OARS Outcome 4:

Increase understanding of ocean acidification impacts to protect marine life by 2030

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OARS *Outcome 4* and how it contributes to the Ocean Acidification Research for Sustainability (OARS) objectives and to the Ocean Decade

One of the proposed Outcomes of OARS is to «increase understanding of ocean acidification impacts to protect marine life by 2030". Reaching the full understanding of the biological response to ocean acidification (OA) is a formidable task that requires a combination of approaches including biological observations, laboratory and field-based experimentation, and modeling, to generate information that can be used interchangeably and broadly. The **vision of OARS Outcome 4** is a healthy ocean sustained through policies and management actions based on accurate and timely information on the impact of OA on marine life. **A focus on timely action will allow us to prioritize data needs and gaps, data valuation, analyses, observations, and research and generate new knowledge** to be used by other Outcomes. OARS *Outcome 4* will also evaluate existing practices and the development of new best practices and contribute to capacity building.

The persistent increase in atmospheric CO_2 from anthropogenic sources is the main driver of OA in the ocean. An overwhelming body of evidence documents OA with an implication that there are potentially significant impacts on marine species and ecosystems. These impacts are intertwined with local expressions of marine life and physical, chemical, and geological drivers. Generally, in the global ocean, upwelling, downwelling, advection and changes in temperature such as with seasons and long-term warming play a major role in modulating and also driving variability in local partial pressure of CO_2 (pCO_2), pH and other parameters of the carbonate system. In the coastal zone, variability in pCO_2 and pH are directly driven by biological and environmental processes. Processes such as river run-off, stratification, and tides influence the chemical and biological processes that affect air-sea exchange of gasses and feedback. Short- and long-term changes in biodiversity can also alter the carbonate cycle of aquatic environments. Understanding these linkages and feedback is required to characterize past scenarios of ocean states, assess present status and trends, and to project possible future scenarios and to recommend management actions to protect marine life.

Outcome 4 is central to the OARS objectives as it bridges between observed and projected chemical changes, biological impacts, and societal consequences.

The complexity of bridging chemical and biological changes associated with OA is often underestimated. Today, projections of OA rely mainly on proxy variables like pH, saturation state, temperature, salinity, and simplistic thresholds to speculate about the status and trends of biodiversity and ecosystem services. However, the impacts of OA on ecosystems are complex and dependent on multiple other conditions. There is a need to consider factors such as adaptation of organisms to local chemical variability, evolutionary processes, ecological interactions, and the modulating role of other environmental drivers or stressors **(Figure 6)**. Global, regional, and local impacts of OA on biology and ecology, whether gradual or stepwise, are not fully resolved. Experimental work often oversimplifies these processes, for instance by focusing on single species and stressors, short-term responses that focus on single life-history stages and responses within a single generation, and static conditions that do not incorporate natural variability. Yet focusing on comprehensive, real-world conditions that encompass multiple life-history stages, responses across generations, and in the context of species interactions is important to fully understand ecosystem-scale changes that ultimately affect ecosystem services.

Results from experimental work and from *in situ* observing efforts are not always well integrated into synthesis and modeling efforts. Conversely, the requirements of modelers for particular datasets and data formats are not well understood or communicated to observers and experimentalists. Ocean observing

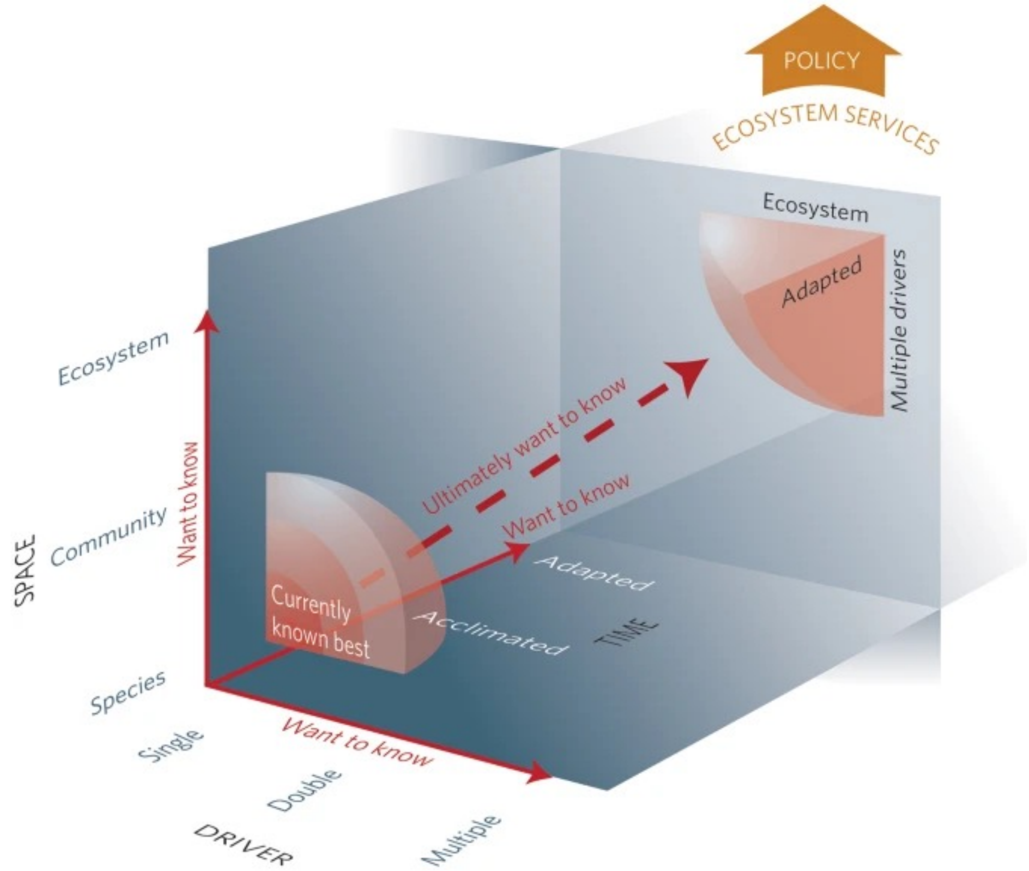

Figure 6: Biological response to ocean acidification: Present state of knowledge and knowledge needs. Most information on the biological impacts of ocean change currently available is on short-term response of single species/strains under the influence of a single driver. *Source:* Riebesell et al., 2015.

data and information delivery systems are often focused on one or a handful of physical and biogeochemical Essential Ocean Variables (EOV)[27] (*Global Ocean Observing System,* n.d.). Historically, however, these observing systems have not included biology and ecosystem EOVs, observations of interactions between organisms and the environment, or observations of interactions among organisms. Although similar marine biology and ecosystem EOV sub-variables are often collected using different methods by different groups, the data are most often managed independently by different observers, and many results are not curated using accepted data management standards. This hinders data sharing, if the data is shared at all. Thus, most marine species and much of the ocean's ecosystems remain under-represented in open databases like the Ocean Biodiversity Information System (OBIS) and the Global Biodiversity Information Facility (GBIF). Further, databases of environmental parameters, including OA parameters (e.g., SDG 14.3.1 data portal)[28], are not linked with other databases, in particular databases that house marine life information (e.g., OBIS and GBIF). To some extent, this has led to slow progress models. Models are simple and lack forecasting skill, leading to assessments about marine life and ecosystem services that are often speculative.

A consequence of all this is that at present, although data are being generated about OA changes and separately about some ecological changes, we are not able to evaluate whether a local resource or ecosystem service is changing, whether it is changing because of a local driver or multiple stressors, or due to larger-scale oceanographic or climate-scale changes.

There is a need to link the entire OA community with those who have a shared interest of protecting and conserving biodiversity in the face of global changes. OARS plays a key role in promoting actions to address the need for broader, more diverse, inclusive, and interdisciplinary collaboration and co-design. There is a need to facilitate inclusion of all researchers interested in monitoring and OA research networks around the world. At present, many early career and international researchers find that much of the science community remains exclusive, based on perceived membership, or requires invitation to the groups or networks that already exist. One problem is that this creates an incentive for parallel networks. The broader benefits of inclusion are improved collaboration, effective sharing of information, fewer duplicate repetitive studies, and an ability to address questions of much larger scale and scope. OARS can facilitate and foster an inclusive network of scientists that is open and accessible to all who are interested. Inclusion of more countries and professionals is a requirement in the quest of diversification in OA research.

Among strategies to strengthen cohesion and relevance of the OA community are active communications between OARS working groups and developing effective links between the biologica oceanographic community and the biogeochemical community engaged in OA research. Priorities in data and information needs will be defined in close collaboration with OARS *Outcome 2* ("Identify data and evidence needs for mitigation and adaptation strategies, from local to global"). Members of the *Outcome 4* working group will be involved in a stakeholder workshop organized by the *Outcome 2* working group. Results of these discussions will guide the work to achieve Outcome 4. The information generated by this working group, jointly with *Outcome 1* ("Enable the scientific community to provide OA data and evidence of known quality") will be central for OARS and will contribute to the improved ability to forecast future changes, drive information-based actions and increase awareness and science capacity, including in developing countries.

OARS *Outcome 4* has a high probability of success because it builds on existing communities including the Early Career Ocean Professionals (ECOPs), the Global Ocean Acidification Observing Network (GOA-ON), the Marine Biodiversity Observation Network (MBON), and the Marine Life 2030 Ocean Decade Program. It will develop stronger links with the Ocean Decade Ocean Best Practices System (Ocean Practices), Digital Twins of the Ocean (DITTO) and observing efforts such as Observing Air-Sea Interactions Strategy (OASIS). It will be important to continue to link these and other communities, such as marine protected area management and planning groups, through ongoing dialogue.

A major benefit of collecting biological information jointly with OA chemical observations is the ability to address major aspects of Sustainable Development Goal (SDG) 14. Specifically, it will directly address SDG 14.3: "Minimize and address the impacts of OA, including through enhanced scientific cooperation at all levels" (SDG Target 14.3). OARS *Outcome 4* will also allow the design of models and the improvement of ocean system components forecasts, including marine life. This entails improving digital twins, which are digital representations of real-life conditions that are used to model the ocean and to understand past, present, and future conditions. These can be scaled to address local to global user needs and will be helpful in advancing our understanding of OA processes and impacts on marine life, in a way that can help management interactions.

27 Essential Ocean Variables: https://goosocean.org/what-we-do/framework/essential-ocean-variables
28 SDG 14.3.1 Data Portal: https://oa.iode.org

Preliminary list of key outputs and products

The OARS *Outcome 4* working group will work in close collaboration with *Outcome 2* and *Outcome 7* working groups ("Develop strategies and solutions to enable countries and regions to include measures to reduce OA in their respective legislation") to engage stakeholders including resource managers, observing system planners and coordinators, and scientists in the co-design of a **priority roadmap** to achieve the vision of OARS. This roadmap will identify the OA Knowledge needed for Decision Making, including information on the data resolution and quality needed for a successful implementation of the needed actions. Working with the *Outcome 7* working group (influence of OA knowledge to guide political decision making) we want to ensure that OA is part of the conversation within international and national decision-making structures e.g., the Convention of Biological Diversity, IPBES (Intergovernmental Panel on Biodiversity and Ecosystem Services), and the UN Framework Convention on Climate Change (UNFCCC). Importantly, OARS *Outcome 4* will ensure an optimal use of existing information to avoid delaying the needed actions to address and minimize the impact of OA.

The second step will be an evaluation of the existing data and information gaps, and identification of the factors responsible for these information gaps (e.g., data sharing, poor communication between communities, time, funds, lack of capacity or best practices). The *Outcome 4* working group will **summarize existing information** (e.g., synthesis, relative thresholds), **generate new knowledge** on biological impacts from existing information (e.g., combining data from chemical and biological observation), and provide **clear recommendations for research and capacity building** that will be shared with other OARS Outcomes.

Examples of outputs in this process include:

<u>An inclusive and diverse community</u>

- Actively includes and promotes researchers at different career stages and from around the world and promotes an interdisciplinary community.
- Promotes and hosts interaction between social and natural scientists.
- Develops an ethics statement and works with the community to adopt these guidelines.
- Establishes better linkage between local and regional groups interested in ecosystem services and role of carbonate system changes.

<u>Summary of existing information</u> (scientific articles, policy documents, database)

- A comprehensive inventory of coastal, estuarine, and ocean observing programs that conduct co-located and simultaneous carbonate system and biological observations and findings related to OA impacts.
    - This will be done jointly with the Global Ocean Acidification Observing Network (GOA-ON), the Global Ocean Observing System (GOOS) and the Ocean Biodiversity Information System (OBIS) (e.g., GOOS BioEco Metadata Portal).
    - Understanding how biological data are curated, formatted, and shared.
    - Advance adoption of data formatting standards and sharing practices.
- Evaluation of existing literature on OA biological impacts in close coordination with:
    - The Ocean Acidification International Coordination Centre (OAICC) bibliographic and biological response databases.
    - The International Ocean Carbon Coordination Project (IOCCP).
    - The Global Ocean Observing System (GOOS).
    - The Ocean Biodiversity Information System (OBIS).
    - The Marine Biodiversity Observation Network (MBON).
    - Ocean Decade programs: Marine Life 2030, SUPREME, OASIS, ECOPs, OceanPractices, and others.
- Identification of baselines for biodiversity at key sites.
    - Establish a process that follows the Framework for Ocean Observing that identifies needs.
    - For example, ongoing OBIS monitoring at UN World Heritage sites.

New knowledge from existing information (scientific articles, policy documents, database)

- Integration of efforts to collect biological observations with OA chemical observations, and vice-versa, using the GOOS Framework for Ocean Observing.
- Identifying data repositories and enabling access, including cross-linking data records of different EOVs collected simultaneously but archived separately.
- Development of synthesis products, theoretical frameworks, biological relative thresholds, and indicators based on existing information, and integrating biological complexity.
- To avoid delaying needed actions, existing information on the impact of OA on marine life and ecosystem services will be communicated to key relevant stakeholders, including the public. A collaboration with communicators will allow to identify the best information to drive change and actions strategically and efficiently.

Recommendations for research and capacity building (best practices, scientific articles, policy documents)

- Developing lists of benefits of observing and applications, consequences for inaction, and guidelines for action in areas where ocean observing has traditionally not been a priority.
- Definition of standards for recording and sharing biological data.
- Implementation of best practices for biological observations to detect and compare OA impacts across marine species and ecosystems.
- Development of best practices for the identification of locally relevant biological indicators integrating environmental, ecological, and evolutionary complexities.
- Development of best practices for laboratory and field-based experimentation integrating the right level of complexity **(Figure 6)**.
- Guidelines for the research and observing community to address information needs, including identifying funding sources.
- Recommendations for improved modeling and forecasting, including models that account for:
  - Species interactions and adaptation.
  - Land-ocean exchanges including freshwater inputs.
  - Ocean-atmosphere exchanges.
  - Improve projection of vulnerability and resilience to OA at all temporal and spatial scales, identification of geographic priorities, and
  - Promote the development of Digital Twin prototypes to help assess the state of the ocean.
- Capacity development materials that explain or allow use of common and standard methods for biological observation and data management standards, including Darwin Core for taxonomic data and Extended Measurements or Facts (e.g., OBIS).

Ultimately, some of the key outcomes envisioned through these broader collaborations include:

- Data from new OA studies that specifically expand our understanding of:
  - How biological and ecological processes respond to OA within a multi-stressor environment over spatial and temporal scales that are relevant to the rate of environmental change,
  - The consequences of OA on complex marine systems and whole ecosystems,
  - The modulating role of human interventions on OA and their impact (e.g., implementation of various marine carbon dioxide removal (mCDR) approaches, including ocean alkalinity enhancement), and
  - The impact of OA on the function and value of those services provided by biological systems to humans.
- Tools and methods for exploring OA impacts on marine organisms, biological processes, populations, habitats, and ecological interactions from genomes to ecosystems.
- Digital tools to synthesize complex biological knowledge and information to visualize, interpret, and gain better conceptual understanding of how biological systems (individuals to ecosystems) work and how they will respond to OA (e.g., Digital Twins).
- Tools and methods to observe and measure biology (abundance, distribution, and processes) over different spatial and temporal scales (e.g., remote sensing, sensors, genomics, imaging, AI/ML) to increase our ability to monitor the response of biology to environmental change.

- Fully integrated (federated) data systems that allow the free flow of data to users, allowing all relevant biological data to be easily discovered and accessed, together with any associated environmental and socioeconomic data.

- Generate synthesis products/indicators formatted in ways that are useful to decision processes and that are co-designed with stakeholders.

Some of these products will be developed in collaboration with other OARS Outcomes and with a broader biology and biogeochemistry community. The efforts should be guided by the general OARS Outcomes.

Priorities and timeline for these outputs and products will be developed in close collaboration with the OARS *Outcome 2* working group and will be based on (1) data needs for action and decision making as well as (2) data availability, (3) the possibility to gather new information in a timely fashion; and (4) the complexity of developing and implementing best practices.

Outcome 4 will also contribute to a reflection on how to evaluate OARS success led by *Outcome 2* focusing on indicators of greenhouse gases, emissions, uptake by the ocean, and marine ecosystem health (e.g., atmospheric CO_2, functional biodiversity, etc.).

Research and outreach activities

<u>An inclusive and diverse community</u>

- promote activities that engage a diverse and interdisciplinary community.

- activities will include natural and social scientists to collaborate jointly with stakeholders and co-design solutions.

<u>Stakeholder workshop</u> (2023, collaboration with OARS *Outcome 2*)

Achieving *Outcome 4* requires developing a **roadmap** that keeps the vision and initial outputs in focus. The OARS *Outcome 4* champions will work in close collaboration with OARS *Outcome 2* to plan and conduct a stakeholder workshop to identify biological data needs and priorities for decision making, and to develop solution implementation. Several members of the OARS *Outcome 4* working group will be directly involved and will share with other members. One of the co-champions of the *Outcome 2* working group (Richard Bellerby) is also directly involved in *Outcome 4* ensuring efficient communication between Outcomes.

The list of possible and desired research and outreach activities can be expected to be very long, and it will be necessary to focus on the preliminary outputs while identifying other priorities. These activities should be viable in the short-term (2022-2023 timeframe) while the Ocean Decade OARS program works with the Ocean Decade and other groups to identify resources, and some intermediate range goals for 2024-2030.

Among the viable first steps that may be achieved with limited funding and on a voluntary basis are activities that directly address some of the key outputs listed in above (Preliminary list of key outputs and products). For example:

<u>Evaluation of the existing data and literature to identify locally relevant thresholds and test new hypotheses (2023-2024)</u>

OBIS and GBIF, other databases holding biological data should be mined to understand where time series observations may be available with which to evaluate changes and thresholds related to OA and other stressors.

Also, the Ocean Acidification International Coordination Centre (OA-ICC), the IOCCP, and other groups host bibliographic databases compiling scientific articles published on OA and ocean carbonate systems. They also have a database of biological responses. These resources can be used to test new hypotheses and identify thresholds (e.g., Vargas et al., 2022). Synthesis and meta-analysis exercises can be time consuming, and we will first focus on case studies. A broad survey of the community will help identify who may already be doing such fundamental meta-analyses.

We will take advantage of a virtual "Meta-analysis training" organized by the OA-ICC in February 2023. The purpose of the event is to use the OA-ICC databases to work on several meta-analysis projects and train participants in the use of these resources. Twelve experienced researchers will be selected, trained and locally relevant projects focusing on the identified priorities will be developed. The OARS *Outcomes 4* working group members will provide mentoring during the process and several scientific articles can be expected by the end of 2024.

<u>Inventory of coastal, estuarine, and ocean observing programs (2023-2024)</u>

A working group will be built to conduct a comprehensive inventory of coastal, estuarine, and ocean observing programs that conduct co-located and simultaneous carbonate systems and biological observations and findings related to OA impacts. The group should work in close coordination with GOOS and OBIS to complement and augment the inventory of biology and ecosystem EOV observing programs, and documents which also collect carbonate parameter data (https://bioeco.goosocean.org/). These assessments can be used to plan case studies and combined with experimental observations, to test new hypotheses.

Members of this working group will be selected from among the OARS *Outcome 4* working group members, the GOA-ON biology working group as well as in other relevant initiatives (e.g., the International Atomic Energy Agency's Coordinated Research Project "Evaluating the Impact of Ocean Acidification on Seafood – a Global Approach" involving 17 countries).

The process should include activities that synthesize knowledge based on biological and acidification observations. This includes identifying data repositories and cross-linking data records of different EOVs. An inventory will need to include an assessment of data formats and management processes used.

An important activity will be to explore the use of observation data to identify performance curves and develop biological indicators and thresholds that consider ecological and environmental complexity and yet simple to understand and useful.

Identifying priorities and strategies for modeling and forecasting (2023)

- A workshop will be organized including members from communities of experimental biology, observation, and modelers that consider the integration of biology with environmental changes including the contribution of land/freshwater ecosystems on OA and its impact on marine life. Specifically, it will address:

  1) biological interactions

  2) response to multiple stressors

  3) impacts of management on the environment and biological responses

  4) interactions among all factors.

Capacity building for common and standard methods, data management standards, and applications in management (2023)

Develop and share capacity building materials that explain or allow the use of common and standard methods and data management standards, including Darwin Core (e.g., OBIS). This can be done through a training workshop for Darwin Core data formatting and sharing of biological data via OBIS; Darwin Core format for taxonomic data and Extended Measurements or Facts. Such training can also include specific recommendations for OA biological observations from Widdicombe et al. (2022) and focusing on five fundamental ecosystem traits and their suite of observable indicators (**Figure 7**): 1) calcified organisms and calcification, 2) autotrophs and primary production, 3) heterotrophs and secondary production, 4) biodiversity and community structure, and 5) genetic and epigenetic adaptation.

These efforts may identify biological monitoring that is already taking place across the world (e.g., status monitoring, MPAs, fisheries, citizen science projects, etc.) and provide suggestions on where to add chemical monitoring efforts. A planning effort will need to be conducted to facilitate co-locating biological, chemical, and other EOV observations. This will require identification of specific biology and ecology EOVs needed to address local and global user needs, and to develop a forecasting ability.

The various working groups will also identify data and best-practice gaps as well as reasons (e.g., funds, capacity, technical) behind those gaps. This will provide science policy recommendations that can be communicated to the relevant stakeholders.

Over the long term, actions and implementation of solutions will require long-time series of co-located chemical and biological observations and new experimental projects using a wide range of approaches and emerging technologies (e.g., Free Ocean CO_2 Enrichment (FOCE) experiments). OARS *Outcome 4* will provide some guidance and best practices on strategies to fill up gaps in data needed for management and policy.

Key inputs to support activities and outputs

To enable the viable short-term activities, OARS *Outcome 4* members will work to identify and collaborate with key experts to address activities, set up realistic timelines and dates for workshops, and resources needed to implement:

- Engage early career groups including the Ocean Decade ECOPS in developing messaging about the importance of links between marine life and OA.
- Meetings or workshops that bring together members with the relevant expertise (e.g., biological, or chemical observation, experimentalists, ecologists, physiologists, evolutionary biologists, modelers, etc.)

Calcifying Organisms and Calcification	Autotrophs and Primary Production	Heterotrophs and Secondary Production
Relative prevalence and success of calcifying organisms Changes in biomass, abundance of biocalcifying species compared to non-calcifying species inorganic to organic biomass ratios **Calcified biostructure morphology** Weight, density, damage or abnormality, dissclution severity, or strength calcified biostructure **Rates of calcification** Rates of calcification or dissolution	**Biomass/standing stock** Total chl a concentrations, phytoplankion cell abundance; microphyto-benthos blomass; blomass of macroalgae and seagrasse **Productivity** Carbon fiocation rates, planktonic, macroalgal or seagrass growth rates **Phenology** Timing of blooms orother rapid growth periods	**Biomass/standing stock** Biomass per Individual; numbers of individuals; average body sizes; percent cover quantification of abundance and blomass of major functional or species groups **Productivity** Gross estimates of pelagic and benthic secondary production from in-situ techniques to algorithms **Phenology** Quantification of changes in the phenology of secondary producers
Biodiversity and Community Structure		
Taxonomic diversity and community composition Identification, quantification (number or blomass) of speces, spedfic taxonomic or functioral groupa present within a community or assemblage at any ghen time **Functional or trait diversity** Identification, quantification (number or blomass) of functional, ecological or behavioral traits		
Genetic Adaptation		
Neutral genetic variation Classic molecular markers (eg, allozymes, mkrosatellites or mtDNA); high-throughput sequencing approaches **Mutation rates** High-throughput sequencing technologies of few loc or whole genomes **Functional genetic variation** Quantitative trait locus (QTL) analysis genome-wide association studies (GWAS); restriction-site associated DNA tags (RAD-seq); RNA secuencing (RNA-seq)		

Figure 7: *Five fundamental ecosystem traits and their observable indicators. Source: Widdicombe* et al., 2023.

- Survey or other method of identifying programs that have in the past, or are, collecting biological and chemical data.
- Close communication with other OARS Outcomes to ensure communication with other scientists (e.g., social science) and stakeholders.
- Close communication across the whole OA community and broader collaborations across communities, particular biological and biogeochemical observation and research programmes relevant for OA, in a purposeful interdisciplinary manner.

Key enablers of success

A minimum of resources, people, and time commitment are required to achieve our short-term goals including the development of a roadmap in collaboration with the OARS *Outcome 2* working group and the short-term activities. Going beyond this to achieve other outputs requires substantial people, coordination, and funding.

It will then be important to develop strategies to have useful interactions between OARS, Marine Life 2030, and other relevant Ocean Decade programs (e.g., DITTO, Ocean Practices, SUPREME, OASIS, iDOOS, Challenger 150) as well as OA initiatives such as GOA-ON and the OA-ICC.

We can take advantage of existing initiatives to train and involve volunteers and Early Career Ocean Professionals interested in the success of the Ocean Decade. For example, the OA-ICC and IOCCP have capacity building programs. Several trainings are planned for 2023 that fits OARS *Outcome 4* goals including a meta-analysis workshop that will fund 12 participants to work on a synthesis project. Other sources of fundings will be explored to organize workshops and meetings.

Further, we need:

- The academic community to understand, engage and support these programmes and deliver the research required.
- Funders of academic research to provide resources for this work. Not just formal funding agencies but also philanthropic investment.
- Industry to engage through the development of new technologies but also those industries that already work in the marine sector and can help with our work (e.g., fisheries, aquaculture, marine tourism and recreation, oil and gas, maritime transport/ships of opportunity) by providing facilities, knowledge, and resources.
- Local communities to provide their knowledge of their own marine systems, undertake activities in their own lives that reduce the potential impacts on marine systems and to call for better decision making, and political action required to better protect and manage the marine environment.
- Educators and communicators (teachers, journalists, film makers, people from the creative arts) to help inform the public on the threats of OA on marine life and what they can do about it (linked to *Outcome 6* ("Increase public awareness of OA, its sources and impacts").
- Policy makers to recognize and use the information generated to support environmental legislation (link to *Outcome 7*).

References

Essential Ocean variables. (n.d.). *Global Ocean Observing System.* https://goosocean.org/what-we-do/framework/essential-ocean-variables/

Riebesell, U., and Gattuso, J. P. 2015. Lessons learned from ocean acidification research. *Nature Climate Change*, Vol. 5, pp. 12-14. https://doi.org/10.1038/nclimate2456

Vargas, C. A., Cuevas, L. A., Broitman, B. R., San Martin, V. A., Lagos, N. A., Gaitán-Espitia, J. D., and Dupont, S. 2022. Upper environmental pCO2 drives sensitivity to ocean acidification in marine invertebrates. *Nature Climate Change*, Vol. 12, pp. 200-207. https://doi.org/10.1038/s41558-021-01269-2

Widdicombe, S., Isensee, K., Artioli, Y., Gaitán-Espitia, J. D., Hauri, C., Newton, J. A., Wells, M. and Dupont, S. (2023). Unifying biological field observations to detect and compare ocean acidification impacts across marine species and ecosystems: what to monitor and why. *Ocean Science, 19*, 101-119. https://doi.org/10.5194/OS-19-101-2023