et al. (2016)	74	Gastropod	*Concholepas*	[mmol/g/hr]	linear +	Positive	0	0.24	9.395E-04
Gazeau et al. (2007)	20	Mollusks	*Crassostrea gigas*	[mmol/g/hr]	linear +	Positive	0	0.61	3.79E+10
Ries et al. (2009), Waldbusser et al. (2011)	28	Mollusks	*Crassostrea virginica*	[mmol/g/hr]	exponential +	Positive	0	0.56	2.611E-04
Noisette et al. (2016), Ries et al. (2009)	173	Gastropod	*Crepidula fornicata*	[mmol/g/hr]	exponential +	Positive	0	0.19	2.799E-03
Garilli et al. (2015)		Mollusks	*Cyclope neritea*	[mmol/g/hr]	neutral	Neutral			
Bove et al. (2020)	27	Coral	*Duncanopsammia*	[mmolm-2/hr]	linear +	Positive	0.002	0.33	5.075E+04
Courtney et al. (2015)	28	Echinoderm	*Echinometra viridis*	[%/h]	linear +	Positive	0.001	0.35	1.304E+04
Courtney et al. (2021)	4	Echinoderm	*Echinometra viridis*	[1/hr]	linear +	Positive	0.024	0.95	2.385E+03
[illegible]	111	Coccolithophore	*Emiliania huxleyi*	[mmol/m-3/hr]	parabolic	Negative	0.013	0.09	6.460E+03
Ries et al. (2009)	18	Echinoderm	*Eucidaris tribuloides*	[mmol/g/hr]	exponential +	Positive	0	0.84	3.592E-04
Kisakurek et al. (2011)	16	Foraminifera	*Globigerinella*	[mmol/hr]	neutral	Neutral			
Kisakurek et al. (2011)	14	Foraminifera	*Globigerinoides ruber*	[mmol/hr]	neutral	Neutral			
Cornwall et al. (2018)	44	Coral	*Goniopora sp.*	[mmolm-2/hr]	neutral	Neutral			
Tatters et al. (2013)	45	Dinoflagellate	*Gonyaulax sp.*	[1/hr]	neutral	Neutral			
Sinutok et al. (2011)	16	Algae	*Halimeda cylindracea*	[mmol/hr]	neutral	Neutral			
Meyer et al. (2016	71	Algae	*Halimeda macroloba*	[mmolm-2/hr]	linear -	Negative	0.616	0.01	9.476E-03
Comeau et al. (2013)	24	Algae	*Halimeda macroloba*	[mmol/g/hr]	parabolic	Negative	0.013	0.12	2.774E-03
Sinutok et al. (2011)	16	Algae	*Halimeda macroloba*	[mmol/g/hr]	parabolic	Negative	0.011	0.5	1.447E-04
Comeau et al. (2013)	62	Coral	*Halimeda minima*	[mmol/g/hr]	neutral	Neutral			
Meyer et al. (2016)	24	Algae	*Halimeda opuntia*	[mmolm-2/hr]	linear +	Positive	0.008	0.28	2.218E-02
Hansen et al. (2007)	31	Dinoflagellate	*Heterocapsa triquetra*	[#/hr]	exponential -	Negative	0	0.91	2.722E-03
Ries et al. (2009)	18	Crustacean	*Homarus americanus*	[mmol/g/hr]	linear -	Negative	0.001	0.48	7.901E-03
Ries et al. (2009)	41	Annelid	*Hydroides crucigera*	[mmol/g/hr]	linear +	Positive	0.073	0.08	2.669E-04
Comeau et al. (2013)	72	Coral	*Hydrolithon reinboldii*	[mmol/g/hr]	linear +	Positive	0.005	0.11	2.586E-03
Cornwall et al. (2018)	23	Coral	*Hydrolithon reinboldii*	[mmolm-2/hr]	neutral	Neutral			
Wang et al. (2019)	4	Dinoflagellate	*Karenia mikimotoi*	[/hr]	linear -	Negative	0.063	0.88	4.947E-04
Comeau et al. (2009), Comeau et al. (2010)	12	Pteropod	*Limacina helicina*	[mmol/g/hr]	linear +	Positive	0	0.85	8.430E+10
Tatters et al. (2013)	45	Dinoflagellate	*Lingulodinium*	[1/hr]	neutral	Neutral			
Comeau et al. (2013)	72	Coral	*Lithophyllum flavescens*	[mmol/g/hr]	exponential +	Positive	0.068	0.08	1.852E-03
Johnson et al. (2021)	420	Algae	*Lithophyllum sp.*	[mmol/g/hr]	linear +	Positive	0	0.1	1.136E-01
Johnson et al. (2018)	99	Algae	Lithophyllum sp.	[mmol/cm-2]	neutral	Neutral			
Vasquez-Elizondo et al. (2015)	4	Algae	*Lithothamnion sp.*	[mmolm-2/hr]	neutral	Neutral			
Ries et al. (2009)	42	Gastropod	*Littorina littorea*	[mmol/g/hr]	linear +	Positive	0	0.34	1.720E-04
Reymond et al. (2013)	179	Foraminifera	*Marginopora rossi*	[%/hr]	linear +	Positive	0	0.19	8.962E-03
Prazeres et al. (2015)	47	Foraminifera	*Marginopora vertebralis*	[%/hr]	linear -	Negative	0.001	0.33	5.481E-04
Uthicke and Fabricius et al. (2012)	47	Foraminifera	*Marginopora vertebralis*	[mmol/g/hr]	linear +	Positive	0	0.27	4.304E-04
Sinutok et al. (2011)	16	Foraminifera	*Marginopora vertebralis*	[mmol/hr]	neutral	Neutral			
Ries et al. (2009)	25	Mollusks	*Mercenaria mercenaria*	[mmol/g/hr]	exponential +	Positive	0	0.83	2.880E+11
Bove et al. (2020)	65	Coral	*Montastraea cavernosa*	[mmolm-2/hr]	linear +	Positive	0.015	0.09	5.047E-01
Ries et al. (2009)	14	Mollusks	*Mya arenaria*	[mmol/g/hr]	linear +	Positive	0	0.73	3.375E-04
Ninokawa et al. (2019)	13	Mollusks	Mytilus californianus	[mmolm-2/hr]	neutral	Neutral			
Ries et al. (2009), Gazeau et al. (2007)	86	Mollusks	*Mytilus edulis*	[mmol/g/hr]	linear +	Positive	0.012	0.07	1.739E-04
Gazeau et al. (2014)		Mollusks	*Mytilus galloprovincialus*	[mmolm-2/hr]	neutral	Neutral			
Garilli et al. (2015)		Mollusks	Nassarius corniculus	[mmol/g/hr]	neutral	Neutral			
Manno et al. (2012)	192	Foraminifera	*Neogloboquadrina*	[mmol/m-3/hr]	linear +	Positive	0	0.71	1.180E+09
Monserrat et al. (2022)	62	Algae	Neogoniolithon brassica-	[mmolm-2/hr]	neutral	Neutral			
Vasquez-Elizondo et al. (2015), Comeau et al. (2018)	26	Algae	*Neogoniolithon sp.*	[mmolm-2/hr]	neutral	Neutral			
Ries et al. (2009)	42	Algae	*Neogoniolithon sp.*	[mmol/g/hr]	parabolic	Negative	0	0.41	3.301E-04
Ries et al. (2009)	54	Coral	*Oculina arbuscula*	[mmol/g/hr]	exponential +	Positive	0	0.86	9.680E+10
Oron et al. (2020)	96	Foraminifera	*Operculina ammonoides*	[mmol/g/hr]	linear -	Negative	0.003	0.09	1.719E-03
Comeau et al. (2013)	72	Coral	*Pavona cactus*	[mmol/m-2/hr]	exponential +	Positive	0	0.21	9.124E-01
Cameron et al. (2019)	30	Mollusks	Pecten maximus	[mmol/g/hr]	neutral	Neutral			
Ries et al. (2009)	12	Crustacean	*Penaeus plebejus*	[mmol/g/hr]	linear -	Negative	0.012	0.48	6.279E-04
Comeau et al. (2019)	49	Coral	*Plesiastrea versipora*	[mmolm-2/hr]	linear +	Positive	0.007	0.15	6.003E-01
Casareto et al. (2009)	14	Coccolithophore	*Pleurochrysis carterae*	[mmol/m-3/hr]	neutral	Neutral			
Brown et al. (2022)	4	Coral	*Pocillopora damicornis*	[mmol/g/hr]	neutral	Neutral			
Comeau et al. (2013), Putnam-Gates et al. (2015), Comeau et al. (2018)	117	Coral	*Pocillopora damicornis*	[mmolm-2/hr]	neutral	Neutral			
Evensen-Edmunds et al. (2016)	60	Coral	*Pocillopora verrucosa*	[mmolm-2/hr]	linear +	Positive	0.013	0.1	0.82969291
Agostini et al. (2021)	35	Coral	*Porites heronensis*	[mmol/m-2/hr]	neutral	Neutral			
Camp et al. (2017)	2	Coral	*Porites lutea*	[mmolm-2/hr]	neutral	Neutral			
Comeau et al. (2013)	72	Coral	*Porites rus*	[mmol/m-2/hr]	linear +	Positive	0.002	0.13	2.028E+04
Briggs-Carpenter et al. (2019), Johnson et al. (2014)	431	Algae	*Porolithon onkodes*	[mmol/m-2/hr]	linear +	Positive	0.001	0.03	8.093E-01
Tatters et al. (2013)	45	Dinoflagellate	*Prorocentrum micans*	[1/hr]	neutral	Neutral			
Hansen et al. (2007)	21	Dinoflagellate	*Prorocentrum minimum*	[mmol/#/h]	exponential -	Negative	0	0.88	1.877E-03
Findlay et al. (2010)	6	Crustacean	*Semibalanus balanoides*	[mmol/g/hr]	neutral	Neutral			
Okazaki et al. (2013)	75	Coral	*Siderastrea radians*	[mmol/m-2/hr]	linear +	Positive	0	0.16	2.788E+03
Okazaki et al. (2013)	64	Coral	*Solenastrea hyades*	[mmolm-2/hr]	exponential +	Positive	0	0.23	2.038E+03
Comeau et al. (2018), Comeau et al. (2019)	64	Algae	*Sporolithon durum*	[mmol/m-2/hr]	exponential +	Positive	0.007	0.15	1.751E-01
Ries et al. (2009)	21	Gastropod	*Strombus alatus*	[mmol/g/hr]	exponential +	Positive	0	0.7	8.77E+10
Krueger et al. (2017)	36	Coral	*Stylophora pistillata*	[mmolm-2/hr]	neutral	Neutral			
Brading et al. (2011)	175	Dinoflagellate	*Symbiodinium sp.*	[#/hr]	linear -	Negative	0.001	0.06	6.632E-03
Fiorini et al. (2011)	2	Coccolithophore	*Syracosphaera pulchra*	[mmol/#/hr]	neutral	Neutral			
Van de Waal et al. (2013)	12	Dinoflagellate	*Thoracosphaera heimii*	[mmol/m-3/hr]	parabolic	Negative	0	0.85	8.16E+07
Ries et al. (2009)	33	Gastropod	*Urosalpinx cinerea*	[mmol/g/hr]	linear +	Positive	0	0.57	8.67E+09

Such responses could be further summed up into positive (linear and threshold positive), negative (linear and threshold negative, parabolic) and neutral responses (Fig. 7) when generalized across the calcification rate against the TA:DIC ratio. Such a summary of responses shows 39.5% species to respond positively (N=38), 21% species to respond negatively (N=20), while 39.5% showed a neutral response (N=38).

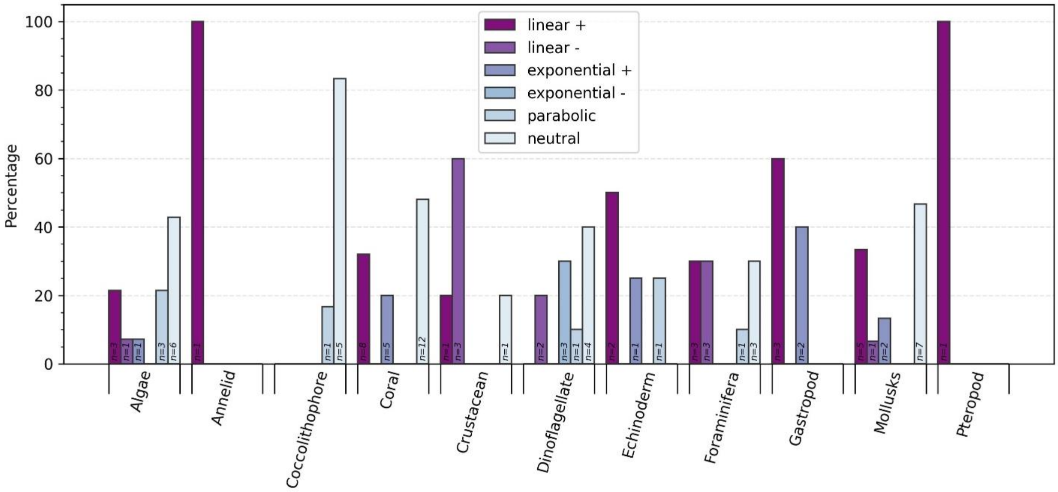


Figure 6: *Categories of calcification rate responses and percentage (%) response across eleven groups (calcifying coralline algae, annelids, coccolithophores, corals, crustaceans, dinoflagellate, echinoderms, foraminifera, gastropods, mollusks, pteropods). The number on the bar indicates the number of studies of species included.*

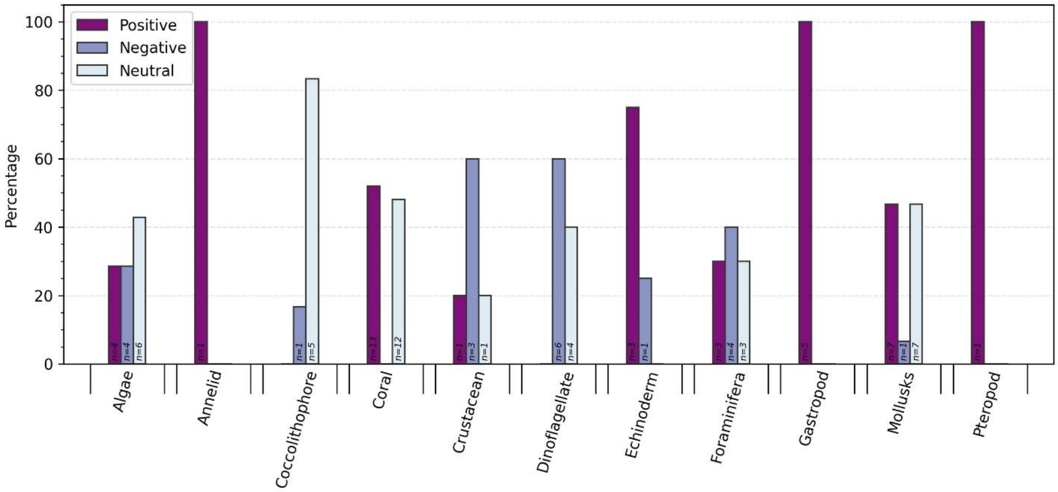


Figure 7: *Summary of percentage (%) responses in calcification rates as positive (linear and threshold positive), negative (linear and threshold negative, parabolic) and neutral across eleven groups (calcifying algae, annelids, coccolithophores, corals, crustaceans, dinoflagellate,*

echinoderms, foraminifera, gastropods, mollusks, pteropods). The number on the bar indicates the number of studies with species *included.*

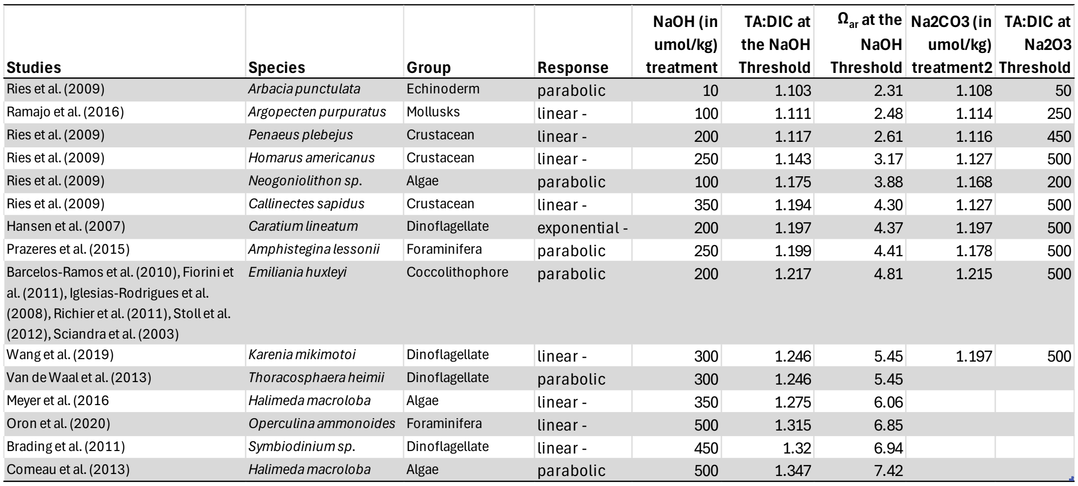
3.5 Evaluating responses to NaOH/Na_2CO_3 additions

Upon added TA, the calcification rate in positive responders will increase, either in a linear or threshold positive response, where calcification plateaus at some point, depending on the species-specific rate of response (Figs. 1, 2, Supplementary Fig. 2). The negative responders (linear or threshold negative and parabolic) will be negatively impacted as follows: first, for the linear negative responders, addition of the Na_2CO_3 will linearly decrease calcification rate, but there is no associated threshold to it; second, for the threshold negative responders, calcification rate will decline in an exponential way until reaching a DIC:TA value, where the response plateaus; third, for the parabolic responders, the calcification rate will initially increase until reaching certain TA:DIC threshold upon which calcification starts declining. We conclude that all the TA:DIC thresholds for negative responders will be species-specific (Table 2).

3.6 Threshold values indicative of negative biological response to OAE

The metrics to evaluate the sensitivity of calcification rate of the negative responders in this study were based on the amount of NaOH or Na_2CO_3 addition required to reduce calcification rate to a half. The greater the TA:DIC ratio value to trigger half calcification rate reduction, the less sensitive species was to NaOH addition (Table 2). The lowest TA:DIC ratio value was found for the species with parabolic and linear negative responses, followed by those with an exponential negative response. The lowest TA:DIC sensitivities ranged from 10 to 100 µmol/kg of NaOH additions, demonstrated for echinoderms, mollusks and red coralline algae. In the range of NaOH additions of 200–500 µmol/kg, dinoflagellates, coccolithophores, crustaceans, green calcifying and foraminifera were found (Supplementary Fig. 2, Table 2).

Table 2: *Studies with negative responders (linear and threshold negative, parabolic) with demonstrated TA:DIC thresholds, indicating the amount for NaOH or Na_2CO_3 needed to reduced calcification rate to half. The value for the TA:DIC threshold is related to the aragonite saturation state.*



Studies	Species	Group	Response	NaOH (in umol/kg) treatment	TA:DIC at the NaOH Threshold	Ω_{ar} at the NaOH Threshold	Na2CO3 (in umol/kg) treatment2	TA:DIC at Na2O3 Threshold
Ries et al. (2009)	*Arbacia punctulata*	Echinoderm	parabolic	10	1.103	2.31	1.108	50
Ramajo et al. (2016)	*Argopecten purpuratus*	Mollusks	linear -	100	1.111	2.48	1.114	250
Ries et al. (2009)	*Penaeus plebejus*	Crustacean	linear -	200	1.117	2.61	1.116	450
Ries et al. (2009)	*Homarus americanus*	Crustacean	linear -	250	1.143	3.17	1.127	500
Ries et al. (2009)	*Neogoniolithon sp.*	Algae	parabolic	100	1.175	3.88	1.168	200
Ries et al. (2009)	*Callinectes sapidus*	Crustacean	linear -	350	1.194	4.30	1.127	500
Hansen et al. (2007)	*Caratium lineatum*	Dinoflagellate	exponential -	200	1.197	4.37	1.197	500
Prazeres et al. (2015)	*Amphistegina lessonii*	Foraminifera	parabolic	250	1.199	4.41	1.178	500
Barcelos-Ramos et al. (2010), Fiorini et al. (2011), Iglesias-Rodrigues et al. (2008), Richier et al. (2011), Stoll et al. (2012), Sciandra et al. (2003)	*Emiliania huxleyi*	Coccolithophore	parabolic	200	1.217	4.81	1.215	500
Wang et al. (2019)	*Karenia mikimotoi*	Dinoflagellate	linear -	300	1.246	5.45	1.197	500
Van de Waal et al. (2013)	*Thoracosphaera heimii*	Dinoflagellate	parabolic	300	1.246	5.45		
Meyer et al. (2016	*Halimeda macroloba*	Algae	linear -	350	1.275	6.06		
Oron et al. (2020)	*Operculina ammonoides*	Foraminifera	linear -	500	1.315	6.85		
Brading et al. (2011)	*Symbiodinium sp.*	Dinoflagellate	linear -	450	1.32	6.94		
Comeau et al. (2013)	*Halimeda macroloba*	Algae	parabolic	500	1.347	7.42		

3.7 Applications of the TA:DIC thresholds related to added NaOH/Na_2CO_3

The DIC:TA thresholds associated with NaOH or Na_2CO_3 addition were applied to assess over what carbonate chemistry conditions and species' habitats the negative biological effects of OAE deployment might happen. We extracted Ω_{ar} vs TA:DIC conditions of the upper 50 m of the water column characteristic for the global ocean conditions, which were derived from the GLODAP dataset and overlaid TA:DIC thresholds for the negative responders and associated amounts of NaOH dosing on top (Fig. 8). We emphasize that we used global data to showcase the application of the thresholds but note that the crossing of the thresholds will be regionally specific.

Some of the TA:DIC thresholds are in the range of 1.108 to 1.2, triggered by lower, i.e. 10–200 µmol/kg NaOH additions, indicating the most sensitive species of the echinoderm *Arbacia punctulata*, crustacean *Panaeus plebejus and* mollusks *Argopecten purpuratus* (Table 2). Most of the thresholds are in the upper range of the observational data, i.e. the TA:DIC of 1.2 and 1.25, triggered by the additions of 250–350 µmol/kg of NaOH. This suggests that for some species a very low dosing is needed to cross the biological threshold in their respective habitats to negatively impact species' calcification rate. Thirds group of TA:DIC thresholds is positioned between 1.25 to 1.35, indicating species that are less sensitive to TA addition, even for additions of ~500 µmol/kg NaOH.

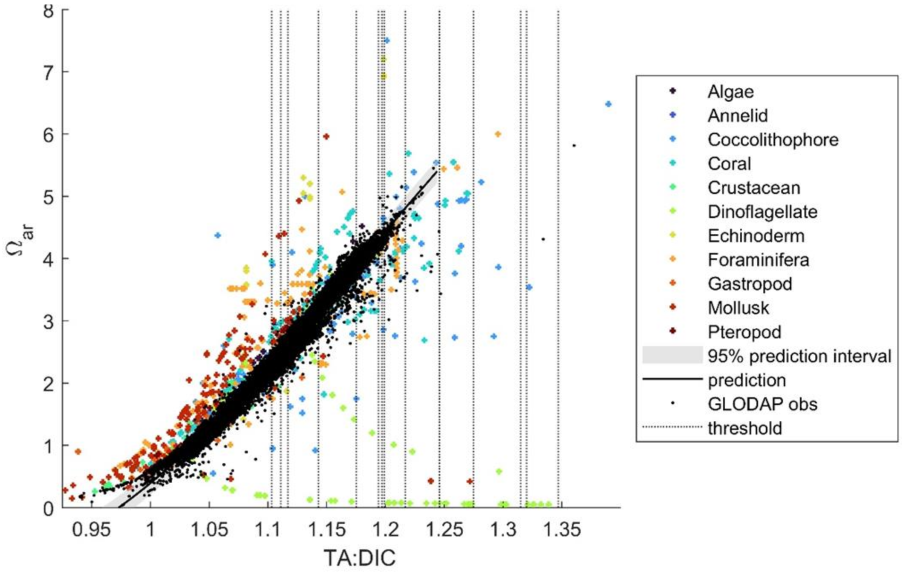


Figure 8: *Global representation of TA:DIC and* Ω_{ar} *data from GLODAP covering the upper 0-50 m depth with the fitted curve, overlaid with the experimental data (Figure 4) of eleven groups from the OA studies with overlaid TA:DIC thresholds associated with the addition of various NaOH dosing (Table 3).*

4. Discussion

OAE is a quickly developing strategy that is already in the field-testing phase despite extremely limited understanding of potential biological implications and environmental concerns. Hence, gaining insights of potential risks for the biological species and communities is essential and timely. In retrospect, it took several decades for the OA research community to get a more accurate and comprehensive understanding and predictions of biological responses to OA (Gattuso and Riebesell, 2015). Without a very clear conceptual strategy for the OAE testing, time scales and efforts might be comparable. Consequently, there is an essential need to develop a conceptual framework of predictive responses and testing appropriate to OAE, while will assist in OAE scaling while avoiding potential risks. This paper aims at developing such a framework, where responses are categorized per species responses against TA:DIC, which helps determine the levels of TA additions and also related thresholds.

4.1. Identified strengths and limitations of the synthesis approach based on OA studies

Prior to conducting this study, several drawbacks were identified that potentially limit such an undertaking: first, insufficient amount of data at the upper range of carbonate chemistry conditions (high pH, high Ω_{ar}); second, experimental data under conditions with no relevance to natural settings (Figs. 4, 8); and third, an insufficient number of validation studies under high TA conditions to validate the results of this meta-analyses study. To overcome the first two limitations, the decision was made to combine multiple OA datasets for a single species with the aim to achieve a greater range in carbonate chemistry conditions, including higher pH, Ω_{ar} experimental values, which should reduce the uncertainty of the predictions. However, combining raw data on species calcification rate proved to be more challenging because even across the same species the reporting of the calcification rates was highly variable. The use of different measuring approaches of calcification rates while conducting OA studies generated data with divergent units that do not allow for the intercomparison of data and results. As different studies for a single species could not be combined, we chose to increase the number of studies and thus, the number of examined species. Based on the response categories from the OA studies (Ries et al., 2009), the hypothesis was that OAE will elucidate same categories of responses, i.e. positive, negative and neutral. Within each of the groups examined, multiple categories of predicted calcification response were found. In this way, we demonstrated that it was possible to develop a useful framework for predicting species-specific OAE responses that can delineate different responders, identify species with greater OAE sensitivity and determine the thresholds where such negative responses could happen.

We further propose a TA:DIC ratio as a chemical-biological proxy although TA:DIC does not of itself drive biological sensitivity, but rather captures carbonate chemistry changes (*sensu* Bach et al., 2019). Because TA:DIC and Ω_{ar} are strongly correlated (Fig. 3), such ratios can then then be used to explain biological responses, e.g. calcification rate changes. The use of the TA:DIC ratio was also done for practical reasons because the additions of TA and/or DIC could be accounted for more easily.

4.2 Synthesizing biological response under OAE additions identifies winner and losers

The greatest certainty in predicting OAE response is possible in species with known calcification mechanisms and parameters involved in this, while the highest uncertainty is related to the groups with unknown calcification mechanisms and where OA experiments did not provide any data at the higher TA:DIC levels. In addition, for the neutral responders or groups with no significant correlation between TA:DIC and calcification rates, it is rather uncertain to predict if such responses will be retained under OAE. While parabolic responders show a physiologically understandable parabolic type of dose-response, positioning the TA:DIC values where the threshold occurs is also highly species-specific and potentially uncertain, meaning that it might depend on other environmental parameters.

The greatest variability in calcification rate response upon NaOH addition was evident in calcifying algae and dinoflagellates, mollusks, in particular the gastropods, where four to five different categories of responses were found. Such variability confirms that the responses to OAE will be species-specific and is related to various calcification mechanisms across the observed groups. Despite such specificity, the responses were summarized across three emerging groups of responses: positive, negative, and neutral (Fig. 7), which we discuss in the context of possible mechanisms of calcification or available OAE experimental studies used for validation.

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Positive responders (40%) show increased calcification rate to OAE additions (Fig. 6), observed in corals, annelids, and pteropods. Moreover, these groups have one of the lowest TA:DIC standard deviation intervals, which additionally supports the highest certainty in predicting their responses to OAE. Corals in general show uniformity in positive responses, although the variability is in a type of the response and predicts that coral species would not be negatively impacted during the OAE field trials. For validation purposes, increased coral calcification was also shown by the field experiment conducted by Albright et al. (2016), as well as for two coral species of *Acropora* and *Siderastre* in the experiments conducted by Palmer et al. (2023).

The metrics to evaluate the sensitivity of calcification rate for the negative responders (negative linear and threshold) to OAE addition was based on the amount of alkalinity addition required to reduce the calcification rate to a half (Fig. 7, Tables 1, 2). The most negative responses are expected in dinoflagellates (57% species), crustaceans (50% species) and foraminifera (38%). As such, these groups are one of the priorities for the future OAE experimental work to determine at which TA: DIC negative response happens. The worst out of these are dinoflagellates that demonstrate negative response in 6 cases, 5 neutral responses and 0 positive (see Table 1, Supplementary Fig. 2). The reason for negative response to OAE in this group is related to the fact that their growth gets limited at higher pH, with further carbon limitation playing a role at very high pH levels and low DIC concentration (Hansen et al., 2002; 2007). On the other hand, crustaceans only demonstrated positive response in one study (Pansch et al., 2014), while remaining results predict either negative or neutral response. While crustaceans are effective in retaining homeostasis at lower pH, they might be less so at higher pH, which was shown in the OA experiments by Ries et al. (2009) for three crustacean species (*Callinectes sapidus*, *Homarus americanus*, *Penaeus plebejus*), confirmed in the OAE study by Cripps et al. (2013) in *Carcinus meanas*. Reduced calcification in crustaceans is likely because the bicarbonate ions modulate their metabolic responses (Maus et al., 2018), as well as potential acid-base imbalance at high pH (Tresguerres et al., 2020).

With respect to the coccolithophores, we note that this was the only group where data compilation on calcification rate across the groups was possible because the OA studies were conducted in a more uniform way, using similar approaches, and reporting the same units. When data for *E. huxleyi* across the comparable studies was compiled (Barcelos-Ramos et al., 2010; Fiorini et al., 2011; Iglesias-Rodrigues et al., 2008; Sciandra et al., 2003; Stoll et al., 2012; Richier et al., 2011), a significant parabolic response was obtained (Supplementary Fig. 2), although the goodness of fit was fairly low (R^2=0.09). Despite lower R^2, we decided to use the compiled dataset because of the increased statistical power. The parabolic response obtained aligns with Langer et al. (2006) and also with the parabolic type responses found in the synthesis study by Paul and Bach (2020) and Bach et al. (2015). The threshold indicates the mechanisms of the coccolithophore growth, which is driven by CO_2, which is reduced with the OAE treatment. The threshold for coccolithophore combined studies was positioned at TA:DIC at 1.217 (Ω_{ar} = 4.81, Table 2), which would be triggered at 200 µmol/kg of added NaOH on a global level. This is a comparable magnitude to the predicted threshold of phytoplankton growth limitation at 100 µatm for some coccolithophore species (Riebesell et al., 1993). It is important to note that when these studies were analyzed

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individually, a mixture of different responses was observed. We emphasize the variability within the coccolithophore responses, which are species-specific and inherently related to the strain adaptation to their innate regional settings and dependent on a variety of other factors (Bach et al., 2015; Gafar and Schultz, 2018), including the longevity of the species, the experimental settings used in the study, for example nutrient-replete vs nutrient deficient conditions, and the presence or absence of (un)suitable light conditions. Interestingly, for other than *E. huxleyi* species, all the other coccolithophores demonstrated neutral responses. For validation purposes, the results of our study could not be compared to Gately et al. (2023) because calcification rates were not studied, and it is urgent that more validation studies for coccolithophores are conducted.

4.3 TA:DIC thresholds related to biological sensitivity

Lastly and most importantly, a set of species-specific thresholds was developed in this study, with demonstrated application across the global Ω_{ar} vs TA:DIC conditions (Table 2, Fig. 8). We limited the upper threshold value to 500 µmol/kg because the biogeochemical model outputs show that while the OAE-related concentration at the injection site might be higher for a short-time, realistic field dosing upon dilution might be low. Wang et al. (2023) reported that the nearfield maxima in the respective investigation area of the Bering Sea is to increase TA by about 10 µmol/kg and farfield by about 1 µmol/kg of NaOH (Wang et al., 2023).

The TA:DIC thresholds upon TA application ranged between 10–500 µmol/kg of NaOH, pointing to the most and least species-specific OAE-related sensitivities, respectively. The lowest TA:DIC threshold is predicted for the echinoderm *Arbacia punctulata*, with the sensitivity value being at least an order of magnitude lower than what the lab experimental OAE trials use in their treatment levels. While the lab experiments aim to gain mechanistic understanding of the OAE response, such high treatment levels are not very realistic with respect to potential level of biological sensitivity in the field. Here, we explicitly emphasize the importance of including much lower additions of TA as the experimental treatment levels to better support biological understanding in the field. Prior to the lab experiments it would be important to identify the most sensitive species with negative response with a threshold at lower TA:DIC range. This is especially pertinent for the groups for which OA experimental data is limited and only distributed at the lowest and the mid TA:DIC ratio, such as mollusks and dinoflagellates (Fig. 8; Supplementary Fig. 2).

4.4 Bringing realism of OAE experiments to the field trials

OAE-related biological responses and risks are not going to depend solely on the concentration of OAE compound used but also on the baseline carbonate chemistry conditions at the site of deployment, such as baseline TA:DIC (pH/Ω_{ar}) and variability of carbonate chemistry parameters across horizontal and vertical depths. Physical parameters of importance are related to the dilution effect, mixing, retention capacity, as well as the rate of the equilibration effects of the air-sea CO_2 uptake (Ferderer et al., 2022; He and Tyka, 2023; Schulz et al., 2023, Wang et al., 2023). Variability on the seasonal and annual scales of the air-sea CO_2 uptake can have impacts not only on the chemical processes related to the variable OAE efficiency, but also for the biological implications related to the crossing of biologically sensitive thresholds. It is the combination of all

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these factors that creates baseline conditions to which biota would ultimately be exposed in their natural environment upon OAE deployment (Wang et al., 2022).

If similar conditions as induced by the OAE field trial are present as part of the natural variability within the species' habitat, it is more likely that the species might be adjusted to it. On the contrary, rapidly induced novel conditions might be the most detrimental. As such, it is worth considering if OAE deployments could be, when possible, carried out not as a single high dosage deployment, but rather as a more continuous, lower dosage application that would eliminate the swings and maxima in conditions, while also allowing more time for species acclimation or migration during the initial injection of the OAE deployment.

What is needed urgently for the community performing biological field trials is a best practice guide for the biological impact and environmental risk monitoring approach, which is currently missing. While the guidance is available for conducting the lab (Iglesias Rodrigues et al., 2023) and field OAE studies (Cyronak et al., 2023), such guide on the environmental risk assessment should set the framework, establish the baseline conditions, identify suitable risk analyses, determine thresholds, and propose the development of regionally specific indicators for monitoring, while also identify the guidance for the regulators. Ideally, such biological and environmental risk monitoring and assessment would be accompanied by the application of the physical mixing models with site-specific biogeochemical processes (Ho et al., 2023; Fennel et al., 2023) that can predict the maximum expected TA increase in the nearfield and farfield, representing a more realistic exposure and better informing of the further experimental work.

4.5 Unknowns about ecological and biogeochemical implications call for the precautionary approach

From an ecological perspective, only 40% of species show neutrality in responses, which indicates that more than half of the examined species are predicted to have either a positive or a negative response. While the implications of a direct negative effect are inherently understood, a positive effect could be ambiguous in its interpretation. Positive responders could indeed benefit directly from the altered conditions induced by OAE in terms of increased calcification, but the indirect implications could be equally important, but are completely unknown at the moment. Would the positive responders benefit in physiological terms, implying they would be ecological winners and could induce a shift on the community level? Substantial species-specific variation in responses to OAE could lead to potential winners and losers, just as expected for the OA or multiple stressors. 40% of positive is a significant number related to potential consequences on the community shifts. The idea that the calcifiers are winners and thus there are (co)-benefits for marine calcifiers is not entirely fitting because it does not take the implication of potential ecological shifts into account. Such co-benefiting effects could only be considered within the context of mitigating effects to ocean acidification, i.e. when these species are negatively impacted by OA and OAE would reverse the negative OA pattern. However, current modelling efforts show that temporal and spatial scope of OAE as a mitigation capacity for OA is variable and might induce great biogeochemical changes that further exacerbate ecological risks (González and Ilyina, 2018; González et al., 2016; Mongin et al., 2021).

While we identified species with predicted positive and negative responses, we also note that this study did not include diatoms in the analyses, which are predicted to be negatively impacted by the carbonate-based OAE (Ferderer et al., 2022), with potential implications for the community shifts (Bach et al., 2019). Furthermore, this study also did not include any of the non-calcifiers in the analyses, where OAE might potentially trigger even greater implications within the calcifying and non-calcifying community, especially when the grazing effects are included, further strengthening the notion of the winner-loser concept and associated risks. As such, overall non-neutral responses should elucidate similar caution to negative responses and determine a precautionary principle in considering the next steps of OAE field implementation.

From the biogeochemical perspective, it could be inferred that OAE will introduce changes in calcification rate across species, potentially resulting in changing carbon export and carbonate counter pump. While species-specific responses in two of the major carbonate producers, i.e. coccolithophores and formanifera (40%) show a negative response, this could have strong effects on biogeochemical fluxes (Riebesell et al., 2017; Bach et al., 2019). On the contrary, increased calcification could result in thicker and denser shells, contributing to faster sinking and increased carbonate fluxes. Changes in calcification could trigger effects on the subsurface total alkalinity at intermediate and deeper depths in the water column, and dissolution on the seafloor (Gehlen et al., 2011) with potential feedback that results in increased CO_2 flux to the atmosphere (Gattuso et al., 2021), although this is projected to occur over centennial time scales (Oschlies et al., 2023).

4.6 Potential confounding effects not delineated in this study

This study only considered the changes in carbonate chemistry due to the addition of carbonate-based compounds, i.e. NaOH or Na_2CO_3. However, other feedstocks contain compounds that could induce biological toxicity due to the presence of the trace metals (Ni, Cu, Ca, Si; Bach et al., 2019), as well as potential negative environmental impacts due to the secondary precipitation (Hartmann et al., 2022; Moras et al., 2022). It also did not examine the sensitivity across different life stages, even though different sensitivities to OAE based are expected based on OA results. Furthermore, we did not consider the impact of multiple stressors, including temperature, dissolved oxygen, light intensity, although they could elicit different biological pathways than OAE alone or have additional confounding effects. As such, experimental lab or field studies or data that involve multiple stressors in their experimental designs was not used. We note that a similar predictive framework of OAE could, in principle, be placed withing the multi stressor conditions given the amount of newly generated studies of the impact of multiple stressors currently.

4.7 Conclusions and next steps

Sufficient certainty in predicting biological responses reduces the risks and supports safe operating space for OAE implementation and scaling up. Overall, given that 60% of examined species showed non-neutral response (either positive or negative), this calls for care in OAE field implementation until the temporal and spatial scales of safe operations are determined and OA mitigation established. The goal of this study is to serve as a baseline for prioritizing experimental and field OAE research and assess environmental risks, eliminating or reducing the risk with the

OAE biological field trials. Such prioritization identifies those species for which experimental work needs to be conducted first. This would involve species with the greatest OAE-related sensitivity (negative responders), species with the greatest uncertainty in response, as well as the species with very strong predicted positive response that could potentially introduce a shift on the community level. In addition, it would also recognize the species for which the existing knowledge is sufficient and there is less immediate need for the OAE experiments.

It is important to consider this study as a first meta-analyses that should be continuously upgraded and cross-validated with the experimental work. Furthermore, we emphasize that our predictions were developed as calcification response of the pelagic organisms only. Similar OA datasets are available for the benthic calcifiers and non-calcifiers and also for other biological responses, including growth, survival, with much greater uniformity of data and units, that could be easily transformed into OAE predictive framework as proposed in this study.

Data availability

No additional data were generated as part of this study, they were all collected from the already published studies. We provide all the information behind the analyzed studies.

Author contributions

NB designed and conceptualized the research, wrote the paper. GP provided the analyses using GLODAP data, provided visualizations and formal analyses. HvdM collected and curated data, conducted formal analyses and provided visualization. MGR has provided formal statistical analyses and visuals. RAF and AD have provided insights, suggestions, and generated discussion about specific parts of the paper. All authors have exchanged numerous insights, mutually contributed to the development of the study, troubleshooting, improvements. All have contributed to the writing of this draft.

Competing interests

The contact author has declared that none of the authors has any competing interests.

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References

Albright, R., Caldeira, L., Hosfelt, J., Kwiatkowski, L., Maclaren, J.K., Mason, B.M., Nebuchina, Y., Ninokawa, A., Pongratz, J., Ricke, K.L. and Rivlin, T., 2016. Reversal of ocean acidification enhances net coral reef calcification. Nature, 531(7594), pp.362-365.

Bach, L.T., Gill, S.J., Rickaby, R.E., Gore, S. and Renforth, P., 2019. CO2 removal with enhanced weathering and ocean alkalinity enhancement: potential risks and co-benefits for marine pelagic ecosystems. Frontiers in Climate, 1, p.7.

Bach, L.T., Riebesell, U., Gutowska, M.A., Federwisch, L. and Schulz, K.G., 2015. A unifying concept of coccolithophore sensitivity to changing carbonate chemistry embedded in an ecological framework. Progress in Oceanography, 135, pp.125-138.

Bach, L. T., and Mackinder, L. C. M.: Experiment: Dissecting the impact of CO2 and pH on the mechanisms of photosynthesis and calcification in the coccolithophore Emiliania huxleyi. PANGAEA, https://doi.org/10.1594/PANGAEA.830627, Supplement to: Bach, L. T., Mackinder, L. C. M., Schulz, K. G., Wheeler, G., Schroeder, D. C., Brownlee, C., Riebesell, U.: Dissecting the impact of CO2 and pH on the mechanisms of photosynthesis and calcification in the coccolithophore Emiliania huxleyi. New Phytol., 199(1), 121-134, https://doi.org/10.1111/nph.12225, 2013.

Barcelos e Ramos, J., Müller, M. N., and Riebesell, U.: Seawater carbonate chemistry and processes during experiments with phytoplankton Emiliania huxleyi (strain Bergen 2005), 2010. PANGAEA, https://doi.org/10.1594/PANGAEA.736022, Supplement to: Barcelos e Ramos, J. et al. : Short-term response of the coccolithophore Emiliania huxleyi to an abrupt change in seawater carbon dioxide concentrations. Biogeosciences, 7(1), 177-186, https://doi.org/10.5194/bg-7-177-2010, 2010.

Bednaršek, N., Naish, K. A., Feely, R. A., Hauri, C., Kimoto, K., Hermann, A. J., Michel, C., Niemi, A., and Pilcher, D.: Integrated Assessment of Ocean Acidification Risks to Pteropods in the Northern High Latitudes: Regional Comparison of Exposure, Sensitivity and Adaptive Capacity. Frontiers in Marine Science, 8, 671497, https://doi.org/10.3389/FMARS.2021.671497, 2021.

Bednaršek, N., Ambrose, R., Calosi, P., Childers, R.K., Feely, R.A., Litvin, S.Y., Long, W.C., Spicer, J.I., Štrus, J., Taylor, J. and Kessouri, F., 2021. Synthesis of thresholds of ocean acidification impacts on decapods. Frontiers in Marine Science, 8, p.651102.

Bednaršek, N., Calosi, P., Feely, R.A., Ambrose, R., Byrne, M., Chan, K.Y.K., Dupont, S., Padilla-Gamiño, J.L., Spicer, J.I., Kessouri, F. and Roethler, M., 2021. Synthesis of thresholds of ocean acidification impacts on echinoderms. Frontiers in Marine Science, 8, p.602601.

Bednaršek, N., Feely, R.A., Howes, E.L., Hunt, B.P., Kessouri, F., León, P., Lischka, S., Maas, A.E., McLaughlin, K., Nezlin, N.P. and Sutula, M., 2019. Systematic review and meta-analysis toward synthesis of thresholds of ocean acidification impacts on calcifying pteropods and interactions with warming. Frontiers in Marine Science, 6, p.227.

Bove, C. B., Whitehead, R. F., and Szmant, A. M.: Seawater carbonate chemistry and gastrovascular cavity pH, calcification of Montastraea cavernosa and Duncanopsammia axifuga. PANGAEA, https://doi.org/10.1594/PANGAEA.927310, 2020.

Brading, P., Warner, M. E., Davey, P., Smith, D. J., Achterberg, E. P., and Suggett, D. J.: Seawater carbonate chemistry and growth rate during experiments with phylotypes of Symbiodinium (Dinophyceae), 2011. PANGAEA, https://doi.org/10.1594/PANGAEA.771293, Supplement to: Brading, P. et al.: Differential effects of ocean acidification on growth and photosynthesis among phylotypes of Symbiodinium (Dinophyceae). Limnol. Oceanogr., 56(3), 927-938, https://doi.org/10.4319/lo.2011.56.3.0927, 2011.

Briggs, A. A., and Carpenter, R. C.: Seawater carbonate chemistry and photosynthesis and photochemical efficiency of Porolithon onkodes. PANGAEA, https://doi.org/10.1594/PANGAEA.920025, 2019.

Brown, K. T., Mello-Athayde, M. A., Sampayo, E. M., Chai, A., Dove, S., and Barott, K. L.: Seawater carbonate chemistry and endosymbiont density, photosynthesis and net calcification rates of reef-building coral Pocillopora damicornis. PANGAEA, https://doi.org/10.1594/PANGAEA.953058, 2022.

Cameron, L. P., Reymond, C. E., Müller-Lundin, F., Westfield, I. T., Grabowski, J. H., Westphal, H., and Ries, J. B.: Seawater carbonate chemistry and physiology and extrapallial fluid pH, calcification rate, and condition factor of the king scallop Pecten maximus. PANGAEA, https://doi.org/10.1594/PANGAEA.919939, 2019.

Camp, E. F., Nitschke, M. R., Rodolfo-Metalpa, R., Houlbrèque, F., Gardner, S. G., Smith, D. J., Zampighi, M., and Suggett, D. J.: Seawater carbonate chemistry and calcification rate, net photosynthesis and respiration rate of reef-building corals. PANGAEA, https://doi.org/10.1594/PANGAEA.880242, Supplement to: Camp, E.F. et al.: Reef-building corals thrive within hot-acidified and deoxygenated waters. Scientific Reports, 7(1), https://doi.org/10.1038/s41598-017-02383-y, 2017.

Casareto, B. E., Niraula, M. P., Fujimura, H., and Suzuki, Y.: Seawater carbonate chemistry, primary production, biomass and calcification of plankton and bacteria, 2009. PANGAEA, https://doi.org/10.1594/PANGAEA.756687, 2009.

Comeau, S., Cornwall, C. E., De Carlo, E. H., Krieger, E., and McCulloch, M. T.: Seawater carbonate chemistry and calcification physiology data in coral reef taxa. PANGAEA, https://doi.org/10.1594/PANGAEA.892655, Supplement to: Comeau, S. et al.: Similar controls on calcification under ocean acidification across unrelated coral reef taxa. Glob. Change Biol., https://doi.org/10.1111/gcb.14379, 2018.

Comeau, S., Cornwall, C. E., Pupier, C. A., DeCarlo, Thomas M., Alessi, C., Trehern, R., and McCulloch, M. T.: Seawater carbonate chemistry and calcification rate, calcifying fluid pH, calcifying fluid DIC, photosynthetic rates, metabolic alteration of pH in the DBL of corals and coralline algae. PANGAEA, https://doi.org/10.1594/PANGAEA.914328, 2019.

Comeau, S., Edmunds, P. J., Spindel, N. B., and Carpenter, R. C.: The responses of eight coral reef calcifiers to increasing partial pressure of CO2 do not exhibit a tipping point. PANGAEA, https://doi.org/10.1594/PANGAEA.833687, Supplement to: Comeau, S. et al.: The responses of eight coral reef calcifiers to increasing partial pressure of CO2 do not exhibit a tipping point. Limnol. Oceanogr., 58(1), 388-398, https://doi.org/10.4319/lo.2013.58.1.0388, 2013.

Comeau, S., Gorsky, G., Alliouane, S., and Gattuso, Jean-Pierre: Seawater carbonate chemistry and shell length of Mediterranean pteropod Cavolinia inflexa larvae during experiments. Laboratoire d'Océanographie de Villefranche, PANGAEA, https://doi.org/10.1594/PANGAEA.733905, Supplement to: Comeau, S. et al. : Larvae of the pteropod Cavolinia inflexa exposed to aragonite undersaturation are viable but shell-less. Marine Biol., 157(10), 2341-2345, https://doi.org/10.1007/s00227-010-1493-6, 2010b.

Comeau, S., Gorsky, G., Jeffree, R., Teyssié, Jean-Louis, and Gattuso, Jean-Pierre: Seawater carbonate chemistry, shell linear extension and calcification during calcein staining and ^{45}Ca experiments with pteropod Limacina helicina, 2009. PANGAEA, https://doi.org/10.1594/PANGAEA.726856, Supplement to: Comeau, S. et al. : Impact of ocean acidification on a key Arctic pelagic mollusc (Limacina helicina). Biogeosciences, 6(9), 1877-1882, https://doi.org/10.5194/bg-6-1877-2009, 2009.

Comeau, S., Jeffree, R., Teyssié, Jean-Louis, and Gattuso, Jean-Pierre: Seawater carbonate chemistry and biological processes during experiments with Limacina helicina, 2009. PANGAEA, https://doi.org/10.1594/PANGAEA.744720, In: EPOCA Arctic experiment 2009 team (2009): EPOCA 2009 Svalbard benthic experiment. PANGAEA, https://doi.org/10.1594/PANGAEA.745083, 2010.

Cornwall, C. E., Comeau, S., DeCarlo, T. M., Moore, B., D'Alexis, Q., and McCulloch, M. T.: Seawater carbonate chemistry and resistance of corals and coralline algae to ocean acidification. PANGAEA, https://doi.org/10.1594/PANGAEA.914886, 2018.

Courtney, T., and Ries, J. B.: Impact of atmospheric pCO2, seawater temperature, and calcification rate on the delta 18O and delta 13C composition of echinoid calcite (Echinometra viridis). PANGAEA, https://doi.org/10.1594/PANGAEA.862558, Supplement to: Courtney, T., and Ries, J.B. : Impact of atmospheric pCO2, seawater temperature, and calcification rate on the delta 18O and delta 13C composition of echinoid calcite (*Echinometra viridis*). Chem. Geol., 411, 228-239, https://doi.org/10.1016/j.chemgeo.2015.06.030, 2015.

Cyronak, T., Albright, R. and Bach, L., 2023. Chapter 4.5: Field Experiments. State of the Planet Discussions, 2023, pp.1-25.

Doney, S.: The consequences of human-driven ocean acidification for marine life. Biology Reports, 1, https://doi.org/10.3410/B1-36, 2009.

Evensen, N. R., and Edmunds, P. J.: Interactive effects of ocean acidification and neighboring corals on the growth of Pocillopora verrucosa. PANGAEA, https://doi.org/10.1594/PANGAEA.867268, Supplement to: Evensen, N.R., and Edmunds, P.J.: Interactive effects of ocean acidification and neighboring corals on the growth of Pocillopora verrucosa. Marine Biol., 163(7), https://doi.org/10.1007/s00227-016-2921-z, 2016.

Feely, R. A., Sabine, C. L., Lee, K., Berelson, W., Kleypas, J., Fabry, V. J., and Millero, F. J. : Impact of anthropogenic CO2 on the CaCO3 system in the oceans. Science, 305(5682), 362–366, https://doi.org/10.1126/SCIENCE.1097329, 2004.

Fennel, K., Long, M.C., Algar, C., Carter, B., Keller, D., Laurent, A., Mattern, J.P., Musgrave, R., Oschlies, A., Ostiguy, J. and Palter, J., 2023. Modeling considerations for research on Ocean Alkalinity Enhancement (OAE). State of the Planet Discussions, 2023, pp.1-47.

Ferderer, A., Chase, Z., Kennedy, F., Schulz, K.G. and Bach, L.T., 2022. Assessing the influence of ocean alkalinity enhancement on a coastal phytoplankton community. Biogeosciences, 19(23), pp.5375-5399.

Findlay, H. S., Kendall, M. A., Spicer, J. I., and Widdicombe, S. : Seawater carbonate chemistry and biological processes during experiments with barnacle Semibalanus balanoides, 2010. PANGAEA, https://doi.org/10.1594/PANGAEA.737438, Supplement to: Findlay, H.S. et al.: Relative influences of ocean acidification and temperature on intertidal barnacle post-larvae at the northern edge of their geographic distribution. Estuar. Coast. Shelf S., 88(4), 675-682, https://doi.org/10.1016/j.ecss.2009.11.036, 2010.

Figuerola, B., Hancock, A. M., Bax, N., Cummings, V. J., Downey, R., Griffiths, H. J., Smith, J., and Stark, J. S.: A Review and meta-analysis of potential impacts of ocean acidification on marine calcifiers from the Southern Ocean. Frontiers in Marine Science, 8, 584445, https://doi.org/10.3389/FMARS.2021.584445, 2021.

Fiorini, S., Middelburg, J. J., and Gattuso, Jean-Pierre: Seawater carbonate chemistry, nutrients, particulate carbon and growth rate of Emiliania huxleyi (AC472), Calcidiscus leptoporus (AC370) and Syracosphaera pulchra (AC418) during experiments, 2011. PANGAEA, https://doi.org/10.1594/PANGAEA.773860, Supplement to: Fiorini, S. et al.: Testing the effects of elevated pCO2 on coccolithophores (Prymnesiophyceae): comparison between haploid and diploid life stages. J. Phycol., 47(6), 1281–1291, https://doi.org/10.1111/j.1529-8817.2011.01080.x, 2011.

Friedlingstein, P., O'sullivan, M., Jones, M.W., Andrew, R.M., Gregor, L., Hauck, J., Le Quéré, C., Luijkx, I.T., Olsen, A., Peters, G.P. and Peters, W., 2022. Global carbon budget 2022. Earth System Science Data Discussions, 2022, pp.1-15

Gafar, N.A. and Schulz, K.G., 2018. A three-dimensional niche comparison of Emiliania huxleyi and Gephyrocapsa oceanica: reconciling observations with projections. Biogeosciences, 15(11), pp.3541-3560.

Gately, J. A., Kim, S. M., Jin, B., Brzezinski, M. A., and Iglesias-Rodriguez, M. D.: Coccolithophores and diatoms resilient to ocean alkalinity enhancement: A glimpse of hope? Science Advances, 9(24), eadg6066. https://doi.org/10.1126/SCIADV.ADG6066, 2023.

Gallego, R., Jacobs-Palmer, E., Cribari, K. and Kelly, R.P.: Environmental DNA metabarcoding reveals winners and losers of global change in coastal waters. P. Roy. Soc. B, 287(1940), p.20202424, 2020.

Gattuso, J.P., Magnan, A.K., Bopp, L., Cheung, W.W., Duarte, C.M., Hinkel, J., Mcleod, E., Micheli, F., Oschlies, A., Williamson, P. and Billé, R., 2018. Ocean solutions to address climate change and its effects on marine ecosystems. Frontiers in Marine Science, 5, p.410554.

Gattuso, J.P., Williamson, P., Duarte, C.M. and Magnan, A.K., 2021. The potential for ocean-based climate action: negative emissions technologies and beyond. Frontiers in Climate, 2, p.575716.

Gazeau, F., Quiblier, C., Jansen, J. M., Gattuso, Jean-Pierre, Middelburg, J. J., and Heip, C. H.R.: Seawater carbonate chemistry and calcification during incubation experiments with Mytilus edulis and Grassostrea gigas, 2006. PANGAEA, https://doi.org/10.1594/PANGAEA.718130, Supplement to: Gazeau, F. et al.: Impact of elevated CO2 on shellfish calcification. Geophys. Res. Lett., 34, https://doi.org/10.1029/2006GL028554, 2007.

Gehlen, M., Gruber, N., Gangstø, R., Bopp, L. and Oschlies, A., 2011. Biogeochemical consequences of ocean acidification and feedback to the earth system. Ocean acidification, 1, pp.230-248.

Gill, S. J.: The response of marine pelagic calcifiers to ocean alkalinity enhancement as a carbon dioxide removal technique [University of Oxford], http://ora.ox.ac.uk/objects/uuid:8d2df498-127c-4341-973f-c567cf9b1ee3, 2022.

González, M.F., Ilyina, T., Sonntag, S. and Schmidt, H., 2018. Enhanced Rates of Regional

Warming and Ocean Acidification After Termination of Large-Scale Ocean Alkalinization. Geophysical Research Letters, 45(14), pp.7120-7129.

González, M.F. and Ilyina, T., 2016. Impacts of artificial ocean alkalinization on the carbon cycle and climate in Earth system simulations. Geophysical Research Letters, 43(12), pp.6493-6502.

Hansen, P. J., Lundholm, N., and Rost, Björn.: Seawater carbonate chemistry and growth rate during experiments with dinoflagellates, 2007. PANGAEA, https://doi.org/10.1594/PANGAEA.718182, In supplement to: Hansen, P.J. et al.: Growth limitation in marine red-tide dinoflagellates: effects of pH versus inorganic carbon availability. Mar. Ecol. Prog. Ser., 334, 63-71, https://doi.org/10.3354/meps334063, 2007.

Hansen, P.J., 2002. Effect of high pH on the growth and survival of marine phytoplankton: implications for species succession. Aquatic microbial ecology, 28(3), pp.279-288.

Hartmann, J., Suitner, N., Lim, C., Schneider, J., Marín-Samper, L., Arístegui, J., Renforth, P., Taucher, J. and Riebesell, U., 2022. Stability of alkalinity in ocean alkalinity enhancement (OAE) approaches–consequences for durability of CO 2 storage. Biogeosciences Discussions, 2022, pp.1-29.

He, J. and Tyka, M.D., 2023. Limits and CO 2 equilibration of near-coast alkalinity enhancement. Biogeosciences, 20(1), pp.27-43.

Ho, D.T., Bopp, L., Palter, J.B., Long, M.C., Boyd, P.W., Neukermans, G. and Bach, L.T., 2023. Monitoring, reporting, and verification for ocean alkalinity enhancement. State of the Planet, 2, pp.1-12.

Iglesias-Rodríguez, M.D., Rickaby, R.E., Singh, A. and Gately, J.A., 2023. Laboratory experiments in ocean alkalinity enhancement research. State of the Planet Discussions, 2023, pp.1-19.

Iglesias-Rodriguez, D. Halloran, P. R., Rickaby, R.E.M., Hall, I. R., Colmenero-Hidalgo, E., Gittins, J. R., Green, D. R. H., Tyrrell, T., Gibbs S.J., von Dassow, P., Rehm, E., Armbrust, E. V., and Boessenkool, K. P.: Seawater carbonate chemistry and processes during experiments with Emiliania huxleyi, 2008. PANGAEA, https://doi.org/10.1594/PANGAEA.718841, Supplement to: Iglesias-Rodriguez, D. et al.: Phytoplankton calcification in a high-CO2 world. Science, 320(5874), 336-340, https://doi.org/10.1126/science.1154122, 2008.

Johnson, M. D., Bravo, L., Lucey, N. M., and Altieri, A.H. : Seawater carbonate chemistry and calcification rate of crustose coralline algafgore. PANGAEA, https://doi.org/10.1594/PANGAEA.939809, 2021.

Johnson, M. D., and Carpenter, R. C.: Seawater carbonate chemistry and net calcification, relative electron transport rates and photosynthetic pigments of Porolithon onkodes. PANGAEA, https://doi.org/10.1594/PANGAEA.924886, 2018.

Johnson, M. D., Moriarty, V., and Carpenter, R. C.: Acclimatization of the crustose coralline alga Porolithon onkodes to variable pCO2. PANGAEA, https://doi.org/10.1594/PANGAEA.835310, Supplement to: Johnson, M.D. et al.: Acclimatization of the Crustose Coralline Alga Porolithon onkodes to Variable pCO2. PLoS ONE, 9(2), e87678, https://doi.org/10.1371/journal.pone.0087678, 2014.

Keul, N., Langer, G., de Nooijer, L. J., and Bijma, J.: Seawater carbonate chemistry and benthic foraminifera Ammonia sp. mass, size, and growth rate during experiments, 2013. PANGAEA, https://doi.org/10.1594/PANGAEA.821209, Supplement to: Keul, N. et al.: Effect of ocean acidification on the benthic foraminifera Ammonia sp. is caused by a decrease in carbonate ion concentration. Biogeosciences, 10(10), 6185-6198, https://doi.org/10.5194/bg-10-6185-2013, 2013.

Kheshgi, H.S., 1995. Sequestering atmospheric carbon dioxide by increasing ocean alkalinity. Energy, 20(9), pp.915-922.

Kisakürek, B., Eisenhauer, A., Böhm, F., Hathorne, E. C., and Erez, J.: Seawater carbonate chemistry and biological processes of foraminifera, Globigerinoides ruber and Globigerinella siphonifera during experiments, 2011. PANGAEA, https://doi.org/10.1594/PANGAEA.763297, Supplement to: Kisakürek, B. et al.: Controls on calcium isotope fractionation in cultured planktonic foraminifera, Globigerinoides ruber and Globigerinella siphonifera. Geochim. Cosmochim. Ac., 75(2), 427-443, https://doi.org/10.1016/j.gca.2010.10.015, 2011.

Kroeker, K. J., Kordas, R. L., Crim, R. N., and Singh, G. G.: Meta-analysis reveals negative yet variable effects of ocean acidification on marine organisms. Ecol. Lett. , 13(11), 1419–1434, https://doi.org/10.1111/J.1461-0248.2010.01518.X, 2010.

Krueger, T., Horwitz, N., Bodin, J., Giovani, Maria-Evangelia, Escrig, S., Meibom, A., and Fine, M.: Seawater carbonate chemistry and photosynthesis, respiration and calcification of common reef-building coral in the Northern Red Sea. PANGAEA, https://doi.org/10.1594/PANGAEA.880318, Supplement to: Krueger, T. et al.: Common reef-building coral in the Northern Red Sea resistant to elevated temperature and acidification. Roy. Soc. Open Sci., 4(5), 170038, https://doi.org/10.1098/rsos.170038, 2017.

Langer, G., and Bode, M.: Seawater carbonate chemistry, growth rate and morphology of Calcidiscus leptoporus (RCC1135) during experiments, 2011. PANGAEA, https://doi.org/10.1594/PANGAEA.763286, Supplement to: Langer, G., and Bode, M.: CO2 mediation of adverse effects of seawater acidification in Calcidiscus leptoporus. Geochem. Geophys. Geosys., 12(5), Q05001, https://doi.org/10.1029/2010GC003393, 2011.

Langer, G., Geisen, M., Baumann, Karl-Heinz, Kläs, J., Riebesell, U., Thoms, S., and Young, J.:

Seawater carbonate chemistry, growth rate and processes during experiments with Coccolithus pelagicus and Calcidiscus leptoporus, 2006. PANGAEA, https://doi.org/10.1594/PANGAEA.721107, Supplement to: Langer, G. et al.: Species-specific responses of calcifying algae to changing seawater carbonate chemistry. Geochem. Geophys. Geosys., 7, Q09006, https://doi.org/10.1029/2005GC001227, 2006.

Leung, J.Y., Zhang, S. and Connell, S.D., 2022. Is ocean acidification really a threat to marine calcifiers? A systematic review and meta-analysis of 980+ studies spanning two decades. Small, 18(35), p.2107407.

Lischka, S., Büdenbender, J., Boxhammer, T., and Riebesell, U.: Seawater carbonate chemistry and biological processes of Limacina helicina during experiments, 2011. PANGAEA, https://doi.org/10.1594/PANGAEA.761910, Supplement to: Lischka, S. et al.: Impact of ocean acidification and elevated temperatures on early juveniles of the polar shelled pteropod Limacina helicina: mortality, shell degradation, and shell growth. Biogeosciences, 8(4), 919-932, https://doi.org/10.5194/bg-8-919-2011, 2011.

Lischka, S., and Riebesell, U.: Synergistic effects of ocean acidification and warming on overwintering pteropods in the Arctic. PANGAEA, https://doi.org/10.1594/PANGAEA.832422, Supplement to: Lischka, S., and Riebesell, U.: Synergistic effects of ocean acidification and warming on overwintering pteropods in the Arctic. Glob. Change Biol., 18(12), 3517-3528, https://doi.org/10.1111/gcb.12020, 2012.

Liu, X., Li, Y., Wu, Y., Huang, B., Dai, M., Fu, F., Hutchins, D.A., and Gao, K.: Seawater carbonate chemistry and phytoplankton stoichiometry, production and community structure in eutrophic coastal waters. PANGAEA, https://doi.org/10.1594/PANGAEA.888813, Supplement to: Liu, X. et al. : Effects of elevated CO2 on phytoplankton during a mesocosm experiment in the southern eutrophicated coastal water of China. Scientific Reports, 7(1), https://doi.org/10.1038/s41598-017-07195-8, 2017.

Lueker, T. J., Dickson, A. G., and Keeling, C. D.: Ocean pCO$_2$ calculated from dissolved inorganic carbon, alkalinity, and equations for K_1 and K_2: validation based on laboratory measurements of CO$_2$ in gas and seawater at equilibrium. Mar. Chem. , 70, 105–119, doi:10.1016/S0304-4203(00)00022-0, 2000.

Maier, C., Hegeman, J., Weinbauer, M. G., and Gattuso, Jean-Pierre: Seawater carbonate chemistry and calcification of Lophelia pertusa during experiments, 2009. PANGAEA, https://doi.org/10.1594/PANGAEA.767577, Supplement to: Maier, C. et al.: Calcification of the cold-water coral Lophelia pertusa under ambient and reduced pH. Biogeosciences, 6(8), 1671-1680, https://doi.org/10.5194/bg-6-1671-2009, 2009.

Manno, C., Morata, N., and Bellerby, R.G.J.: Seawater carbonate chemistry, survival rate, shell size, calcification rate of the planktonic foraminifer Neogloboquadrina pachyderma (sinistral) in a laboratory experiment. PANGAEA, https://doi.org/10.1594/PANGAEA.830908, Supplement to: Manno, C. et al. : Effect of ocean acidification and temperature increase on the planktonic foraminifer Neogloboquadrina pachyderma (sinistral). Polar Biol., 35(9), 1311-1319, https://doi.org/10.1007/s00300-012-1174-7, 2012.

Manríquez, P. H. Jara, M. E., Seguel, M.E., Torres, R., Alarcon, E., Lee, M. R., and Dam, H. G.: Ocean acidification and increased temperature have both positive and negative effects on early ontogenetic traits of a rocky shore keystone predator species. PANGAEA, https://doi.org/10.1594/PANGAEA.869291, 2016.

Maus, B., Bock, C. and Pörtner, H.O.: Water bicarbonate modulates the response of the shore crab *Carcinus maenas* to ocean acidification. J. Comp. Physiol. B., 188, 749–764, https://doi.org/10.1007/s00360-018-1162-5, 2018.

Meyer, F. W., Vogel, N., Diele, K., Kunzmann, A., Uthicke, S., and Wild, C.: Effects of high dissolved inorganic and organic carbon availability on the physiology of the hard coral Acropora millepora from the Great Barrier Reef. PANGAEA, https://doi.org/10.1594/PANGAEA.869416, 2016.

Meyer, F. W., Vogel, N., Teichberg, M., Uthicke, S., Wild, C., and Diaz-Pulido, G.: The physiological response of two green calcifying algae from the great barrier reef towards high dissolved inorganic and organic carbon (DIC and DOC) availability. PANGAEA, https://doi.org/10.1594/PANGAEA.868094, 2015.

Mongin, M., Baird, M.E., Lenton, A., Neill, C. and Akl, J., 2021. Reversing ocean acidification along the Great Barrier Reef using alkalinity injection. Environmental Research Letters, 16(6), p.064068.

Monserrat, M., Comeau, S., Verdura, J., Alliouane, S., Spennato, G., Priouzeau, F., Romero, G., and Mangialajo, L.: Seawater carbonate chemistry and the recruitment of macroalgal marine forests. PANGAEA, https://doi.org/10.1594/PANGAEA.955425, 2022.

Moras, C.A., Bach, L.T., Cyronak, T., Joannes-Boyau, R. and Schulz, K.G., 2022. Ocean alkalinity enhancement–avoiding runaway CaCO 3 precipitation during quick and hydrated lime dissolution. Biogeosciences, 19(15), pp.3537-3557.

National Academies of Sciences, Engineering, and Medicine, 2021. A research strategy for ocean-based carbon dioxide removal and sequestration.

Ninokawa, A., Takeshita, Y., Jellison, B. M., Jurgens, L. J., and Gaylord, B.: Seawater carbonate chemistry and mussel respiration and calcification rates. PANGAEA, https://doi.org/10.1594/PANGAEA.915978, 2020.

https://doi.org/10.5194/egusphere-2024-947
Preprint. Discussion started: 17 April 2024

Noisette, F., Bordeyne, F., Davoult, D., and Martin, S.: Assessing the physiological responses of the gastropod Crepidula fornicata to predicted ocean acidification and warming. PANGAEA, https://doi.org/10.1594/PANGAEA.860508, Supplement to: Noisette, F. et al.: Assessing the physiological responses of the gastropod Crepidula fornicata to predicted ocean acidification and warming. Limnol. Oceanogr., 61(2), 430-444, https://doi.org/10.1002/lno.10225, 2016.

Okazaki, R., Swart, P. K., and Langdon, C.: Stress-tolerant corals of Florida Bay are vulnerable to ocean acidification. PANGAEA, https://doi.org/10.1594/PANGAEA.833005, Supplement to: Okazaki, R. et al.: Stress-tolerant corals of Florida Bay are vulnerable to ocean acidification. Coral Reefs, 32(3), 671-683, https://doi.org/10.1007/s00338-013-1015-3, 2013.

Ong, E. Z., Briffa, M., Moens, T., and Van Colen, C.: Seawater carbonate chemistry and respiration, clearance and calcification rates of the common cockle Cerastoderma edule. PANGAEA, https://doi.org/10.1594/PANGAEA.949749, 2017.

Oron, S., Evans, D., Abramovich, S., Almogi-Labin, A., and Erez, J.: Seawater carbonate chemistry and calcification, respiration, and photosynthesis of the widespread diatom-bearing LBF Operculina ammonoides. PANGAEA, https://doi.org/10.1594/PANGAEA.929866, 2020.

Oschlies, A., Bach, L., Rickaby, R., Satterfield, T., Webb, R.M. and Gattuso, J.P., 2023. Climate targets, carbon dioxide removal and the potential role of Ocean Alkalinity Enhancement. State of the Planet Discussions, 2023, pp.1-11.

Palmer, R. M.: Alkalinity enhancement, thermal stress and their impacts on the physiology of three Caribbean coral species: Acropora Cervicornis, Pseudodiploria strigosa and Siderastrea siderea. In University of Miami. https://scholarship.miami.edu/esploro/outputs/graduate/Alkalinity-Enhancement-Thermal-Stress-and-their/991031772314902976, 2022.

Pansch, C., Schaub, I., Havenhand, J. N., and Wahl, M.: Habitat traits and food availability determine the response of marine invertebrates to ocean acidification. PANGAEA, https://doi.org/10.1594/PANGAEA.831428, Supplement to: Pansch, C., Schaub, M., Havenhand, J. N., and Wahl, M.: Habitat traits and food availability determine the response of marine invertebrates to ocean acidification. Glob. Change Biol., 20(3), 765-777, https://doi.org/10.1111/gcb.12478, 2014.

Paul, A.J. and Bach, L.T., 2020. Universal response pattern of phytoplankton growth rates to increasing CO2. New Phytologist, 228(6), pp.1710-1716

Prazeres, M., Uthicke, S., and Pandolfi, J. M.: Ocean acidification induces biochemical and morphological changes in the calcification process of large benthic foraminifera. PANGAEA, https://doi.org/10.1594/PANGAEA.848419, 2015.

Putnam, H. M., and Gates, R. D.: Preconditioning in the reef-building coral Pocillopora damicornis and the potential for trans-generational acclimatization in coral larvae under future climate change conditions. PANGAEA, https://doi.org/10.1594/PANGAEA.859356, Supplement to: Putnam, H.M., and Gates, R.D.: Preconditioning in the reef-building coral Pocillopora damicornis and the potential for trans-generational acclimatization in coral larvae under future climate change conditions. J. Exp. Biol., 218(15), 2365-2372, https://doi.org/10.1242/jeb.123018, 2015.

Ramajo, L., Marbà, N., Prado, L., Peron, S., Lardies, M. A., Rodriguez-Navarro, A., Vargas, C. A., Lagos, N. A., and Duarte, C. M.: Biomineralization changes with food supply confer juvenile scallops (Argopecten purpuratus) resistance to ocean acidification. PANGAEA, https://doi.org/10.1594/PANGAEA.860506, Supplement to: Ramajo, L. et al.: Biomineralization changes with food supply confer juvenile scallops (Argopecten purpuratus) resistance to ocean acidification. Glob. Change Biol., 22(6), 2025-2037, https://doi.org/10.1111/gcb.13179, 2016.

Renforth, P. and Henderson, G., 2017. Assessing ocean alkalinity for carbon sequestration. Reviews of Geophysics, 55(3), pp.636-674.

Reymond, C. E., Lloyd, A., Kline, D. I., Dove, S., and Pandolfi, J. M.: Decline in growth of foraminifer Marginopora rossi under eutrophication and ocean acidification scenarios. PANGAEA, https://doi.org/10.1594/PANGAEA.833683, Supplement to: Reymond, C.E., et al.: Decline in growth of foraminifer Marginopora rossi under eutrophication and ocean acidification scenarios. Glob. Change Biol., 19(1), 291-302, https://doi.org/10.1111/gcb.12035, 2013.

Richardson, K., Steffen, W., Lucht, W., Bendtsen, J., Cornell, S.E., Donges, J.F., Drüke, M., Fetzer, I., Bala, G., von Bloh, W. and Feulner, G., 2023. Earth beyond six of nine planetary boundaries. Science advances, 9(37), p.eadh2458.

Richier, S., Fiorini, S., Kerros, Marie-Emmanuelle, von Dassow, P., and Gattuso, Jean-Pierre: Seawater carbonate chemistry, particulate inorganic and organic carbon and growth rate of Emiliana huxleyi (RCC1216) duirng experiments, 2011. PANGAEA, https://doi.org/10.1594/PANGAEA.770439, In supplement to: Richier, S. et al.: Response of the calcifying coccolithophore Emiliania huxleyi to low pH/high pCO2: from physiology to molecular level. Marine Biol., 158(3), 551-560, https://doi.org/10.1007/s00227-010-1580-8, 2011.

Riebesell, U., Wolf-Gladrow, D.A. and Smetacek, V., 1993. Carbon dioxide limitation of marine phytoplankton growth rates. Nature, 361(6409), pp.249-251.

Riebesell, U., Bach, L.T., Bellerby, R.G., Monsalve, J.R.B., Boxhammer, T., Czerny, J., Larsen, A., Ludwig, A. and Schulz, K.G., 2017. Competitive fitness of a predominant pelagic calcifier impaired by ocean acidification. Nature Geoscience, 10(1), pp.19-23.

Riebesell, U. and Gattuso, J.P., 2015. Lessons learned from ocean acidification research. Nature Climate Change, 5(1), pp.12-14.

Ries, J. B., Cohen, A.L., and McCorkle, D.C.: Seawater carbonate chemistry and biological processes during experiments with calcifiing organisms, 2009. PANGAEA, https://doi.org/10.1594/PANGAEA.733947, Supplement to: Ries, J.B., et al.: Marine calcifiers exhibit mixed responses to CO2-induced ocean acidification. Geology, 37(12), 1131-1134, https://doi.org/10.1130/G30210A.1, 2009.

Ries, J.B., 2011. A physicochemical framework for interpreting the biological calcification response to CO2-induced ocean acidification. Geochimica et cosmochimica acta, 75(14), pp.4053-4064.

Schulz, K.G., Bach, L.T. and Dickson, A.G., 2023. Seawater carbonate system considerations for ocean alkalinity enhancement research. State of the Planet Discussions, 2023, pp.1-24.

Sciandra, A., Harlay, J., Lefèvre, D., Lemee, R., Rimmelin, P., Denis, M., and Gattuso, Jean-Pierre: Seawater carbonate chemistry and processes during experiments with Emiliania huxleyi (TW1), 2003. PANGAEA, https://doi.org/10.1594/PANGAEA.727841, Supplement to: Sciandra, A. et al.: Response of coccolithophorid Emiliania huxleyi to elevated partial pressure of CO2 under nitrogen limitation. Mar. Ecol. Prog. Ser., 261, 111-122, https://doi.org/10.3354/meps261111, 2003.

Seabold, S., and Perktold, J.: statsmodels: Econometric and statistical modeling with python. In 9th Python in Science Conference, 2010, Austin, 28 June-3 July, 2010, 57-61.

https://doi.org/10.25080/Majora-92bf1922-011

Sinutok, S., Hill, R., Doblin, M. A., Wuhrer, R., and Ralph, P.J. : Seawater carbonate chemistry, calcification rate, oxygen production, maximum quantum yield, symbiont density, chlorophyll concentration and crystal width of Halimeda macroloba, Halimeda cylindracea and Marginopora vertebralis during experiments, 2011. PANGAEA, https://doi.org/10.1594/PANGAEA.774792, Supplement to: Sinutok, S. et al. : Warmer more acidic conditions cause decreased productivity and calcification in subtropical coral reef sediment-dwelling calcifiers. Limnol. Oceanogr., 56(4), 1200-1212, https://doi.org/10.4319/lo.2011.56.4.1200, 2011.

Sordo, L., Duarte, C., Joaquim, S., Gaspar, M. B., Matias, D.: Seawater carbonate chemistry and growth and survival of juveniles of the striped venus clam Chamelea gallina. PANGAEA, https://doi.org/10.1594/PANGAEA.937477, 2021.

Stoll, H. M., Cruzado, A., Shimizu, N., and Kanamaru, K. : Seawater carbonate chemistry and B/Ca, calcification rate of Emiliania huxleyi and Coccolithus braarudii. PANGAEA, https://doi.org/10.1594/PANGAEA.949913, 2012.

Sulpis, O., Lauvset, S. K., and Hagens, M.: Current estimates of K_1^* and K_2^* appear inconsistent with measured CO_2 system parameters in cold oceanic regions. Ocean Sci. 16(4), 847–862, doi:10.5194/os-2020-19, 2020.

Tatters, A. O., Schnetzer, A., Fu, F., Lie, A..Y.A., Caron, D. A., and Hutchins, D. A.: Short- versus long-term responses to changing CO2 in a coastal dinoflagellate bloom. PANGAEA, https://doi.org/10.1594/PANGAEA.823381, Supplement to: Tatters, A.O., et al.: Short- versus long-term responses to changing CO2 in a coastal dinoflagellate bloom: implications for interspecific competitive interactions and community structure. Evolution, 67(7), 1879-1891, https://doi.org/10.1111/evo.12029, 2013.

Tresguerres, M. and Hamilton, T.J., 2017. Acid–base physiology, neurobiology and behaviour in relation to CO2-induced ocean acidification. Journal of Experimental Biology, 220(12), pp.2136-2148.

Uthicke, S., and Fabricius, K.E.: Seawater carbonate chemistry, productivity and calcification of Marginopora vertebralis in a laboratory experiment. PANGAEA, https://doi.org/10.1594/PANGAEA.831207, Supplement to: Uthicke, S., Fabricius, K.E.: Productivity gains do not compensate for reduced calcification under near-future ocean acidification in the photosynthetic benthic foraminifer species Marginopora vertebralis. Glob. Change Biol., 18(9), 2781-2791, https://doi.org/10.1111/j.1365-2486.2012.02715.x, 2012.

Van de Waal, D. B., John, U., Ziveri, P., Reichart, Gert-Jan, Hoins, M., Sluijs, A., and Rost, B.: Seawater carbonate chemistry and growth, calcification of Thoracosphaera heimii in a laboratory experiment. PANGAEA, https://doi.org/10.1594/PANGAEA.824705, Supplement to: Van de Waal, D.B., et al. : Ocean Acidification Reduces Growth and Calcification in a Marine Dinoflagellate. PLoS ONE, 8(6), e65987, https://doi.org/10.1371/journal.pone.0065987, 2013.

Vásquez-Elizondo, R. M., andEnríquez, S.: Coralline algal physiology is more adversely affected by elevated temperature than reduced pH. PANGAEA, https://doi.org/10.1594/PANGAEA.860802, Supplement to: Vásquez-Elizondo, R.M., and Enríquez, S.: Coralline algal physiology is more adversely affected by elevated temperature than reduced pH. Scientific Reports, 6, 19030, https://doi.org/10.1038/srep19030, 2016.

Waldbusser, G. G. Voigt, E. P., Bergschneider, H., Green, M. A., and Newell, R.I. E.: Seawater carbonate chemistry and calcification rate of eastern oyster Crassostrea virginica, 2011. PANGAEA, https://doi.org/10.1594/PANGAEA.758181, Supplement to: Waldbusser, G.G., et al. : Biocalcification in the Eastern Oyster (Crassostrea virginica) in Relation to Long-term Trends in Chesapeake Bay pH. Estuar. Coast., 34(2), 221-231, https://doi.org/10.1007/s12237-010-9307-0, 2011.

Wang, X., Feng, X., Zhuang, Y., Lu, J., Wang, Y., Gonçalves, R.J., Li, X., Lou, Y., and Guan, W.: Seawater carbonate chemistry and physiology and toxicity of dinoflagellate Karenia mikimotoi. PANGAEA, https://doi.org/10.1594/PANGAEA.923683, 2019.

Wang, M., Overland, J.E. and Stabeno, P., 2012. Future climate of the Bering and Chukchi Seas

https://doi.org/10.5194/egusphere-2024-947
Preprint. Discussion started: 17 April 2024

projected by global climate models. Deep Sea Research Part II: Topical Studies in Oceanography, 65, pp.46-57.

White, M. M., Drapeau, D.T., Lubelczyk, L. C., Abel, V. C., Bowler, B. C., and Balch, W. M.: Seawater carbonate chemistry and calcification of an estuarine coccolithophore. PANGAEA, https://doi.org/10.1594/PANGAEA.923623, 2018.

Zhang, M., Fang, J., Zhang, J., Li, B., Ren, S., Mao, Y., and Gao, Y.: Seawater carbonate chemistry and calcification and respiration of Chlamys farreri. PANGAEA, https://doi.org/10.1594/PANGAEA.949604, 2011.