An annotated literature database to support research on marine carbon dioxide removal (mCDR) and fisheries impacts

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Key Words: literature database, marine carbon dioxide removal, mCDR, fisheries, ecological impacts

Abstract

As atmospheric carbon dioxide concentrations rise, research interest in marine carbon dioxide removal (mCDR) is accelerating due to the ocean's role in absorbing carbon dioxide from the atmosphere. While characterizing the carbon removal efficiency of mCDR techniques is critical, it is equally important to understand the potential implications of mCDR for environmental and ecological processes as well as ocean-dependent industries and communities, including fisheries. Though direct studies on the biological and ecosystem impacts of mCDR remain limited, decades of research in associated research fields have examined how environmental changes similar to those produced by different mCDR approaches may impact marine organisms and ecosystems. Existing literature from these broader fields can therefore offer valuable insight to the possible impacts of mCDR on biological systems. This project consolidated and annotated literature at the intersection of mCDR and fisheries to create a database of studies related to biological responses, ecosystem changes, and fisheries impacts. By structuring this literature into a searchable database, we offer the first iteration of a platform that can be used to expand the knowledge base of mCDR and accelerate synthesis of fisheries-relevant research. The open source *mCDRxFisheres Literature Database*, developed using the R Shiny app lit-tag-builder, contains 870 publications and provides an interactive open-source online interface for users to download, search, filter, and visualize content using mCDR and fisheries-focused annotations. Here we describe the database curation methodology, including an exploratory comparison of manual and artificial intelligence (AI) tagging methods, and present a summary of the database contents to demonstrate its application in examining the intersection of mCDR and fisheries research. We identify avenues for the research community to leverage and expand this effort to continue cultivating this database and consolidating related knowledge, including through the International Council for the Exploration of the Seas (ICES) mCDR and Fisheries and Aquaculture Working Group. These efforts will help increase attention to critical research questions regarding the interaction of mCDR and fisheries, including potential positive and negative environmental, ecological, and socio-economic impacts.

Introduction

Carbon dioxide removal is recognized as a necessary strategy, alongside emissions reductions, to reach emission targets and global climate goals (IPCC, 2023; Smith et al., 2024). Given the ocean's natural ability to absorb and durably store carbon dioxide (CO_2), marine carbon dioxide removal (mCDR) techniques have emerged as a promising set of CDR strategies (NASEM, 2022; Cross et al., 2023; Doney et al., 2024). Research on mCDR is in its infancy and accelerating, focused on the viability of different mCDR methods for sequestering CO_2 efficiently and permanently, as well as the potential biological and ecosystem impacts that could result from altering ocean processes. Proposed mCDR approaches may be deployed in a diverse range of marine habitats and span both biotic methods (ocean nutrient fertilization (ONF), macroalgae cultivation and sinking, artificial upwelling and downwelling) and abiotic methods (ocean alkalinity enhancement (OAE), direct ocean removal (DOR)); see NASEM 2022, Cross et al., 2023 for detailed reviews of mCDR methods. All of these methods alter the biogeochemistry of the ocean, either through carbonate chemistry manipulations (abiotic mCDR) or stimulation of biological productivity and export (biotic mCDR), which may directly or indirectly impact marine organisms, ecosystems, and the industries and communities that rely upon them, such as fisheries, aquaculture, and Indigenous communities (Grabb et al., 2025).

The mCDR research community has increasingly recognized the need to prioritize investigation of the biological and ecosystem effects, including positive and negative impacts of these various mCDR approaches, in order to determine whether the potential benefits may outweigh the possible adverse impacts on ocean ecosystems and communities (Roberts et al., 2024; Doney et al., 2024; Grabb et al., 2025; Grabb et al., 2026). Potential positive and negative impacts from mCDR deployments can impact fisheries through environmental, socio-economic, and/or regulatory processes (Grabb et al., 2025; Grabb et al., 2026). Assessing how the growing mCDR sector may negatively or positively influence and/or provide opportunities (i.e. job opportunities, spatial planning, incorporation into existing infrastructure, etc.) to fishing industries enables identification of beneficial collaborations and an opportunity to minimize adverse impacts. For example, understanding potential environmental impacts can inform spatial and temporal decisions about the testing and implementation of specific mCDR techniques. Some mCDR techniques such as OAE and DOR aim to increase ocean alkalinity and/or pH, which could help mitigate climate stressors such as ocean acidification (Orr et al., 2005; Cross et al., 2023). However, further research is required to understand how organisms might thrive or survive in response to changing carbonate chemistry in their environment, especially during vulnerable stages of growth and development (Goldenberg et al., 2024 OAE paper; Hudspith et al., 2017). The addition of alkalinity and nutrient sources through mineral feedstocks may also introduce trace metals or chemical compounds that may be toxic to organisms (Montserrat et al., 2017), or may stimulate local primary productivity while favoring certain species or robbing nutrients from downstream processes (Roberts et al., 2024). The potential impacts of mCDR at a species level could also have cumulative, downstream effects on marine food webs and population dynamics (Roberts et al., 2024; Goldenberg et al., 2024 AU paper; Wu et al., 2023) with important consequences for fisheries and ecosystem health. Targeted research on these biological and ecosystem impacts has not yet been widely conducted but is accelerating through laboratory experiments, mesocosm studies, field trials, and modeling efforts (Goldenberg et al., 2024 OAE paper; Gim et al., 2018; Berger et al., 2023). Recent efforts to develop frameworks for mCDR environmental impact assessments (Hourglass Climate, 2025; PML Applications, 2025; Ocean Visions, pending; Grabb et al., 2026) and synthesize the state of knowledge on mCDR and fisheries (ICES Themed Set on mCDR and Fisheries, 2025-2026) are expected to spur further research in this critical area.

While targeted studies are urgently needed to understand the benefits and risks of mCDR, this nascent field should also draw knowledge from well-established fields that have investigated the biological and environmental impacts of biogeochemical changes in ocean carbonate chemistry, nutrient availability, and other scenarios that might result from mCDR approaches. Published literature from these associated fields, including ocean acidification, aquaculture, blue carbon, and others, offers not only relevant data but also best practices and lessons learned that can help inform mCDR experimental design, monitoring networks, collaboration, and community engagement (e.g., Findlay et al., 2025). Recent efforts to leverage scientific knowledge and experience from associated fields include the perspective on lessons learned from the Global Ocean Acidification Observing Network (GOA-ON) by Findlay et al. (2025). Tools such as the Ocean Visions mCDR Field Trial Activities Database (Ocean Visions, 2025a) and Ecosystem Activities Database (Ocean Visions, 2025b), the Carbon to Sea OAE Literature Database (Carbon to Sea, 2025), and the Ocean Acidification International Coordination Centre Bibliographic Database (OA-ICC, 2026) have also been developed to consolidate and improve access to knowledge for mCDR and related fields. Given the complexity and urgency of the research questions at the intersection of mCDR and fisheries, fisheries-centered efforts to consolidate relevant knowledge from diverse disciplines and accelerate the knowledge base for decision making are critically needed (ICES WKmCDR, 2025; Grabb et al., 2025).

In this study, we present the open-source, built-for-purpose *mCDRxFisheries Literature Database*, which specifically targets published literature at the intersection of mCDR and its potential biological and ecosystem impacts critical to fisheries. This structured and searchable literature database consolidates publications related to mCDR and fisheries from a variety of associated fields, increasing access to relevant bodies of knowledge that can inform mCDR research across foundational research that started prior to the development of the mCDR and has continued since. These included mCDR-specific studies, studies from associated fields that address technical or foundational science relevant to mCDR approaches (e.g., ocean acidification), and fisheries-relevant studies that investigate biological responses to the biogeochemical changes that mCDR may produce in marine ecosystems. After manually collating the database of 870 publications, we systematically tagged all manuscripts with defined criteria to enhance the searchability and usability of the database and created an open-source app for the research community to use, available at: https://connect.fisheries.noaa.gov/mcdrxfisheries-lit-db-viewer/.

In this paper, we present a narrative synthesis of the database, recognizing that the available literature related to biological mCDR impacts does not yet present enough data to support a robust quantitative meta analysis. We describe the creation and contents of the annotated database, and offer examples of how the database can be utilized as a starting point for systematic reviews in the future and as a resource for identifying key intersections of mCDR, fisheries, and associated fields. We also present an exploratory application of an AI-based tool, Elicit (https://elicit.com/), to execute the same methods that we completed manually. We determined that this 2025-era AI tool was similarly, if not less, efficient at database creation, requiring a similar amount of time and level of oversight by a subject matter expert, leading us to prioritize our manual methods to build the database rather than utilizing AI assistance (Becker et al., 2025).

The *mCDRxFisheries Literature Database* can be leveraged by the mCDR and fisheries communities to inform research efforts, provide an infrastructure for scientific synthesis, inform science-based decision making, and provide a vehicle for community-building and literacy. For example, this database is currently being utilized to consolidate the limited literature on mCDR impacts on biological organisms as the basis for a state of knowledge mCDR and fisheries review (see ICES Themed Set on mCDR, Fisheries, and Aquaculture). We refer the reader to Gurney-Smith et al. (in review) for scientific synthesis of the database contents presented in this paper. There has also been growing interest in the database from the National Academies of Sciences, Engineering, and Medicine Marine Carbon Dioxide Removal Standing Committee (NASEM mCDR Standing Committee ICES Briefing, 2026), U.S. and Canada government agencies, mCDR organizations focusing on developing environmental impact assessments (EIA), and other mCDR practitioners. Briefings to these groups have emphasized the intended utility of this database: its trends, gaps, and key intersections in the consolidated literature spanning mCDR and adjacent fields can be quickly identified by users, and leveraged as a starting point for further systematic review on specific topics within the mCDR/fisheries domain. This database can also be adapted to expand its relevance to other sectors and critical research gaps as the mCDR field progresses. For example, this database has already been a resource for the creation of a targeted database focused on biological thresholds associated with mCDR exposures (McElhany et al., 2026a). The database description presented within this paper enables users to understand the scope, utility, bias, and limitations of this new resource, which is the first attempt to provide a consolidated collection of fisheries-relevant literature for the mCDR community. The *mCDRxFisheries Literature Database* is open-source and flexible by design, and will be periodically updated and curated by the ICES mCDR Fisheries and Aquaculture Working Group.

Compiling the literature database

The *mCDRxFisheres Literature Database* was curated between February and July 2025 by systematic searches in Google Scholar and sourcing of papers from existing community-generated databases (Figure 1). Google Scholar was selected to provide broad, interdisciplinary coverage of peer-reviewed literature and expert reports. All searches were conducted in English to reduce opportunities to mis-translate literature and/or bias searches in only a few other languages, recognizing that there is prominent literature in other languages this database does not capture. The open-source citation management software Zotero was used to create a reference library[1].

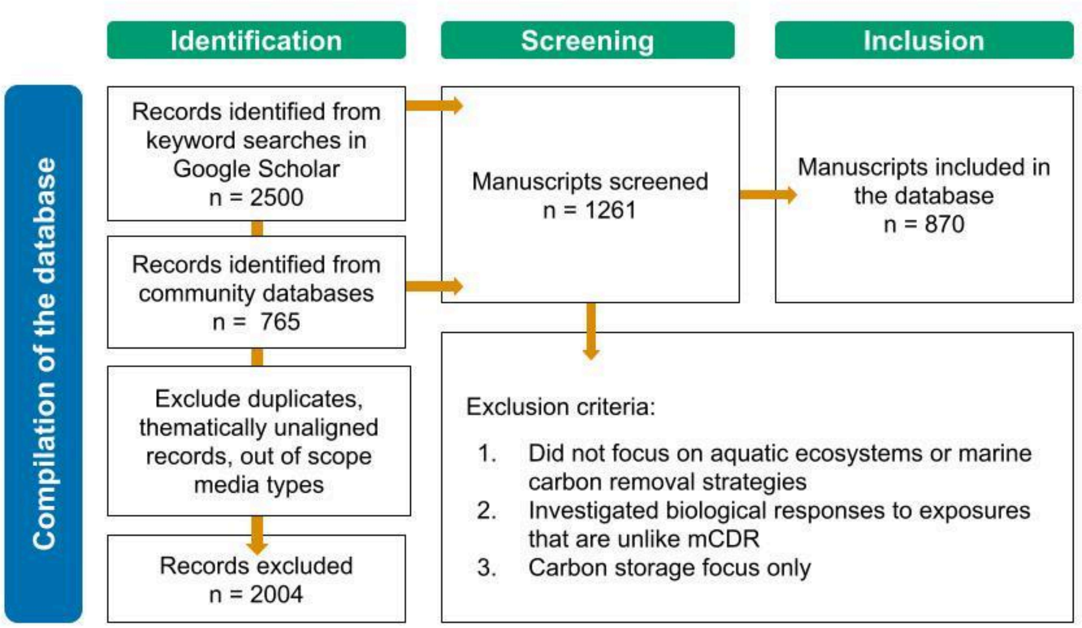

Figure 1: PRISMA flow chart (created based on https://www.prisma-statement.org/ methodology) illustrating the database creation process. The methodology outlined in this paper enables users to leverage the database for scoping and systematic reviews.

The Google Scholar searches targeted literature focused on the six most commonly identified mCDR approaches: OAE, DOR, ONF, macroalgae cultivation and sinking, artificial upwelling, and artificial downwelling (NASEM, 2022; Cross et al., 2023) (Supplemental Table 1, “mCDR methods”). Various terms were used for each of the six mCDR techniques (e.g. for ONF, search terms included: mCDR ONF, mCDR OIF, ocean iron fertilization, ocean nutrient fertilization). Additionally, search terms were used to

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[1] Zotero: https://www.zotero.org/

systematically identify papers in related research fields that examined the potential biological impacts of biogeochemical changes that could be associated with mCDR methods (Supplemental Table 1, “Similar biogeochemical manipulations”). These search terms targeted studies of marine biological sensitivity to carbonate chemistry manipulations expected for OAE and DOR (e.g., elevated pH, elevated alkalinity, low CO_2) and increased nutrient concentrations that could be related to ONF, macroalgae cultivation and sinking, artificial upwelling, or artificial downwelling. We iteratively tested alternative terms and synonyms to ensure broad coverage of topics that align with the database scope. To focus on the most foundational research that is highly cited, manuscripts from the top 100 Google Scholar results (sorted by relevance) for each search term were added to the Zotero library. We also identified two community-generated databases from the International Council for the Exploration of the Seas (ICES) Workshop on Marine Carbon Dioxide Removal (ICES WkmCDR, 2025) and the Carbon to Sea Initiative (Carbon to Sea, 2025) that were relevant to the scope of our effort. Of the 3265 total records identified, duplicates and thematically non-aligned entries were removed during a first-pass review. We further excluded media in blog, web article, news report, and video format. The remaining records (n=1261) were then subjected to a formal screening based on specific in-scope and out-of-scope criteria.

Titles and abstracts were screened to assess relevance, and full texts were reviewed when necessary. From the initial set of papers, we identified those relevant to the scope of the *mCDRxFisheries Literature Database* based on the following criteria: 1) the paper addressed one of the six targeted mCDR approaches or foundational science relevant to the implementation of these mCDR approaches , and/or 2) the paper investigated a biological response to a biogeochemical exposure that an mCDR approach could reasonably be expected to produce in a marine ecosystem (e.g. ocean acidification studies were included if experiments included treatments that raised the pH compared to baseline conditions). Papers were excluded from the database if the paper: 1) did not focus on aquatic ecosystems or marine carbon removal strategies, 2) investigated biological responses to exposures that are not similar to expected mCDR exposures, or

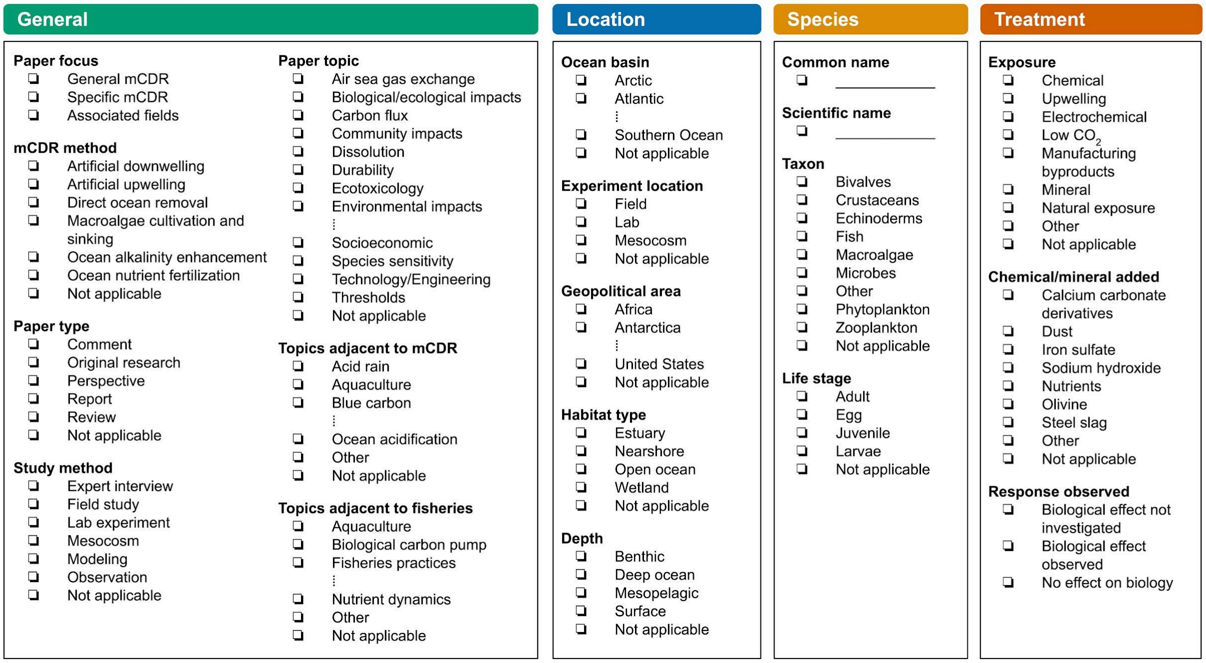
3) focused only on carbon storage in the ocean, not carbon removal by marine processes (e.g., subseafloor injection or terrestrial biomass sinking). We included peer-reviewed journal articles, journal article preprints, books and book sections, conference papers, expert reports, and theses. Conference abstracts were excluded in addition to the web and news articles, blogs, and videos excluded during first-pass review. The final database contained 870 papers.

The manuscripts in the database were published by 290 different entities, including scientific journals and organizations that have produced scientific reports. The top 20 scientific journals represented in this database are summarized in Supplemental Table 2; the five most represented journals are *Biogeosciences, Frontiers in Marine Science, Marine Ecology Progress Series, Environmental Research Letters,* and *Frontiers in Climate.* In addition to journals, 50 organizations have published reports and manuscripts that are included in the database (Supplemental Table 3).

Annotating the literature database

We used the open-source R Shiny app lit-tag (https://connect.fisheries.noaa.gov/lit-tag/) (McElhany et al., 2026b) to annotate each publication in the reference library according to predefined criteria and thematic categories. The required inputs for the lit-tag app are an exported Zotero library and a user-created Excel file containing notes fields and predefined tags grouped into categories nested within broader domains. Notes fields allowed free-form input and were used to record brief statements about the mCDR and fisheries relevance of each publication. The tagging process was completed manually for each paper in the database. We reviewed all abstracts and assigned tags based on the pre-defined tagging criteria described below to create a structured and searchable database. The domains, categories, tags, and tagging criteria were defined specifically to identify relevant literature at the intersection of mCDR and fisheries (see Supplemental Materials Section 1). Before tagging the entire database, we tested the tags on a small subset of the database (~300 papers) and iteratively refined the categories and tags to ensure the tagged database would provide an effective structure that aligns with the scope of this work. The tags applied to the database are described briefly below, with detailed tagging criteria available in the Supplemental Materials Section 1. In addition to personalizing the lit-tag app for the *mCDRxFisheries Literature Database*, as presented in this study, the lit-tag platform has also been used to create a database focused specifically on literature relevant to estimating biological thresholds for carbonate chemistry changes created by mCDR (McElhany et al. 2026a).

Database tags



General

Paper focus
- ☐ General mCDR
- ☐ Specific mCDR
- ☐ Associated fields

mCDR method
- ☐ Artificial downwelling
- ☐ Artificial upwelling
- ☐ Direct ocean removal
- ☐ Macroalgae cultivation and sinking
- ☐ Ocean alkalinity enhancement
- ☐ Ocean nutrient fertilization
- ☐ Not applicable

Paper type
- ☐ Comment
- ☐ Original research
- ☐ Perspective
- ☐ Report
- ☐ Review
- ☐ Not applicable

Study method
- ☐ Expert interview
- ☐ Field study
- ☐ Lab experiment
- ☐ Mesocosm
- ☐ Modeling
- ☐ Observation
- ☐ Not applicable

Paper topic
- ☐ Air sea gas exchange
- ☐ Biological/ecological impacts
- ☐ Carbon flux
- ☐ Community impacts
- ☐ Dissolution
- ☐ Durability
- ☐ Ecotoxicology
- ☐ Environmental impacts

⋮
- ☐ Socioeconomic
- ☐ Species sensitivity
- ☐ Technology/Engineering
- ☐ Thresholds
- ☐ Not applicable

Topics adjacent to mCDR
- ☐ Acid rain
- ☐ Aquaculture
- ☐ Blue carbon

⋮
- ☐ Ocean acidification
- ☐ Other
- ☐ Not applicable

Topics adjacent to fisheries
- ☐ Aquaculture
- ☐ Biological carbon pump
- ☐ Fisheries practices

⋮
- ☐ Nutrient dynamics
- ☐ Other
- ☐ Not applicable

Location

Ocean basin
- ☐ Arctic
- ☐ Atlantic

⋮
- ☐ Southern Ocean
- ☐ Not applicable

Experiment location
- ☐ Field
- ☐ Lab
- ☐ Mesocosm
- ☐ Not applicable

Geopolitical area
- ☐ Africa
- ☐ Antarctica

⋮
- ☐ United States
- ☐ Not applicable

Habitat type
- ☐ Estuary
- ☐ Nearshore
- ☐ Open ocean
- ☐ Wetland
- ☐ Not applicable

Depth
- ☐ Benthic
- ☐ Deep ocean
- ☐ Mesopelagic
- ☐ Surface
- ☐ Not applicable

Species

Common name
- ☐ ____________

Scientific name
- ☐ ____________

Taxon
- ☐ Bivalves
- ☐ Crustaceans
- ☐ Echinoderms
- ☐ Fish
- ☐ Macroalgae
- ☐ Microbes
- ☐ Other
- ☐ Phytoplankton
- ☐ Zooplankton
- ☐ Not applicable

Life stage
- ☐ Adult
- ☐ Egg
- ☐ Juvenile
- ☐ Larvae
- ☐ Not applicable

Treatment

Exposure
- ☐ Chemical
- ☐ Upwelling
- ☐ Electrochemical
- ☐ Low CO_2
- ☐ Manufacturing byproducts
- ☐ Mineral
- ☐ Natural exposure
- ☐ Other
- ☐ Not applicable

Chemical/mineral added
- ☐ Calcium carbonate derivatives
- ☐ Dust
- ☐ Iron sulfate
- ☐ Sodium hydroxide
- ☐ Nutrients
- ☐ Olivine
- ☐ Steel slag
- ☐ Other
- ☐ Not applicable

Response observed
- ☐ Biological effect not investigated
- ☐ Biological effect observed
- ☐ No effect on biology

Figure 2. Predefined tags applied to publications in the *mCDRxFisheries Literature Database*. Tags are grouped into domains ("*General*", "*Location*", "*Species*", "*Treatment*") and categories (e.g., "*Paper focus*", "*Paper topic*", "*mCDR method*", etc). Ellipses (⋮) indicate that not all tag options are included in the figure for brevity.

The "*General"* domain of the database tags included categories of multiple choice tags that differentiated papers based on the general alignment of the paper with the database's purpose: identifying intersections between mCDR and fisheries research

(Figure 2, Supplemental Materials Section 1). Papers were categorized into three groups based on whether they addressed mCDR generally (“General mCDR”), focused on one of the six specific mCDR techniques (“Specific mCDR”), or did not explicitly mention mCDR yet were relevant to the scope of this study (“Associated fields”). The type of paper (e.g., original research, review, comment, etc.) was also defined and for original research articles, the methodology of the study was categorized (e.g., laboratory experiment, modeling, field study). To indicate the general topic(s) of each paper and assist searching and filtering by the user, an inexhaustive list of paper topics related to mCDR were assigned. For papers from associated fields, additional topic tags were assigned to identify the key intersection(s) with mCDR and/or fisheries.

The “*Location*” domain categorized papers by geographic, ecosystem, and experimental locations with multiple choice tag options (Figure 2). Papers were tagged when a field, sampling, and/or modeling location was available, with the nearest and/or adjacent location selected when the study location was identified with greater specificity than the tag options. Ocean basin and geopolitical area tags provided general geographic information while habitat type and ocean depth tags captured information about the study ecosystem. Experimental location tags indicated the methodological approach that was defined within the papers (i.e., whether the study was performed in a lab, mesocosm, or field site).

The “*Species*” domain included optional text-box input for the scientific and common name(s) of the species studied or discussed in the paper (Figure 2). If species and/or taxon information was explicitly mentioned, a taxon tag was selected from a multiple choice predetermined list. Life stage(s) studied were also selected from multiple choice tag options if reported in the paper.

The “*Treatment*” domain provides a broad category for the type of “Exposure” used within the study, such as a biogeochemical manipulation and/or feedstock (e.g., chemical, mineral, etc.) with multiple choice tag options (Figure 2). This domain also included more specific information about the “chemical/mineral” added, if applicable and mentioned within the study. These tagging categories were predetermined based on common mCDR approaches and feedstocks and refined based on the literature within the database. Recognizing that the exposures associated with mCDR activities and experiments are evolving as new techniques and feedstocks are explored , we included an “other” tag option to capture study scenarios not described by the tags defined. A tag for biological effect indicated whether a biological response to the exposure was investigated and, if so, whether an effect was observed. We intentionally omitted directionality (i.e., positive or negative categorization) for these effects, since such characterization requires context-dependent interpretation and there is not yet scientific consensus on beneficial versus detrimental outcomes in complex physiological responses or marine ecosystems. The biological effect tag provides a means of filtering for studies that examine biological responses, enabling database users to identify and carefully interpret these experiments in the context of their specific research question.

Quality assurance and control

After the tagging was completed, we implemented quality assurance and control (QA/QC) checks to ensure that all papers met the inclusion criteria and were assigned a complete set of tags for all categories. We performed quality control checks using the viewer module of the lit-tag app (McElhany et al., 2026b) which allows searching, filtering, and visualization of literature databases built with lit-tag-builder. Bibliographic information that was captured using Zotero’s metadata retrieval during database curation (e.g., title, authors, journal, publication year, abstract) was checked manually for completeness and accuracy. For the papers that were included in the database (n=870), the tagging process (which relied on reading the abstract and checking the body of the paper if there was any doubt) and QA/QC on average required around 15 minutes per paper.

Open source access

The *mCDRxFisheries Literature Database* is available in a stand-alone version of the lit-tag viewer module, *mCDRxFisheries Literature Database Viewer* (McElhany et al., 2026b), developed specifically for this project. The app provides an interface for users to interact with the database, which exists as a comma-separated values (csv) file containing the bibliographic information, notes, and tag values associated with each publication. The database csv file can be downloaded directly from the app, along with the Zotero library (.ris) and categories (Excel spreadsheet) files used as inputs to the R Shiny app lit-tag-builder. See the Supplemental Documents and Supplemental Materials Section 5 for the database csv file and categories Excel file used for the analysis presented in this study. A beta version of the database was initially shared via the app with small groups of researchers in the mCDR and fisheries communities for testing and feedback. The *mCDRxFisheries Literature Database Viewer* app is available at https://connect.fisheries.noaa.gov/mcdrxfisheries-lit-db-viewer/ . The database will be updated periodically through the ICES mCDR Fisheries and Aquaculture Working Group to ensure it is a living resource for the mCDR, fisheries, and aquaculture communities.

High-Level Trends in the *mCDRxFisheries Literature Database*

The following sections provide an initial exploration of the database content, revealing broad research patterns and highlighting areas requiring more focused investigation at the mCDR and fisheries intersection. Of the 870 publications in the database, the majority of the papers (n=502) address specific mCDR methods and/or foundational science, technology, or engineering topics directly relevant to the development or application of mCDR (Figure 3). The database includes 87 general mCDR papers, many of which are reviews and reports synthesizing current knowledge and the state of the field. Also included in the database are a significant number of publications (n=281) from associated fields that did not specifically mention mCDR, but are relevant to the intersection of mCDR and fisheries as defined by our inclusion criteria. The three major types of studies include laboratory experiments (n=242), reviews or synthesis (n=233), and modeling studies (n=223). Other less common types of methods used include field studies (n=125), observations (n=43), mesocosm studies (n=48), and expert interviews (n=8). In total, 42% (n=366) of the database is original research that focuses on specific mCDR techniques.

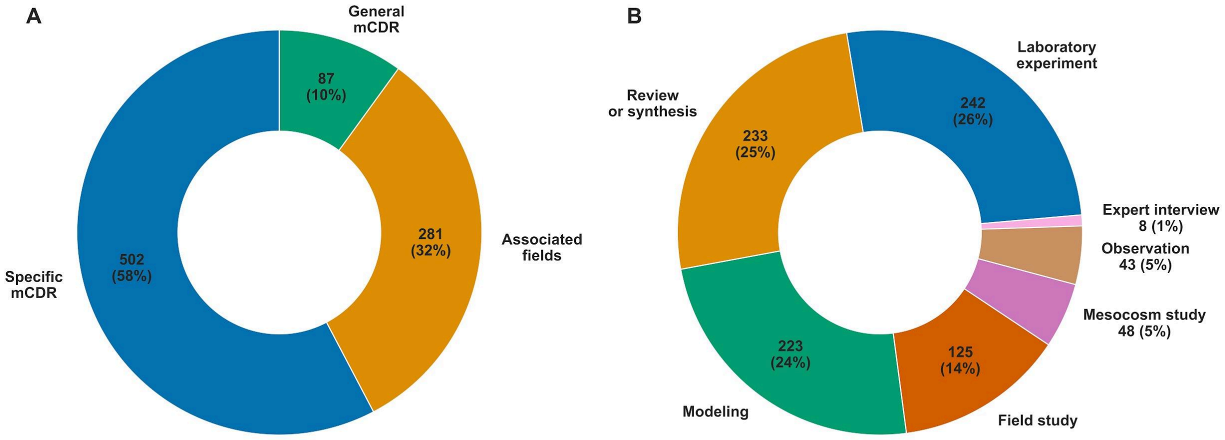


Figure 3. Pie charts of the (A) overall focus and (B) type of study of the 870 papers in the database. The overall focus categorizes papers that explicitly address mCDR methodologies (“Specific mCDR”), provide a general overview of the mCDR field (“General mCDR”), or are not focused on mCDR but fit within the scope of this study (“Associated fields”). Note that individual papers may be tagged with multiple study types, such that the total number of counts in (B) is greater than the total number of papers.

Most of the mCDR-specific papers focus on OAE (Figure 4A, n=208) and ONF (Figure 4B, n=130). A significant number of papers focus on macroalgae cultivation and sinking (Figure 4C, n=84) and artificial upwelling (Figure 4E, n=65), while only a few studies research DOR (Figure 4D, n=20) and artificial downwelling (Figure 4F, n=9). For the more common mCDR methodologies in the database (OAE, ONF, macroalgae cultivation and sinking, and artificial upwelling), there are a few early studies from the 1970s to 1990s that conducted foundational research applicable to these mCDR technologies and their potential to sequester carbon (Roels et al., 1970; Orr et al., 1992; Kheshgi and Haroon, 1995; Takano et al., 1995; Joos et al., 1991). In OAE, macroalgae cultivation and sinking, and artificial upwelling research, there was an exploration period from the late 1990s until 2019, during which a few studies per year (range 0–10 per year, 0–2 publications per year in most years) explored methodologies, biological impacts, and technological advancements. Most of these studies were model-based and published as reviews, high-level reports, and perspective pieces. Artificial upwelling papers included some field experiments, mainly testing technological developments (Seo et al., 2015; Yang et al., 2017). Following the Intergovernmental Panel on Climate Change report in 2019, which established that carbon removal strategies are needed in addition to emissions reductions to reach net-zero (IPCC, 2019), a rapid increase in research interest and funding for mCDR (Smith et al., 2024; Boettcher, 2023) led to an increase in publications. To date, the highest number of publications for any mCDR approach in the database was in 2024, when 56 studies were published on OAE (note that 2024 is the most recent complete year in the database, which was completed in July 2025). The rapid increase in publications across OAE, artificial upwelling, and macroalgae cultivation and sinking mirrors the OAE trend presented by the Carbon to Sea Initiative based on their own collation of relevant literature for their pending database (Carbon to Sea 2025).

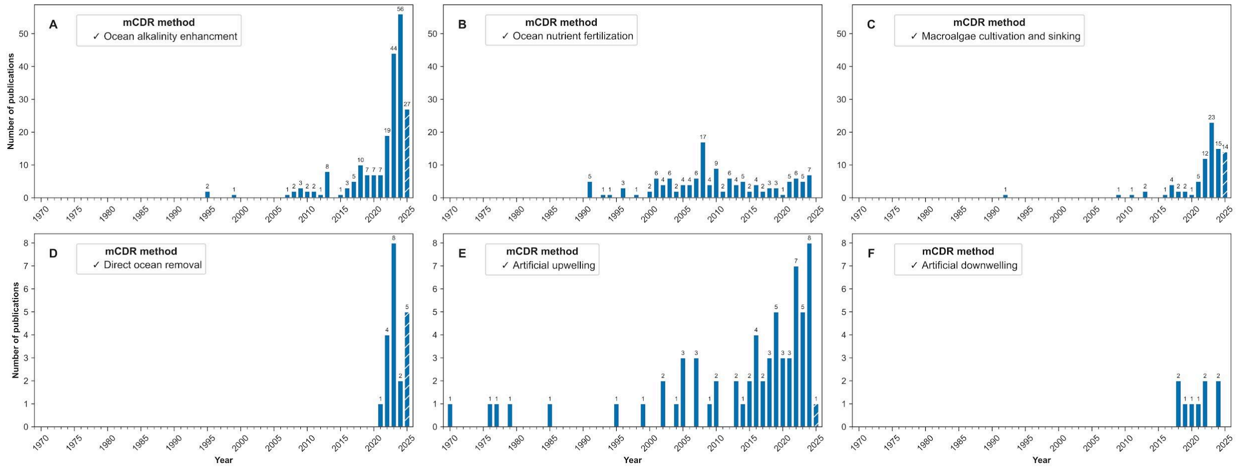


Figure 4. Number of database publications over time for each of the six main mCDR methods: (A) ocean alkalinity enhancement (n=208), (B) ocean nutrient fertilization (n=130), (C) macroalgae cultivation and sinking (n=84), (D) direct ocean removal (n=20), (E) artificial upwelling (n=65), and (F) artificial downwelling (n=9).

Crosshatched bars for the year 2025 indicate that the database includes only papers published between January and July 2025 and therefore does not represent an entire year.

The publication of ONF studies follows a unique trend among the mCDR approaches in the database, reflecting early interest in this approach and early-stage field trials that resulted in a steady publication rate throughout the 1990s and early 2000s. The highest annual number of studies focused on ONF occurred in 2008 (n=17). Since the first publication in 1994 (Watson et al., 1994), there have been 39 additional field studies and 30 modelling studies published on ONF. Prior to 2024, there was only one laboratory study conducted (Zettler et al., 1996) and to date, only three mesocosm studies total (Hall et al., 2001; Veldhuis et al., 2007; Zhang et al., 2022).

The fewest studies have been published on DOR and artificial downwelling. Papers focused on DOR have only been published since 2021, with the most publications in 2023 (n=8). Similarly, papers on artificial downwelling have only been published between 2018 and 2024 with only one to two papers published in a given year.

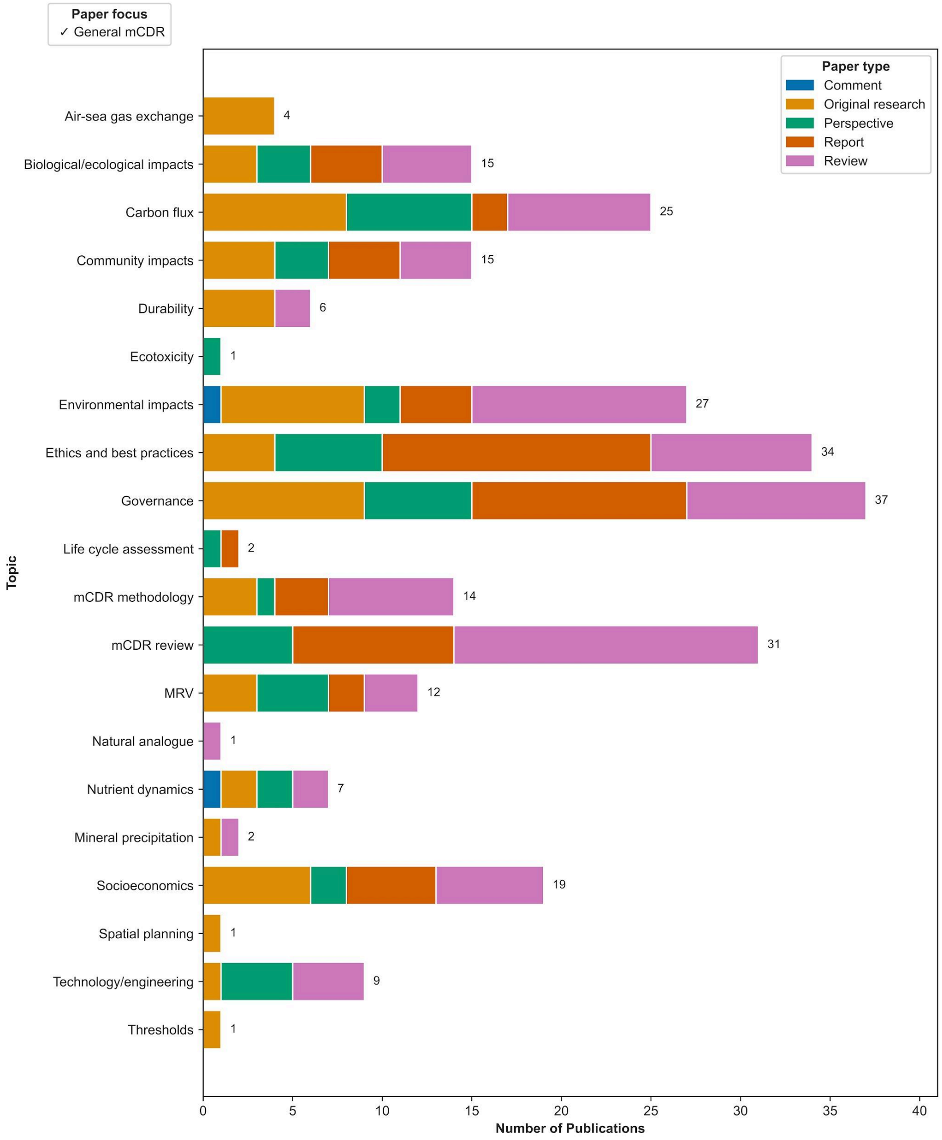


Figure 5. Paper topics within the “General mCDR” category of the database. Topic(s) were assigned to papers to indicate applicability to broad areas of mCDR research. Topics that were not assigned to any papers within the “General mCDR” category are not displayed. The unassigned topics included dissolution, precipitation, mCDR pilot, and species sensitivity (these topics were assigned to other papers outside of the “General mCDR” category). Paper type is displayed with the proportional stack variable, representing the relative contributions of each paper type: comment, original research, perspective, report, and review. The key in the upper left corner displays the

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filtering criteria applied to the database tags to extract the visualized subset of publications.

Beyond the papers focused on the six specific mCDR methods, the database contains general mCDR literature and papers from associated fields that meet our inclusion criteria. Papers identified as “General mCDR” literature are those that addressed a range of interdisciplinary mCDR topics, yet were not specifically focused on any particular methodology. This subset of papers (n=87) is largely composed of reviews, reports and perspective pieces, while original research makes up only 23%. The topics covered by the general mCDR literature span scientific understanding, technical development, policy, and social dimensions (Figure 5). The majority of the papers focus on topics related to major mCDR research priorities (NASEM, 2022; Doney et al., 2024), including quantification of carbon fluxes and carbon removal potential, environmental impacts, ethics and best practices, socioeconomics, and mCDR governance. Topics especially relevant to fisheries – biological and ecological impacts (n=15), ecotoxicology (n=1), thresholds (n=1), spatial planning (n=1) – are underrepresented in the general literature, and the topic of species sensitivity to mCDR was not tagged for any of the 87 general mCDR papers. While these fisheries-related topics are found at higher rates in the specific mCDR literature, these research areas have only become a focus in recent years (Roberts et al., 2024; Goldenberg et al., 2024 OAE; Goldenberg et al., 2024 AU; ICES WkmCDR, 2025; Grabb et al., 2025) and have not yet been widely synthesized in reviews and reports.

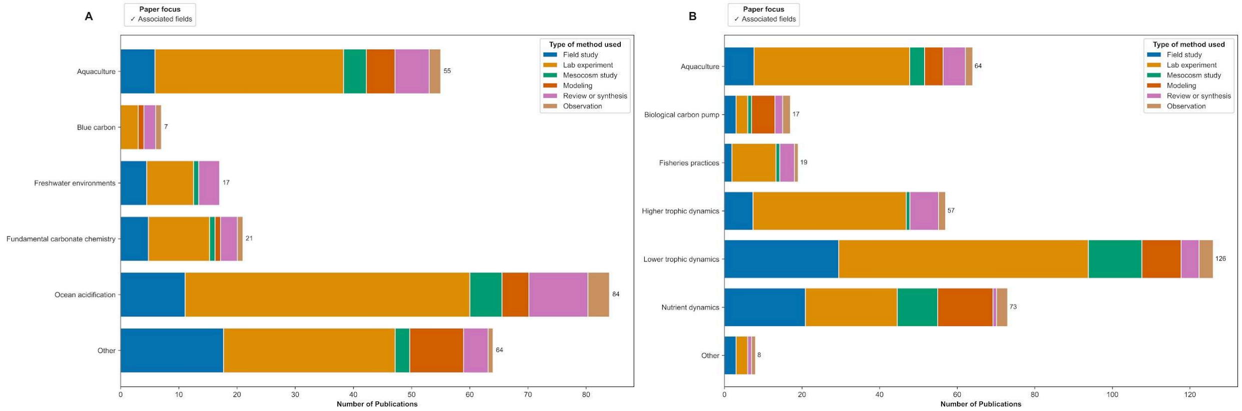

Figure 6. Paper topics relevant to (A) mCDR and (B) fisheries within the “Associated fields” category of the database. Topic(s) were assigned to papers to identify key intersections with fields such as aquaculture and ocean acidification from which relevant papers were drawn in our systematic search. The type of method used in each study (e.g., laboratory study, field study, modeling etc.) is displayed with the proportional stack variable, representing the relative contributions of each type of method to the overall count. The key in the upper left corner of each panel displays the filtering criteria applied to the database tags to extract the visualized subset of publications.

Our search terms related to biological impacts of mCDR-like biogeochemical manipulations (e.g., elevated pH and nutrient enrichment) captured 281 papers from associated fields that meet our inclusion criteria (Figure 3). We included a category of tags to identify the topical intersections of these papers with mCDR, shown in Figure 6A. The most prevalent mCDR-related topic among papers from associated fields is ocean acidification, a closely related field of research on the marine carbonate chemistry system and ecosystem responses that offers insights and expertise to the mCDR field (Findlay et al., 2025). Our systematic search returned a total of 277 papers related to ocean acidification, only 41% of which were determined to be within the scope of the database; the excluded papers were those that assessed only carbonate chemistry changes and impacts associated with ocean acidification, while papers included contain mCDR-relevant science such as experimental treatments that raised pH above baseline conditions or explored ocean acidification mitigation co-benefits (Figure 7). There is increasing recognition that mCDR research can benefit from leveraging the wealth of knowledge and lessons learned from the ocean acidification community (Findlay, et al., 2025), and the prevalence of ocean acidification literature in our database underscores that decades of field and laboratory research on environmental impacts and biological sensitivity to ocean acidification can be directly utilized to assess mCDR impacts on fisheries (Hurd et al., 2019; Gim et al., 2018). This also reflects the use of search terms that relate specifically to the biogeochemical alterations associated with mCDR pathways (i.e., similar exposures like high pH, increased alkalinity, low CO_2; see search terms in the Supplemental Table 1). Of the ocean acidification papers that are within the database scope, there are 53 papers reporting on laboratory studies that involved experimental treatments similar to an mCDR exposure (e.g., high pH treatment) for taxon including bivalves, crustaceans, echinoderms, fish, and plankton (Kristinsson et al., 2003; Boulais et al., 2018; Cripps et al., 2013; Mos et al., 2020). Relevant ocean acidification papers also include all study types (i.e., mesocosm, field, modeling, and observational studies) except for expert interviews.

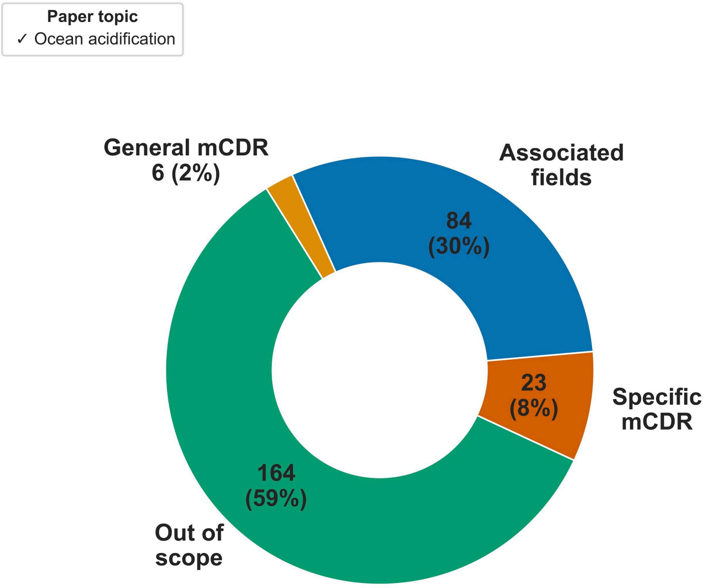

Figure 7. Pie chart of the overall focus (“Specific mCDR”, “General mCDR”, or "Associated fields”) of papers tagged with the “Ocean acidification” topic. The pie chart also displays the large percentage (59%) of ocean acidification papers that were identified through our systematic search but were determined to be outside the scope of the database as defined by our inclusion criteria. The out-of-scope papers were not included in the database for further analysis. The key in the upper left corner displays the filtering criteria applied to the database tags to extract the visualized subset of publications.

Aquaculture is another prevalent mCDR-related topic in the database with 55 studies from associated fields, largely related to the effects of marine carbonate chemistry on micro- and macroalgae studied through lab experiments (Figure 6A). The topics of blue carbon (n=7), freshwater environments (n=17), and fundamental carbonate chemistry (n=21) are not widely represented in the database, a consequence of not being targeted by our “Similar biogeochemical manipulations” search terms (Supplemental Table 1). Finally, the broad “other” categorization captures an assortment of topics that can be linked to mCDR, ranging from technological development of systems that might be deployed for mCDR to ecotoxicology studies of ballast water treatment systems (Renforth et al., 2013; de Lannoy et al., 2018; Elskus et al., 2015) (Figure 6A).

Figure 6B similarly displays the fisheries-related topics among papers from associated fields that fit within the scope of our database (e.g., aquaculture, biological response studies of higher or lower trophic levels). Lower trophic level dynamics are overwhelmingly represented in the database (n=126) and most of these were studies conducted in the laboratory (n=70) and field (n=32). Given that investigations of higher trophic level dynamics often involve more complex experimental studies and modeling of food web dynamics, it is of no surprise that fewer publications have reported on higher trophic level dynamics (n=57), with majority of these being conducted in the lab (n=43). Aquaculture is again a dominant field, with slightly more papers tagged for aquaculture in the fisheries-related category (Figure 6B, n=64) relative to the mCDR-related category (Figure 6A) due to inclusion of studies related to aquaculture practices beyond those related to carbon removal (e.g., water quality management in shellfish and finfish aquaculture). Nutrient dynamics (n=73) is also a common theme among fisheries-related publications in the database; the majority of those papers looked at nutrient dynamics related to phytoplankton (n=41) across field, lab, and mesocosm studies. Some studies in the database focused on fisheries practices (n=19), most of which (n=12) are laboratory studies that also investigated aquaculture, higher trophic level dynamics, biological and ecological impacts, and species sensitivity. Papers from associated fields that addressed “other” topics related to fisheries (n=8) focus on subjects such as calcification, coastal ecosystems (i.e., coral reefs, seagrass ecosystems), and ship discharge (Albright et al., 2016; Ricart et al., 2021; Cangelosi et al., 2013) (Figure 6B).

Interpreting Fisheries-Specific Tags

Database tags in the *Species*, *Treatment*, and *Location* domains allow further interrogation of the literature related to fisheries impacts, the primary intended use of this tool. To demonstrate the types of metadata contained in these tags and provide an overview of the fisheries-specific information contained in the database literature, we summarize findings related to taxon studied, mCDR and mCDR-like biogeochemical exposures, natural analogs for mCDR, ecotoxicity, and spatial planning. The following sections provide a deep dive into these topics as an example for how the database can be further interpreted to provide insights that address users' goals and interests.

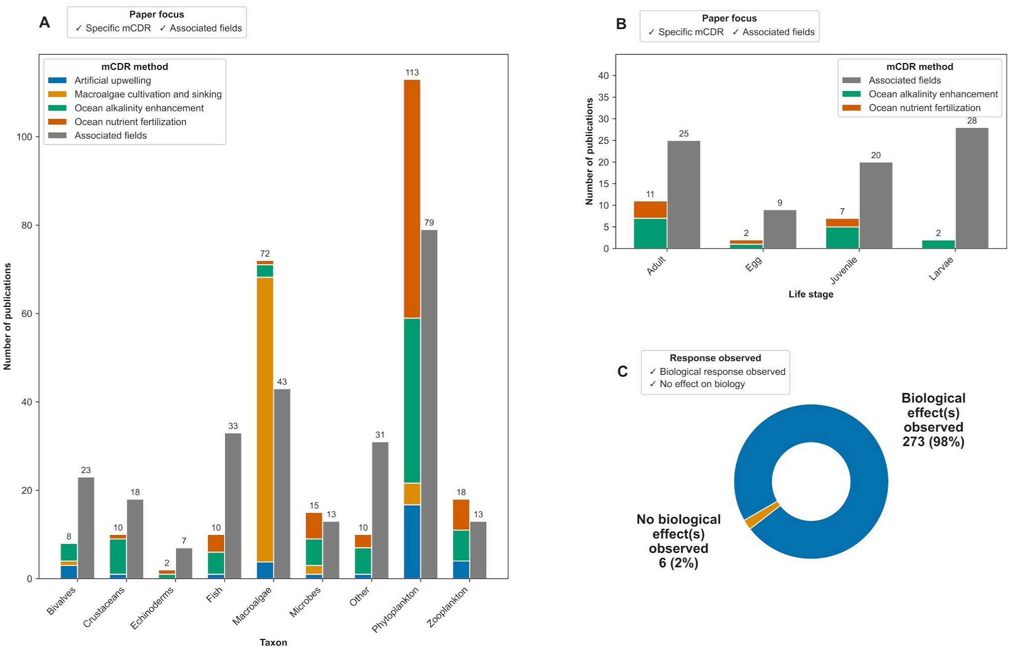

Figure 8. Fisheries-specific paper tags categorize papers in the database that examine (A) various taxa of aquatic organisms in both "Specific mCDR" and "Associated fields" papers, (B) life stages studied in biological response experiments in both "Specific mCDR" and "Associated fields" papers, and (C) biological effects observed during studies that tested organism responses to biogeochemical manipulations. In panels (A) and (B), the mCDR method is displayed with the proportional stack variable for "Specific mCDR" papers (colored bars) while twin bars display the absolute count of papers from "Associated fields" (gray bars). The key in the upper left corner of each panel displays the filtering criteria applied to the database tags to extract the visualized subset of publications.

Taxonomic tags

Within the fisheries-relevant literature, we find that studies of lower trophic level biological responses dominate compared to investigations of higher trophic level responses (Figure 6B). Taxonomic tags in the database reveal that phytoplankton are by far the most studied group, reported in 113 mCDR-specific papers (Figure 8A) and 79 papers from associated fields that addressed species response for phytoplankton. The majority of the mCDR studies on phytoplankton focused on ONF and OAE, while fewer are related to implementation of artificial upwelling and macroalgae cultivation and sinking. Macroalgae were also a highly studied group among mCDR-specific papers (n=72), mainly in the context of macroalgae mCDR (n=68) along with a few papers that assessed macroalgae cultivation coupled with artificial upwelling (n=1) or ONF (n=4). Macroalgae responses were also the topic of three OAE papers and 43 papers from associated fields. The other identified taxonomic groups have been studied at much lower rates in the mCDR-specific literature; bivalves, crustaceans, echinoderms, and fish are reported in a combined 30 instances and there are 15 and 18 microbe and zooplankton studies, respectively (Figure 8A).

Some biological response studies focused on specific life stages, typically egg, larval, juvenile, and adult. Life stage tags were included in the database when this information was available. The majority of the papers reporting life stage are from associated fields, such as ocean acidification, while the few mCDR-specific papers are from ONF and OAE studies only (Goldenberg et al., 2024 OAE; Duan et al., 2023; Hudspith et al., 2017) (Figure 8B). The substantial contribution from the ocean acidification field is likely a result of recognition among the ocean acidification community of the importance of understanding potential ecosystem and biological impacts on vulnerable life stages such as eggs, larvae, and juvenile stages (Zavell et al., 2024; Stillman et al., 2020; Miller et al., 2016).

Across the biological response literature, we assigned tags to indicate whether the study identified a biological effect in response to the experimental conditions (natural exposure or biogeochemical manipulation). A paper that observed a biological effect is one in which an effect on the organism was detected; the tag does not indicate whether the effect is positive or negative (or imply positive or negative impacts at any scale), given that effects are context-dependent and may have different implications across different disciplines. Of the papers in the database that tested for biological effect(s) in response to an exposure (n=279), all but 6 reported an observed effect (Figure 8C). The small subset of papers that did not observe a biological effect to the treatment (i.e., null result) investigated bivalves, fish, macroalgae, and zooplankton, with majority of the studies focusing on macroalgae cultivation (Liu et al., 2022; Lian et al., 2023; Li et al., 2022; 2023). The one study that found no response to OAE treatments suggested that key fisheries species may be resilient to water chemistry changes under OAE (Goldenberg et al., 2024 OAE). While there are a small number of studies within the database that looked for a biological response and did not observe one, this may be a result of publication bias, or the “file-drawer effect” where null results and statistically non-significant data are not published (Kozlov, 2024. If the small number of studies that did not observe a biological response is representative of natural biological responses, then this would support the broad conclusion that marine organisms across taxa respond when the biogeochemical conditions of their environment are altered. Determining if there are wide responses to mCDR perturbations that are significant to real world conditions and assessing the directionality, magnitude, and practical relevance of potential biological effects to conditions expected for mCDR deployments remains a research priority (Roberts et al., 2024; Grabb et al., 2025). As we developed our pre-defined tagging criteria, we identified a major challenge in applying fixed-structure tags to complex biological studies: studies may examine multiple species, multiple life stages, and multiple treatment types or exposure levels, with papers consequently reporting nuanced findings that require knowledge of the experimental context for interpretation. The *mCDRxFisheries Literature Database* provides a useful starting point for future synthesis work to delve into the experimental conditions and results of these relevant biological studies.

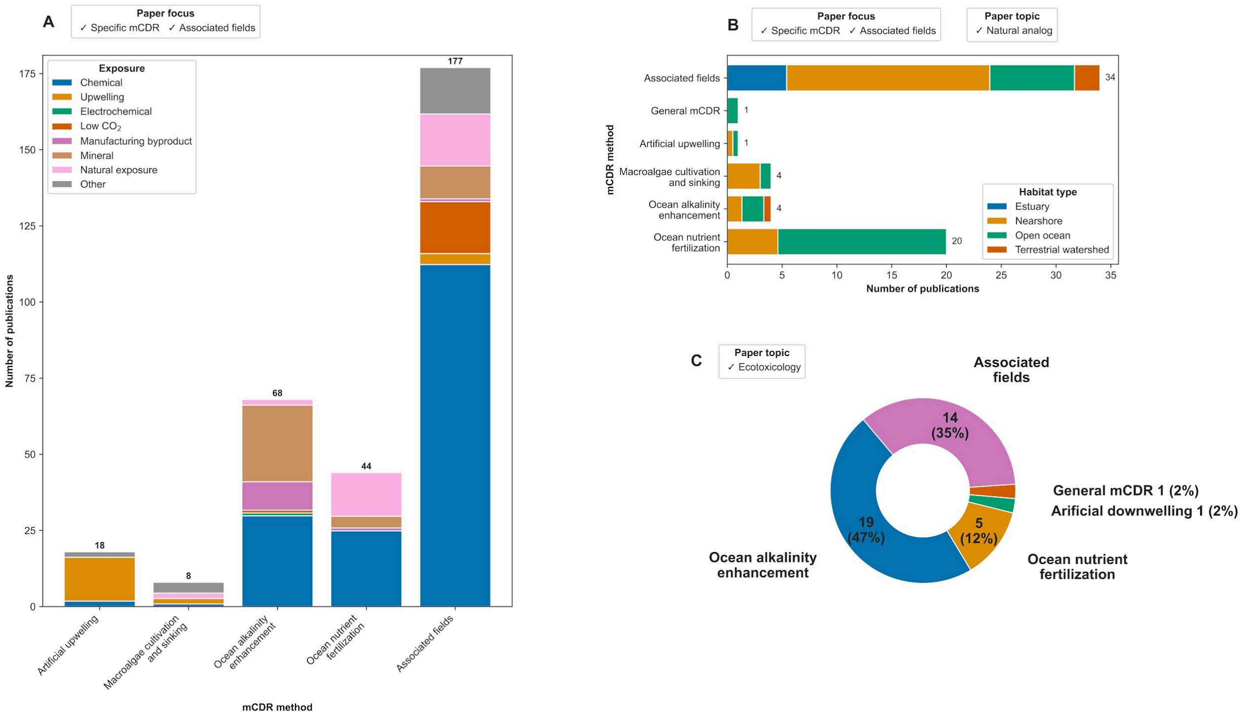

Figure 9. Number of papers reporting (A) biogeochemical exposures applied as experimental treatments in both “Specific mCDR” and “Associated fields” papers, (B) habitat types studied as natural analogues for mCDR in both “Specific mCDR” and “Associated fields” papers, and (C) ecotoxicity experiments. In panels (A) and (B), the category of interest (exposure and habitat type, respectively) are displayed with the proportional stack variable for each of the represented mCDR methods in “Specific mCDR” and for “Associated fields” papers. The pie chart in panel (C) displays all papers assigned the ecotoxicity topic, showing distribution of papers between paper focus categories (“General mCDR”, “Associated fields”, and “Specific mCDR”) with “Specific mCDR papers broken down by mCDR method. The key in the upper left corner of each panel displays the filtering criteria applied to the database tags to extract the visualized subset of publications.

Biogeochemical exposures

To broadly characterize the range of experimental conditions studied, the database contains tags describing the exposure, or biogeochemical manipulations, used in experiments during specific mCDR research (Figure 9A). The majority of the exposure experiments that have been conducted have focused on OAE methods (n=68), with ONF studies (n=44) also making up a large portion of the exposure studies. Fewer exposure studies have focused on artificial upwelling (n=18) and macroalgae cultivation and sinking (n=8), while none have been conducted for DOR or artificial downwelling. Interestingly, within the database, there are more instances of relevant exposure studies in associated fields (n=177) than in mCDR-specific investigations (n=138). Most of these studies from associated fields looked at chemical interventions (n=125) with a notable influence from the ocean acidification literature across all exposure types. In fact, most of the ocean acidification literature included in the *mCDRxFisheries Literature Database* relates to exposure studies (61 out of 84 ocean acidification studies total), indicating that our systematic search successfully targeted relevant biological impact studies outside of the mCDR-specific literature.

Of these exposure studies, the most common type of exposure tested in mCDR-specific studies was chemical (n=61), with over half of these studies focused on OAE methods (n=32) and slightly fewer focused on ONF (n=26). Common chemicals used were sodium hydroxide (NaOH) and iron sulfate ($FeSO_4$) for OAE and ONF, respectively. A number of studies used minerals (n=31) including olivine, gypsum, peridotite, and lime for OAE and iron oxides for ONF. Some studies of OAE, and one of ONF, also investigated exposure to manufacturing byproducts such as steel slag and concrete, which can increase alkalinity and also introduce bioavailable iron (Sugie et al., 2011). While OAE using both mineral feedstocks and effluent from electrochemical processes is being explored (NASEM, 2022), the database shows that most studies of biological responses have not directly tested electrochemical sources of alkalinity but rather used commercially available chemicals such as sodium hydroxide (NaOH) to simulate the alkalinity addition to experiments.

Other exposures tested in the mCDR-specific studies include exposure to deep water through upwelling, which mainly is found in studies that investigate artificial upwelling of nutrient-rich deep water (n=16), and exposure to sources that provide natural analogues for mCDR, like iron from dust, volcanic ash, and hydrothermal vents (n=19). A similar number of studies from associated fields looked at naturally occurring high pH conditions, upwelling, nutrient enrichment, and river runoff that might serve as natural analogues for mCDR exposures.

Natural analogues

Studies of natural exposures and environmental changes that introduce similar conditions mCDR pathways without deliberate human intervention may provide insight into the fundamental ocean processes that mCDR methods are based upon and potential feedbacks and impacts on the Earth system and biosphere. The database contains one paper in the “General mCDR” category that addressed natural analogues for mCDR, arguing that natural analogues should become the “third interconnecting pillar” to help bridge the gap between numerical simulations and experimental studies (Bach and Boyd, 2021; Subhas et al., 2023). This idea motivated the inclusion of the natural analogue tag in this database. In addition to the one “General mCDR” paper, 63 other studies within the database researched natural analogue, with 29 focused specifically on mCDR and 34 conducted in associated fields (Figure 9B).

The majority of the mCDR-specific natural analogue papers relate to ONF (n=20) (Figure 9B). All of these studies focused on the open ocean, with six also including nearshore environments. These studies investigated natural iron additions to the ocean through processes such as shallow hydrothermal vents (Bonnet et al., 2023), volcanic ash, aeolian dust (Gao et al., 2003), and runoff from landmasses rich in iron (e.g., volcanic islands) (Hunt et al., 2021; Robinson et al., 2016). A few studies (n=4) considered natural analogues for OAE, focused on examples of natural alkalinity additions from deglacial pulses of neutralized carbon from the Pacific seafloor (Green et al., 2024), natural carbonate chemistry gradients throughout the ocean (Lehmann and Bach, year), and erosion of carbonate-bearing sedimentary rocks (Wallmann et al., 2022). One paper provides an overview of potential natural analogues for OAE across Earth systems, identifying rivers and their plumes, glacial fjords, whiting events, and basinal seas with elevated alkalinity as ecosystems that can offer insights to OAE

(Subhas et al., 2023). Of the few macroalgae papers that offer natural analogues (n=4), three focused on nearshore macroalgae and seaweed growth and carbon removal (Krause-Jensen et al., 2016; Ould et al., 2022; Queiros et al., 2023), while one investigated the carbon removal potential of the Great Atlantic Sargassum belt (Bach et al., 2021).

Natural analogue studies from mCDR-associated fields include publications on carbon export and OA mitigation by seaweed and kelp forests (Filbee-Dexter, 2024; Hirsh et al., 2020; Ricart et al., 2021), river outflow influence on carbon sequestration (Amergian et al., 2022; Subramaniam et al., 2008), high pH and salmon fisheries (Foldvik et al., 2022), natural upwelling effects on phytoplankton blooms (Barciela et al., 2000; Casareto et al., 2017), historical trends related to iron fluxes to the ocean (Lambert et al., 2021; Martinez-Garcia et al., 2014), and ocean acidification and climate change effects on ecosystems (Rastrick et al., 2018).

Ecotoxicity

When considering mCDR interventions, potential impacts on biology include ecotoxicity due to the addition of trace metals associated with feedstocks. This is specifically relevant to OAE and ONF, which propose to add materials (e.g., olivine, iron oxides, steel slag, etc.) to the ocean that may contain contaminants toxic to biology. Overall, 40 studies within the database addressed the topic of ecotoxicity, with 25 of them focused specifically on mCDR and 14 manuscripts from associated fields (Figure 9C). One paper was categorized as general mCDR, as it presented environmental genomic techniques that might be used to monitor ecotoxicity in biological organisms (Hook et al., 2024).

Of the studies that focused on mCDR specific techniques, 19 are focused on OAE and 5 on ONF (Figure 9C). The OAE studies are primarily laboratory experiments testing the chronic and acute toxicity of olivine, a commonly proposed feedstock for mCDR, for a range of marine organisms including zooplankton (Flipken et al., 2023), phytoplankton (Gately et al., 2023; Guo et al., 2022, Li et al., 2024; Xin et al., 2024), and benthic invertebrates (Jankowska et al., 2024; Jones et al., 2025). Of the 5 ONF studies, ecotoxicity was the main topic of investigation in only one paper, which looked at the potential ecotoxicity of contaminants during ONF and impact on the success of marine invertebrate broadcast spawners (Hudspith et al., 2017). Additionally, one paper on artificial downwelling addressed ecotoxicity concerns, noting that this approach offers advantages over other mCDR methods since downwelling systems would not introduce terrestrial material to the ocean and therefore would not lead to issues with heavy metal toxicity (Tyka et al., 2022). Ecotoxicity was also addressed in some database papers from associated fields, mainly laboratory studies testing ecotoxicity of relevant trace metals (e.g., Cu, Zn, Ni, Pb, Cd) for a range of organisms including phytoplankton, macroalgae, and crustacean (Ho et al., 1999, Brand et al., 1986; Geddie et al., 2019).

Spatial Planning

Table 1. Papers assigned a “spatial planning” tag in the paper topic category, indicating relevance to spatial and geographic considerations for mCDR research and implementation. This table summarizes high-level information contained within the paper tags for each individual publication, demonstrating how the database can be filtered and summarized as a starting point for systematic review of literature related to fisheries impacts of mCDR.

Another pressing topic for fisheries communities with respect to mCDR deployments is the potential for spatial conflict in shared ocean spaces (Grabb et al. 2025; Stelzenmueller et al., 2016; Pol and Ford, 2020). We included a spatial planning tag in our annotations of paper topic to identify published literature addressing aspects of this impact such as spatial squeeze (i.e., additional spatial pressure on ocean usage), suitability of particular ocean regions for mCDR, and estimated ocean area required to reach climate-relevant scales of carbon removal. Only 14 mCDR studies are associated with the spatial planning topic including those that are focused generally (n=1) and specifically (n=13) on mCDR (Table 1). Across mCDR methods, the most represented is macroalgae cultivation and sinking (n=7), which is perhaps not surprising given the spatial requirements of seaweed farming and question of scalability for biotic mCDR approaches (Chaudhair et al. 2024; Kim et al., 2024). Spatial planning of OAE field trials is also a common theme among this subset of papers, focused on factors ranging from coastal sediment type (Geerts et al. 2025) to the amount of fishing activity in a given region (Marx et al. 2025). Five of the 14 total papers are review papers that addressed questions of spatial planning at a high level, but identified significant uncertainties given limited original research to draw from (Table 1). While most of the spatial planning papers in the database have some direct relevance to fisheries, most commonly through estimation of ocean area or infrastructure required for an mCDR approach, only two explicitly incorporated data related to fishing activity and higher trophic levels (Marx et al. 2025, Alevizos & Barillé 2023). Though mCDR research related to spatial planning has increased in recent years, mirroring the overall trend in the number of OAE and macroalgae cultivation and sinking publications (Figure 4), spatial suitability studies that consider fisheries-specific parameters (e.g., migration corridors for fisheries species, nursery habitats, high productivity fishing areas) are critically needed (Grabb et al., 2025; ICES Themed Set on Fisheries and Aquaculture, 2025-2026).

Leveraging the Database for Research Synthesis

Across the *General*, *Species*, *Treatment*, and *Location* tag domains, the *mCDRxFisheries Literature Database* contains a wealth of metadata for this large collection of publications related to the intersection of mCDR and fisheries. In this paper, we have summarized its contents at a high level and demonstrate its use in identifying fisheries-specific research and gaps. We have also presented examples of how the database can be filtered to investigate trends and key intersections relevant to a user's particular interests. The database is intended to provide a starting point for researchers, communities, and decision makers to identify literature focused on specific and related mCDR and fisheries topics, extract study information using the assigned tags, and initiate syntheses to summarize the state of knowledge on mCDR and fisheries impacts.

As just one example, we refer the reader to the summary of spatial planning studies in Table 1. The table was generated by filtering the database in the *mCDRxFisheries*

Literature Database Viewer (McElhany et al., 2026b for “General mCDR” and “Specific mCDR” papers with a tag for the spatial planning topic area. This search yielded a relatively small number of papers that could be closely reviewed for fisheries relevance, data, key findings, or other information found in the full text. The brief synthesis of these papers provided above reveals that most of the mCDR spatial planning literature does not specifically address fisheries concerns, like spatial conflict between mCDR deployments and fishing activities or impacts on important fisheries areas. In addition to revealing a key gap in mCDR research, this finding also identifies an opportunity to look to other associated fields to identify literature that can inform fisheries-centered spatial planning and future mCDR research. Just as we defined a project scope related to biological and ecological impacts of biogeochemical changes, further efforts might expand the systematic search to include biological and ecological impacts of increased ocean use and infrastructure from associated fields like offshore wind or commercial aquaculture (e.g., Cavan et al., 2022, Johnson et al. 2024). A similar approach can be used for any topic or area of interest within the scope of the database, keeping in mind the focus of the database on the intersection of mCDR and fisheries and referencing the selection criteria metadata provided here and in Supplemental Materials Section 1. The database is already being utilized in these ways for scientific synthesis (Gurney-Smith et al., In Review, McElhany et al., 2026a) and shared broadly with researchers, suppliers, verifiers, decision-makers, regulators, and community members spanning both mCDR and fisheries.

This database was constructed with a specific lens, targeting literature related to the biological and ecosystem impacts related to fisheries from mCDR activities. It is critical for users to understand the criteria that went into building this database (e.g. Figure 1 and 2; Supplemental Materials) when interpreting its contents, given the inherent biases that are introduced during the construction and tagging of the database. It is important to note how this intent has shaped the database contents, such as the dominance of papers tagged for “biological and ecological impacts” (n=378) and “environmental impacts” (n=256) topics compared to those tagged “community impacts” (n=26) and “ethics and best practices” (n=68). When summarizing the database contents, we drew from carefully defined subsets of the database to avoid overinterpreting trends that might be an artifact of the search terms. For instance, social science studies are clearly underrepresented in the database, which contains only 8 studies that used expert interviews as a methodology and only 26 papers that assessed societal community impacts (of which less than half are original research articles). Because social science and community impacts were not targeted by our biogeochemistry-focused search terms, this result must be precisely interpreted. The small number of social science papers identified through our method-specific search terms (e.g., ocean alkalinity enhancement, direct ocean removal) may be interpreted as reflecting a lack of mCDR method-specific social science research, but do not imply that there is no relevant social science research in associated fields. Rather, those associated fields must be searched through a social science lens during future studies, which is beyond the scope of this work. We recommend that researchers use the database to initiate synthesis efforts by filtering, searching, and visualizing metadata related to their topic of interest. Reviews related to the impacts of mCDR on fisheries, biology, and ecosystems can directly leverage the database, such as those being prepared for the ICES mCDR and Fisheries Themed Set (2025-2026). Adjacent topics may require additional tailored literature searches, but can use the database to identify papers and key intersections beyond the mCDR–fisheries focus of this work. The comprehensive metadata and tagging criteria provided in the Supplemental Materials Section 1 should be used to guide syntheses and interpretation of the tags in the database.

An advantage of *mCDRxFisheries Literature Database* is its flexibility and applicability to the broader field of mCDR. While the database primarily offers insight to the intersection between mCDR and fisheries with a focus on biological impacts, there are opportunities to expand this database further to understand additional potential mCDR impacts and intersections with other industries and sectors. For example, this database did not consider the physical impacts of mCDR on marine ecosystems, such as water processing, increased ship activity, and new marine and coastal infrastructure (Grabb et al., 2025). These potential impacts also intersect with industries such as offshore wind or desalination. Identifying such points of intersection and related fields from which mCDR efforts can draw lessons will further strengthen the knowledge base for mCDR research and development.

Further, new user-defined tags can be applied to the *mCDRxFisheries Literature Database* as research priorities evolve and novel mCDR techniques emerge. The process of creating this database included iterative refinement of the tags used, for example expanding the initial set of tags for treatment exposures from “chemical”, “mineral”, “low CO_2”, and “electrochemical” to include exposures that were commonly found during abstract review such as “deep water” and “manufacturing byproducts.” The definition of tags is inherently not all-encompassing, resulting in the use of the general “other” tag to capture exposures beyond the pre-defined options. The tags used in this study may be refined and expanded to annotate papers with a greater level of detail, or to add new tag options that were not included. Importantly, we note that we defined six specific mCDR methods based on NASEM 2022 (artificial downwelling, artificial upwelling, DOR, macroalgae cultivation and sinking, OAE, and ONF). There are emerging carbon removal strategies that do not neatly fit into any of these six categories, like those that cross the land-ocean boundary (e.g., storage of captured industrial emissions or terrestrial biomass in the deep ocean) (Wang et al., 2024; Xing et al., 2022; Lu et al., 2015). Novel methods are continuously emerging, requiring further refinement of the categories applied here. To learn how features of the lit-tag app can be used to adapt and expand the *mCDRxFisheries Literature Database*, readers are referred to McElhany et al. (2026b).

Comparing manual database creation to AI methods

We recognize that there may be future opportunities for database collation, annotation, and analysis using novel computing processes, such as artificial intelligence (AI)-powered research tools. While AI is continually developing and rapidly accelerating, we briefly explored whether 2025-era AI tools might make the process of database annotation more efficient compared to our iterative and manual process of defining initial categories and tags, applying tags to database papers, QA/QC-ing around one third of our database (300+ papers), and amending the predefined categories based on the range of paper topics we reviewed. We researched several AI tools and per recommendation from Google Gemini AI, we chose to assess an AI tool called Elicit (https://elicit.com/) which uses language models for literature review and keyword search to annotate up to 50 papers at a time. We asked Elicit to perform two tasks that mapped to our manual efforts to 1) define and refine categories and 2) tag papers with our categories and metadata criteria (see Supplemental Materials Section 4), using two subsets of 50 papers from our database (one subset from 2024 and one subset from 2025).

Mirroring our process of defining and refining our categories and tags, we asked Elicit to interpret the key themes and identify keywords based on the intersection of mCDR and fisheries within the two subsets of papers. The identified key words were very high-level (i.e., “Carbon-Biology Interaction”, “Fisheries Systems Component”, “Marine Carbon Dioxide Removal Focus”*)* and were defined by the prompt, not by the paper content given the key words remained unchanged between the 2024 and 2025 subsets of papers. We also asked Elicit to assign tags from the *mCDRxFisheries Literature Database* categories (Figure 2) using our tagging criteria (Supplemental Materials Section 4). While Elicit was able to assign tags to papers, it did not follow directions to assign only one tag per paper, was not able to distinguish the scientific nuances of different tags in topic categories (*e.g.,* differences between “mCDR”, “ocean acidification”, and “blue carbon”), and could not decipher if organisms mentioned in the text were experimental subjects or merely mentioned.

Based on these simple tests, we conclude that manual input and oversight by a subject matter expert would still be required when tagging a database with AI. If we were to iteratively ask Elicit to identify key words and assign tags to papers, the process of training the AI would mirror our manual tagging process in that a knowledgeable human must understand the nuance in the tag criteria and verify the iterative results of the tagging process, which requires manual QA/QC with review of the publications. Such AI tools might be useful for identifying relevant papers that were not captured by keyword searches, more effectively finding literature from associated fields that could broaden the knowledge base. Our experience suggests that using 2025-era AI to perform the categorization and tagging of the *mCDRxFisheries Literature Database* would not have saved time or resources (Becker et al., 2025). It is likely that future AI tools may provide a more efficient means of database creation and maintenance and these opportunities will have to be continually assessed during the database updates.

A tool for the broader mCDR community

The utility of the *mCDRxFisheries Literature Database* is not limited to research efforts. This database can be and already has been mined to inform policy and community decision-making and provide insights to other ocean-users and sectors. The collated and annotated literature can quickly be searched, filtered, and visualized to create summaries of the topics that have been researched and illustrate remaining gaps in the mCDR literature and associated fields. For example, participants of the ICES mCDR and Fisheries workshops (ICES WkmCDR, 2025) are currently using this database to consolidate the state of knowledge, synthesize biological effects of mCDR, and identify research gaps (See ICES Themed Set on mCDR and Fisheries, 2025-2026). A subset of this database has already been adapted to interpret biological thresholds associated with mCDR (McElhany et al., 2006a) and there has been immense interest from mCDR researchers, practitioners, and decision-makers to receive briefings on this database and access to the open-access link. The co-authors are also leveraging the database to summarize the state of ecological science on mCDR for policymakers. This manuscript describes the robust process and criteria used to build the database, providing critical transparency and identifying bias to guide users in interpreting and analyzing the database for their own purpose. As a science-based tool that can be used to investigate specific topics that align with the end-user's interest, the database makes mCDR literature more accessible and digestible. Given the need to increase mCDR literacy and establish enabling conditions for sectors like fisheries to participate in decision-making processes related to mCDR (Schumann et al., 2025), this tool can help direct users to specific studies that can inform their interests. More built-for-purpose tools like this database are needed to provide the accessible knowledge base required to move the mCDR field forward, including supporting current initiatives to develop robust frameworks for monitoring, reporting, and verification (MRV), permitting, and environmental impact assessments (PML Applications, 2025).

Conclusion

The *mCDRxFisheries Literature Database* consolidates mCDR papers that are relevant to fisheries, providing an open-source tool for accessing, searching, and summarizing the state of knowledge on potential biological and ecological impacts of mCDR. It is intended to be a living tool which will be curated, expanded and utilized by future efforts including the ICES mCDR Fisheries and Aquaculture Working Group to address key intersections between mCDR and ocean-based industries and coastal communities. The methodology presented in this paper may be applied to update the *mCDRxFisheries Literature Database* as relevant scientific literature continues to be published, or to generate new related databases using the open source lit-tag app (McElhany et al., 2026b). Foundational research relevant to mCDR methods and biological impacts has been conducted on these topics since before the emergence of the carbon removal sector. This database provides access to these existing bodies of knowledge, connecting the dots between the emerging field of mCDR and established fields of research and accelerating understanding of potential fisheries impacts and overlaps.

Acknowledgements

We acknowledge Libby Jewett for inspiring the creation of the database and Gabby Kitch for guidance. We are grateful to Jahnelle Howe for early testing with the shiny app development and Lisa Methratta for supervisory support during this project. The ICES mCDR Fisheries and Aquaculture steering committee served as testing bed and the pending ICES Working Group on mCDR Fisheries and Aquaculture served as an audience to help guide the purpose of this database. We are also thankful to the beta testers of the app, as well as David Keller for sharing his insight on the Carbon to Sea OAE database.

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Supplemental Material

Title: An annotated literature database to support research on marine carbon dioxide removal (mCDR) and fisheries impacts

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Key Words: literature database, marine carbon dioxide removal, mCDR, fisheries, ecological impacts

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Supplemental Material Section 1: Tagging Criteria Metadata

1.1 General

mCDR focus: This criterion differentiates papers that address mCDR generally without focus on any specific method(s) (*general_mcdr*), papers that specifically address one or more mCDR methodology (*specific_mcdr*), and papers that do not address mCDR but are within the scope of the inclusion criteria (*associated_fields*). Papers that do not explicitly mention carbon removal were considered to be *specific_mcdr* when the paper addressed foundational science, technology, or engineering topics directly relevant to the development or application of mCDR method(s) (e.g., testing of an artificial upwelling device for stimulating productivity).

mCDR method: Specific mCDR method(s) discussed in the papers are selected for those papers identified as *specific_mcdr*. Six methods are included: *artificial_downwelling*, *artificial_upwelling*, *direct_ocean_removal*, *macro_algae_cultivation_and_sinking*, *ocean_alkalinity_enhancement*, and *ocean_nutrient_fertilization* (microalgae growth and sinking or storage).

Paper type: Papers are identified as *comment*, *original_research*, *perspective*, *report*, or *review*. In cases where a paper might fit multiple selections, the single best tag was applied.

Type of method used: The type of method(s) used are selected for *original_research* papers to describe the methodology applied in the research study. Selections include: *expert_interview*, *field_study*, *lab_experiment*, *mesocosm*, *modeling*, and *observation*. In cases where none of the listed methods applied to the study, *not_applicable* is selected.

Paper topic: The paper topic category includes an inexhaustive selection of specific research areas and subfields that may apply to mCDR or mCDR-related studies (e.g., measurement, verification and reporting (*mrv*), biological response studies (*species_sensitivities*), or policy recommendations (*governance*)). Topics addressed and/or discussed in the paper were selected to assist users in filtering, but selections do not necessarily capture all topics mentioned in the paper.

Adjacent topic to mCDR: Selected adjacent topics categorize papers from non-mCDR fields that may intersect with mCDR research. For example, *acid_rain* may be relevant to enhanced weathering mCDR, *aquaculture* and *blue_carbon* may overlap with biological mCDR approaches and techniques often used in mCDR, and *ocean_acidification* may be relevant to biological sensitivity experiments and alkalinity enhancement. Papers that relate to general carbonate chemistry are tagged as *fundamental_carbon_chem*.

Adjacent topic to Fisheries: Selected adjacent topics identify how papers may be relevant to fisheries research. For example, *aquaculture* activities can supplement wild fisheries, changes in the *biologic_carbon_pump* may alter food webs, *fisheries_practices* may describe management, conservation, and other human-related activities, *higher_trophic* indicates studies of species that may be higher in the food web and/or harvested, *lower_trophic* indicates studies of species at the base of the food web (e.g., plankton), and *nutrient_dynamics* applies to studies that examine nutrient cycling that may impact marine life.

1.2 Location

Ocean basin: The ocean basin is defined for papers that explicitly take place within or examine a specific region of the ocean (e.g., *arctic*, *atlantic*, *global*, *pacific*, *southern_ocean*, etc.). These include field studies conducted in the ocean, model studies that simulated global or regional ocean basins, and experimental studies that obtained samples from a specific location in the ocean. The nearest and/or adjacent ocean basin was chosen if the study location was identified with greater specificity than the tag options. The *global* tag typically applies to model domains that span global systems, as well as papers that use a global framework for a review or an assessment.

Geopolitical area: The geopolitical area is defined when explicitly mentioned in the paper. The geopolitical area (e.g., *africa*, *antarctica*, *australia*, *canada*, *europe*, *united_states*, etc.) may indicate the location where original research was performed, or it may refer to the geographic and/or political area discussed in a comment, perspective, report, or review paper. The geopolitical tags were broadly defined and are not comprehensive; the nearest applicable region may have been selected.

Habitat type: The habitat type is defined when explicitly mentioned in the paper. Papers that include sample collection, field studies, and/or modeling in specific habitats are tagged to indicate the habitat types(s) (e.g., *estuary*, *nearshore*, *open_ocean*, *wetlands*, etc.).

Depth: The depth is defined for papers that specifically collected samples from, modeled, or investigated phenomena at specific ocean depth(s): *benthic*, *deep_ocean*, *mesopelagic*, or *surface*.

Experiment location: The experiment location is defined for original research papers that conducted experiments in the *laboratory*, a *mesocosm*, or in the *field*.

1.3 Species

Species common name: The common name(s) of species studied or discussed in the paper are listed if reported by the authors.

Species scientific name: The scientific name(s) of species studied or discussed in the paper are listed if reported by the authors.

Taxon: The taxon of the species studied or discussed in the paper is selected for species belonging to the following groups: *bivalve*, *crustacean*, *echinoderm*, *fish*, *macroalgae*, *microbes*, *phytoplankton*, and *zooplankton*. For papers that include species of other taxonomic groups, the tag *other* is selected.

Life stage: The life stage(s) of the species studied or discussed in the paper are selected if reported by the authors. Life stages include *adult*, *egg*, *juvenile*, and *larvae*.

1.4 Treatment

Exposure: Exposure describes the type of intervention that was applied to the study system during an experiment. These interventions include chemical additions to the system (*chemical*), addition of deep water through upwelling (*upwelling*), electrochemical alteration of water chemistry (*electrochemical*), direct manipulation of carbon dioxide levels (i.e. via bubbling and mixing) (*low_co2*), addition of manufacturing by-productions (i.e. slag, concrete, etc.) (*manufacturing_byproduct*), and mineral additions (*mineral*). In cases where natural processes that mimic these interventions were utilized for experiments, *natural_exposure* is selected. For papers that apply other types of exposure, the tag *other* is selected. Simulated exposures in modeling studies are not considered (*not_applicable*), nor are review papers that describe or synthesize experimental results to avoid duplicative counting of original research and subsequent reviews.

Chemical/mineral added: For studies that involve chemical or mineral exposure, the specific chemical(s) and/or mineral(s) applied are selected if reported by the authors. Common additions include: *calcium_carbonate_derivatives*, *dust, iron_sulfate*, *sodium_hydroxide*, and *olivine*. For studies that utilize other materials, the tag *other* is selected.

Response observed: This criterion identifies whether a biological response was assessed and reported in the paper when an exposure was noted. Selection of *no_effect_on_biology* indicates that an experimental study with one or more exposure(s) found no species response for the biological parameters measured. Selection of *biological_effect_observed* indicates that an experimental study with one or more exposure(s) identified at least one species response for the biological parameters measured. Studies that did not assess biological response are tagged *biological_effect_not_investigated*.

Supplemental Material Section 2: Table for Google Scholar Search Terms

Supplemental Table 1. Search terms used in Google Scholar to compile the literature database.

● **Target**	● **Search Term**
● mCDR methods	● mCDR OAE
	● ocean alkalinity enhancement
	● alkalinity enhancement
	● mCDR OIF
	● mCDR ONF
	● ocean iron fertilization
	● ocean nutrient fertilization
	● macroalgae cultivation for carbon removal
	● macroalgae sinking for carbon removal
	● biomass cultivation for marine carbon dioxide removal
	● biomass sinking for marine carbon dioxide removal

	• direct ocean carbon capture and storage
	• direct ocean removal
	• artificial upwelling
	• artificial downwelling
• Similar biogeochemical manipulations	• high pH + marine biological sensitivity
	• elevated pH + marine biological sensitivity
	• increased alkalinity + marine biological sensitivity
	• elevated alkalinity + marine biological sensitivity
	• low pCO2 + marine biological sensitivity
	• low DIC + marine biological sensitivity
	• nutrient enrichment + marine biological sensitivity
	• iron enrichment + marine biological sensitivity
• General topic	• mCDR and fisheries
	• mCDR and aquaculture

Supplemental Material Section 3: Tables for Bibliographic Data

Supplemental Table 2. Top 20 journals represented in the database with number of publications.

No.	Journal Name	Number of publications in the database
1	Biogeosciences	39
2	Frontiers in Marine Science	32
3	Marine Ecology Progress Series	28
4	Environmental Research Letters	28
5	Frontiers in Climate	23
6	Deep Sea Research Part II: Topical Studies in Oceanography	19
7	Limnology and Oceanography	15
8	Ocean Engineering	15
9	Nature	14

10	Science of The Total Environment	14
11	Geophysical Research Letters	13
12	Marine Biology	13
13	Environmental Science & Technology	12
14	Global Biogeochemical Cycles	11
15	Journal of Experimental Marine Biology and Ecology	11
16	Guide to Best Practices in Ocean Alkalinity Enhancement Research	11
17	Geochimica et Cosmochimica Acta	10
18	Science	10
19	Marine Pollution Bulletin	9
20	Aquaculture	8

Supplemental Table 3. Publishing organization of reports and manuscripts included in the database.

No.	**Organization Name**
1	Aalto University
2	Aspen Institute Energy & Environment Program
3	CDRXIV
4	Center for Open Science
5	Copernicus Publications
6	Earth System Dynamic Discussions
7	EarthArXiv
8	ElgarOnline
9	Elsevier
10	Energy Futures Initiative
11	ESS Open Archive
12	Exploring Ocean Iron Solutions
13	Frontiers Media SA
14	GEOMAR Helmholtz Centre for Ocean Research Kiel
15	Geophysical Research Letters
16	GESAMP
17	GHGT-16
18	Heriot-Watt University
19	ICES Scientific Reports
20	Intergovernmental Panel on Climate Change (IPCC)

21	IOC-UNESCO
22	National Academies Press
23	Natural Resources Defense Council
24	NETL Conference on Carbon Sequestration
25	Norwegian University of Science and Technology
26	OceanNETs
27	Offshore Technology Conference
28	Oregon State University
29	Pergamon
30	Research Square
31	Secretariat of the Convention on Biological Diversity
32	Simon Fraser University
33	Social Science Research Network
34	Solar Energy Research Inst., Golden, CO (USA)
35	Springer International Publishing
36	Springer Netherlands
37	The Ocean Foundation
38	U.S. Department of State
39	U.S. National Oceanic and Atmospheric Administration (NOAA)
40	U.S. National Renewable Energy Laboratory (NREL)
41	U.S. Pacific Northwest National Laboratory (PNNL)
42	Université Paris sciences et lettres
43	University of Exeter
44	University of Minnesota Duluth
45	University of Oxford
46	Vesta
47	Wiley
48	Woods Hole Oceanographic Institution
49	World Resources Institute
50	Zenodo

Supplemental Material Section 4: Application of AI tool Elicit

4.1 How could AI be used?

To choose the appropriate AI app, we asked Gemini to inform us of the best mechanism to do this process using this prompt: “We reviewed the abstracts of 1200 scientific papers relevant to marine carbon dioxide removal and fisheries. We then created a database of tags for each of the papers with information useful for mCDR researchers, such as the type of study, mCDR method and location. We would now like to compare our database to an AI analysis of the same set of papers using the same tag categories. How would you recommend we conduct the AI analysis for the comparison?”. One of the top recommended methodologies was Elicit, using the pro version (cost $499 per year). Elicit has the ability to find, summarize, and review literature based on user prompts.

To explore the applicability of using artificial intelligence (AI) tools to develop a database similar to the *mCDRxFisheries Literature Database*, we tested a similar tagging process as we conducted manually within this study using an AI tool, Elicit (developed by Ought), Pro version (cost $499 per user per year), which uses language models to help automate research workflows, literature review, find ‘seed articles’, and mine for keywords/subject headings. Since Elicit can only load in 100 papers and annotate 50 at a time, we loaded all 73 papers published in 2025 (from January to July) from the *mCDRxFisheries Literature Database*. Elicit only accepted the papers that it could access the full manuscript or PDF, which resulted in 49 papers. We asked Elicit to perform two tasks that mapped to our manual efforts to define and refine categories and tag papers, respectively: 1) extract 10 categories and key words related to the papers, and 2) assign categories to the papers that aligned with the categories and metadata defined manually and described within this manuscript.

4.2 Defining categories based on papers

To identify categories and keywords that aligned with the papers within the database, we first asked Elicit a prompt to identify keywords based on the papers provided. To inform Elicit of our mCDRxFisheries general tags and definitions, we provided it with the metadata descriptions and general tags before conducting the keyword search (See next section). The prompt we used was “Looking at the tags and papers within the database, can you pull out 10 keywords that are highlighted within the papers related to the intersection of marine carbon dioxide removal and fisheries? Then can you assign the key words to each paper according to the key words that they address?”. Using this prompt, we received ten key words and descriptions from Elicit:

- *Carbon-Biology Interaction: Does the study explicitly or implicitly address interactions, relationships, or connections between carbon management and marine biological systems?*
- *Fisheries Systems Component: Does the study examine fisheries systems, fish populations, fishing activities, or marine biological systems in marine environments?*
- *Marine Carbon Dioxide Removal Focus: Does the study address marine carbon dioxide removal techniques, technologies, or marine carbon management approaches?*
- *Marine Environment Focus: Does the study focus on marine environments rather than being limited solely to terrestrial, freshwater, or atmospheric carbon systems without marine components?*
- *Marine vs Non-Marine Systems: Does the study focus on marine ecosystems rather than being limited to non-marine aquaculture systems or focusing exclusively on fisheries economics/social aspects without environmental components?*
- *Review and Policy Studies: Is the study a systematic review, meta-analysis, or policy/management study in marine carbon management or fisheries science, OR does it meet the methodology criterion above?*
- *Study Type and Methodology: Is the study an empirical research study (experimental, observational, field study) or a modeling/simulation study related to marine carbon cycling and fisheries?*
- *Technical Content Adequacy: Does the study contain substantial technical content (i.e., is it a full research paper rather than just a conference abstract, editorial, or opinion piece without substantial technical detail)?*

Elicit then suggested to improve our prompt since it states that “more precise questions work better, try adding elements like research methodologies”. The improved prompt that it recommended was: “*What are the key thematic keywords emerging from a systematic content analysis of papers at the intersection of marine carbon dioxide removal and fisheries?*”

The results of this selection provided these keywords and descriptions:

- *CDR-Fisheries Intersection: Does this study address interactions between marine carbon removal methods and fisheries systems?*
- *Carbon removal component: Does this study include discussion of carbon removal or climate mitigation (rather than focusing solely on fisheries management without CDR components)?*
- *Marine application relevance: Does this study focus on marine-based approaches (rather than solely on atmospheric carbon capture or industrial carbon storage without marine application)?*
- *mCDR Focus: Does this study examine marine carbon dioxide removal (mCDR) techniques in marine environments?*
- *Marine CDR methods: Does this study focus on ocean alkalinization, enhanced weathering, blue carbon, or other marine-based carbon sequestration methods?*
- *Marine Environment Scope: Does this study include marine components (rather than focusing solely on terrestrial or freshwater carbon removal)?*
- *Study Type: Is this study an empirical study, modeling study, review paper, or policy analysis (rather than a conference abstract, editorial, or opinion piece without substantial content)?*

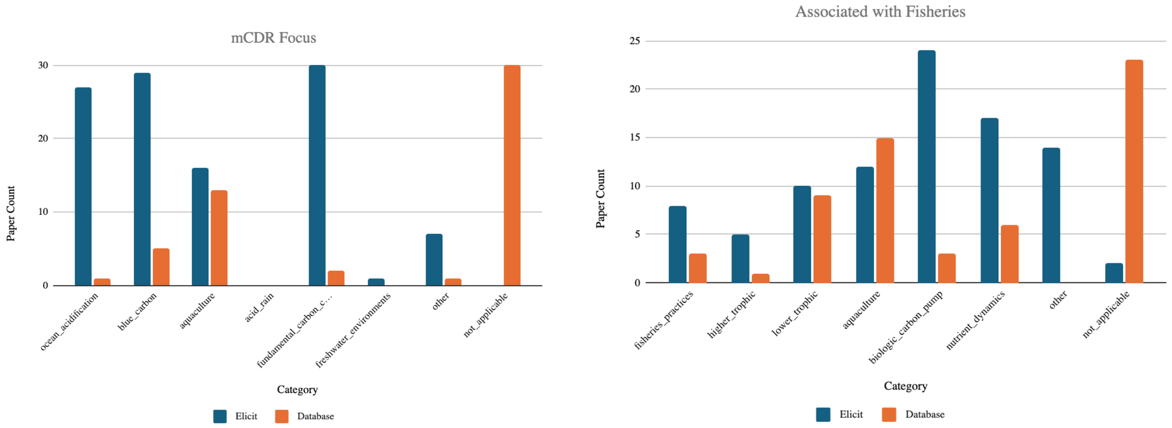
We then repeated the two prompts with 30 of the 49 papers to assess how Elicit would interpret and choose keywords based on different subset of papers. Elicit appeared to conduct the same analysis and came up with the same results for the prompts and assignments. To understand how these prompts would change with a new set of paper, we added 50 papers from the mCDRxFisheries Databased published in 2024 (authored by authors ended in letters A to H) and asked the same prompts. Elicit provided the same categories for each prompt, no matter what set of papers we provided it. While our intention was for Elicit to determine and refine the keywords based on the paper content, as we had done during our manual tagging of the database, Elicit appears to return key words based on the prompt and/or remember its previous responses and rely on what it determine the first iteration rather than learning from new papers. Additionally, even though we provided Elicit explicitly with the types of mCDR that we defined as mCDR, when providing the key words, it redefined mCDR techniques and included techniques that we purposefully did not include, such as blue carbon.

4.3 Tagging papers using mCDRxFisheries Database categories

To test the ability for Elicit to assign tags to papers, we used four mCDRxFisheries database tags and provided the metadata criteria. To assign the rules for each tag, we used the following formula for the prompts:

- For mCDRxFishiers categories:
  - Prompt: *Indicate the “category name”. “Paste description of category from metadata”*
- For categories that only were designed to have one answer, the end of the prompt was amended with the following:
  - Add to Prompt: *Only choose one answer for each paper that best categorizes the paper.*
- For categories that contain “other” and “not applicable” choices, the following text was added to the end of the prompt, respectively:
  - Add to prompt: *If the paper addressed other types of topics that are adjacent to mCDR that are not listed explicitly, choose "other".*
  - Add to prompt: *If there are no adjacent to mCDR topic within the paper, choose "not applicable".*

Supplemental Figure 1 shows the difference in the assigned tags of papers associated with mCDR and Fisheries based on Elicit’s AI generated assignments and the manual method. While Elicit was able to assign tags to papers, we noticed a few trends. First off, even though we asked Elicit to only assign one tag per paper for some categories (i.e. mCDR focus), it still assigned multiple tags to some papers. Additionally, we found that Elicit routinely assigned more tags to papers than we had assigned manually. This was particularly noticeable for the mCDR relevant tags, where Elicit assigned 27, 29, and 30 of the 49 papers to be associated with ocean acidification, blue carbon, and fundamental carbon chemistry, respectively, while we only tagged 1, 5, and 2 papers, respectively. This suggests that the nuances between ocean acidification, blue carbon, and fundamental carbon chemistry in relation to mCDR are difficult to assess for Elicit. This may require either additional AI training, more explicit definitions, and/or an informed human perspective to distinguish between these topics, especially during these nascent stages of the mCDR field while these nuances are still being established. We see similar trends within the fisheries adjacent topics, where Elicit also assigned more tags (8, 24, and 17, respectively) to papers within the fisheries practices, biologic carbon pump, and nutrient dynamics compared to those manually assigned (3, 3, and 6 respectively), which may similarly indicate the nuances that are difficult to distinguish within these categories.



Supplemental Figure 1: *Total paper count (x-axis) for papers that were tagged across categories (y-axis) using AI Elicit (blue) and manual tagging database (orange). Graphs display results for the mCDR Focus categories (left) and associated with fisheries categories (right).*

Elicit also auto-generates suggested tagging categories that can then be assigned to papers. To test this function, we used the “organism” tag to assess how the auto-generated tags performed against our manual tagging (Supplemental Table 4). We found that these auto-generated tags produced unique answers for each tag and did not decipher which answers were important to the study. While Elicit is thorough at including all organisms listed within the study, the manual tagging method allowed us to be selective and include only organisms that were key to the study and assessed for responses from an mCDR related intervention. Additional automated tags were tested, but we found that these tags provided summaries of topics within the paper that were unique to each paper, not categorized by standard choices or tags that would enable large comparisons across papers.

***Supplemental Table 4**: Elicit results from auto-generated tags "organism" (Elicit Organism) and manually assigned tags within mCDRxFisheries database (Database Organism).*

Author	**Elicit Organism**	**Database Organism**
Alami	Nannochloropsis	Nannochloropsis
Ali	Not mentioned (no living organisms were studied in the paper)	NA
Baatz	mangroves, seaweed	NA
Bednarsek	- Calcifying algae - Corals - Dinoflagellates - Mollusks - Gastropods - Pteropods - Coccolithophores - Annelids - Crustaceans - Echinoderms - Foraminifera	NA
Berger	seaweed, phytoplankton	NA
Boyd	Not mentioned (the paper does not specify any organisms under study)	NA
Briscoe	loggerhead sea turtle (Caretta caretta)	Caretta caretta
Britton	Ecklonia radiata	Ecklonia radiata
Canvin	kelp	NA
Carballo	Not mentioned (no specific organisms are mentioned in the paper)	NA
Craik	phytoplankton, seaweed/kelp	NA
Deng	Saccharina japonica, Gracilariopsis Lemaneiformis	Saccharina japonica; Gracilariopsis Lemaneiformis
Doney	Phytoplankton, Macroalgae	NA
Doney	macroalgae	NA
Duarte	- Saccharina latissima (kelp) - Ulva spp. (sea lettuce) - Other seaweed species (as listed in the table)	Seaweed
English	Sargassum natans	Sargassum
Faucher	Emiliania huxleyi	Emiliania huxleyi
Geerts	Not mentioned (the paper does not focus on	NA

	specific organisms as subjects of study)	
GESAMP	Sargassum, kelp (Macrocystis), Laminaria, Saccharina	NA
Halloran	Not mentioned (the paper does not involve living organisms as subjects)	NA
Hughes	seaweed	NA
Jiao	macroalgae	NA
Jin	Not mentioned (no living organisms are mentioned in the paper)	NA
Karunarathn	Not mentioned (no living organisms are studied in the paper)	NA
Kennedy	Not mentioned (the study is a systematic review and does not involve direct study of living organisms)	NA
Kim	Ecklonia cava	NA
Lehmann	coccolithophores	NA
Lindland	Not mentioned (the study does not involve living organisms as subjects)	NA
Liu	Not mentioned (the study does not involve living organisms)	NA
Maboloc	purple sea urchin (Heliocidaris crassispina)	NA
Macraedie	Seagrasses (Zostera marina), Seaweed (macroalgae)	NA
Mariani	fish	NA
Markich	- Macrophiothrix caenosa (brittle star) - Cyanobium sp. (cyanobacteria)	NA
Marx	Not mentioned (the paper does not specify any particular organism as the subject of study)	NA
Nair	macroalgae	NA
Nawaz	forage fish, juvenile salmon	NA
Niffenegger	Not mentioned (no living organisms are studied in the paper)	NA
Oberlander	Thalassiosira pseudonana, Diacronema lutheri (formerly Pavlova lutheri)	Thalassiosira pseudonana; Diacronema lutheri
Oschlies	Microalgae, Macroalgae	NA
Ou	Not mentioned (the study does not involve living organisms as subjects)	NA
Paul	plankton	NA
Pilcher	Not mentioned (the paper does not involve living organisms as subjects)	NA

Ramirez	- Nanoeukaryotes-2 (Chrysochromulina) - Synechococcus spp.	NA
Ramos	phytoplankton, bacterioplankton	NA
Raven	Macroalgae (e.g., kelp), Microalgae	NA
Siebert	macroalgae	NA
Simpkins	Ecklonia radiata, Scytothalia dorycarpa	Ecklonia radiata and Scytothalia dorycarpa
Suessle	- Synechococcus (picoeukaryote) - Diatoms - Chrysochromulina spp. (non-calcifying haptophyte)	NA
Tyka	Not mentioned (the paper does not involve living organisms as subjects of study)	NA

4.4. Comparing AI to manual methods

There was a significant difference in tagging processes conducted by Elicit compared to the manual tagging process, yet the first round of AI tagging may reflect the results of the first iteration of manual tagging. If we were to iterate additionally on identifying key words and assigning tags to papers, it may be possible to train Elicit to tag the papers with the same criteria that we developed through the manual *mCDRxFisheries Literature Database* tagging process, which also required many iterations and testing on hundreds of papers. This still requires a knowledgeable human to train Elicit, understand the nuances between the categories (i.e. ocean acidification, blue carbon, and mCDR) and interpret the iterative results of the tagging process to refine the criteria and assess if the results are aligned with the goals. Regardless of the need for additional training to enhance the AI process, there are also additional barriers that we identified by using AI to conduct a tagging process. Given that Elicit can only load 100 papers at once and analyze 50 in one session, this would require over a dozen iterations of all of the same steps to complete the database analysis that the *mCDRxFisheries Literature Database* required. There is also a required subscription cost for Elicit ($499 per user per year) and a measurable climate impact from using AI to generate large-scale analysis, which can be perceived to be at odds with researching climate solutions. With building a database using AI, there is also a need to decipher what to use to perform quality assurance/quality control (QA/QC) checks again. Similar to how we QA/QC'd around one third of the database (300+ papers), using AI may still require a human to verify and validate a large number of papers manually to ensure the criteria are properly assigned.

While we encountered a few challenges with using Elicity to perform the same *mCDRxFisheries Literature Database* manual tagging process, we also recognize the power of AI when used appropriately and find that there may be some powerful applications to use AI in studies similar to this one. For example, if AI is used in combination with manual methods, AI may be able to provide a first pass on the papers and identify overarching key themes and high-level summaries that can then inform the next steps in analyzing the database. While iterating on the criteria to input into Elicit and/or training Elicit further would require a large time and knowledge investment up front, compared to manual methods, once Elicit was trained and verified to produce trustworthy tagging and categorization, additional papers could be processed through the database quickly and routinely. This is a major advantage for a database in the long term since Elicit could help process new papers to keep the database up to date and change in workforce personnel, capacity, and/or priorities would not hinder the ability to process new papers using the same criteria. In fact, it is unlikely that building an AI tool to perform the categorization and tagging of the *mCDRxFisheries Literature Database* would have saved our research team time and resources so far (Becker et al., 2025), yet in years to come the investment in training Elicit may have paid off in the long run and offered an unbiased way to continuously update the database.

Overall, we see Elicit and other similar AI platforms as powerful tools that can complement manual methods in the future. However, the AI powered tool tested here does not replace a knowledgeable and informed human. A human is still needed to design the prompts, train Elicit, run iterations on assessments, QA/QC, and provide insight on the nuanced decisions. AI can, however, be leveraged to enhance the manual process, provide additional insights, and build automated pipelines that could be used for longevity in the future.

Supplemental Material Section 5: Database csv and Categories Excel Files

Please refer to Supplemental Documents for the Database csv file (mCDRxFisheries_Literature_Database_20251210) and Categories Excel file (mCDRxFisheries_TagCategories_20251210_Submission) that were used in the mCDRxFisheries Literature Database app for the analysis within this paper.