Final Report of Joint PICES/ICES Working Group

on

Ocean Negative Carbon Emissions (ONCE)(WG-46)

edited by

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Executive Summary

Working Group 46 on Ocean Negative Carbon Emissions (ONCE) was proposed as a Joint Working Group of PICES and ICES participants. The main purpose of the group was to identify current knowledge gaps in negative carbon emissions in the oceans, and propose future research directions and applications to the enhancement of ocean negative carbon emissions. The Terms of Reference for the Working Group proposed that working group members discussed the theoretical basis, implementation guidelines, and evaluation of the benefits, challenges and impacts of ONCE.

In the three years since Working Group 46 was formed, knowledge gaps were discussed in negative carbon emissions in the oceans, especially in the coastal regions, which will help innovation both in theory and technology to achieve ONCE. The group member organized electronic annual meetings, Co-Chair meetings, and Task Team meetings to exchange ideas and discuss ongoing research results. A roadmap for Ocean Negative Carbon Emission eco-engineering in sea-farming fields was proposed by parts of WG members resulting Global Ocean Negative Carbon Emissions (Global-ONCE) Program was approved by the Intergovernmental Oceanographic Commission (IOC) of the United Nations Educational Scientific and Cultural Organization (UNESCO) in the framework of the United Nations' call for Decade Actions of Ocean Science for Sustainable Development and the United Nations Decade Initiative Plan, which reviewed the mechanisms of carbon pumps behind this scenario. A future research direction was proposed with wastewater alkalinity addition to the enhancement of ocean negative emissions. An UN-decade program was proposed and endorsed with the name of Global Ocean Negative Carbon Emissions (Global-ONCE).

Introduction

In addition to drastic cuts in emissions of fossil fuel derived carbon dioxide (CO_2) into the atmosphere, ocean negative carbon emission (ONCE) approaches will be necessary to capture and sequester the CO_2 from residual emissions to reach the Paris Agreement to limit global warming to 2.0°C or perhaps even 1.5°C by the end of this century. The ocean has a large capacity to sequester carbon and has absorbed approximately 25% of the CO_2 produced by fossil fuel combustion and cement production since the beginning of the industrial revolution. Ocean Negative Carbon Emissions (ONCE) have the potential to contribute to negative emissions, which require us to understand the mechanisms and processes involved.

The majority of the organic carbon in the ocean is in the form of refractory dissolved organic matter (DOM), the amount of which is equivalent to the total inventory of atmospheric CO_2. The previous PICES/ICES Joint Working Group -33 on "Climate Change and Biologically-driven Ocean Carbon Sequestration" highlighted the importance of microbial processes in the production of refractory DOM (RDOM) in the ocean. However, there are significant gaps in knowledge between understanding of these natural processes of sequestration and their potential application as a negative emission technology. In addition, our knowledge gaps of other ocean carbon sequestration mechanisms and processes, such as the solubility pump, the carbonate pump, and the different components of the biological pump, limits their potential application, individually or jointly, for mitigating climate change.

The PICES/ICES Joint Working Group WG46/WGONCE on Ocean Negative Carbon Emissions (ONCE) was formed with the aim of identifying current knowledge gaps in negative carbon emissions in the ocean, and proposing future research directions and applications to the enhancement of negative carbon emissions. The Working Group was designed as a joint effort to link the science, assessment, and management communities, and thus to enhance our understanding of ONCE. WG46/WGONCE aimed at promoting interdisciplinary exchanges among different research communities by bringing together experts with backgrounds in ocean science (biological, biogeochemical, chemical, and physical oceanography) and engineering, to develop theoretical bases, provide guidelines, and evaluate the implementation of ONCE, chaired by scientists from both the PICES and ICES communities.

WG 46 Achievements with Respect to Terms of Reference

1. Identify current knowledge gaps in negative carbon emission in the oceans.

Two working group task teams TT1a and TT1b were formed towards this Term of Reference. TT1a focused on reviewing and proposing terminologies and definitions that were consistent with "nature-based" solutions ('natural climate solutions'– defined by Griscom et al. 2017 – referring to terrestrial habitats/coastal blue carbon), while TT1b aimed at comparing the assumptions and conclusions of existing studies on proposed ONCE methods to summarize some key questions that are worthy of global attention.

As part of discussions within TT1a we reviewed a recent publication by Doug Wallace – working group co-chair – discussing how terminologies were contributing to enabling or impeding funding of ONCE approaches in different nations, and compared the terminologies used within the most recent reports and plans published in the nations represented by working group members.

Within TT1b we reviewed a number of recent publications, including : Gattuso et al., 2021, the Ocean Visions roadmaps (https://oceanvisions.org/work/ocean-based-carbon-dioxide-removal/) and the US Ocean Carbon and Biogeochemistry program summer workshop presentations (https://web.whoi.edu/ocb-workshop/ocb2021-negative-emissions/), the US National Academies of Sciences, Engineering and Medicine research strategy for ocean carbon dioxide removal (CDR) (https://www.nationalacademies.org/our-work/a-research-strategy-for-ocean-carbon-dioxide-removal-and-sequestration#sectionWebFriendly), and the IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (Chapter 5) (https://www.ipcc.ch/srocc/)

A collation / consensus of the knowledge gaps identified in these publications includes:

1) How to attribute additional CO_2 removal to a particular intervention? The knowledge of variability in current carbon sequestration, modeling, and *in situ* tools for evaluation and attribution, and the design of controlled field and modeling experiments are necessary.

2) How to quantify the effectiveness of the CO_2 removal? This may be achieved by applying *in situ* tools for monitoring the stability and longevity of CO_2 removal as part of long-term controlled field experiments;

3) How to quantify/prevent any detrimental environmental impacts? To investigate unexpected indirect effects, appropriate monitoring and attribution protocols need to be developed as part of the design of controlled field and modeling experiments.

2. Propose future research directions and applications to the enhancement of

negative carbon emissions;

(1) Developing additional long-term time series stations to observe carbon sequestration in representative coastal and offshore waters.

The task team TT2 and part of TT3 addressed this Term of Reference. The key issues that were addressed were:

1) Investigation on the possibility of setting up a global network of ocean time-series stations not only for observations but also for understanding ONCE processes by deliberately planning for them to be sites for experimentation/intervention.

2) As part of research by some of the WG members on ONCE approaches, integrated carbon sequestration experimental platforms were set up in the subtropical sea near Xiamen, Fujian, China and a coastal aquaculture area near Qingdao, Shandong, China.

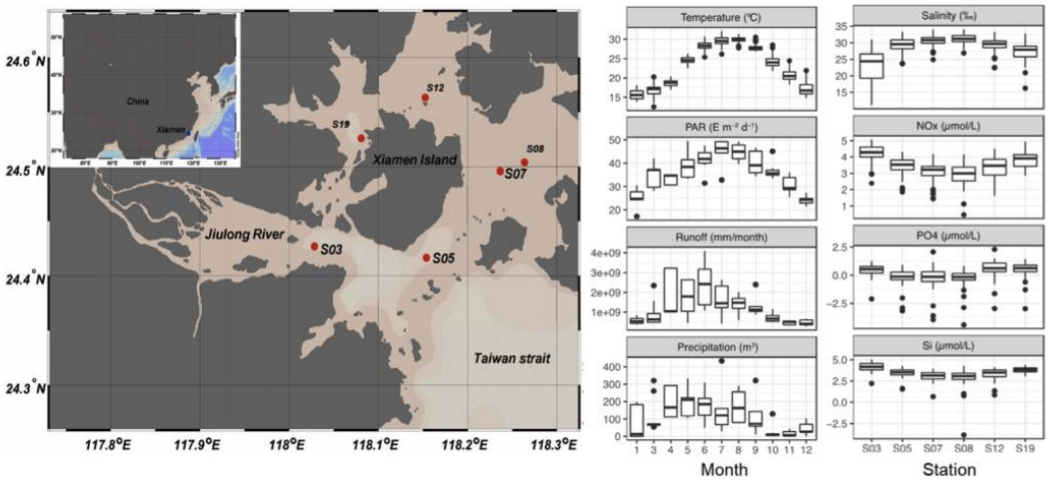

Figure 1. Time-series sampling in the coast around Xiamen, Fujian, China (Wang et al., unpublished.)

3) One Working Group member (Douglas Wallace, PICES WG Co Chair) has been involved in developing a multidisciplinary ocean time series station in Halifax, Canada, with a combination of innovative experiments, a testbed for the development of new technologies and long-term monitoring of marine carbon cycling.

(2) Proposing integrated experimental studies to better understand carbon sequestration under paleo-, current and future oceanic conditions.

Task team TT3b was formed to address this Term of Reference. Some Working Group

members proposed potential experimental studies on ONCE mechanisms in aquaculture fields through the following approaches (Figure 2):

1) Clean energy-driven artificial upwelling to bring up high nutrient containing water from the lower part of the water column to the euphotic zone to enhance carbon fixation and boost an algal bloom;

2) Application of clay minerals such as modified montmorillonite to draw down the bloom biomass;

3) Enhance microbial metabolic processes which increase alkalinity under hypoxic conditions;

4) Application of an alkaline mineral such as olivine to induce carbonate precipitation.

These combined abiotic and biotic processes should work together to achieve comprehensive carbon storage in the form of particulate organic and inorganic carbon burial and recalcitrant dissolved organic carbon, thereby simultaneously maximizing the efficiency of organic carbon sequestration in the aquaculture fields and other coastal areas. Through careful investigations of ONCE approaches, integrated carbon sequestration experimental studies were conducted in the subtropical sea near Xiamen, Fujian, China and a coastal aquaculture area near Qingdao, Shandong, China.

A paper entitled "A roadmap for Ocean Negative Carbon Emission eco-engineering in sea-farming fields" by some WG members was published on ONCE approaches, namely BCMS[1]. A comprehensive BCMS-based ONCE eco-engineering roadmap is proposed in this paper towards achieving the twin goals of enhancement of the carbon sink alongside remediation of the ecosystem. BCMS would be best implemented in sea-farming fields.

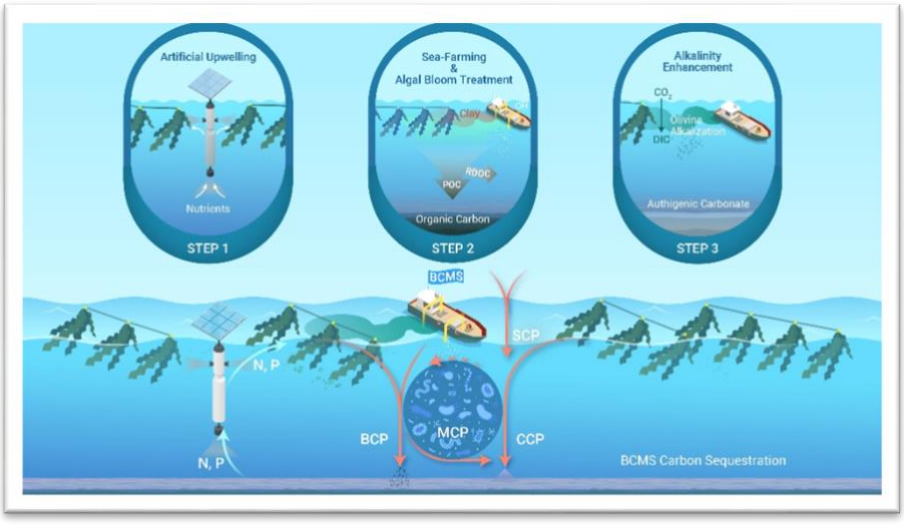

Figure 2. An illustration of the BCMS ecoengineering approaches
POC: Particulate Organic Carbon, RDOC: Refractory Dissolved Organic Carbon, N,P: Nitrogen and phosphorus

Another approach to remove CO2 is the utilization of alkalinity minerals (e.g., Olivine, Brucite) in sewage and acidification oceanic regions to increase carbon sequestration. This method can dissolve alkaline minerals from natural environments, thereby significantly enhancing carbon sequestration and helping to mitigate ocean acidification. This approach offers a practical and scalable solution to contribute to the global effort to combat climate change.

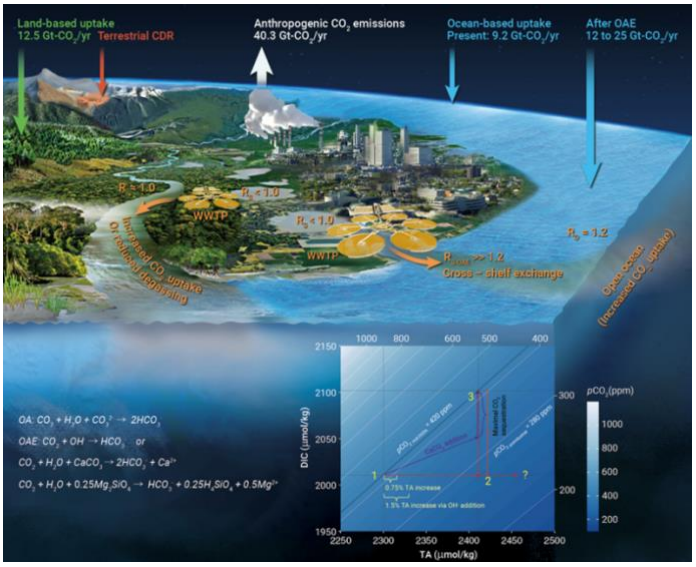

Figure 3. Wastewater alkalinity addition as a novel ocean negative carbon emissions approach

The state-of-the-art experimental facilities can contribute to proposed OAE factory studies and carbon storage mechanisms, such as the Marine Environmental Chamber System (MECS), which is presently under construction in Qingdao, Shandong, China, and the Aquatron Laboratory located at Dalhousie University in Canada. These facilities simulate natural environment, provide high frequency sampling for multiple biological, chemical and physical samples, to find the best practice.

Figure 4. Research strategies for ocean carbon storage mechanisms and effects[3]

(3) Proposing an international collaborative project or program dedicated to ocean negative carbon emissions.

An international collaborative program, named the Global Ocean Negative Carbon Emissions (Global-ONCE) Program was officially approved and launched on World Oceans Day, 8 June 2022. This is a significant initiative approved by the Intergovernmental Oceanographic Commission (IOC) of the United Nations Educational, Scientific, and Cultural Organization (UNESCO). It is in the framework of the United Nations Decade of Ocean Science for Sustainable Development.

The Global-ONCE program is led by five leading research organizations[2], the North Pacific Marine Science Organization (PICES), the International Council for the Exploration of the Sea (ICES), the Surface Ocean-Lower Atmosphere Study (SOLAS), the Integrated Marine Biosphere Research (IMBeR) network, and the World Climate Research Program (WCRP China). The partners involve 79 universities or institutions from 33 countries.

The key objectives of Global ONCE are: 1) Construction of a network of coastal and ocean study sites and experimental infrastructure; 2) Provision of the science, technology and governance frameworks for assessment, implementation and monitoring of adaptation and mitigation approaches; 3) Improved technical and personnel capacity and ocean literacy; and 4) Improved ocean-climate mitigation and adaptation strategies, policies and governance.

Global-ONCE will undertake and facilitate the science required to evaluate and implement eco-technological interventions, including learning from paleo-oceanic carbon processes to predict the future, restoring impacted marine ecosystems, fostering nature-based systems of land-sea integrated management, upwelling manipulation, microbial-driven comprehensive carbon sequestration, adjustment of nutrients, dissolved oxygen and pH. At this stage, the Global-ONCE program is planning to develop an international network of field stations and research facilities; co-design interdisciplinary collaborative research; develop an evaluation framework for mitigation and adaptation approaches; co-ordinate capacity building; facilitate equitable policy, governance and societal understanding.

Conclusions and Future Plans

Working Group 46 identified parts of the current knowledge gaps in negative carbon emissions in the oceans, published papers, and propose future research directions and applications to the enhancement of CO_2 sequestration. Research by Working Group members have addressed the aims set out under the initial Terms of Reference. One of

our commitments lies in establishing long-term time series stations, such as Xiamen Time-series Station, to measure carbon-related parameters, which was open access for the general public.

References

1. Cai, W. J., & Jiao, N. (2022). Wastewater alkalinity addition as a novel approach for ocean negative carbon emissions. *The Innovation*, *3*(4).

2. Griscom, B. W., Adams, J., Ellis, P. W., Houghton, R. A., Lomax, G., Miteva, D. A., ... & Fargione, J. (2017). Natural climate solutions. *Proceedings of the National Academy of Sciences*, *114*(44), 11645-11650.

3. Jiao, N., Zhu, C., Liu, J., Luo, T., Bai, M., Yu, Z., ... & Cai, W. J. (2023). A roadmap for Ocean Negative Carbon Emission eco-engineering in sea-farming fields. *The Innovation Geoscience*, *1*(2), 100029.

4. Liu, J., Robinson, C., Wallace, D., Legendre, L., & Jiao, N. (2022). Ocean negative carbon emissions: A new UN Decade program. *The Innovation*, *3*(5).

5. Jiao, N.,, & Dai, M. (2022). Research strategies for ocean carbon storage mechanisms and effects. *Chinese Science Bulletin*, *67*(15), 1600-1606.

Appendix 1

WG 46 Terms of Reference

WG 46 term: 2020-2023
Extended 1 year to 2024
Parent Committee: BIO and POC

1. Identify current knowledge gaps in negative carbon emission in the oceans.
2. Propose future research directions and applications to the enhancement of negative carbon emissions including the items below:
   (1) Developing additional long-term time series stations to observe carbon sequestration in representative coastal and offshore waters.
   (2) Proposing integrated experimental studies to better understand carbon sequestration under paleo-, current and future oceanic conditions.
   (3) Proposing an international collaborative project or program dedicated to ocean negative carbon emissions.

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Appendix 3

Publications Related to WG 46 Research

(1) WANG, Yuze, et al. (2021). Advocating eco-engineering approach for ocean carbon negative emission. Bulletin of Chinese Academy of Sciences (Chinese Version), 36(3), 279-287.

(2) Jiao, N (2021) Developing Ocean Negative Carbon Emission Technology to Support National Carbon Neutralization, Bulletin of Chinese Academy of Sciences (Chinese Version) 36. DOI: https://doi.org/10.16418/j.issn.1000-3045.20210123001

(3) Cai, W. J., & Jiao, N. (2022). Wastewater alkalinity addition as a novel approach for ocean negative carbon emissions. The Innovation, 3(4), 100272.

(4) Liu, J., Robinson, C., Wallace, D., Legendre, L., & Jiao, N. (2022). Ocean negative carbon emissions: A new UN Decade program. The Innovation, 3(5), 100302.

(5) Jiao, N. et al. (2020). Microbes mediated comprehensive carbon sequestration for negative emission in the ocean. National Science Review 7: 1858-1860.

(6) Jiao, N. et al. (2021). Excessive greenhouse gas emissions from wastewater treatment plants by using the chemical oxygen demand standard Science China Earth Science 65: 87-95.

(7) Wang, F. et al. (2021). Technologies and perspectives for achieving carbon neutrality

(8) Jiao, N., Luo, T., Chen, Q., Zhao, Z., Xiao, X., Liu, J., ... & Robinson, C. (2024). The microbial carbon pump and climate change. *Nature Reviews Microbiology*, 1-12.

Appendix 4

Relevant Presentations by WG 46 Member

<u>The WG held an "Ocean Negative Carbon Emissions (ONCE) for Carbon Neutralization" Workshop on October 24 in Seattle during the 2023 PICES Annual Meeting.</u>

The chief scientist of Global ONCE, Prof. Nianzhi Jiao delivered the opening remarks, Prof. Curtis Suttle, Fellow of the Royal Society of Canada, along with ONCE Working Group member Prof. Jung-Ho Hyun, presented reports during the workshop. The event facilitated academic discussions among experts, scholars, early-career professionals, and students from the USA, South Korea, Canada, China, and other countries.

<u>The WG annual meeting was held in Xiamen 5-7 November</u>

The 2023 Annual meeting of Working Group (WG) 46 the Joint PICES/ICES Working Group on Ocean Negative Carbon Emissions was held in Xiamen, China and online from November 5 to 7, 2023. The meeting was chaired by the four co-chairs, namely, Prof. Nianzhi Jiao, who is Global ONCE's co-chair and Chief Scientist, Prof. Carol Robinson from the University of East Anglia and Global ONCE's co-chair, Dr. Douglas Wallace, who is a Fellow of the Royal Society of Canada, and Prof. Louis Legendre, who is a Fellow of the European Academy of Sciences. There were 12 members plus 3 observers (WG 46 Endnote 1) in attendance. During the meeting, past activities and ToR of the WG were reviewed. Updates on the progress made by each task team were provided, and two joint reports were discussed, and work began on drafting them. The agenda for the meeting is presented as WG 46 Endnote 2. The first joint report focuses on "Advancements in Ocean Negative Carbon Emissions Research: What is Happening, and What Comes Next?" The second report addresses "Environmental Changes Potentially Caused by mCDR.

Appendix 5

Meeting Report and Topic Session/Workshop Summaries from Past Annual Meetings

2021

PICES-2021, Online (hosted by China)

- Reviewing recent activities and gatherings of the WG, and build upon the rationale for WG 46.
- Updating on the progresses made by each task team within the WG are provided and discussing further steps for WG 46.

Kick-off Meeting, due to COVID-19, on July 8, 2021

- To introduce the rationale for establishing WG 46 and clarify the objectives (terms of reference).
- Creating task teams to address the ToRs.
- Discussing a logo design and setting up Working Group website: https://meetings.pices.int/members/working-groups/wg46.

Co-Chairs' meeting,2021

- Discussing the structure, specific arrangements, and length of the annual meeting.
- Prof. Jiao also shares the updates on ONCE progress in China.

Meeting of the Chinese members sub-group,2021

- Sharing progress made towards the scientific objectives of WG 46.
- Discussing tasks on preparations for the WG annual meeting.
- Views on the next steps to assist in the achievement of WG objectives are also exchanged.

Task team 2 meeting

- Using data from coastal and open ocean time-series and macrocosm facilities to assess proposed ocean negative carbon emission models.
- Members discuss the links between TT2 and TT1 and highlight the knowledge gaps related to time-series.
- TT2 agrees that instead of proposing a new time-series station, it is more feasible for the TT to take advantage of the international nature of the Working Group to re-define the capabilities of time-series by focusing on the need of carbon measurement bases on the established time-series.

Task team 3a meeting

- The aim of the meeting is to propose integrated experimental studies to better understand carbon sequestration under paleo-, current and future oceanic conditions.
- Considering the travel restrictions due to the pandemic, it would be too difficult for members to conduct field investigation altogether in the near future, but TT3a would like to collect experimental designs and ideas from all the members of WG46.
- Further clarifies the deliverable of TT3a in which research directions need to be prioritized based on funding availability, readiness of implementation, research interest of the members, policies in different regions, etc.

The meeting of task team 3b

- Participating members agree to narrow down the scope of methods for discussion to ensure more in-depth exploration and original findings.

2022

Background

Working Group 46, a joint PICES/ICES Working Group on Ocean Negative Carbon Emissions (ONCE), was established with all members being officially assigned on April 6, 2021. Due to COVID-19, four meetings were convened virtually, including one meeting to plan a side event at the UN Ocean Conference (Nianzhi Jiao, Carol Robinson, and scientists in related fields), a side event at the UN Ocean Conference, one meeting of the WG Co-Chairs and one 2022 annual business meeting.

The PICES-2022 annual meeting, online conference

- Reviewing the past activities and meetings of the WG, updating on the progress made towards achieving the Terms of Reference (ToRs) and discussing further steps for the WG.

2022 activities and actions towards achieving Terms of Reference

1. UN Ocean Decade Program Global ONCE

- Objectives of Global ONCE, some of which are an extension of those of WG 46:
  1) Develop an international network of field stations and research facilities;
  2) Develop an evaluation framework;
  3) Develop capacity and ocean literacy and
  4) Facilitate equitable policy and governance.
- The objective of WG 46 to propose an international program on ocean negative carbon emissions has been achieved.

2. UN Ocean Conference side event

- The aim of the side event was to discuss how ocean carbon storage and negative emission technologies contribute to the UN Sustainable Development Goals, to

stimulate discussion and to encourage people to get involved in Global ONCE.

3. ONCE – progress in China

- Five Missions of ONCE in China, funded by MOST (Ministry of Science and Technology of China):

1) Developing innovative research Scientific Goal: Use a combination of BCP (Biological Carbon Pump)-CCP (Carbonate Counter Pump)-MCP (Microbial Carbon Pump) to achieve synergistic carbon storage.

2) Construction of ONCE research platforms (RPs)

RP1: Marine Environmental Chamber System;
RP2: Intelligent Simulation System of Marine Platform;
RP3: Oceanic Residence Research Platform;
RP4: Seabed Scientific Observation Network;
RP5: Marine Ranching Facilities.

3) Demos in the field for ONCE approaches

Demo 1: Land-Ocean Integrated Eco-engineering;
Demo 2: Seaweed Farming Environment–Artificial Upwelling;
Demo 3: Ocean Alkalinity Enhancement–Wastewater Treatment Plants.

4) International communications

5) Science popularization: ONCE Virtual Lab for Earth System Science

4. Talks at PICES-2022, Busan, Korea

- Prof. Nianzhi Jiao and Dr. Rui Zhang presented at the POC and BIO meetings via Zoom and requested the establishment a new working group to continue the activities after the term of WG46.

5. Report to ICES 2022 [to be submitted end 2022], completed ToR

- Dr. Jihua Liu prepared a draft of the 2022 Interim Working Group e-evaluation for WG members to edit and update progress made.

6. Review actions towards achieving ToR

Planned deliverables WG 46 include:

1) Research papers, journal special issues or sections and reviews of the science related to ocean based negative carbon emission approaches;
2) A proposal for future research directions in ocean based negative carbon emissions;
3) An outreach product for the general public; and
4) A final report for ICES and PICES summarizing the results of the Working Group.

Appendix 6

Literatures/Publications filtered by year for keywords related to ocean negative carbon emissions in Web of Science

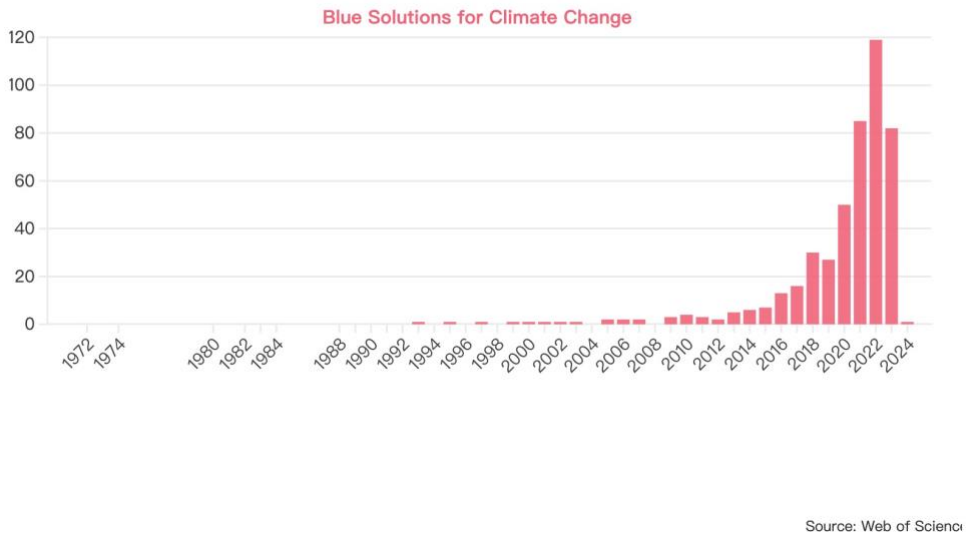

Figure 5. Keyword: “Blue Solutions for Climate Change”

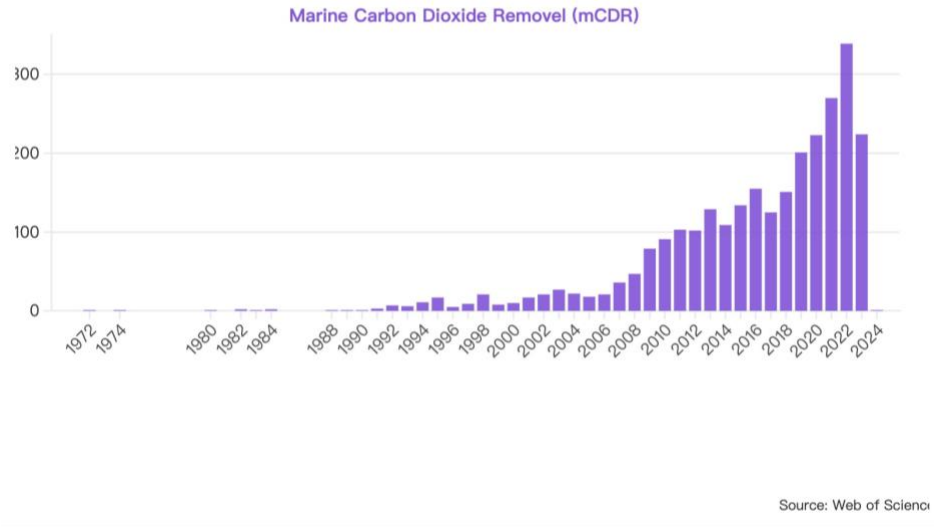

Figure 6. Keyword: “Marine Carbon Dioxide Removel (mCDR)”

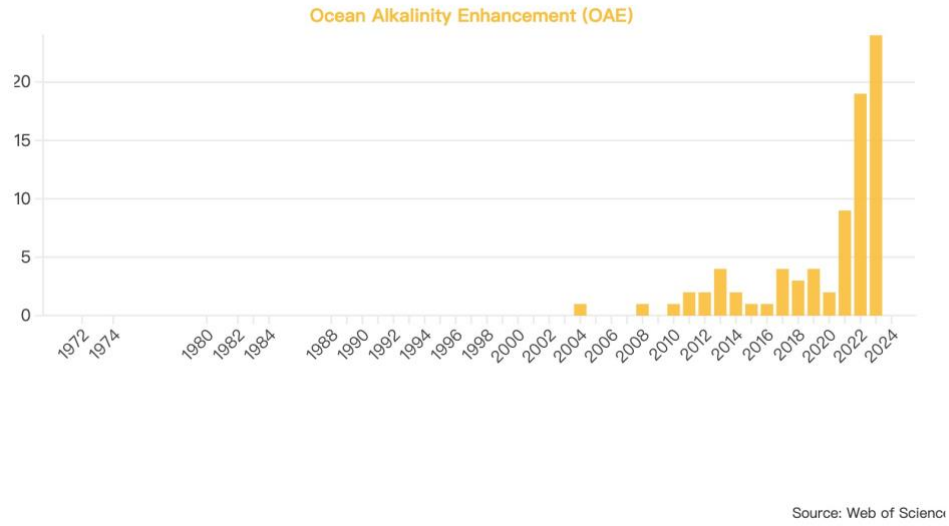

Figure 7. Keyword: “Ocean Alkalinity Enhancement (OAE)”

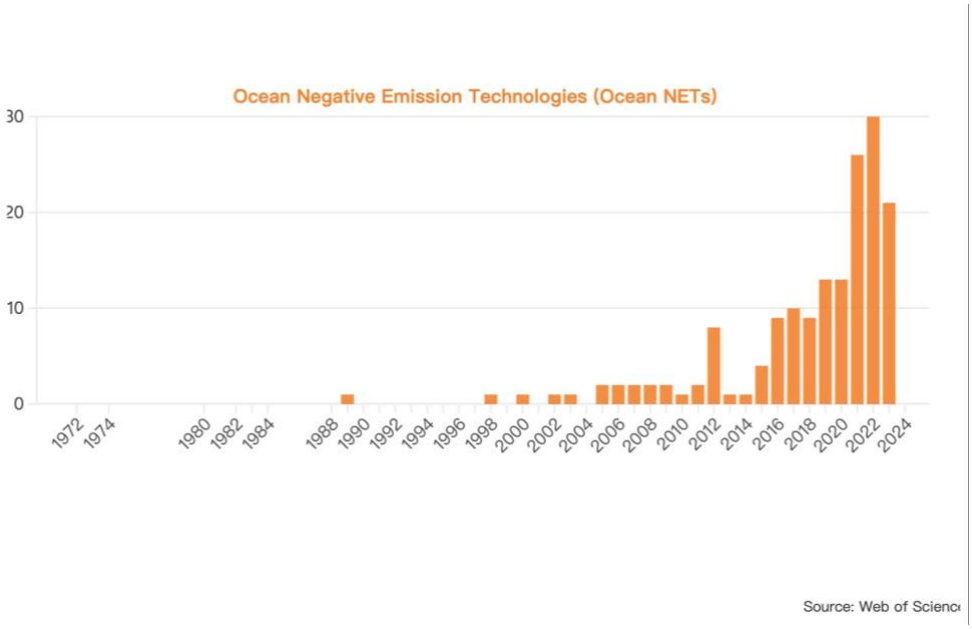

Figure 8. Keyword: “Ocean Negative Emission Technologies (Ocean NETs)”

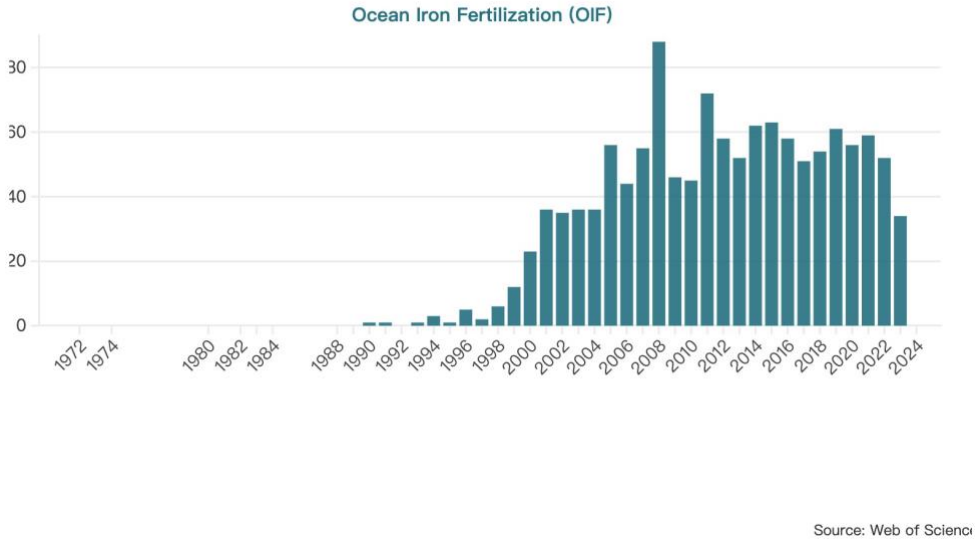

Figure 9. Keyword: “Ocean Iron Fertilization (OIF)”