Response to comments from reviewer #2 on manuscript egusphere-2026-1597

We appreciate the thoughtful comments from reviewer #2. In this document, the reviewer comments are in black and our responses are in blue.

McElhany et al. summarize the currently proposed marine carbon dioxide removal (mCDR) methods and their potential impacts on carbonate chemistry and different marine species. The review analyzes over 300 studies and compiles 276 biological thresholds. This represents a substantial amount of work, and it is challenging to identify safe thresholds for mCDR deployment. Therefore, limiting the scope to pH and alkalinity thresholds is reasonable. I appreciate the authors' time and effort in producing this valuable synthesis, and I hope they find the following comments helpful.

Major comments:

1. **Page 44:** It would be helpful to re-emphasize which groups of organisms are most sensitive to pH change and to summarize the general optimal or safe pH ranges for different marine taxa in the Discussion. Based on the results presented, phytoplankton appear to be more sensitive than invertebrates and fish. This is likely to be one of the key take-home messages that readers will be interested in.

   We consider it premature to make conclusions about which taxa are most sensitive and what pH ranges are optimal or safe given the disproportionate representation of certain taxa in the current body of literature and the variation of estimates within taxa. As we outline in the discussion, the data are sparse, difficult to compare and present a wide range of threshold response levels. Although our study provides a useful first step, additional studies and analysis will be needed to make generalizations. Setting a “safe” level based on our data would require a value judgement about how precautionary to be, which is beyond the scope of our paper.

2. **Line 940:** In the Results section, you identify optimal pH ranges for different groups of organisms. Therefore, I am not sure why the Discussion states that "there is no obvious biological tipping point for species sensitivity." Although the dataset has limitations, I think it is equally important to discuss the patterns that were observed, as well as the limitations of the analysis.

   We did not identify an optimal pH range. A few studies identified a positive effect of a pH above ambient levels, which is not necessarily an optimal pH for those species given how few pH treatments are included in most experiments. We would be very hesitant to extrapolate from those studies to an optimal range that could be applied across species. We note in the discussion that some species show a negative effect at pH values only slightly above ambient (e.g. 8.3), which is lower than the pH observed for a positive response for other species. We do not see any obvious tipping point in the data.

3. **Figure 3:** Please define the abbreviations (e.g., Pop. Growth, Pos. Response). I also found the distinction between "taxon" and "study type" somewhat confusing, as field studies necessarily involve particular groups of organisms. I suggest specifying

which organisms or communities were investigated in the field studies (are they phytoplankton? Benthic community? etc). If this cannot be done here, it should at least be clarified in Figure 7 where key biological responses were summarized.

We will define the abbreviations in the legends. We agree that the distinction between taxon and study type in Figure 3 can be confusing. We will modify the summary figures to display results only by taxa. For the figure, we will display information from the “study type” papers in the appropriate taxonomic groups. In the text, we will keep the distinction between taxa and study type. As described on page 14, there are advantages in grouping the review of certainty types of studies.

Minor comments:

1. **Line 65:** More references are needed here in addition to Fuhrman et al. (2023).

   We will add more references, such as 1) National Academies of Sciences, Engineering, and Medicine (2018) Negative Emissions Technologies and Reliable Sequestration: A Research Agenda, and 2) Edwards MR, Geden O, Gidden MJ, Lamb WF, Minx JC, Nemet GF, Smith SM, Bellamy R, Brutschin E, Diaz Anadon L, Fuss S, Grassi G, Johnstone I, Lebling K, Lunstrum A, Müller-Hansen F, Portugal-Pereira J, Probst B, Vaughan NE (2026) The State of Carbon Dioxide Removal, 3rd Edition.

2. **Box 1:** It would be helpful to include an illustration about the different mCDR methods and their underlying mechanisms.

   The focus of our paper is on how organisms respond to carbonate chemistry, not on how mCDR changes carbonate chemistry. Rather than make the introduction longer, we will add some more references where readers can find more information with good illustrations of the different methods such as 1) Cross JN, Sweeney C, Jewett EB, Feely RA, McElhany P, Carter B, Stein T, Kitch GD, Gledhill DK (2023) Strategy for NOAA Carbon Dioxide Removal Research, a white paper documenting a potential NOAA CDR science strategy as an element of NOAA’s climate interventions portfolio and 2) Oschlies A, Bach L, Fennel K, Gattuso J (2025) Perspectives and challenges of marine carbon dioxide removal, Frontiers in Climate 6 (2025): 1506181.

3. **Box 1:** In OAE, there are two distinct approaches: equilibrated OAE and unequilibrated OAE. These are not simply different stages of the same process but represent two different implementation strategies. Specifically, equilibrated OAE involves enclosing a body of seawater, adding alkalinity, allowing the water body to equilibrate with atmospheric CO_2, and then releasing it back into the ocean. These two approaches have different carbonate chemistry and therefore different biological implications. For example, equilibrated OAE results in much smaller changes in pH and DIC upon release.

   We will add a sentence describing the differences between equilibrated and unequilibrated mCDR. As noted in response to the previous comment, the description of mCDR methods is not the focus of our paper, so we will keep our clarification on OAE brief.

4. **Line 81:** "...which may contain harmful compounds." Please specify what these harmful compounds may be.

We will add “(e.g., nickel or other metals)”

5. **Line 84:** "...leading to a variety of possible coastal ecosystem effects." Please elaborate on what these potential coastal ecosystem effects are.

   Because this is not the focus of our paper, we will keep our elaboration brief. We will add an example and a reference: "like food-web changes due to an artificial reef effect of energy support structures at sea (Le Marchand et al. 2026)". Le Marchand M, Hemery LG, Araignous E, Bănaru D, Ben Rais Lasram F, Copping A, Fulton EA, Hasselman DJ, Le Loc’h F, Martínez ML, Niquil N, Rose D, Safi G (2026) How can an ecosystem approach support integrated management of marine renewable energy? An initial assessment from an environmental point of view, Sustainable Futures, 11, p.101872.

6. **Box 2 (Page 5):** It is unclear what "system" refers to in this box. Does it refer to the seawater carbonate system, or the broader Earth system including both the atmosphere and the ocean? Please clarify this, as air–sea CO_2 exchange is important for explaining the concepts presented here.

   We are referring to the carbonate system and will clarify this in the text.

7. **Box 2 (Page 6):** "As seawater pH or carbonate saturation state (Ω) increases, brucite, calcium carbonate, and other compounds may precipitate out of solution." Does $Mg(OH)_2$ generally precipitate with increasing seawater pH or Ω? This sentence appears to overgeneralize the conditions under which secondary mineral precipitation occurs. While $CaCO_3$ precipitation is a well-recognized consequence of increased carbonate saturation state, $Mg(OH)_2$ precipitation is not generally expected under typical seawater OAE conditions and has mainly been reported under specific circumstances (e.g., localized high pH or incomplete dissolution of added brucite). I suggest revising the sentence to distinguish between these processes and avoid implying that increases in seawater pH or Ω generally promote precipitation of both phases. In addition, Suitner et al. (2024a) and Suitner et al. (2024b) appear to refer to the same publication. Please check and correct the duplicate citation.

   Since it is not the focus of our paper, we do not discuss the frequency of any particular type of precipitate, only that precipitation of these minerals is possible at elevated pH. We state this explicitly. Although not a detail we need to include in our paper, we note that brucite precipitation was observed in the recent Ebb Carbon OAE field trials (Project Macoma Scientific Report; https://drive.google.com/drive/folders/1E-VMMnXJuSj0XhzronovLR9OcyOJxcRc) .

8. **Box 2 (Page 6):** I suggest citing Eq. (1) after "...which pushes the system to a new equilibrium with a lower pH."

   We thank the reviewer for suggesting this, and in the new version of the manuscript we will make this change.

9. **Box 2 (Page 7):** "...followed by a slow reduction in pH if conditions lead to precipitation." Please specify what type of precipitation is being referred to here.

   We will clarify that precipitation of $Mg(OH)_2$ can result in relatively fast decreases in pH and precipitation of CaCO3 in relatively slow decreases.

10. **Box 2 (Table):** "As indicated by the asterisk (*) in the table, at equilibrium and to the extent that OAE causes CDR, the pCO_2 in the ocean and atmosphere will be slightly lower than before alkalinity addition." My understanding is that because CO_2 has

been permanently transferred from the atmosphere into the ocean, the atmosphere contains slightly less CO_2 than before. Consequently, the final equilibrium pCO_2 of both the atmosphere and ocean should also be slightly lower than the initial value. Is this interpretation correct? If so, please explain this more clearly so readers can better understand.

Your interpretation is correct. We will clarify this statement.

11. **Box 2 (Table):** "The pre-equilibrium state will differ from that shown in the table if the alkaline material is carbonate-based (e.g., $CaCO_3$ or Na_2CO_3)." Is $CaCO_3$ directly used for OAE? It's hard to dissolve right?

    Calcium carbonate has been proposed and tested as a source of alkalinity, though as noted by the reviewer, it does not dissolve as readily as some other materials. We will a citation regarding the potential use of calcium carbonate: Eisaman MD, Geilert S, Renforth P, Bastianini L, Campbell J, Dale AW, Foteinis S, Grasse P, Hawrot O, Löscher CR, Rau GH, Rønning J (2023) Assessing the technical aspects of ocean-alkalinity-enhancement approaches.

12. **Box 2 (Table):** Why does the HCO_3^- concentration decrease in the pre-equilibrium OAE scenario? HCO_3^- can shift toward CO_2, but CO_3^{2-} can also convert to HCO_3^-. Please explain this more clearly.

    As shown in the Box 2 figure Bjerrum plot, a sudden increase in pH is associated with a decrease in HCO_3^- and an increase in CO_3^{2-}.

13. **Box 2 (Table):** Please specify whether the pCO_2 shown refers to seawater or the atmosphere to avoid confusion. In addition, what is the difference between the white and black arrows?

    We will clarify that pCO_2 refers to seawater. The black arrows point up and the white arrows point down. The black and white is just for visual clarity. There is a typo we will fix in the preprint Box 2 table: the black arrow for saturation state with the removal of CO_2 should be pointing up.

14. **Table 1:** CO_3^{2-} concentration and Ω are also affected by calcification. What do "dissolution" and "fertilization" refer to in this table? Please clarify these terms and double-check that the information is consistent with Box 2.

    Dissolution refers to dissolution of biological calcium carbonate and fertilization refers to external fertilization where gametes are exposed to seawater. We will add this information in the text.

15. **Line 149:** I suggest replacing "phytoplankton" with "coccolithophores or other calcifying phytoplankton."

    We will clarify this in the new version of the manuscript.

16. **Line 177:** Please change "is focused on" to "focuses on."

    We will amend.

17. **Box 3:** Consider replacing "discriminate changes in the system" with "detect meaningful changes in the system" or "distinguish meaningful changes from natural variability".

    We will amend.

18. **Line 189:** Please explain what is meant by "potential biological impacts of mCDR."

    We will modify the text and add a clarifying sentence: "The other potential biological impacts can be from diverse issues like toxic metal exposure, food web or nutrient disruption, increased marine traffic, entrainment in pumping systems, etc."

19. **Table 6:** Please remove the extra unit "µmol kg^{-1}" and ensure that units are presented consistently throughout the manuscript. In some places, the unit is written as µmol kg^{-1}, while elsewhere a different format is used.

    We will fix the units typo in table 6 and ensure units are formatted correctly throughout the paper.

20. **Figure 7:** Please see comment before. It would be helpful to indicate which organisms were included under the OA experiments and field studies (e.g., fish, phytoplankton communities, benthic invertebrates).

    Similar to the modifications we will make to Figure 3 described above, we change the Figures 7 and 8 categorize all to the threshold by taxa and not include study type.

21. **Figure 8:** It may be better to use µmol L^{-1} instead of mmol L^{-1} in the first subplot. Please also label each subplot.

    Using mmol seems tidier without all those extra zeros. All of the subplots already have labels.

22. **Line 1024–1026:** I do not agree with this suggestion, as pH is more commonly reported than H^+ concentration in both experimental studies and field measurements.

    Fair enough. We will suggest inclusion of both terms to emphasize that the scale of biological response is generally unknown.

23. **Line 1034–1037:** I appreciate the authors' emphasis on the importance of other carbonate chemistry parameters. I also encourage them to discuss which parameters are most practical for evaluating the biological impacts of mCDR based on the dataset they compiled. For example, DIC may be a particularly important parameter because it directly influences photosynthesis and fish physiology (as mentioned in Lines 121–126).

    Agree. Note that our table 1 has columns for CO_2, HCO_3^- and CO_3^{2-}, but not DIC.