MarineGEO Science Framework

Taking the pulse of coastal ocean life—together

v 1.0

MarineGEO Mission

As a global partnership, we discover how coastal ecosystems work
—and how to keep them working—through science

MarineGEO Vision

Healthy and diverse coastal ecosystems,
revealed through networked science and safeguarded by an informed society

Overview

The oceans harbor a great share of Earth's biological diversity, driving much of its productivity, providing more than half of the oxygen we breathe, and feeding billions of people worldwide. Yet the marine environment is changing rapidly on local and global scales, profoundly affecting ocean life and the services it provides to humanity. To protect marine ecosystems and the multitude of services they provide to humanity, we need to understand the health of these ecosystems and how they are changing. Scientific discovery and fundamental understanding of marine life and the benefits it provides to people are key frontiers to forging a sustainable future. Solving such global scientific and conservation challenges requires global coordination and communication.

Led by the Smithsonian Institution, the **Marine Global Earth Observatory (MarineGEO)** is a network of scientists collaborating around the world to understand how coastal marine ecosystems work, how they are changing over the long term, and how to maintain their function in a rapidly changing future (**Box 1**). Biodiversity is the heart of all ecosystems, so understanding species interactions is essential for ecosystem management and central to our mission. Since both marine life and people are concentrated along coastlines, we focus on nearshore benthic habitats, from the tideline to scuba depth (20 m), including coral and oyster reefs, seagrass meadows, rocky shores, kelp and mangrove forests, marshes, sediments and human-made structures.

In brief, MarineGEO is a (1) globally distributed, collaborative network; (2) focused on linking environmental change, biodiversity, and ecosystem functioning; (3) in the coastal zone where biodiversity and people concentrate; by (4) integrating a standard toolkit of observation, experiments, and knowledge synthesis; and (5) leveraging the power of shared, open data.

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Guiding Questions

Our research addresses the following overarching questions, which we elaborate in *MarineGEO Science Themes*, below:

- *What is the current condition of marine life and ecosystems across the globe?*
- *How and why are coastal ecosystems changing under natural and human influence?*
- *How do marine ecosystems work, and how can we restore them when degraded?*
- *How are marine habitats and ecosystems connected?*

The MarineGEO Network

MarineGEO is a globally distributed community—the network is people. We engage scientists around the world. By connecting and supporting this global community, we can tackle global questions together that no individual can address alone (**Box 2**). As a team of partners, our research integrates long-term monitoring of core habitats and key species using standardized, intercomparable protocols, coordinated experiments designed by the network, and data sharing and knowledge synthesis to understand how ecosystems work, how they are changing, and the implications of that change.

MarineGEO's value proposition is the power, global reach, and influence that networked science provides to participants. Our goal is to make rigorous, collaborative science accessible and effective for all. Partners work together to design research that addresses the overarching questions via an open, collaborative process. The Smithsonian coordinates the network, builds member capacity through training and toolkit development, centrally manages data, supports research initiatives and synthesis, and collaborates in fundraising. Partners in turn are responsible for supporting and conducting the core research at their sites, sharing data, and organizing logistics when other partners visit their sites. Partners also support the network by serving on working groups that guide our scientific direction, encourage communication and feedback, and help define strategies that advance our collective mission (see information on MarineGEO Working Groups here [URL]). The network relies on innovation from all partners and chooses the best ideas and proposals.

Box 1. MarineGEO in brief

The MarineGEO Niche

- Globally distributed, open network
- Focused on coastal benthic systems and their biodiversity
- Leveraging collaboration
- Standardized toolkit
- Data sharing for bigger science
- Integrating:
  - Core long-term observations
  - Coordinated experiments
  - Knowledge synthesis
- Training and mentoring

Science themes

- Marine biodiversity and ecosystem function in an era of rapid environmental change
- Distribution and condition of coastal ecosystems
- Integrating place-based and comparative global ecology

MarineGEO Network Membership

Membership in the MarineGEO network follows a process of application and dialogue. We envision three types of partnerships, listed in increasing order of commitment (see the MarineGEO Partnership Framework for further details):

- A **MarineGEO Project Partner** is an institution or individual who agrees to collaborate on a defined, and finite project and share the data, with no long-term obligation.
- A **MarineGEO Ecosystem Observatory** is an institution or institutions who agree to conduct annual monitoring for an extended period and participate in annual coordinated experiments at a particular geographic site using the MarineGEO standard toolkit and to share data according to MarineGEO terms. The Smithsonian (MarineGEO Central) and the partner institution(s) establish an observatory through a Memorandum of Understanding (MOU), which is intended as a long-term commitment. An Ecosystem Observatory focuses on 3 or more habitats at the site. A Habitat Observatory targets 1-2, and monitoring may be less frequent depending on habitat type and geography.
- A **MarineGEO Hub** is an Observatory that agrees to contribute a larger role and take on greater responsibility within the network, focusing on a geographic region or research theme. This may involve committing to help recruit, train, and coordinate MarineGEO partners within a region or theme. Hubs are established through a MOU between the Smithsonian and the partner institution(s). Each Hub holds a seat on the MarineGEO Executive Committee.

Box 2. MarineGEO research. Core activities are done at all observatories.

Standardized time-series observations

- Observatory habitats
  - Core: Identify habitats with MarineGEO Central
  - Extended: Map habitats
- Environment:
  - Core: temperature, salinity, turbidity
  - Extended: pH, O_2, others
- Community composition (Core)
  - Benthic species cover
  - Foundation species condition
  - Fish species abundance
- Ecological Processes (Core)
  - Consumption
  - Invertebrate recruitment

Coordinated network experiments (Core)

- Design and conduct annual project
  - Submit proposal (optional)
  - Rank proposals for local site
  - Lead project research at site
- Contribute to manuscript writing

Data management (Core)

- Submit site data promptly
  - Standardized format, templates
  - Site-led QAQC
- Receive data products from MarineGEO Central promptly
  - Data approved for sharing
  - Site data in central repository
  - Basic data visualizations

Knowledge synthesis

- Attend biennial network workshops
  - Stay current, interact with network
  - Collaborate on project design
  - Nurture new ideas, directions
- Contribute to synthesis groups
- Integrate data from observations, experiment, and data mining

MarineGEO Core Research

Long-term observations

Monitoring takes the pulse of ocean life, tracking ecosystems' vital signs. Regular monitoring provides a shared, cross-network knowledge base for analysis of ecological change and for designing experiments that address its causes and consequences. All MarineGEO Observatories monitor a core suite of environmental and ecological parameters, using standardized protocols in key nearshore habitats,

typically at least annually, and share these via the MarineGEO data system. Synthesis of these data contributes to indicators of ecological health and status, supports accounting of local biodiversity, tracks change through time, and aids in diagnosing causes of change. Measured variables are vetted by MarineGEO Working Groups and focus on key environmental drivers, foundation species, biodiversity, and community structure and interactions (Box 2). Core research requirements at each observatory are specified in the partnership agreement between the partner institution(s) and the Smithsonian. The Smithsonian and partner institution(s) launch a new observatory site together by identifying core monitoring sites and habitats and (ideally) conducting the first field campaign together, including training. The partner site institution's staff are then responsible for conducting the continuing annual monitoring and associated research.

Coordinated experiments

Experiments provide diagnostic tests of what causes change. The value of coordinating experiments across the network is greater power to diagnose and interpret causes and effects across a range of conditions from local to global scales. MarineGEO is unique among marine networks and observing systems in our fundamental emphasis on coordinated experiments.

In contrast to the long-term monitoring, MarineGEO's coordinated experiments vary among years and are designed by the network to address specific hypotheses (see *The MarineGEO Research Cycle*, below). This is accomplished through a regular bottom-up process where the MarineGEO community identifies priority research themes and collectively evaluates proposals from network members. We develop these themes into self-contained research projects that can build on observations from core network monitoring and are deployed by partners throughout the network. Smithsonian MarineGEO Central provides coordination, modest material support, and staff support to assist partners in leading the network project.

Examples of recent coordinated projects undertaken by MarineGEO include (1) Ocean Bitemap (2016), which explored the geography of top-down processes by measuring predation pressure and fish species composition in seagrass and unvegetated habitats across 46 sites; (2) the Panamex experiment (2018-2019), which tested top-down impacts on benthic communities by tracking community development on settling plates with and without predators at 36 sites spanning a wide latitudinal range in the Americas; and (3) the global seagrass survey (2019-2020), which compared seagrass bed characteristics and associated faunal communities to model the effects of habitat structure on energy flow through these systems at >100 sites worldwide.

Knowledge Synthesis

Data analysis, synthesis, and interpretation transform data into knowledge. The ultimate goal of research is knowledge and application. MarineGEO thus considers knowledge synthesis a central part of our mission, and we support opportunities for network members to work together on these activities. MarineGEO's distributed design capitalizes on environmental and biological gradients across space to quantify broad-scale patterns in biodiversity, ecological processes, and human impacts, and to use these patterns to test hypotheses relating to causes of change and future trajectories. Long-term, standardized monitoring, targeted research campaigns across regions, coordinated experiments, and data mining all provide the raw material for such analysis and synthesis. Prior examples of these types of syntheses include the interacting influences of

biodiversity, environment, and human impacts on global reef fish biomass, working with the Reef Life Survey[1]; and tests of how marine protected areas improve degraded ecological functions[2].

MarineGEO Science Process

MarineGEO research is designed by the community of partners using a transparent framework for decision making. Research balances long-term commitment to answering big, global-scale questions with hypothesis-driven projects designed to generate products on time scales of student theses and grant cycles.

The MarineGEO Research Cycle

Long-term observations, connected across the network, are described above as a core element of MarineGEO research. These form a growing scaffold on which hypothesis-driven research projects can be built. In this section we describe a process for identifying frontier questions and pursuing innovative research projects to answer them.

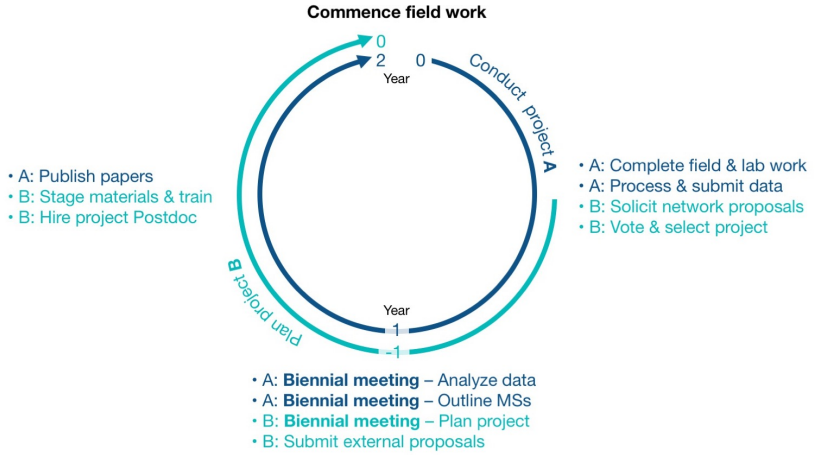

Figure 1. The MarineGEO network project cycle. The cycle from proposal to completion and publication requires 3-4 years. Two cycles run concurrently, with planning for the next (B, light) while the first (A, dark) is implemented and analyzed.

MarineGEO employs a collaborative model following a two-year cycle (Figure 1). In 2019, MarineGEO first sponsored a Request for Proposals from all partner observatories to design a network-wide research project to be conducted the following field season, with partial support from MarineGEO Central. This competition is intended to be annual. Submitted proposals are shared among network partners, who rank their interest and commitment to participate, and one proposal is chosen with this input from the network. Emphasis is on projects that address the overarching MarineGEO Guiding Questions above, can complete field and laboratory work in about one year, require relatively modest commitment from partners, and promptly produce peer-reviewed publications and other products. MarineGEO intends to support a postdoctoral scholar dedicated to the network project to provide intellectual and logistical co-leadership for the year of field work, plus an additional year of support for analysis, synthesis, and manuscript writing to ensure timely publication of products. The process is as follows:

[1] Duffy JE et al., 2016. *PNAS*, 113:6230-6235.
[2] Cheng BS et al. 2019. *Ecology* 100:e02617.

- Network partners submit proposals for coordinated network research projects annually.
- Science Working Group evaluates proposals for network projects.
- MarineGEO Central coordinates formal process for decision-making and makes final decisions.

We use a similar review process to evaluate suggested modifications of core monitoring protocols.

The MarineGEO Toolbox

The MarineGEO Toolbox refers to a standard set of research protocols, data templates, instructional resources, and best practices used by all partners (available open-access to anyone). The toolbox is designed to ensure rigorous, intercomparable research across the network, and to make such research as easy and effective as possible for partners. Thus, we emphasize simple protocols suited to small teams with modest resources, supplemented with DNA barcoding, drone mapping, and remote sensing. Employing the toolbox involves the following actions:

- Partners agree to adopt best practices, including interoperable protocols and data ontologies.
- MarineGEO Central shares protocols and resources via the MarineGEO website.
- MarineGEO Central and experienced partners train new partners in use of the toolkit.
- Partners report quantitative indicators for comparison against reference states or targets at their site and work together to compare these across the network.

1.1 The MarineGEO Data System

Shared data are the key to answering big questions. MarineGEO Central is building a robust, user-friendly, and open data system for managing and serving the network's shared data to meet the needs of our diverse stakeholders. The MarineGEO data system is based at the Smithsonian but linked to other open-access repositories and has the following features (some under construction):

- An effective and intuitive portal for standardized, well-curated data;
- Community guidelines and policy for data release, sharing, attribution, access, and use;
- Code, tools, and collaborative workspaces for data analysis and visualization;
- Data deposition in established, international data portals (e.g., OBIS, GBIF, BOLD, and GenBank) to maximize integration and interoperability;
- Metrics to track data use.

MarineGEO Science Themes

MarineGEO research aligns core long-term observations and experiments conducted across the network to answer our Guiding Questions:

What is the current condition of marine life and ecosystems across the globe?

For a surprisingly large part of the world ocean we have little or no information on marine life. Basic exploration and discovery remain a key frontier. MarineGEO addresses this question by:

- Synthesizing legacy data and knowledge at partner sites.
- Conducting baseline surveys and regular monitoring, emphasizing Essential Ocean Variables[3] and Essential Biodiversity Variables[4], which are broadly accepted indicators for global observing and conservation planning:
  - Biogenic habitat extent and condition,
  - Foundation species and key interactors (diversity, demography, and interactions).
- Documenting Biodiversity through intensive, place-based BioBlitzes and annual surveys:
  - Species of concern (threatened, endangered),
  - Non-indigenous species (NIS),
  - Geographic range extensions.
- Synthesizing emergent patterns across regional and global gradients.

How and why are coastal ecosystems changing under natural and human influence?

Conserving and managing ecosystems requires understanding mechanisms underlying biological responses to forcing, including changing climate, land use, pollution, coastal development and fishing. MarineGEO addresses this question by:

- Monitoring key environmental drivers, organisms that are especially sensitive to change, and indicators through time.
- Comparing biological responses to environment across space.
- Conducting coordinated experiments to test hypotheses addressing mechanisms of change.

How do marine ecosystems work, and how can we restore them when degraded?

Diverse organisms interact to create habitat and drive ecosystem processes. We need to know how stressors affect ecosystems and what promotes resilience to anticipate change, minimize degradation, and restore functioning. MarineGEO addresses this question by:

- Designing coordinated experiments to test hypotheses about mechanisms of change and biological mechanisms of resistance and resilience.
- Analyzing food-web connections.
- Focusing on foundation species and key interactions with strong roles in ecosystems.
- Leveraging ecological restoration projects to test hypotheses and identify best practices.

How are marine habitats and ecosystems connected?

The ocean is continuous, marine organisms often travel long distances, and local events can ripple throughout the ocean. MarineGEO addresses this question by:

- Conducting genetic analyses of population structure and connectivity across space.
- Comparing how biodiversity varies across geography.
- Analyzing of the natural and human processes that move species, including non-indigenous species, among regions.

[3] http://www.goosocean.org/index.php?option=com_content&view=article&id=14&Itemid=114
[4] https://www.frontiersin.org/articles/10.3389/fmars.2018.00211/full

Establishing a MarineGEO Observatory

A MarineGEO Observatory is established through a process of application, dialogue, and co-development by the partner institution(s) and Smithsonian of a research plan for the site, formalized in a Memorandum of Understanding (MOU). This process is described in the MarineGEO Partnerships Framework (URL).

The **MarineGEO Seascape** defines the spatial footprint of a MarineGEO observatory, encompassing the variety of and connections among habitats within the region, roughly on the order of 1-10 km^2. The MarineGEO Seascape spans the intertidal zone to roughly the depth limit of normal scuba accessibility (~20 m).

The specific suite of observations conducted through time at a given site (**Box 2**) are negotiated between the partner institution(s) and Smithsonian MarineGEO Central when the partnership is formalized. These will include at least the core set of research activities conducted at all observatory sites (summarized in **Box 2**), including annual monitoring of basic environmental parameters, abundance of foundation species, associated biodiversity and key interactions, and basic ecosystem process assays (e.g., predation, carbon storage) in common nearshore habitats at the site. All MarineGEO research activities follow standard protocols, current versions of which are hosted on the MarineGEO GitHub site[5]. Following are key elements of establishing the Observatory (Figure 2).

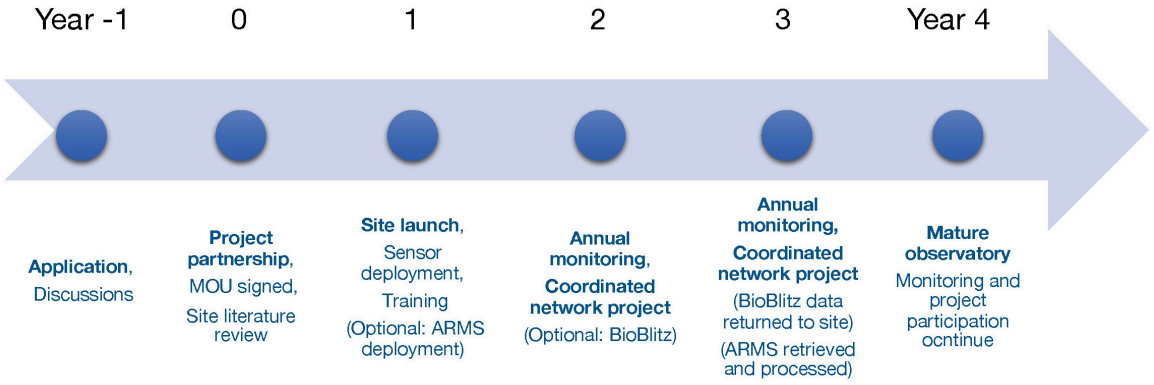

Figure 2. Establishment of a MarineGEO Observatory. The idealized timeline and steps will vary somewhat depending on local interests, capacity, and resources.

Background knowledge synthesis

A first step is to establish an ecological baseline against which to measure environmental and biological change at each site. This begins with synthesis of existing literature and data on the environment, history, and ecology of the site as a foundation for MarineGEO research. Normally, a new MarineGEO Observatory is launched by Smithsonian and local partners through a collaborative field campaign to identify sites for long-term research, map and survey habitats,

[5] For current MarineGEO protocols, see: https://marinegeo.github.io

establish site infrastructure and sensors, and train partners in standard protocols. Site and habitat selection prioritizes sites under long-term study and/or of broad interest to local partners. Example topics of local interest may include presence of IUCN red-listed species, known non-native or invasive species, or identification of climate-sensitive sentinel species for special emphasis.

Once a site is established (2-3 years), Smithsonian and partners may optionally mount intensive biodiversity censuses, depending on the partners' available resources and time. These may include a "BioBlitz" to collect voucher specimens, images, and DNA barcodes; and/or deployment of Autonomous Reef Monitoring Structures for standardized sampling of cryptic invertebrate diversity.

Seascape map

A recommended early step in establishing a MarineGEO Observatory is a map of the seascape, quantifying the distribution of habitats. Seascape maps can be built from drone or satellite imagery, using GIS to delineate the distribution of coastal habitats and key land use features. Mapping can be repeated as site resources allow to track changes in habitat cover through time. Mapping is also valuable for tracking habitat extent because impacts of environmental change are often detected first at edges of patches, edges of the geographic range, or at depth limits.

Environmental sensor array

Each MarineGEO observatory establishes basic environmental observing capacity around the time of site launch. This consists at least of an array of continuous temperature sensors and regular measurements of salinity and water clarity. Partners are encouraged to identify local or regional sources of meteorological, sea level, and water quality data (nutrients, suspended chl). In addition, partners are strongly encouraged to measure or locate nearby sources of data for other important abiotic variables such as pH and dissolved O_2.

Establishing biological reference points

Biological reference points ("baselines") are established early for the site, typically during a formal site launch field campaign involving both Smithsonian and partner scientists. Core quantitative surveys focus on foundation species in selected habitats of local interest (e.g., corals, mangroves, oysters, seagrasses), and fishes and benthic macroinvertebrates in those habitats. Depending on capacity and resources, establishing the site can also include in subsequent years an intensive BioBlitz and/or deployment of Autonomous Reef Monitoring Structures (ARMS) to obtain standardized sampling of highly diverse cryptic organisms.

Long-term research

After the first year, core site research and operations are led by the site's partner institution(s) and Principal Investigator(s). These include annual monitoring and coordinated network projects, and QAQC and management of site data in cooperation with MarineGEO Central's data team.

MarineGEO Products

Rigorous science is judged largely by impactful peer-reviewed publications, which will always be central to MarineGEO (see https://marinegeo.si.edu/research/publications). MarineGEO also provides other resources to make collaboration and knowledge application easy and rewarding.

Networked biodiversity resources. MarineGEO aspires to make marine biodiversity knowledge available to everyone. Following established pipelines, we collect, catalogue, photograph, sequence, and archive organisms in secure, open-access repositories. These include the Smithsonian's National Museum of Natural History and host country museums (vouchers); iNaturalist and Encyclopedia of Life (images); Barcode of Life Database (BOLD) and Genomic Observatories MetaDatabase (GEOME) (DNA sequences); and Ocean Biogeographic Information System (OBIS) and Global Biodiversity Information Facility (GBIF) (biodiversity metadata).

Toolkit: Online resources. MarineGEO provides an open-source toolkit of resources for documenting and surveying marine life and habitats (https://marinegeo.github.io/). This resource, currently under construction, is intended to include standardized protocols, field datasheets, data templates, instructional videos, and other resources. MarineGEO also hosts a data submission portal (URL) that streamlines and standardizes the process of data submission.

Toolkit: Analytical. MarineGEO is developing an analytical toolbox using the open-source software R. This package is intended to facilitate the ability of network partners and others to obtain, visualize, analyze, and report on MarineGEO standard data and compare across sites.

A collaborative space. To foster community interaction and engagement, MarineGEO strives to provide regular communications and online forums for discussion and coordination. These include a quarterly newsletter, an e-mail listserv for real-time interaction, an in-person biennial MarineGEO workshop/symposium, and participation in major scientific meetings. Future plans include regular remote seminars offered by MarineGEO Central and our partners on topics of network interest.

Outcomes

By the end of the current strategic planning period in 2024, we expect to achieve these outcomes:

- MarineGEO is a global network of partners collaborating to track and understand changes in coastal life and ecosystems using shared, interoperable tools.
- MarineGEO is a global leader in coastal marine life observation and research, recognized through high-impact publications and substantive contributions to ocean science, conservation, and public outlets.
- MarineGEO provides a rich, interoperable, open knowledge base from each partner site, serving the network's data and interpretation on environment, biodiversity, and ecology.
- MarineGEO provides an open, user-friendly web portal for submitting, sharing, and serving well-curated, well-annotated, and reproducible data on coastal marine life and ecosystems.
- MarineGEO supports and co-develops established university field course curricula, and mechanisms for student and staff exchanges, that build capacity internationally and strengthen partnership within the MarineGEO network.