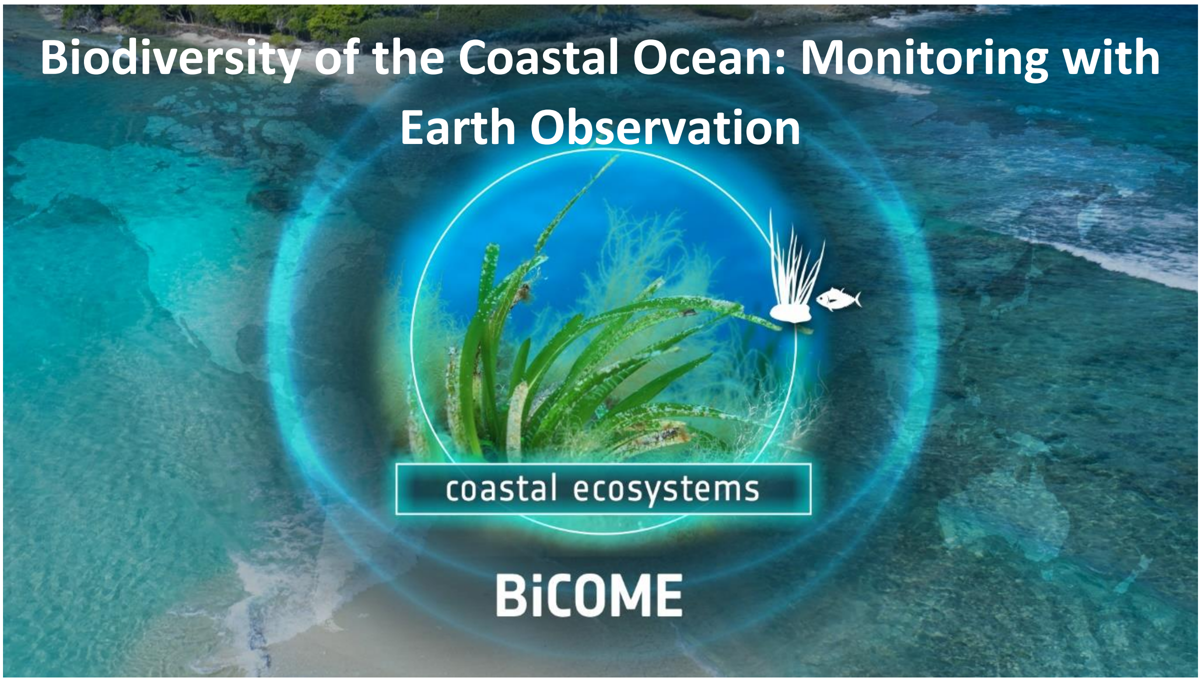
Earth Observation Science for Society” element of FutureEO-1 BIODIVERSITY+ PRECURSORS



D1.1 Requirements Baseline

Issue 5.0

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CONTRACT REPORT

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Acronyms

AC	Atmospheric Correction
ATBD	Algorithm Theoretical Basis Document
CBD	Convention on Biological Diversity
CMEMS	Copernicus Marine Services
EBV	Essential Biodiversity Variable
ECV	Essential Climate Variable
ESA	European Space Agency
EOV	Essential Ocean Variable
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
CERTO	Copernicus Evolution - Research for harmonised and Transitional water Observation
DESIS	DLR Earth Sensing Imaging Spectrometer
EnMAP	Environmental Monitoring and Analysis Program
GOOS	Global Ocean Observing System
IPBES	Intergovernmental Science Policy Platform on Biodiversity and Ecosystem Services
DESIS	DLR Earth Sens-ing Imag-ing Spec-trom-e-ter
OCCCI	Ocean Colour Climate Change Initiative
PRISMA	Hyperspectral Precursor and Application Mission
PVR	Product Validation Report
SDG	UN Sustainable Development Goals
EnMAP	Environmental Monitoring and Analysis Program
SPTM	Science and Policy Traceability Matrix
VENµS	Vegetation and Environment monitoring on a New MicroSatellite
PVR	Product Validation Report

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1 Introduction

Increasing pressure on nature due to anthropogenic drivers is leading to a global reduction in biodiversity with associated loss of benefits from biodiversity at the planetary scale. In coastal environments, the most important direct drivers of biodiversity loss are: fishing, land and sea use, climate change, and pollution. These drivers have accelerated in the last 50 years (IPBES, 2019) and are predicted to continue (Leclère et al, 2020), despite international efforts in the last decades (Convention on BioDiversity, CBD, Aichi targets). To guide further action, it is therefore urgent and important to develop “fit-for-purpose” observation tools. These observations should be capable of assessing and monitoring how the community structure and function of coastal ecosystems is being affected by, and will respond to, the anthropogenic and natural drivers in a changing climate. This overarching topic translates into high priority overall research questions such as (Muller-Karger et al., 2018a):

- How will biodiversity change with land and sea uses and pollution compounded with climate change? How will these changes affect the ecology and biogeochemistry of coastal habitats?
- What are the relationships between the biodiversity and coastal ecosystem function and services?
- Which regions are hot spots of resilience or sensitivity to drivers?

These high-level questions encapsulate three elements that must be clarified and made more concrete: mapping of coastal biodiversity, detection of change, and attribution of the change to single or multiple drivers.

The answers to these can only be addressed by the combination of observations of the Essential Biodiversity Variables (EBVs, Pereira et al., 2013) along with environmental variables and direct drivers.

Muller-Karger et al. (2018a) reviewed the EBVs for some coastal ecosystems and assessed the extent to which they could be monitored in different coastal habitats through spectral reflectance measured from satellites. It emerged that EBVs relevant to ecosystem structure and class (i.e. functional type and fragmentation/heterogeneity) would be tractable using spectral radiometry.

The focus of BiCOME is to investigate the extent to which EBVs for coastal ecosystems can be derived from state-of-the-art remote sensing radiometry and how these tools can be used for answering fundamental questions about biodiversity.

1.1 Purpose and scope

To this end, the purpose of this report is, for each ecosystem included in BiCOME, to 1) examine the overall framing questions from Muller-Karger et al. (2018a) within the context of the particular threats and requirements of each of the types of environments under consideration, and define specific questions for the Case Studies in the project and other situations specific to various types of coastal ecosystems; and 2) define observational requirements and identify relevant algorithms and datasets for mapping biodiversity from space and for product validation.

Here we use a combination of literature review (policy and scientific), a survey (with in person interviews) of the Early Adopters in the project, and interactions with the Scientific Advisory Group of BiCOME and with the other ESA Biodiversity+ projects.

The report is structured as follows: first we describe the overall framework for our approach and the format of the SPTM, then each ecosystem specifics are presented and discussed, including both the science and the pilot study specific requirements. For each ecosystem, we compile the specifics in a Science and Policy Traceability Matrix (SPTM), revised and updated from the proposal, highlighting the link between scientific questions and their relevance to policy, observables, requirements (minimum and ideal), algorithms, and datasets. The SPTM (in a separate xls file) is the main output of this activity and this document is its guide.

2 Framework and format of the revised SPTM

The connection between scientific questions and policy requirements to Essential Ocean Variables (EOV) and Essential Biodiversity Variables (EBV) for marine ecosystems has been explored previously (Muller-Karger et al., 2018a; Muller-Karger et al., 2018b; Dierssen et al., 2021). However, the specific remote sensing products and potential algorithms have not yet been fully mapped to the EBV-EOV-environment combinations and will be the framework used to structure the SPTM. The process (Figure 1) can be followed in the SPTM.

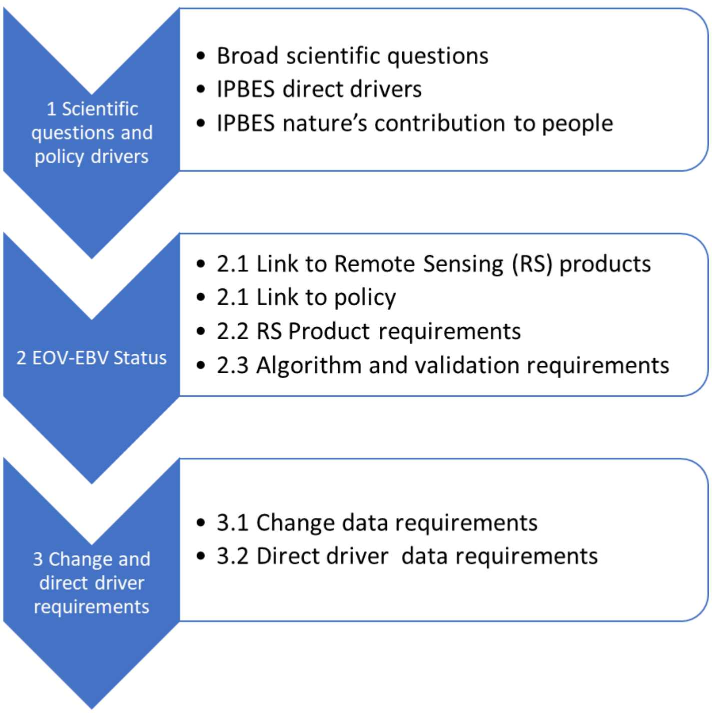

Figure 1: Sequential process for the construction of the Science and Policy Traceability Matrix (SPTM) in the spreadsheet. The numbered items correspond to the tabs in the spreadsheet.

2.1 Aligning broad scientific questions with policy drivers

Following an extensive review, Miloslavich et al. (2018) summarised the broad scientific questions to be addressed by an observing system to monitor marine biological variables (i.e. Essential Ocean Variables). If we adapt the same framework for remote sensing of coastal biodiversity, the higher level questions are:

1. *what are the status and change of the biodiversity in the ocean*
2. *have there been biogeographical or ecological shifts in their diversity, distribution and abundance in response to human alterations.*

These two overarching questions were then broken down into specific questions by Miloslavich et al. (2018) (see their Appendix Table S7) for each Essential Ocean Variable (EOV). The condition of an ecosystem is its quality, measured by its abiotic and biotic characteristics. Ecosystem condition is described by variables related to the composition, structure and function which in turn is an indicator of the ecosystem health (or its integrity). Ultimately, ecological health supports its capacity to deliver ecosystem services. For example, for subtidal seagrass, species diversity might be related to pelagic fish community breeding areas or to different rates of carbon sequestration. Questions about state, the instantaneous condition of an ecosystem (Constable et al.,2016) are then connected to change over time and those changes related to direct drivers (environmental or man-made). This logic is maintained throughout the SPTM (Figure 1).

The Essential Ocean Variables that will be the focus in BiCOME are listed in Table 1, and include: phytoplankton biomass and diversity (PHY) and macroalgal cover and composition (MAC), seagrass cover and composition (SEA), as well as invertebrate abundance and distribution (INV). The definition of invertebrate abundance and distribution as an EOV is under discussion in GOOS. Here, we will address only one particular case of invertebrate, namely the polychaete reefs by the honeycomb worm *Sabellaria alveolata*.

Table 1 List of Essential Ocean Variables from Miloslavich et al. (2018) with the emerging EOV proposed in this report. Codes are defined for the Science and Policy Traceability Matrix. Some EOV are not included in BiCOME but on the associated ESA biodiversity project BOOMS: Biodiversity in the Open Ocean: Mapping, Monitoring and Modelling.

Essential Ocean Variable	Abbreviation code for the SPTM	Section in the report
Phytoplankton biomass and diversity	**PHY**	**Section 5 and BOOMS**
Zooplankton biomass and diversity	ZOO	BOOMS
Fish abundance and distribution	FSH	BOOMS
Sea turtle, seabird and marine mammal abundance and distribution	TBM	BOOMS
Hard coral cover and composition	COR	Not discussed
Macroalgal canopy cover	**MAC**	**Section 5**
Seagrass cover	**SEA**	**Sections 3 and 4**
Mangrove cover and composition	MAN	Not discussed
Invertebrate abundance and distribution (*emerging)	**INV**	**Section 3**

Because of the different observation conditions, we separate the EOVs studied in BiCOME into three environments (i.e., epipelagic, subtidal and intertidal), and some of the EOV are included in more than one environment (e.g., seagrass is in subtidal and intertidal environments). So, for each EOV-environment combination, a series of scientific questions will be identified. In BiCOME, we will focus on some of those wider questions and adapt them for the specific Pilot Studies.

The main scientific questions should address knowledge gaps in the IPBES report (IPBES, 2019). The IPBES report (IPBES, 2019) identified five main direct drivers of biodiversity loss:

- changes in land and sea use,
- overexploitation,
- climate change,
- pollution,
- invasive alien species impacting marine habitats.

This report also identified marine and coastal areas as being undersampled and understudied. Key knowledge gaps include the lack of inventories of understudied ecosystems such as ocean, coastal, seabed, and wetlands. There is also a lack of data from monitoring ecosystem status (such as seagrass extent, density and species richness of a seagrass bed or temperate invertebrate reefs such as those created by the honeycomb worm *Sabellaria sp*.). International, regional and national drivers to curb biodiversity loss are gaining pace. The CBD, the EU Biodiversity Strategy, and the SDGs all aim to halt biodiversity loss by 2030. The vision of the CBD is to live “in harmony with nature” by 2050 (CBD, 2021). These missions are grounded in targets and monitoring programmes to help achieve them. Remote sensing can be a key provider of monitoring data of marine and coastal ecosystems (Miloslavich, et al. 2018; Muller-Karger, et al. 2018b). All knowledge gaps relevant for coastal ecosystems are presented in Table 2, however BiCOME will focus only on addressing those in bold.

Table 2: Selected sectors and Knowledge gaps relevant to coastal ecosystems and to remote sensing from the non-exhaustive list of Knowledge Gaps in Appendix 4 of the IPBES report (IPBES, 2019)

Sector	Knowledge gaps (in data, indicators, inventories, scenarios)
Data, inventories and monitoring on nature and the drivers of change	• Data on ecosystem processes (including rates of change) that underpin nature’s contributions to people and ecosystem health • **Data from monitoring of ecosystem condition (generally less well represented than ecosystem extent)** • Data on changing interactions among organisms and taxa • Impacts of increasing CO_2 upon the total Net Primary Production of marine systems and consequences for ecosystem function and nature’s contributions to people • Syntheses of how human impacts affect organismal traits • Indicators on the global extent and consequences of biotic homogenization • Global spatial datasets on key threats, e.g., data on patterns in the intensity of unsustainable exploitation of species and ecosystems • **More comprehensive understanding of how human-caused changes to any Essential Biodiversity Variable class (e.g., ecosystem structure) have impacts on others (e.g., community composition) and on nature’s contributions to people**

	• Monitoring of the long-term effects of dumped waste, especially radioactive material and plastics • Data on the impacts of war and conflict on nature and nature's contributions to people
Gaps on biomes and units of analysis	• **Inventories on under-studied ecosystems**: freshwater, Arctic, **marine/ocean, seabed,** and wetlands
Nature contribution to people (NCP) -related gaps	• Data on the status of species and nature's contributions to people linked to specific ecosystem functions • Systematic indicators to report the status and trends for categories of nature's contributions to people • Data and information on NCP 9: the role of nature and nature's contributions to people in mitigating or reducing vulnerability to disasters
Links between nature, nature's contributions to people and drivers with respect to targets and goals	• Need for indicators for Aichi Biodiversity Target 15 on ecosystem resilience and contribution of biodiversity to carbon stocks • Better quantitative data to assess the Sustainable Development Goals and Aichi Targets where qualitative indicators have been dominant
Potential policy approaches	• Data on the impacts of climate change on marine and coastal governance regimes • Data on the monitoring of policy effectiveness to adapt and adjust policies and to share lessons

In addition to addressing the knowledge gaps, it is important to identify the areas of the nature's contribution to people that the scientific questions are related to. According to the CBD, biodiversity nature's contribution to people (relevant to coastal ecosystems) can be grouped into three categories (numbers follow original numbering in (IPBES, 2019)):

1. Regulation of environmental processes, including: (4) regulation of climate, (5) regulation of ocean acidification, (7) regulation of coastal water quality, (9) regulation of hazards and extreme events, (10) regulation of detrimental organisms and biological processes
2. Materials and assistance , including: (12) food and feed, (13) materials and assistance, (14) medicinal, biochemical and genetic resources
3. Non material, including: (15) learning and inspiration, (16) physical and psychological experiences, (18) maintenance of options

Tables 3 to 8 are a summary of the selected science questions, direct drivers, IPBES knowledge gaps and Nature's contributions to people per Essential Ocean Variable and per environment that will be addressed in BiCOME (in SPTM tab is "*1_Scientific questions policy*"). In Sections 3, 4 and 5 the specific questions being addressed during BiCOME for each Pilot Study will be further expanded and justified and mapped into the general questions.

Table 3: Selection of the scientific questions and direct drivers related the Essential Ocean Variable: Macroalgal canopy cover and composition in the intertidal environment. The macroalgal canopy cover will not be addressed in BiCOME explicitly, but as a secondary part to seagrass canopy cover, therefore there is no explicit SPTM for intertidal macroalgal canopy cover. The scientific questions are derived from Miloslavich et al. (2018) review. Also included in this table is the link to knowledge gaps identified through IPBES and IPBES Nature's Contribution to people (NCP).

Generic Questions	Direct Drivers	IPBES Knowledge Gaps addressed	IPBES Nature's contribution to people
1.- What is the status of macroalgal canopy cover? 2.- What is the status of macroalgal diversity? 3.- What is the change in macroalgal canopy cover? 4.- What is the change of macroalgal diversity in the (coastal) ocean? 5.- How are macroalgal communities affected by severe events? 6.- Are changes in macroalgal extent and condition affecting fishes or other important species?	Changes in land use Climate change	Data from monitoring of ecosystem condition in coastal waters More comprehensive understanding of how human-caused changes to any Essential Biodiversity Variable class (e.g., ecosystem structure) have impacts on others (e.g., community composition) and on nature's contributions to people	7 Regulation of coastal water quality 10 Regulation of detrimental organisms and biological processes

Table 4 Selection of the generic scientific questions and direct drivers related the Essential Ocean Variable: Seagrass canopy cover and composition in the intertidal environment and addressed in BiCOME. This list of generic questions is given in spreadsheet sptm_intertidal_seagrass_v5.0, tab 1_Scientific questions policy. *Specific questions for BiCOME are listed in Table 10. The generic scientific questions are derived from Miloslavich et al. (2018) review. Also included in this table is the link to knowledge gaps identified through IPBES and IPBES Nature's Contribution to people (NCP).*

Generic Questions	Direct Drivers	IPBES Knowledge Gaps addressed	IPBES Nature's contribution to people
1 What is the status of seagrass cover in intertidal areas? 2 What are the changes of seagrass cover in intertidal areas? 3 How is seagrass cover affected by severe events? 4 How is seagrass cover affected by anthropogenic impacts? 5 Are changes in seagrass cover affecting other important species?	Changes in land use Climate change	Data from monitoring of ecosystem condition in coastal waters More comprehensive understanding of how human-caused changes to any Essential Biodiversity Variable class (e.g., ecosystem structure) have impacts on others (e.g., community composition) and on nature's contributions to people	7 Regulation of coastal water quality 10 Regulation of detrimental organisms and biological processes

Table 5: Selection of the scientific questions and direct drivers related the Essential Ocean Variable: Invertebrate abundance and composition in the intertidal environment and addressed in BiCOME. This list of generic questions is given in spreadsheet sptm_intertidal_invertebrates_v5.0, tab 1_Scientific questions policy. Specific questions for BiCOME are listed in Table 11. The scientific questions are derived from Miloslavich et al. (2018) review. Also included in this table is the link to knowledge gaps identified through IPBES and IPBES Nature's Contribution to people (NCP).

Generic Questions	Direct Drivers	IPBES Knowledge Gaps addressed	IPBES Nature's contribution to people
1 What is the status of benthic invertebrate abundance? 2 What is the change in benthic invertebrate abundance? 3 How are benthic invertebrates abundance affected by severe events? 4 Are changes in benthic invertebrate abundance affecting intertidal biodiversity?	Changes in land use Climate change	Data from monitoring of ecosystem condition in coastal waters More comprehensive understanding of how human-caused changes to any Essential Biodiversity Variable class (e.g., ecosystem structure) have impacts on others (e.g.,	7 Regulation of coastal water quality 10 Regulation of detrimental organisms and biological processes

		community composition) and on nature's contributions to people	

Table 6: Selection of the scientific questions and direct drivers related the Essential Ocean Variable: seagrass cover in the sub-tidal environment and addressed in BiCOME. A broader list of questions is given in spreadsheet sptm_subtidal_seagrass_v3.5, tab 1_Scientific questions policy, but these are not included in the BiCOME study. The scientific questions are derived from Miloslavich et al. (2018) review. Also included in this table is the link to knowledge gaps identified through IPBES and IPBES Nature's Contribution to people (NCP).

Generic Questions	Direct Drivers	IPBES Knowledge Gaps addressed	IPBES Nature's contribution to people
1.- What is the status of seagrass cover in subtidal areas? 2.- What are the changes of seagrass cover in subtidal areas? 3.- How is seagrass cover affected by severe events? 4.- How is seagrass cover affected by anthropogenic impacts?	Climate Change- anthropogenic pressures	Data from monitoring of ecosystem condition in coastal waters More comprehensive understanding of how human-caused changes to any Essential Biodiversity Variable class (e.g., ecosystem structure) have impacts on others (e.g., community composition) and on nature's contributions to people	7 Regulation of coastal water quality 10 Regulation of detrimental organisms and biological processes

Table 7: Selection of the scientific questions and direct drivers related the Essential Ocean Variable: Macroalgal cover and composition in the epipelagic environment and addressed in BiCOME. A broader list of questions is given in spreadsheet sptm_floating_epipelagic_v3.42, tab 1_Scientific questions policy, but these are not included in the BiCOME study. The scientific questions are derived from Miloslavich et al. (2018) review. Also included in this table is the link to knowledge gaps identified through IPBES and CBD Nature's Contribution to people (NCP).

Generic Questions	Direct Drivers	IPBES Knowledge Gaps addressed	IPBES Nature's contribution to people
1.- What is the status of macroalgal cover? 2.- What is the status of macroalgal diversity? 3.- What is the change in macroalgal cover? 4.- What is the change of macroalgal diversity in the (coastal) ocean? 5.- How are macroalgal communities affected by severe events? 6.- Are changes in macroalgal extent and condition affecting fishes or other important species?	Changes in land use; Climate change	Data from monitoring of ecosystem condition in coastal waters More comprehensive understanding of how human-caused changes to any Essential Biodiversity Variable class (e.g., ecosystem structure) have impacts on others (e.g., community composition) and on nature's contributions to people	7 Regulation of coastal water quality 10 Regulation of detrimental organisms and biological processes

Table 8: Selection of the scientific questions and direct drivers related the Essential Ocean Variable: Phytoplankton biomass and diversity in the epipelagic environment and addressed in BiCOME. A broader list of questions is given in spreadsheet sptm_phytoplankton_v3.4, tab 1_Scientific questions policy, but these are not included in the BiCOME study. The scientific questions are derived from Miloslavich et al. (2018) review. Also included in this table is the link to IPBES Gaps and IPBES Nature's Contribution to people (NCP).

Generic Questions	Direct Drivers	IPBES Knowledge Gaps addressed	IPBES Nature's contribution to people
1.-What is the status of phytoplankton diversity in the (coastal) ocean? 2.-What is the change of phytoplankton diversity in the (coastal) ocean? 3.-What is the biogeography in phytoplankton communities? 4.-Have there been biogeographical shifts in phytoplankton communities? 5.-Has there been a change in extent and location of algal blooms? 6-How do we relate phytoplankton diversity change to pollution and nutrients? 7.-How do we relate phytoplankton diversity change to climate change?	Changes in land use; changes in pollution and water quality; Climate change	Data from monitoring of ecosystem condition in coastal waters More comprehensive understanding of how human-caused changes to any Essential Biodiversity Variable class (e.g., ecosystem structure) have impacts on others (e.g., community composition) and on nature's contributions to people	4 Regulation of climate 5 Regulation of ocean acidification 7 Regulation of coastal water quality 10 Regulation of detrimental organisms and biological processes

2.2 Connecting scientific questions and policy drivers with remote sensing through Essential Ocean and Biodiversity variables

To translate the questions of the biodiversity research and policy communities into requirements for the remote sensing community, it is necessary to first introduce a common language through some definitions and choice of terminology.

The first set of definitions and concepts concern the variables used. We have adopted the Essential Biodiversity Variables (EBV) and Essential Ocean Variables (EOV) concepts (Figure 2) as recommended by GOOS.

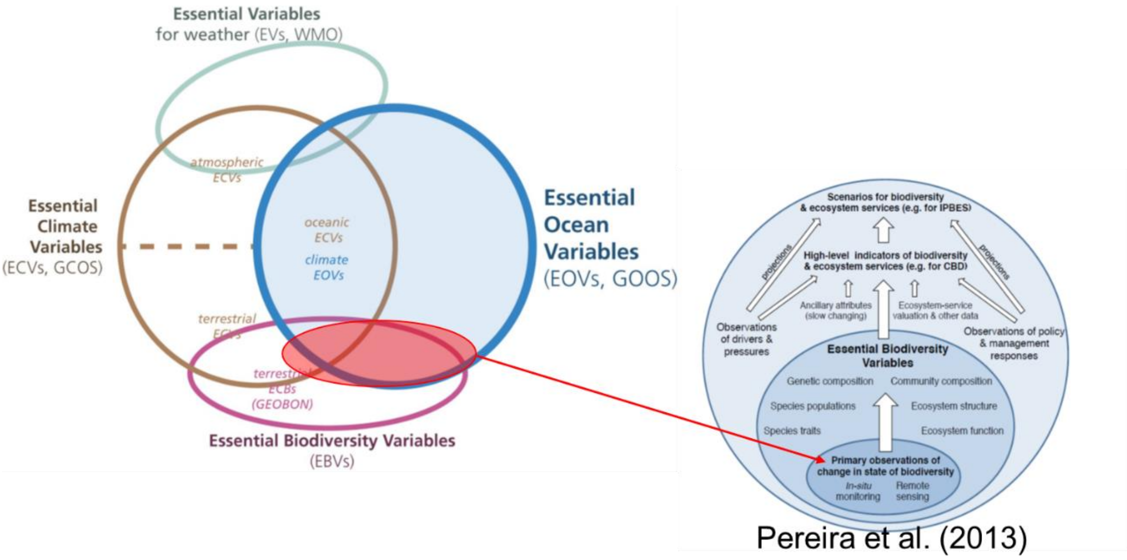

Figure 2: Expanding the relationship between Essential Ocean Variables (EOV) and Essential Biodiversity Variables (EBV). From Muller-Karger MBON (2021) slide, citing Pereira et al. (2017) and Framework for Ocean observing (GOOS, 2012).

Generic Essential Biodiversity Variables (EBV) characterising biodiversity at different levels of the ecosystem (defined by Pereira et al. (2013) and updated online (https://geobon.org/ebvs/what-are-ebvs/) are summarised in Table 9.

Table 9 Essential Biodiversity Variables (EBV) classes and EBV names from https://geobon.org/ebvs/what-are-ebvs/ (March 2022). Explanation of EBV class is from Skidmore et al. (2021).

EBV class	EBV names	Examples of Observable EBV
1 Species population (a local species population)	1 Species distribution	Species presence-absence
		Occurrence probability
		Number of individuals of single taxa
	2 Species (population) abundance	Biomass per taxonomic group
		Density of individuals of a single taxonomic group
	3 Species (population) structure (Size/vertical distribution)	NA?
2 Species traits (trait of an organism of known species that can be monitored at a local level)	4 Phenology	Timing, such as day of year of flowering, leaf sprouting, egg laying, etc. of a particular species
	5 Natal dispersion distance	NA
	6 Movement	NA
	7 Demographic traits	NA
	8 Morphology traits (Skidmore et al.,2021)	Variation in physical attributes of organisms as body mass, of the same species
	9 Physiological traits (Skidmore et al.,2021)	Chemical concentrations, such as leaf nitrogen or phosphorus concentrations.
3 Community Composition (composition of a community that can be monitored at a global level)	10 Taxonomic and phylogenetic diversity	The diversity of species identities, and/or phylogenetic positions, of organisms in ecological assemblages.
	11 Trait diversity	The diversity of functional traits of organisms in ecological assemblages.
	12 Community abundance	The abundance of organisms in ecological assemblages
	13 Species interactions/interaction diversity	The diversity and structure of multi-trophic interactions between organisms in ecological assemblages.
4 Ecosystem structure (an ecological structure that can be monitored at a	15 Live cover fraction	The horizontal (or projected) fraction of area covered by living organisms, such as vegetation, macroalgae or live hard coral.
	16 Ecosystem extent and fragmentation	

global level)	17 Ecosystem distribution	horizontal distribution of discrete ecosystem units
	18 Ecosystem vertical profile	The vertical distribution of biomass in ecosystems, above and below the sea surface.
5 Ecosystem functioning (an ecological function monitored over time at a global level)	19 Ecosystem phenology	NA?
	20 Primary Productivity	NA?
	21 Net ecosystem production (Muller-Karger et al., 2018)	NA?
	22 Ecosystem disturbances	NA?

For each EOV and environment combination, the EBV are defined and matched to the closest remote sensing product and algorithms. For clarity, in our work we will use *status* as a synonym for *condition*, thus resilience or risks to the ecosystem are derived from our status variables (Smit et al., 2021) and not inherently a characteristic of the ecosystem component. One important assumption of our framework is that the observable EBV are related to the status of the ecosystem, and, although some of them imply some changes with time (e.g. phenology, production), these changes are at shorter time scales than the phenomena of interest.

The following step is to link the observable EBV to tractable remote sensing variables. For this step we have followed the proposal by Skidmore et al. (2021), linking "typical remote sensing enabled biodiversity variable names" to "remote sensing biodiversity products". In the SPTM, we have attributed them to the combination EBV-EOV-Ecosystem and given them a development level ("routine"; "demonstrated in some limited cases"; "not yet proven"; "obtained from combining satellite with models"). This combination results in a unique code (Remote sensing product number) linking questions to EBV-EOV-Ecosystem-satellite products, which guarantees traceability, for the questions addressed by this project and for future projects addressing remaining questions.

Furthermore, each Remote sensing product number is mapped to the relevant international initiatives and policies on biodiversity:

- Drivers (from Miloslavich et al., 2018; CBD, MSFD)
- Policy relevant (CBD post 2020)
- Policy relevant (MSFD, WFD)
- CBD Aichi Biodiversity targets
- Sustainable Development Goals

The Remote sensing product number is linked to the general observational product requirements (threshold/ideal): spatial coverage; spatial resolution, ground sampling distance, m/pixel; temporal coverage; temporal frequency, frequency of observations (e.g. daily, weekly, biweekly, monthly), accuracy. The Remote sensing product number is also linked to specific requirements of the algorithms that will be used in this study. To note here, different algorithms can be used for identifying the same remote sensing product in two ways: 1) different algorithms can be available to obtain the same remote sensing product (e.g. % dominance of Diatoms in one pixel); 2) different algorithms can be used for different species for instance in the EBV *species distributions*. The remote sensing product specifications for algorithms sheet also contains the description of the remote sensing input data needed, the minimum and ideal spectral resolutions required, as well as the non-remote sensing input data required (e.g. Look up tables), the characteristics of the output provided by the algorithm, and the validation dataset types and sources. This information will feed into D2.1 Biodiversity + Development Database and D2.2 Algorithm Theoretical Baseline Document.

Finally, the remote sensing products selected for status EBV for each EOV-EBV is linked to key global questions of trends/changes and pressures guided by Miloslavich et al. (2018) for general questions. In addition, key questions around trends/change and pressures are formulated for each case study to ensure applicability for the end users.

3 Intertidal ecosystems

Intertidal areas consisting of soft sediment and emerging at low tide cover more than 10000 km^2 worldwide along the 35000 km^2 of the tidal coastline (Murray et al. 2019). The main soft-sedimentary intertidal habitats (seagrass, microphytobenthos[1], macroalgae, oyster reefs, and polychaetes reefs e.g. the honeycomb worm *Sabellaria alveolata*) are impacted by human activities, biotic interactions, and climate change. Seagrass are significantly affected by many anthropogenic activities (McKenzie et al. 2020), microphytobenthos is impacted by the global reduction of tidal flats (Murray et al. 2019), while the Pacific oyster is an invasive species with a poleward expansion (Thomas et al. 2016) which can impact local habitats such as polychaete reefs in Western Europe (Bajjouk et al. 2020). With the adapted spatial, spectral, temporal characteristics, EO can assess several EBVs for these habitats. In combination with relevant anthropogenic drivers and climate variables, EO-derived information can help answer the main scientific questions related to the intertidal habitats as summarised in the SPTM. By definition, the intertidal zone is the dynamic frontier area between the ocean and the coastline and is alternatively submerged (high tide) and emerged (low tide). In comparison with submerged aquatic vegetation (SAV, Vahtmäe et al., 2006; Klemas, 2013; Hossain et al., 2015; Traganos et al., 2018; Traganos, & Reinartz 2018; Kutser et al., 2020) and coral reefs EO studies (Hochberg et al., 2003; Mumby et al., 2004; Hedley et al., 2016), the remote sensing of emerged benthic communities has received much less attention, despite being very productive and diverse ecosystems.

The aim of this section is three-fold. Firstly, it is to refine the scientific and policy questions for the pelagic ecosystems, secondly to summarise the current remote sensing approaches to measure pelagic biodiversity from remote sensing, and thirdly to define the characteristics of the datasets required to improve the contribution of remote sensing to addressing those questions.

3.1 Science questions

For the intertidal habitats, there are two existing Essential Ocean Variables (EOVs): seagrass and macroalgae, and two emerging EOVs: microbial diversity and benthic invertebrates (Miloslavich et al. 2018). Microphytobenthos belongs to the EOV microbial diversity while oyster and polychaete reefs correspond to the EOV benthic invertebrates. For these four EOV, the overarching scientific questions are related to 1) the description of status and changes of these habitats, 2) the identification and quantification of anthropogenic pressures impacting these habitats, 3) the identification and quantification of climate change on these habitats, 4) the deconvolution of anthropogenic and climate change effects. For the two macrophyte EOV, the specific questions are about the status and changes of seagrass/macroalgae cover and associated diversity, the detection of ecological shifts in response to climate change, the impact of anthropogenic pressures and severe events (i.e. storms, heatwaves), and the carbon sequestration in response to disturbances. The two emerging EOVs share the same questions about their status/changes and associated diversity. For oyster reefs the main question is about biogeographical shifts in response to climate change and the impact of this invasive species on receiving ecosystems. For polychaete reefs the questions are mainly related to anthropogenic impacts (epibionts from aquaculture) and severe events. In the framework of BiCOME,

[1] Unicellular microalgae and cyanobacteria colonizing superficial sediments and forming large biofilms during low tide.

we will focus on scientific questions related to the diversity of intertidal seagrass meadows (Table 4) and polychaete reefs (i.e., reefs of the honeycomb worm *Sabellaria alveolata*, Table 5). The link is made more explicit in Tables 10 and 11 below.

Table 10: Relationship between the generic questions (Section 2.1) for intertidal seagrass canopy cover sptm_intertidal_seagrass_v5.0, tab 1_Scientific questions. References supporting questions are in the SPTM.

Generic Questions	Specific Questions for BiCOME
1 What is the status of seagrass cover in intertidal areas?	What is the extent and condition of seagrass cover? More specifically, is it possible o discriminate seagrass from green macroalgae, and what is the density and extent of intertidal seagrass?
2 What are the changes of seagrass cover in intertidal areas?	How did the extent and condition of seagrass cover change over the last decades? (Interannual variability of seagrass health index)
4.- How is seagrass cover affected by anthropogenic impacts?	Is there an impact of shellfishing on seagrass cover?
5.- Are changes in seagrass cover affecting other important species?	Do changes in seagrass cover affect herbivorous birds? In particular, are changes in seagrass extent and condition affecting Brent goose Branta b. bernicla population, a protected migratory waterbird wintering in seagrass meadows along the European Atlantic coasts?

Table 11: Relationship between the generic questions (Section 2.1) for intertidal invertebrate abundance sptm_intertidal_invertebrates_v5.0, tab 1_Scientific questions. References supporting questions are in the SPTM.

Generic Questions	Specific Questions for BiCOME
1 What is the status of benthic invertebrate abundance?	What is the extent and condition of polychaete reefs in intertidal areas? In particular, what is the colonization of polychaete reefs by epibionts?
2 What is the change in benthic invertebrate abundance?	How did the extent and condition of polychaete reefs change over the last decades? (Interannual variability)
3 How are benthic invertebrates abundance affected by severe events?	How will polychaete reefs change with climate and anthropogenic pressures? In particular, does aquaculture affect the status of polychaetes reefs?

3.2 Policy questions

All the intertidal sites are covered by national (*e.g.* National Nature Reserve in France), European (*e.g.* Natura 2000 network), and international designations (*e.g.* RAMSAR convention on Wetlands) translated into regional/national management policies. As an example, one of the case-study sites in France, the Gulf of Morbihan, has designations as a Nature Reserve, Natural areas of ecological, faunistic and floristic interest (ZNIEFF), a Biotope Protection Order, a hunting reserve, a Natura 2000 perimeter (SPA, SCI), and is designated as Ramsar site 517 (https://rsis.ramsar.org/ris/517). *Zostera* seagrass beds, *Sabellaria* reefs and intertidal mudflats are also OSPAR habitats identified by the Oslo and Paris conventions (OSPAR) strategy for the protection and conservation of ecosystems and biological diversity (https://www.ospar.org/work-areas/bdc/species-habitats/list-of-threatened-declining-species-habitats/habitats).

Seagrass, macroalgae and polychaete reefs are bioindicators (Biological Quality Element, BQE) of the water quality for the Water Framework Directive (WFD, 2000/60/EC) and the Marine Strategy Framework Directive (MSFD; 2008/56/EC). They are used to monitor and evaluate the ecological status of transitional (estuaries) and coastal water bodies throughout Europe (see in particular Table

4: question 7). Microphytobenthos is not yet a biological indicator but could be an alternative to seagrass and macroalgae in turbid areas (Trobajo and Sullivan, 2010). For seagrass and macroalgae, the metrics included in the calculation of an Ecological Quality Ratio (EQR) used to determine a water body's quality status are the taxonomic composition (species richness), the areal extent (total surface occupied by the seagrass meadow or macroalgal belts), and density or biomass. The EQR should respond to an identified pressure (*e.g.,* eutrophication for all marine plants). However, satellite data are not recognised for the WFD statutory monitoring and reporting (Papathanasopoulou et al., 2019) even though their improved spatial and temporal coverage is a strong argument to complement conventional sampling (Zoffoli et al., 2021; Oiry and Barillé, 2021). Satellite observation can also help fill the gaps with regards to large-sized water bodies (Papathanasopoulou et al., 2019). The policies are increasingly requesting a baseline for these BQE and the identification of a reference status against which to detect anthropogenic impacts. In many cases, the Directives' requested temporal measurement frequency of 6 years does not allow a clear identification of the trends for bioindicators and pressures (Zoffoli et al., 2021). Policy relevant specific indicators are linked to EBV in the SPTM (tab 2.1_EOV_EBV_STATUS).

3.3 Intertidal Early Adopters specific requirements

Three intertidal Early Adopters are working in BiCOME. They are located around Brittany and Normandy in France and each have slightly different questions they would like to address using Earth Observation tools (see next Tables).

Table 12: Summary of Early Adopters requirements, research focus and reason to join BiCOME

	Research focus	Reason for monitoring	Reason for joining BiCOME
Maison de la Baie (Mont Saint Michel Bay)	Measure epibionts of *Sabellaria* reefs, anthropogenic pressures nearby	Monitoring the Natural Heritage of the Bay, restoring a traditional fishery	To make better use of RS data
SMBB (Bourgneuf Bay)	Assess the impact of recreational and commercial clam fishing in seagrass beds, interactions between habitats and waterfowl and map *Sabellaria* reefs in relation to anthropogenic pressures	To manage Natura 2000 sites in the Bay, for the Water Framework Directive	To be able to get more and more regular data than through fieldwork (both spatial and temporal extent)
Bio-littoral (South of Brittany)	Differentiate between seagrass and macroalgae, assess anthropogenic pressures (eg. anchoring)	To fulfil requirements of monitoring for the Water Framework Directive	To co-develop a methodology to differentiate between macroalgae and seagrass

Maison de la Baie

The Maison de la Baie is an association to promote the natural and human heritage of the bay of Mont Saint-Michel. While one objective of their mission is environmental education for schools and the general public, they also monitor the natural heritage of the bay and are involved in the restoration of a traditional fishery. In addition, they work closely with the mussel producers of the Mont Saint-Michel Bay.

Their monitoring activities are focused on oyster and mussel epibionts colonising and impacting the largest polychaete reef in Europe. Their current *in situ* monitoring methods are based on the use of quadrats to assess epibiont percent cover. They also monitor the reef conservation status in several sectors of the reef area which is 220 ha in total (Saint-Anne reef) in addition to a smaller reef (Champeaux, 4 ha). Monitoring takes place seasonally with the aim of understanding the impact of anthropogenic pressures in the vicinity of the reefs and their effects on them. They also want to gain deeper understanding of the functioning and interactions of these reefs. Some of the work has been carried out with IFREMER who are also holding the data.

They would like to use remote sensing products to get a better understanding of anthropogenic impacts on the reefs and to assess the conservation status of the reefs (Table 5: questions 1, 2, 5 and 6; RS products 1.1.1.INV.INT, 1.3.14.INV.INT, 1.4.15.INV.INT, and 1.4.16.INV.INT). Currently, they are not using any satellite-derived data and would therefore like to be trained in the use of QGIS and would like to receive products in maps and shapefiles. Ideally, they would like to receive products to assess the usefulness of BiCOME outputs 1-2 times per year.

Table 13: Stakeholder requirements of the Maison Baie, Mont Saint-Michel

Maison de la Baie	Current	Best (Ideal)	Minimum (Threshold)
Survey area	Baie of Mont Saint-Michel	Same	Same
Spatial resolution	1 m^2 (*in situ* quadrates)	10 cm (drone multispectral)	Same
Temporal resolution	4 $year^{-1}$	Same	Same
Level of detail of measurements	Epibionts	Epibionts, conservation status of reefs	

Syndicate Mixte de la Baie de Bourgneuf (SMBB)

Another Early Adopter, the Syndicate Mixte de la Baie de Bourgneuf (SMBB), is responsible for the the management of Natura 2000 areas (FR5200653, FR52120009) including a larger intertidal seagrass meadow (*Zostera noltei*) and the second largest polychaete reef (*Sabellaria alveolata*) in France after Mont Saint-Michel Bay. They use *in situ* seagrass data provided by IFREMER to fulfil Water Framework Directive commitments and monitor one polychaete reef in the Bay using *in situ* measurements of reef percentage cover. They have previously used Sentinel-2-derived maps of seagrass meadows in the frame of the H2020 CoastObs project (Zoffoli et al., 2020) and would like to be able to use Sentinel-2 observations regularly.

The SMBB is particularly interested in being updated on new developments to (i) assess the impact of shell fishing (recreational and professional clam fishing) on the seagrass habitat (Table 4: questions 1 – 4, and 6 – 8; RS products 1.1.1.SEA.INT, 1.4.15.SEA.INT, 1.4.16.SEA.INT), (ii) investigate the interactions between seagrass and migratory waterfowls (Table 4: questions 5, 9; RS products 1.1.1.SEA.INT, 1.1.3.SEA.INT, 1.1.4.SEA.INT, 1.4.15.SEA.INT, 1.4.16.SEA.INT, 1.4.18.SEA.INT), and (iii) map the *Sabellaria alveolata* reef in relation to natural and anthropogenic pressures (Table 5: questions 1, 2, 5 and 6; RS products 1.1.1.INV.INT, 1.3.14.INV.INT, 1.4.15.INV.INT, and 1.4.16.INV.INT).

Table 14: Intertidal Early Adopter SMBB current versus ideal survey scales

SMBB	Current	Best (Ideal)	Minimum (Threshold)
Survey area	Baie de Bourgneuf	Same	Same
Spatial resolution	One reef only	10 m seagrass, < 1m for polychaete reefs	30 m seagrass, 1 m for polychaete reefs
Temporal resolution	Not regular	1 month^{-1}	1 year^{-1}
Level of detail of measurements	Seagrass extent and percentage cover, polychaete reef extent and percentage cover (one reef only)		

SMBB would like to receive data in map form and shapefiles to be easily accessible in GIS software. They would also like a short training session to ensure they use the data in the correct way.

Bio-Littoral

The Early Adopter, Bio-Littoral, is a private research society specialising in marine biodiversity assessments, including those needed for the Water Framework Directive. They are paid by the French Biodiversity Office to carry out surveys in the South of Brittany. Their focus is on marine habitats and mainly on seagrass beds, to measure the extent, density and health status of this intertidal habitat. They also assess maerl beds and *Sabellaria* sp. reefs.

Currently they use satellite images from Pléïades, then go in the field to ground truth. Bio-Littoral surveys 1-2 meadows per year using fieldwork and use satellite images to identify the meadows they need to prioritise (5).

Table 15: Intertidal Early Adopter Bio-Littoral current versus ideal survey scales

Bio-Littoral	Current	Best (Ideal)	Minimum (Threshold)
Survey area	Coastal areas of Southern Brittany	Same	Same
Spatial resolution	1-2 meadows year^{-1}	2 m	Same
Temporal resolution	1 year^{-1} through fieldwork, satellite	1 year^{-1}, best if in September	1 year^{-1}, best if in September
Level of detail of measurements	Differentiate between macroalgae and eelgrass, other damage through anchoring etc	Indicator to differentiate macroalgae from eelgrass from satellite images	

They would like to be able to use satellite derived images to differentiate between macroalgae and eelgrass so they can use this to assess the health status of the meadow (Table 4: questions 7, 8; RS products 1.1.1.SEA.INT, 1.4.15.SEA.INT, 1.3.14.SEA.INT, 1.4.16.SEA.INT). To do this they would like to get a methodology to carry out their EO analysis independently. They would also like an indicator to help with the differentiation between macroalgae and eelgrass. One requirement is the need for images during low tide. They need to be able to estimate reliability in percentage for the Office of Biodiversity.

They can share data but need permission from the Office of Biodiversity which owns the data.

3.4 Algorithms available

Many different vegetation indices (VI) have been commonly applied to multispectral remote sensing images to map intertidal vegetation (Table 16) in the different test sites of the project, including the normalised difference vegetation index (NDVI; Tucker, 1979), normalised difference aquatic vegetation index (NDAVI; Villa et al., 2013, 2014), water adjusted vegetation index (WAVI; Villa et al., 2014), soil-adjusted vegetation index (SAVI; Huete, 1988), atmospherically resistant vegetation index (ARVI; Kaufman and Tanre, 1992), modified narrow-band NDVI (mNDVI; Bargain et al., 2012), and modified normalised difference (mND; Sims and Gamon, 2002). Recent intercomparison exercises demonstrated that the NDVI was one of the most robust indices (Barillé et al., 2011; Zoffoli et al., 2020; Costa et al., 2021) for the detection of intertidal primary producers. The baseline algorithms will then be based on the NDVI, which combines the two advantages of being applicable to S2 at its highest spatial resolution (10 m) and of ensuring continuity with the Landsat and SPOT legacy. The baseline discrimination of the intertidal EBV will be performed using NDVI thresholds commonly applied to discriminate microphytobenthos, macroalgae, seagrass, and schorre vegetation (Méléder et al.; 2003; Echappé et al., 2018; Zoffoli et al. 2020). For benthic invertebrates, the baseline requirement is a Very High Resolution (VHR) DEM model combined with multispectral data.

Table 16: Characteristics of direct detection of intertidal EOV from remote sensing. NA is not available in BiCOME

Question	EOV	Remote sensing biodiversity products	Remote sensing product	Algorithm references	SPTM reference
1	Seagrass (intertidal)	presence/absence: seagrass	1.1.1.SEA.INT	Zoffoli et al. (2020)	SPTM_intertidal_seagrass/ 2.3_Algorithm_req_in_val
1	Seagrass (intertidal)	Seagrass above-ground biomass	1.1.3.SEA.INT	Zoffoli et al. (2020)	SPTM_intertidal_seagrass/ 2.3_Algorithm_req_in_val
1	Seagrass (intertidal)	Seagrass density (percent cover)	1.1.4.SEA.INT	Zoffoli et al. (2020)	SPTM_intertidal_seagrass/ 2.3_Algorithm_req_in_val
1	Seagrass (intertidal)	timing of NDVI annual peak: seagrass, MPB, and green macroalgae	1.2.5.SEA.INT	Zoffoli et al. (2020)	SPTM_intertidal_seagrass/ 2.3_Algorithm_req_in_val
1	Seagrass (intertidal)	seagrass species diversity	1.3.11.SEA.INT	NA	SPTM_intertidal_seagrass/ 2.3_Algorithm_req_in_val
1	Seagrass (intertidal)	epiphytes (seagrass, macroalgae)	1.3.14.SEA.INT	NA	SPTM_intertidal_seagrass/ 2.3_Algorithm_req_in_val
1	Seagrass (intertidal)	percent cover: seagrass	1.4.15.SEA.INT	Zoffoli et al. (2020)	SPTM_intertidal_seagrass/ 2.3_Algorithm_req_in_val
1	Seagrass (intertidal)	Extent: seagrass	1.4.16.SEA.INT	Zoffoli et al. (2020)	SPTM_intertidal_seagrass/ 2.3_Algorithm_req_in_val
1	Seagrass (intertidal)	seagrass total biomass (modeled below-ground biomass + measured above-ground biomass)	1.4.18.SEA.INT	NA	SPTM_intertidal_seagrass/ 2.3_Algorithm_req_in_val
10	Seagrass (intertidal)	Primary production (modelling)	10.5.20.SEA.INT	NA	SPTM_intertidal_seagrass/ 2.3_Algorithm_req_in_val
1	Benthic invertebrates	presence/absence: polychaetes reef	1.1.1.INV.INT	Brunier et al. (2022)	SPTM_intertidal_invertebrates/2.3_Algorithm_req_in_val
1	Benthic invertebrates	epibionts (oysters reef, polychaetes reef)	1.3.14.INV.INT	Brunier et al. (2022)	SPTM_intertidal_invertebrates/2.3_Algorithm_req_in_val

3.5 Datasets available

Input data

A regional spatial coverage of the dataset is the minimum requirement and a coverage of the european seaside would be ideal. The data should at least cover 2018 to present to be able to assess the temporal variability, but a coverage from 1985 to present would be ideal. Details on the datasets requirements as inputs are in Tab 2.2_RS_Product_Requirements. The following satellite datasets will be used:

- Pléïades
- SPOT and Landsat archive

- Sentinel-2 data
- VENµS data (a request for images acquisition is currently being evaluated by CNES)
- PRISMA images (tasking will be requested in the next months)

Validation data

Validation data will be based on in situ measurements (mostly quadrats, percent cover, and dGPS contouring) and drone acquisitions (see SPTM Tab 2.3_Algorithm_req_in_val for more details). The data will be obtained by compiling in-house data acquired during previous projects (e.g., H2020 CoastObs) and data acquired in the frame of BiCOME. The data will be published on Gbif.

Pressures data

Datasets on pressures (including pollutant and nutrient measurements) as well as environmental information such as health status metrics measured for the WFD.

3.6 Potential limitations of the approach

For intertidal seagrass meadows, the baseline products are based on vegetation indices combined to threshold values to discriminate angiosperms from other intertidal vegetation. This works for monospecific meadows that can be found in many coastal areas. However, when green macroalgae such as *Ulva*. sp. are also present in intertidal areas, they can be confused with seagrass. Indeed, they share the same pigmentary composition (chlorophyll a,b and carotenoids) and cannot be spectrally discriminated at a multispectral resolution. A higher spectral resolution is required with more complex algorithms based on machine learning methods using radiometry and texture. A higher spatial resolution should also reduce the issue of mixed pixels. Using machine learning will be a perspective to improve the baseline products.

For intertidal honeycomb polychaete reefs, a baseline product can provide the spatial distribution of macroalgae and mussels colonising the reef. However, due to their spectral complexity, it is not possible to map wild oysters with multispectral sensors. This epibiont colonise the reef and is associated to a degraded status of the bioconstruction. For this specific habitat, we considered that a Digital Elevation Model (DEM) was a baseline product to map reef elevation that was obtained so far at a very high spatial resolution with drones. It is a strong constraint and limitation, and we will consider the possibility to obtain a DEM with very high resolution satellite data (metric or sub-metric).

3.7 Conclusions

For the intertidal vegetation, there is an overall alignment between the scientific and the Early adopter requirements. In terms of questions (Table 10 and 11 for scientific and Table 12 for the Early adopters), the question 1 (what is the status?) and question 2 (what is the change?) in both EOV for this case are needed by the three Early Adopters, either to support monitoring. To evaluate impact of human activities more advanced products are needed.

Baseline multispectral products have been demonstrated to work well on monospecific habitats such as the large meadows of *Zostera noltei* or large mudflats covered by biofilms of microphytobenthos. However, in the case of more complex habitats, when different types of vegetation are mixed, baseline algorithms are not operational anymore. This is the case of the *Zostera noltei* seagrass meadow that can be mixed with green macrophytes of the genus *Ulva* spp. This is a serious limit to mapping marine angiosperm habitats. One of the objectives of BiCOME is to develop advanced products to identify the diversity of intertidal vegetation using multispectral sensors such as Sentinel-2. We will use a combination of very high spatial resolution drone data, multispectral satellite data, and very high spectral resolution satellite data (PRISMA hyperspectral data) to map the intertidal biodiversity. We will apply this methodology to the largest European intertidal honeycomb polychaete reefs (*Sabellaria alveolata*). BiCOME intertidal advanced products will also be developed to answer the specific questions of our Early Adopters: for Maison de la Baie: anthropogenic pressures on polychaetes reefs (eg. Benthic trawling, recreation fishing...), for Bio-Littoral: discrimination between seagrass meadow and green macroalgae, and for the Syndicat Mixte of Bourgneuf Bay: investigating the relationships between seagrass extent and the population of the Brent goose (*Branta bernicla*), a wintering herbivorous bird.

Table 17 summarises the requirements from scientific users and Early Adopters for seagrass canopy cover EOV. Spatial resolution requirements are similar, but temporal resolution is more stringent for scientific users. This is expected as scientists know that current capabilities of remote sensing satellites (e.g. Sentinel 2) have higher revisit frequencies. In terms of products, Early adopters are more demanding than scientists (i.e. cover type distinction), and in BiCOME we will be addressing those needs as described above. Areas for development beyond BiCOME would be to develop remote sensing derived products to input in carbon fixation models.

Table 18 summarises the requirements from scientific users and Early Adopters for the intertidal invertebrate abundance EOV. Spatial resolution requirements are more stringent for Early Adopters, as they use already drones in the area. Perhaps an avenue to explore is how to combine the finer spatial resolution from drones with satellite observations. Temporal resolution is more stringent for scientific users, aligned with the capabilities of remote sensing satellites (e.g. Sentinel 2) which have higher revisit frequencies. In terms of products both communities of users seem to have similar requirements. So overall, a greater spatial resolution would allow the greater breakthroughs.

Table 17: Summary of requirements for intertidal seagrass from scientific and Early adopters

	Scientific needs (Threshold/Ideal)	Early adopters needs (Threshold/Ideal)
Spatial resolution (GSD, m/pixel)	30m/10m or less	30m / 10 or less (2m)
Revisit frequency	Quarterly/monthly	Annual/monthly
Products characteristics	Binary Pixel cover/ % coverage	Seagrass extent and percentage cover / Indicator to differentiate macroalgae from eelgrass from satellite images

Table 18: Summary of requirements for intertidal invertebrates from scientific and Early adopters

	Scientific needs (Threshold/Ideal)	Early adopters needs (Threshold/Ideal)
Spatial resolution (GSD, m/pixel)	30m/10m or less	10 cm / 10cm
Revisit frequency	twice a year (spring, autumn) / monthly	quarterly/quarterly

Products characteristics	Polychates reef spatial distribution map/ Epibionts spatial distribution map	epibionts cover / epibiont cover and conservation status of reefs

4 Subtidal ecosystems

Subtidal coastal ecosystems can provide to many different types of habitats such as mud, rock, seagrass, coral reefs to name a few. Many of these habitats belong to the most productive marine systems and provide a host of ecosystem services. For example, seagrass beds and other vegetated systems have been recognised as highly important in climate regulation and carbon stocks (Duarte, 2016).

4.1 The aim of this section is three-fold. Firstly, it is to refine the scientific and policy questions for the pelagic ecosystems, secondly to summarise the current remote sensing approaches to measure pelagic biodiversity from remote sensing, and thirdly to define the characteristics of the datasets required to improve the contribution of remote sensing to addressing those questions. Science questions

First, we are analysing the impact of human use (e.g., deforestation, overfishing, poor land use, coastal mining, oil spills, eutrophication) on subtidal biodiversity between 2015 and 2022 using time series of annual Normalized Difference Seagrass Index (NDSgI), seagrass extent, satellite derived bathymetry (SDB), vertical attenuation coefficient of downwelling irradiance (K_d), modelled eutrophication, and chlorophyll a concentration from satellite as proxies of biodiversity health, sedimentation, and primary productivity in optically shallow waters. Second, we are studying the seasonal and interannual (2015-2022) variability of subtidal biodiversity in response to climate change-induced events including floods, cyclones, and extreme thermal anomalies using time series of NDSgI, seagrass extent, sea surface temperature, SDB, K_d, mangrove extent and mangrove height. Third, we are assessing the potential of seagrasses as nature-based solutions to climate change by scaling up the EO data sets to estimate the country-scale seagrass extent which will be paired with country-specific seagrass carbon estimates (Gullström et al. 2021) to produce a Tier 2 inventory of mean and range of seagrass carbon stocks in Mozambique and Indonesia. The rationale behind this assessment is to enhance seagrass integration into the Nationally Determined Contributions of Mozambique and Indonesia, which could benefit coastal biodiversity through climate regulation. Fourth, we are utilising all the produced Earth Observations and identifying potential hotspots of subtidal biodiversity resilience or sensitivity to the net force of human and natural drivers.

Understanding the drivers and extent of biodiversity loss, the % of seagrasses effectively protected, and the "winners" and "losers" across these complex, interconnected seascape configurations enable transparent data-driven insights into: a) suitable sites for seagrass restoration (Target 1); b) the design of MPAs to effectively protect well-connected hotspots of coastal biodiversity (Target 2); and c) more intact seagrass carbon sinks which can be bundled with coastal protection or biodiversity maintenance to streamline innovative seagrass protection financing mechanisms beyond carbon crediting allowing near-future biodiversity resilience. See Table 19**Error! Reference source not found.** for a summary linking general top level questions to specific questions in BiCOME.

Table 19: Relationship between the generic questions (Section 2.1) for subtidal seagrass composition sptm_subtidal_seagrass_v3.5, tab 1_Scientific questions.

Generic Questions	Specific Questions for BiCOME
1 What is the status of seagrass cover in subtidal areas?	What is the extent and condition of seagrass cover?
2 What are the changes of seagrass cover in subtidal areas?	How did the extent and condition of seagrass cover change over the last decade?
3 How is seagrass cover affected by severe events?	How is the extent and condition of seagrass cover impacted by heatwaves?
4.- How is seagrass cover affected by anthropogenic impacts?	How is the extent and condition of seagrass cover impacted by human activities such as coastal developments and hence increased coastal eutrophication and decreased light availability in the local scale?

4.2 Policy questions

The IPBES Global Assessment report (IPBES, 2019) identified marine and coastal areas as being under-sampled and understudied. Key knowledge gaps include the lack of inventories of understudied ecosystems such as ocean, coastal, seabed, and wetlands. There is also a lack of data from monitoring ecosystem condition (such as health of a seagrass bed or mangrove density).

Seagrass beds provide key ecosystem services to coastal communities (such as food provision and bioremediation of waste) as well as global communities (e. g. climate regulation) (Beaumont et al., 2007; Potts et al. 2014, Nordlund et al. 2018). Monitoring their extent, status, and changes to these are key to address the CBD, IPBES and EU requirements. It will help with ecosystem-based management, threat prevention (because seagrass beds are able to reduce coastal erosion), and food security directly through providing fish and invertebrates found in seagrass beds and through provision of nursery areas for juvenile fish and invertebrates (Jackson et al. 2015). Monitoring from space is a useful way to look for deterioration through anthropogenic pressures but also to measure restoration success (Bandeira, S. December 2021, during the EA interview). Restoration is also an important target in the CBD, with a target of an increased extent of natural ecosystems under Goal A of the post2020 framework and Aichi Target 15 dedicated to the restoration of natural habitats, a target which has not been achieved (Secretariat CBD, 2020).

4.3 Subtidal Early Adopters specific requirements

The subtidal pilot studies largely overlap with marine sections of the Bazaruto Archipelago National Park (BANP) in Mozambique, and the Komodo National Park, the Kepulauan Wakatobi Marine National Park and the Aru Island in Indonesia. The Indonesian study arear were added after the initial Early adopters survey, so no specific requirements are available. Key questions addressed in this study site are to assess satellite-derived bathymetry estimation as well as to measure the extent of seagrass dominated benthic habitats (Table 20).

The BANP covers 1400 km^2 around the Bazaruto Archipelago and is an important area for megafauna, chiefly dugongs and turtles both of which depend on healthy seagrass meadows. In addition, artisanal fishing in seagrass meadows is important for local communities. This site needs user-friendly ways to measure the extent of seagrass meadows and to be able to assess changes over time. The stakeholders of BiCOME at this site are the African Parks organisation and a university based marine botanist. Regarding the three Indonesian case studies, those feature an areal extent of more than 15,600 km^2 of hot spots of subtidal biodiversity of up to 13 seagrass species, 500 coral species and more than 2500 fish species. Liaison with local seagrass scientists highlighted the importance of mapping the three targeted case studies due to the broader lack of spatially-explicit mapping data at suitable regional spatial scales and accuracies. Further liaison is ongoing to receive suitable multi-temporal field data on seagrass and habitat extent, as well as bathymetry.

Table 20: BANP Early Adopters research focus, reason for monitoring and reason for joining BiCOME

Research focus	To extend their monitoring area (currently mostly fieldwork, with some RS)
Reason for monitoring	To manage seagrass beds sustainably, protection in the marine park and for the sake of dugongs, cyclone damage
Reason for joining BiCOME	To be able to use RS in the regular monitoring of the research area

Currently, they struggle to measure the extent of seagrass meadows in the BANP and monitoring can only be carried out at irregular intervals of up to twice per year. There is also an urgent need to understand the ecological state of the seagrass habitats and to understand the diversity of seagrass species and of the species associated with seagrass beds. The monitoring that they carry out and need to develop further is important to aid the Mozambique Ocean Governance. They do not currently collect data for CBD or SDGs but this will likely be needed in the future.

Their methods include small scale assessment of species diversity of seagrass meadows by fieldwork, for example intertidal transects to measure the extent of seagrass. They have tried Google Image Engine, Landsat and - in other areas – drones and made use of the Allen Coral Atlas (Allen Coral Atlas) and UNEP Seagrass publications (Ocean Data Viewer (unep-wcmc.org)). All methods tested so far have been moderately successful. One issue is the scale of the area they need to assess. Dugongs move over long distances and so ideally they would like to monitor 3000 km^2, which includes the BANP, to assess all dugong habitats.

Regular monitoring about four times a year of seagrass extent and status will help the stakeholders to achieve their monitoring goals because their main interest is seasonal changes. In particular, cyclones occur in one season and it is paramount to understand the impact of these cyclones on the subtidal marine habitats. They need detailed maps of habitat extents to fulfil questions around ocean governance of Mozambique. Currently they see less need to be able to report to SDGs or CBD but this would be a bonus (Table 21).

Table 21: Subtidal Early Adopter current versus ideal survey scales (both stakeholders represented in this table)

Bazaruto National Park	Current	Best (Ideal)	Minimum (Threshold)
Survey area	Small areas of BANP only	3000 km^2	1400 km^2
Spatial resolution	3 m (but fieldwork)	5-10 m	30 m
Temporal resolution	1-2 year^{-1}	4 year^{-1}	4 year^{-1}
Level of detail of measurements	Species of seagrass, dugong tracks		

For ease of access, they would like to receive any BiCOME products in form of maps and if possible in an interactive format to allow zooming in and questioning the data. An online tool similar to the Allen Coral Atlas that is updated regularly would be a useful means of accessing the data they need. One stakeholder also expressed his wish for any products to be extended to the entire country or including and south of the BANP.

4.4 Algorithms

Subtidal seagrasses are identified from optical satellite images using machine learning algorithms in the Google Earth Engine (GEE) cloud platform. At the moment, the available optical satellite images used for this work are the Sentinel-2 (10-m spatial resolution) and Planetscope (5-m spatial resolution) NICFI archives which are already integrated into the GEE environment. The Planetscope images were recently introduced into our work due to its higher resolution as well as clearer seawater area on the tropical area, where cloud and cloud shadow artefacts are abundant in the Sentinel-2 images due to limited available processed data.

As the input for the machine learning image classification, we feed the first 5 bands of Sentinel-2 (coastal aerosol, blue, green, red, and red edge bands), the derived object features (mean, standard deviation, median), Grey Level Co-occurrence Matrix (GLCM) layers, and Principal Component Analysis (PCA) layers together with the training data. The bands available in the Planetscope images are blue, green, red, and near infrared. Therefore, similar to that of Sentinel-2, we processed the object features, GLCM, and PCA layers from these bands. Support Vector Machine (SVM) and Random Forest (RF) are selected as the classification methods (Table 22).

Table 22 Algorithms corresponding to the subtidal seagrass

Question	EOV	Remote sensing biodiversity products	Remote sensing product	Algorithm references	SPTM reference
1	Seagrass (subtidal)	presence/absence : seagrass	1.1.1.SEA.SUB	Traganos et al. (2018); Tassi and	SPTM_subtidal_seagrass/2.3_Algorithm_req_in_val

				Vizzari (2020)	
1	Seagrass (subtidal)	Seagrass species diversity	1.3.11.SEA.SU B	Traganos et al. (2018); Tassi and Vizzari (2020)	SPTM_subtidal_seagrass/2.3_Algorithm_req_in_va l
1	Seagrass (subtidal)	Seagrass extent	1.4.11.SEA.SU B	Traganos et al. (2018); Tassi and Vizzari (2020)	SPTM_subtidal_seagrass/2.3_Algorithm_req_in_va l

4.5 Datasets

The following datasets will be used:

- Input datasets for subtidal seagrasses and satellite-derived bathymetry (SDB):
    - Sentinel 2 L2A at 10m covering 100% all our selected study sites [2015-2029 (expected)]
    - PlanetScope surface reflectance images at 5m covering 100% all our selected study sites (2015-ongoing)
    - ENMAP images at 30m, expected to cover 100% all our selected study sites (when available; September 2022 onwards)
    - Training data polygons from Allen Coral Atlas existent in and/or in the vicinity of our selected study sites (5m resolution; pan-tropical benthic habitat maps) (2018-2020)
- Validation datasets:
    - Presence/absence data points on seagrasses and in-situ collected bathymetry from WWF (all our selected study sites in Mozambique; 2015-2019
    - In-situ collected validation data points from Allen Coral Atlas project existent in and/or in the vicinity of all our selected study sites (5m resolution; pan-tropical benthic habitat maps) (2018-2020)
    -
- Pressures datasets
    - Sea Surface Temperature (SST) time series (Mozambique and Indonesia) from OCCI
    - Light availability (kd490) time series (Mozambique and Indonesia) from OCCI
    - Coastal Eutrophication (Mozambique and Indonesia) at 4 km between 2003-2021 (Maure et al. 2021)

4.6 Potential limitations from the approach

Potential limitations here are the usual showstoppers in subtidal remote sensing approaches: clouds, waves, adjacency effect, confusion between similar dark targets like seagrasses, optically deep waters and macroalgae, and impact of benthic habitats on shallow water bathymetry. We will resolve the limitations induced by clouds and waves by employing multi-temporal Sentinel-2 composites instead of single image approaches. By integrating percentile and/or median multispectral image composites we automatically filter out the outliers of clouds and waves, which are common obstacles over tropical shallow systems. The application of POLYMER-corrected images will alleviate the adjacency effect by mapping its spatially explicit impact and reducing it in turn on the multi-temporal composites. Adjacency effect can influence nearshore pixels by increasing the reflectance of subtidal pixels due to mixed pixels situation with above-tide higher-reflectance sand pixels. This can create a positive bias in bathymetry and benthic habitat maps which certainly requires resolution before mapping.

The confusion of similarly looking (reflecting) subtidal seagrasses, macroalgae and optically deep waters will be resolved by employing water column correction approaches by HYGEOS which will in turn produce true benthic reflectances of seagrasses and neighboring dark targets. In addition, we will employ a dense training dataset of benthic habitats, a strategy that we are confident it will accurately detect and differentiate seagrasses from neighboring dark targets. Last but not least, high-reflecting and low-reflecting habitats like very shallow sand and seagrasses, respectively, can impact accurate satellite-derived bathymetry estimations, especially applying the automated baseline approach. We will tackle this limitation by integrating more feature spaces in the automated bathymetry estimation like texture and HSV which will enhance the differentiation of surface and benthic reflectances, producing more accurate and less biased depth estimates.

4.7 Conclusions

Table 23 summarises and compares the scientific and Early adopters needs. Spatial resolution requirements are similar among the two communities.

Table 23 Summary of requirements for subtidal seagrass from scientific and Early adopters

	Scientific needs (Threshold/Ideal)	Early adopters needs (Threshold/Ideal)
Spatial resolution (GSD, m/pixel)	30m/10m or less	30m /5m
Revisit frequency	twice a year (summer, winter) / quarterly	Quarterly/Quarterly
Products characteristics	Extent of seagrass coverage/species of seagrass	Extent of seagrass coverage/species of seagrass

Our approach for the mapping of subtidal seagrasses here will be based on a combination of well-established and validated coastal aquatic remote sensing algorithms and simple statistical pre-processing to reduce environmental interference in the satellite-derived products. In addition to the envisaged resolutions of the common showstoppers in remote sensing of underwater targets like seagrasses, we identify one main potential future avenue that goes beyond the scope of the BiCOME project: the potential spatial harmonization and amalgamation of existing big reference data on seagrass extent and satellite-derived bathymetry, especially towards the required scalability of our herein algorithms. We envisage that the development of large-scale automated training data annotations using machine learning and big spaceborne lidar data like ICESat-2 (Thomas et al., 2021) would render similar endeavours more time and cost efficient, increasing the relevant automation in the future. Such a potential development would allow scientists to produce synthetic reference data which will be used in turn to train and validate older remotely sensed products in remote coastal aquatic sites, which usually lack temporally coincident in situ data collections, in contrast to our case studies and endeavours in BiCOME.

5 Pelagic ecosystems

Pelagic ecosystems include the entire water column from the sea surface to just above the seabed and can be divided by water depth and distance from the shore (Kaiser et al., 2011). They feature constantly moving water masses in which oceanographic and features such as currents, waves, ocean fronts and surface turbulence occur at a variety of time scales (Dickey-Collas et al., 2017). Many marine organisms depend on the pelagic ecosystem as habitat for some or all of their life stages (Dickey-Collas et al., 2017). According to depth, the pelagic ecosystem can be separated into epipelagic (top 200m), mesopelagic (200 to 1000 m), bathypelagic (1000 to 4000 m) and abyssopelagic (below 4000 m). In BiCOME we will focus on the epipelagic and on areas on the coastal shelf down to a depth of 50 m. This is an operational definition chosen as the baseline of our study. The epipelagic coastal environment is very diverse due to compound effects of bathymetry, shorelines and tidal variations
The aim of this section is three-fold. Firstly, it is to refine the scientific and policy questions for the pelagic ecosystems, secondly to summarise the current remote sensing approaches to measure pelagic biodiversity from remote sensing, and thirdly to define the characteristics of the datasets required to improve the contribution of remote sensing to addressing those questions.

5.1 Science questions

Biodiversity includes genetic diversity, species diversity, functional diversity, and ecosystem diversity. Genetic diversity goes beyond the scope of remote sensing, so we focus here on the other three types of diversity. Measures of biodiversity include abundance, distribution and structure.

Measures of pelagic biodiversity amenable to remote sensing can be characterised for two main communities: floating macro-algal vegetation and phytoplankton.

Whereas the context of evaluating the current status, trends, and drivers of trends remains common for pelagic, intertidal, and sub-tidal ecosystems, what sets pelagic ecosystems apart from the other two is that this is a free-floating ecosystem, at the mercy of all physical forcing, whereas the other two coastal ecosystem types are anchored to the ground and are either fully submerged all the time (sub-tidal ecosystems) or submerged some of the time (inter-tidal zones). The dynamic, floating nature of pelagic ecosystems introduces a requirement for higher temporal resolution for biodiversity observations. Whereas seasonal time scales might be considered the dominant mode of intra-annual variability for sub-tidal zones, with an added component of variability associated with tidal cycles for the inter-tidal zone, the pelagic system is subject to variability at a daily scale, and an hourly scale becomes more important the closer we get to the shore. This dynamic aspect imposes an additional requirement of being able to observe not only the mean state of the ecosystem and its biodiversity but also the variability around the mean. The phenology (or the timing of the life-cycle events over the course of a year) of phytoplankton is particularly important for the ecosystem as a whole, and the finer the scale at which we can observe phytoplankton phenology, the better equipped we would be to detect shifts in phenology in response to climate change. Remote sensing, with its high spatial coverage and high temporal revisit frequencies, is particularly important for observation of the ecosystem and its biodiversity at appropriate time and spatial scales, and for understanding the current status and trends in pelagic ecosystems.

As a first-order approximation, one might argue that the closer we get to the land, the higher the impact of human activities on marine ecosystems. Therefore, one might be tempted to believe that anthropogenic stresses may be largely ignored in pelagic, coastal ecosystems, as we move away from the coast. But the world-wide presence of plastic pollution has raised the awareness of long-term impacts of pollutants, once they enter the marine ecosystems. So, a key question for the pelagic ecosystems is to identify the temporal and spatial scales at which the impact of pollutants on biodiversity become negligible in the coastal environment. Though many types of pollutants are invisible to remote sensing, satellite observations have been particularly useful for identifying the flow patterns from rivers into coastal waters. Further investigations into sources and sinks of pollutants are best addressed in collaboration between Earth Observation and modelling. Such an effort would be essential to go beyond status and trends to identifying the stresses that coastal ecosystems are facing; however this goes beyond the scope of BiCOME. We have identified the following questions that can be addressed in BiCOME concerning linkages between land and coastal ecosystems:

1- How will the diversity of marine biota in coastal zones change with climate? Within this project, this question can be addressed through studying the seasonal and interannual (2000-2022) variability of pelagic biodiversity in response to climate change- using time series of key species (diatoms) coverage, blooms and pelagic habitats defined from spectral water quality changes.
2- How will the diversity of life in coastal zones change with increased human uses? This can be explored in BiCOME by studying impact of changes in turbidity and nutrient supply from rivers and land drainage, due to land uses on pelagic algae (spectral water quality) between 2000 and 2022. We can also explore the utility of ocean-colour data to investigate the occurrences of nuisance blooms such as floating algal vegetation at user-selected sites.

In BiCOME we will test the questions above, in relation to phytoplankton blooms and floating vegetation. Table *24* and Table 25 highlight the links between specific BiCOME questions and the higher level questions in Section 2.1. We will investigate the potential to improve the results by using hyperspectral data (from ASI satellite PRISMA or NASA PACE test data) where available and where feasible. The temporal changes or trends will be examined using machine learning algorithms as well as the relationships to pressures (using riverine turbidity as a proxy, where a link with BIOMONDO project could be further developed).

Table 24: Relationship between the generic questions (Section 2.1) for phytoplankton blooms and biogeography in sptm_pythoplankton_v5.0, tab 1_Scientific questions.

Generic Questions	Specific Questions for BiCOME

1.-What is the status of phytoplankton diversity in the (coastal) ocean?	What is the diatom abundance and distribution in coastal waters
2.-What is the change of phytoplankton diversity in the (coastal) ocean?	What is the change in diatom abundance in coastal waters?
3.-What is the biogeography in phytoplankton communities?	What is the spectral quality of the underwater light field and seascapes in coastal waters?
4.-Have there been biogeographical shifts in phytoplankton communities?	How will change in diversity affect the optical quality of water? Investigate spectral water quality and associated biodiversity.
5.-Has there been a change in extent and location of algal blooms?	What is the change in extent and location of chlorophyll blooms in coastal waters? Can we infer community structure from chlorophyll concentration?
6-How do we relate phytoplankton diversity change to pollution and nutrients?	How will the diversity of marine life in coastal zones change with increased human uses? Studying changes in turbidity and nutrients from rivers due to land uses on pelagic algae (Diatoms) and spectral water quality between 2000 and 2022.
7.-How do we relate phytoplankton diversity change to climate change?	How will the diversity of life in coastal zones change with climate? Studying the seasonal and interannual (2000-2022) variability of pelagic biodiversity in response to climate change-induced floods and cyclones pelagic habitats defined from spectral water quality changes

Table 25: Relationship between the generic questions (Section 2.1) for floating vegetation in sptm_floating_epipelagic_v5.0, tab 1_Scientific questions.

Generic Questions	Specific Questions for BiCOME
1.- What is the status of macroalgal canopy cover?	What is the extent of coverage of macroalgal and floating vegetation in coastal waters?
2.- What is the status of macroalgal diversity?	What is the diversity of macroalgal vegetation and floating vegetation in coastal waters?
3.- What is the change in macroalgal canopy cover?	What is the change in macroalgal and floating vegetation cover?
4.- What is the change of macroalgal diversity in the (coastal) ocean?	How is the proportion of macroalgal vs floating vegetation changing in the coastal environment?
5.- How are macroalgal communities affected by severe events?	How will the diversity of life in coastal zones change with climate? Studying the seasonal and interannual (2015-2022) variability of pelagic biodiversity in response to climate change-induced floods and cyclones
6.- Are changes in macroalgal extent and condition affecting fishes or other important species?	How will change in diversity affect ecology and biogeochemistry in coastal areas?

5.2 Policy questions

Key policy questions in the pelagic that can be addressed through BiCOME revolve around coastal water phytoplankton communities and processes and the occurrence of algal rafts which can be considered as opportunistic species.

Several of the scientific questions address also key policy needs such as knowledge gaps listed in IPBES Global Assessment Report, 2019. A key knowledge gap identified is the lack of monitoring ecosystem processes and condition, especially in coastal and marine areas. Monitoring of coastal processes and ecosystem conditions is key to understanding and managing changes due to anthropogenic drivers such as climate change or land use change.

Invasive species are one of the five main threats to biodiversity identified in the CBD (CBD post2020, 2021). In the context of the case studies of BiCOME we would like to add opportunistic species to this group because they can be as harmful and in both case study sites can be considered as either invasive or opportunistic. Aichi Target 9 calls for invasive alien species to be prevented and controlled for which data is needed to understand the condition and processes in pelagic ecosystems. Descriptor 2 of the MSFD aims for invasive alien species to be controlled at a level at which they do not adversely alter the ecosystem.

Under Sustainable Development Goal (SDG) 14 dedicated to life below water, Target 14.2 is devoted to protecting and restoring ecosystems with the following stated goal: "by 2020, sustainably manage and protect marine and coastal ecosystems to avoid significant adverse impacts, including by strengthening their resilience, and take action for their restoration to achieve healthy and productive oceans." Though the statement does not explicitly mention biodiversity, it is intimately linked to biodiversity. It might be safe to say that the target for 2020 has not been met and that the condition of many marine ecosystems is still in decline (IPBES, 2019). Thinking of how this policy requirement may be met requires us to understand coastal biodiversity: its status and trends and its stressors.

Target 14.1 in fact states: "By 2025, prevent and significantly reduce marine pollution of all kinds, in particular from land-based activities, including marine debris and nutrient pollution." The UN has recognised two indicators of pollution, which are coastal eutrophication and marine plastic debris density. The measure of coastal eutrophication, adopted by GEO Blue Planet at the Global Scale and by CMEMS at the level of European monitoring, are based on satellite-based (Ocean Colour Climate Change Initiative) data on chlorophyll concentrations. This points to how UN level reporting requirements on coastal pollution are met through the impact of certain pollutants (in this case nutrients) on the marine ecosystems.

Though SDG Goal 15 that deals with life on land mentions the importance of biodiversity, SDG Goal 14 on life below water only goes to the level of ecosystems, perhaps in recognition of the huge challenge in addressing questions related to marine biodiversity. This gap in the SDG Policy Statement also points to another important question: why does marine biodiversity matter? In the long-term, answering that question requires that we understand better how the marine ecosystem, and the biodiversity that underpins it, functions. We can see BiCOME as a small step in that direction, contributing to our understanding of status and variations in coastal biodiversity.

5.3 Pelagic Early Adopters Specific Requirements

Two Early Adopters are situated in two very different marine environments, one in a coastal lagoon (Lake Vembanad) in India and the other on the Caribbean island of Martinique (Table 26). Forecasting the arrival of large rafts of *Sargassum* are a key need in the Caribbean. Forecasting can create a time window to organise clean-up crews (EA interview with Martinique case study site, January 2022). For Lake Vembanad EAs, forecasting is also important, as well as being able to find the exact location of the seaweed rafts and their outlines. In both cases, this knowledge will enable the removal or eradication of the opportunistic species rafts. After removal, use of the ocean surface for boat traffic, fisheries and other users can then carry on safely.

Table 26: Pelagic Early Adopters research focus, reason for monitoring and reason for joining BiCOME

	Research focus	Reason for monitoring	Reason for joining BiCOME
Lake Vembanad, India	Extent of water hyacinth rafts and phytoplankton, zooplankton blooms linked to Cholera	To assess, monitor and manage health threats due to Cholera, and to forecast and manage WH rafts	They would like better access to RS data in formats that are easier to access
Martinique	Consistent data with little errors to allow forecasting of Sargassum rafts, reduced reflectance, sub surface rafts	To allow forecasting to manage rafts near and onshore	To create and test a script to download and interpret suitable data with little researcher input

Nansen Environmental Research Centre (NERCI), India

The stakeholders at Vembanad Lake are two scientists at the Nansen Environmental Research Centre (NERCI), India (Table 26). They carry out regular monitoring of the lake and three coastal stations to monitor phytoplankton and water hyacinth development. The monitoring is used to assess climate related and seasonal changes as well as to assess health threats to the local residents due to bacteria such as *Vibrio* cholera. Currently, they use in-situ measurements of water samples collected by boat and raw satellite data downloaded from Copernicus. The area of research is 100 km^2.

Table 27: Pelagic Early Adopter NERCI at Lake Vembanad current versus ideal survey scales

NERCI	Current	Best (Ideal)	Minimum (Threshold)
Survey area	100 km^2	same	same
Spatial resolution	500 m	5 m	20 m
Temporal resolution	Monthly	every 2-3 days	every 16 days but reliable
Level of detail of measurements	Phytoplankton, zooplankton, benthos		

To make satellite data more accessible to them they would like to have data in a georeferenced raster format or as point shape files. They also pointed out that they are limited by Copernicus policy to make data only available upon request once it is older than 30 days (Table 27).

Early Adopter in Martinique

The Eastern Caribbean islands, Martinique, Guadalupe and others are negatively affected by large floating Sargassum rafts. These can span in size to 1 km wide and up to 10 km long. Upon reaching the islands they break up into smaller rafts, land on beaches, and tangle up in coral reefs. They have negative effects on the local communities who need to be able to predict when such events take place so that they can organise clean up teams. The Early Adopter works for the French National

Research Centre and for a private company in Martinique. His aim is to create models that can forecast Sargassum strandings (when and where they occur). To this end, he has created a mathematical model by combining surface current models, such as those used in oil slick forecasting, Sentinel, Landsat and MODIS data and other data source. This model is now used by Meteo France to help local communities with these forecasts. However, there are still large errors that need to be addressed. Satellite images are too unreliable because of shadows, and sun glare in particular nearshore, and Sargassum that is submerged even by a few cm cannot reliably be detected. While offshore the detection works better, nearshore is difficult and this is where BiCOME would be useful (Table 28).

Table 28: Pelagic Early Adopter Martinique current versus ideal survey scales

Martinique	Current	Best (Ideal)	Minimum (Threshold)
Survey area	Area of Martinique and Guadelupe	Same	Same
Spatial resolution		20 m^2 for rafts	Same
Temporal resolution	Weekly	Daily	
Level of detail of measurements	Too much error and unreliable nearshore	Consistent, with very little errors for forecasting	

Their current approach consists of using the model created and offshore data from Sentinel. However, due to the errors in the pictures the information is not very reliable meaning that the forecasting is not accurate enough. They also need to be better able to follow the trajectory of the raft by having more frequent data. In addition, they cannot afford to download large images or data sets so would like to have a script to download the appropriate satellite images and to assess them with little researcher input. They are also working on similar questions in another project and are hoping for co-development between BiCOME and the EU project CESAR.

To be able to use such products there may be need for a short training course. Shapefiles or GEOTIFF products are useful for them. For indirect detection there are two approaches: first is to define seascapes (also known as biogeographic provinces or ecoregions in the literature) from physical and biological properties of the water masses; second is to combine biodiversity indices with physical properties of the environment using large data (with satellite data or no) using machine learning.

5.4 Algorithms

A recent review (Kavanaugh et al. 2021) summarises the current state-of-the-art approaches to measuring biodiversity from ocean colour remote sensing. Methods are grouped around four strategies, which can be in essence condensed into: direct characterisation diversity (mainly at the photosynthetic primary producer level) and indirect through the definition of habitats or seascapes. The direct classification of organisms has been done for phytoplankton size classes and for major phytoplankton functional types (reviewed by Bracher et al. (2017)); and the role of remote sensing in this context has been assessed by IOCCG Report No. 15 on Phytoplankton Functional Types. In the pelagic study in BiCOME we are only focusing on the detection of blooms of specific groups of phytoplankton and floating vegetation and on the seascape definition. Table 29 summarises, and extends from the proposal, the characteristics of the algorithms that will be tested. The biogeography of the sea (Longhurst, 2007), provides a framework to explore the fragmentation of the oceanic pelagic ecosystems into biomes and their provinces, related to the physical conditions. Recent work has focused on dynamic changes of these, or seascapes (Muller-Karger et al.,2014). In the project we will explore new definitions of seascapes using the Optical Water Types as a starting point (Jackson et al., 2017) and take into consideration the synergy with the BOOMS project. In addition, as a modelling study, we will explore the niche definition as proposed by Holtrop et al. (2020). The aspect of phytoplankton functional group domination by diatoms and seascapes will be extended into the open ocean through the work in the project BOOMS.

There are a few algorithms that have been proposed for remote sensing of floating algal vegetation, and they all make use of the reflectances in the visible and infrared domains. It has been demonstrated that the water-leaving reflectances in the red and infrared parts of the spectrum associated with floating vegetation are always high compared with the extremely low reflectances of water in the same spectral domain, and this spectral feature has been at the base of algorithms for detecting floating algal vegetation (Hu 2009; Gower and King 2011). Recognising that extremely turbid water might be confused with floating algal vegetation, Dogliotti et al. (2018) proposed additional conditions using RGB colours to distinguish between highly-turbid waters and floating vegetation. Some of the floating algal vegetation algorithms are generic, designed to identify any floating vegetation on water, whereas some of the others are designed to identify particular types such as Sargassum (e.g. Dierssen et al. 2015) or water hyacinth (Dogliotti et al. 2018), both of which have nuisance value in regions where they are not endemic. The questions to address here are whether these algorithms are generally applicable at multiple coastal sites and whether they can be implemented on an operational basis. One of the activities in Work Package 3.5 will be to test them at an independent site and evaluate their performance, and then implement a Sentinel-2 version of the best-performing algorithm for routine use. This is a task that requires considerable effort. To minimise the effort within this modest project, we will make use of our (PML) ongoing work in the Vembanad Lake and Estuarine System in the south-west coast of India.

One measure of marine biodiversity is the density of the organisms. In the case of phytoplankton, the relevant measure is chlorophyll concentration. In the coastal environment, which tends to be optically complex, detection of even this most basic measure of phytoplankton biodiversity can be difficult (Sathyendranath, Ed., 2000). However, in recent years, significant progress has been achieved through the use of algorithms that rely on signals in the red and infrared parts of the spectrum (e.g. Gilerson et al. 2010), especially when the concentrations are greater than 1 mg m^{-3}. We will explore the use of such chlorophyll algorithms designed for application in coastal waters, when implemented with OLCI data, after processing by POLYMER, at our test site in the coastal waters of Kochi. We will also explore whether this type of algorithm can be implemented closer to shore, at high spatial resolution compatible with coastal and near-shore requirements, by testing their performance in the near-shore and estuarine waters of the Vembanad Lake system.

Table 29: Characteristics of direct detection of floating vegetation and phytoplankton blooms from ocean colour remote sensing.

Vegetation focus	Algorithm	Wavebands (in nm); sensor(s)	Reference	Study Area in BiCOME	Test site in BiCOME
Generic	Floating Algae Index	645, 859, 1240; MODIS	Hu (2009)	Multiple	Vembanad Lake/Estuarine system
Generic	Virtual Baseline Floating Macroalgae Height	Bands 2-4 of HJ-1 and Landsat	Xing and Hu (2016)	Yellow Sea, East China Sea	
Water hyacinth *Eichhornia crassipes*	Floating Vegetation Identification	Red, NIR, SWIR, on MODIS-Aqua, L8/OLI and S2A/MSI+RGB	Dogliotti *et al.* (2018)	Río de la Plata	Vembanad Lake/Estuarine system
Sargassum	Maximum Chlorophyll Index	681, 709, 754 nm on MODIS and SeaWiFS	Gower and King (2011)	Gulf of Mexico, Atlantic	Caribbean waters
Sargassum	Sargassum Index	630, 650 nm on PRISM (hyperspectral airborne imager)	Dierssen *et al.* (2015)	Atlantic	Caribbean waters
Cyanobacteria	Floating Vegetation Identification	645, 859, and 1240nm on MODIS	Hu et al. (2010)	Lake Tahou, China	Vembanad Lake/Estuarine system
Sargassum	Alternative Floating Algae Index	667,748,869 on MODIS	Wang & Hu (2016)	Central West Altantic	
Phytoplankton	% Diatoms	at least wavelengths of 412,443, 490, 510, 555, 670 nm	Sathyendranath et al. (2001,2004); Jackson et al (2010)	Western English Channel	Western Channel Observatory

5.5 Datasets

The datasets are separated by Essential Ocean Variables in this case. Within each EOV, data are further classified into input for algorithms, validation and pressures. Full details are on SPTM sptm_phytoplankton_v3.4; and sptm_floating_epipelagic_v3.42; Tab 2.3_Algorithm_req_in_val.

5.5.1 Phytoplankton blooms and seascapes

- Input datasets for phytoplankton blooms direct detections
  - OC-CCI v4 4Km
  - OC-CCI v5 1Km
  - PRISMA on selected images with verified bloom
- Input datasets for seascapes (optical water types) studies
  - OC-CCI (Merged sensor)
  - CERTO (S3 and S2)
  - PRISMA on selected images
- Validation datasets
  - Phytoplankton abundance data from L4 time series monitoring station
  - Hyperspectral Remote sensing reflectance from Western Channel Observatory
- Pressures datasets
  - River flow from Environmental Agency UK and India
  - Cyclone and storm frequency ECMWF
  - Nutrients fluxes from PML – NERC Locate project
  - Turbidity (not independent from ocean colour derived EBV – potential link to BioMondo)
  - Marine Protected Areas maps

5.5.2 Floating vegetation

Datasets are detailed in the SPTM and will be separated into input, validation and pressures datasets. Examples of some of the datasets:

- Input datasets for floating algae and vegetation
  - Sentinel 3 at 300m (Martinique offshore)
  - Sentinel 2 at 20m (Vembanad and Martinique) -> does not meet minimum req. (i.e. 20m^2)
  - PRISMA on selected images with verified bloom and floating vegetation
- Input datasets for phytoplankton blooms direct detections
  - OC-CCI v4 4Km
  - OC-CCI v5 1Km
  - PRISMA on selected images with verified bloom
- Pressures datasets
  - River flow from India
  - Cyclone and storm frequency ECMWF

- Nutrients fluxes from PML – NERC Locate project
- Turbidity (not independent from ocean colour derived EBV – potential link to BioMondo)
- Marine Protected Areas maps

5.6 Challenges and potential limitations from the approach

The main challenge is the difficulty in inversion of satellite visible radiometry in coastal waters. This problem is related to atmospheric correction, effects from high turbidity, adjacency effects from nearby land masses and contamination due to bottom reflectance artifacts. These are inherent limitations to coastal studies, and will affect the second order information that we are attempting to extract from the remotely sensed ocean colour, i.e. the biodiversity of phytoplankton or floating vegetation. It is not the remit of BiCOME to do extensive radiometric validation of the products used, but rather to stretch the use of state of the art products (e.g. CCI or CERTO) to test if there is any potential to extract additional information on biodiversity using the new EBV framework. For coastal areas, we will limit the study to areas where the adjacency effect will be limited, moderate turbidity and bottom effects minimal.

Additional challenges come from the limited revisit frequency that the radiometric sensors offer, at the high spatial resolution required to match coastal variability. The limitation imposed by 2-3 day revisit by Sentinel-2 or daily revisit from Sentinel-3 means that the study will not be able to address structures of surface waters due to tidal movements. Detection of ephemeral floating macrophytes near the coast will be undetected and only more permanent (patches lasting more than 3 days) will be addressed in this study.

5.7 Conclusions

The requirements for epipelagic coastal phytoplankton diversity products are mainly scientific, and related to Climate change impacts. This is mainly addressed currently by biogeochemical models, which include diversity (Henson et al., 2021). However, with a spatial resolution of 2.5x2 degrees, the coastal regions are not yet resolved. In this respect, we rely on the spatial/temporal resolution from the OCCCI. In the near future, the NASA PACE mission is hyperspectral and well adapted to pelagic coastal areas, so implementing the hyperspectral information in the long term datastream will be interesting and challenging.

With respect to the floating vegetation, Table 30; Early adopters are familiar with the use of remote sensing products, hence the alignment between their requirements and those in the scientific community. It is interesting that for some Early adopters, there are important requirements such as quantification of submerged mass, which would allow them to prepare better for the large arrivals of Sargassum to shore.

Table 30 Summary of requirements for epipelagic floating vegetation from scientific and Early adopters

	Scientific needs (Threshold/Ideal)	Early adopters needs (Threshold/Ideal)
Spatial resolution (GSD, m/pixel)	20m / greater than 20m	20m/5m
Revisit frequency	Weekly/daily or greater	fortnight/daily
Products characteristics	Coverage by floating vegetation/separation among floating vegetation	Coverage by floating vegetation/separation among floating vegetation and total mass (below surface)

6 General conclusions

The challenges facing the detection of coastal biodiversity by remote sensing are huge. Waters are optically-complex (compared with open-ocean waters) which makes it difficult to disentangle the contributions to the satellite signal from biological and abiotic factors. Furthermore, the time and spatial scales at which the observations have to be made to meet scientific requirements are rarely, if ever, met by existing ocean-colour sensors, such that one often tries to make do with sensors designed primarily for land applications, with radiometric specifications that are less than ideal for aquatic applications; admittedly, all the scientific requirements cannot be met uniquely through satellites, necessitating combinations of in situ and satellite observations or development of indirect methods to detect the target through proxy variables.

Through the translational effort from this report, we have attempted to match definitions of Essential Biodiversity Variables to those variables observable from remote sensing, to align and contribute to marine ecosystems global observing systems (Satterthwaite et al. 2021).

BiCOME is meeting these challenges strategically: we have partitioned the investigations into inter-tidal, sub-tidal and pelagic environments, allowing us to focus on the problems specific to those environments, and engaging experts specialising in each of those environments; we have targeted aspects of biodiversity observations from space, which have been demonstrated to perform successfully in the past, while at the same time exploring ways in which the boundaries could be pushed further away, using new technologies on the horizon, such as hyperspectral satellite sensors; we have engaged with the user community from the start, with the objective of tailoring the products, to the extent possible, to meet their requirements; and we plan to explore direct as well as indirect approaches to reach our target.

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Appendix 1: Glossary

	Definition	Source
Community	A community of plants and animals characterized by a typical assemblage of species and their abundances.	https://www.biodiversitya-z.org/content/community-ecological
Population	A group of individuals of the same species, occupying a defined area, and usually isolated to some degree from other similar groups. Populations can be relatively reproductively isolated and adapted to local environments.	https://www.biodiversitya-z.org/content/population
Ecosystem structure	The biophysical architecture of an ecosystem. The composition of species making up the architecture may vary.	https://www.biodiversitya-z.org/content/ecosystem-structure
Ecosystems	dynamic complex of plant, animal and micro-organism communities and their non-living environment interacting as a functional unit	CBD definition [URL3]
Ecosystem functional type	groups of ecosystems or patches of the land surface that share similar dynamics of matter and energy exchanges between the biota and the physical environment. The EFT concept is analogous to the Plant Functional Types (PFTs) concept, but defined at a higher level of the biological organization. As plant species can be grouped according to common functional characteristics, ecosystems can be grouped according to their common functional behavior.	https://en.wikipedia.org/wiki/Ecosystem_Functional_Type
Biome	The largest community unit that is convenient to recognize. In a given biome the lifeform of the climatic climax vegetation is uniform.	Odum (1971) as cited in Longhurst (2007)
Province	Sub-basing scale partition based on physical and biological variables, with geographical constratins (i.e. related to a specific location in the ocean)	Longhurst (2007)
Seascape	Complex ocean spaces, shaped by dynamic and interconnected patterns and processes operating across a range of spatial and temporal scales	Pittman et al (2021)
Status	The instantaneous condition of an ecosystem.	Constable et al. (2016)
Trend	A general tendency or direction of change over long time. Such changes may be in the mean and/or variability of status, such as the frequency of extreme events.	Constable et al. (2016)
Attribution	The process of determining and assigning the cause of a trend.	Constable et al. (2016)

Pressure	The anthropogenic stressors on marine biodiversity and ecosystems.	Constable et al. (2016)
Drivers	Societal need that produces a pressure on the ecosystem and biodiversity	Constable et al. (2016)
Indicator	"Quantitative or qualitative metric or indices that provides reliable means to measure a particular phenomenon or attribute - used for measuring change. Often linked to a management/research question."	Smit et al. (2021)
Metric	"A metric is a calculated quantitative or composite numerical value based on one or more variables and which constitutes the data to inform an indicator."	Smit et al. (2021)
Index	"An index is a single score/metric made by combining several other metrics, sometimes by straightforward addition but often in more complex ways, to measure some given variable. A quantitative, scaled composite variable that is used to demonstrate the state or impacts of various drivers/pressures on the ecosystem."	Smit et al. (2021)