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Towards Earth Observation supported monitoring of freshwater biodiversity	

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Contributors	Petra Philipson (Brockmann Geomatics) Susanne Thulin (Brockmann Geomatics) Jorrit Scholze (Brockmann Consult) Carsten Brockmann (Brockmann Consult) Tamara Keijzer (PBL) Miguel Dionisio Pires (Deltares) Marieke Eleveld (Deltares) Tineke Troost (Deltares) Daniel Odermatt (EAWAG) Jelle Lever (EAWAG)

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Executive Summary

The European Space Agency activity called Biodiversity+ Precursors is a contribution to the joint ESA and European Commission Flagship Action on Biodiversity and Vulnerable Ecosystems, launched in February 2020, to advance Earth System Science and its response to the global challenges that society is facing. The activity includes three parallel Earth System Science studies focusing on terrestrial, freshwater and coastal ecosystems. BIOMONDO is the freshwater study, with focus on biodiversity in lakes, wetlands, rivers and streams.

All three Precursors included an analysis of the major knowledge gaps and science questions on biodiversity and vulnerable ecosystems, an assessment of how recent and future Earth Observation systems can help address these scientific challenges in biodiversity knowledge and a demonstration of the Earth System Science approaches with a number of pilot studies called Earth System Science Pilots for Biodiversity. All three Precursors finalized with the development of a Science Agenda and a scientific roadmap, serving as a basis for the implementation phase of the EC-ESA actions to further increase global Earth Observation supported monitoring of biodiversity.

Based on an in-depth-analysis of the relevant sources for scientific and policy priorities, the main knowledge gaps and challenges in freshwater biodiversity monitoring were identified. The findings were used in BIOMONDO to develop three pilot studies that integrate Earth Observation data and biodiversity modelling using advanced data science and information and communications technology. Each pilot addresses objectives and knowledge gaps corresponding to one of the following drivers of global environmental change in freshwater ecosystems: pollution and nutrient enrichment (Pilot 1), climate change (Pilot 2), and habitat change (Pilot 3). More specifically, in pilot 1 we have explored the opportunity to upgrade ecosystem modelling by integrating EO data into Delft3D. Delft3D is a 3D modelling suite to investigate hydrodynamics, sediment transport and morphology, and water quality for fluvial, estuarine and coastal environments. In pilot 2 we explored the use of Earth Observation based water temperature to quantify the impacts of increases in temperature and heat waves on freshwater fish diversity. In this pilot we used a novel phylogenetic heat tolerance model, created by PBL as part of the GLOBIO model suite, which estimates thermal tolerance of freshwater fish species. In pilot 3 we combined Earth Observation data and the modelled degree of geographic range fragmentation, expressed as a connectivity index, for monitoring and assessing the impact of dam construction and removal on biodiversity, including the effects on habitat fragmentation and water quality.

The pilot studies were implemented and validated for selected sites to showcase the applicability and impact for science and policy. The generated products constitute the so called BIOMONDO Experimental Dataset, and the results have been presented, assessed, and discussed with external Biodiversity Experts, Early Adopters (policy stakeholders) and the designated Advisory Board, all presented in Ch. 6.

To support the interpretation of the datasets, Thematic Ecosystem Change Indices, referred to as TECIs, were developed. TECIs are anomaly detection algorithms derived with machine learning techniques, overcoming challenges such as temporal and spatial data gaps and with the ability to handle big data. TECIs provide information on the extent and intensity of changes in ecosystems. The BIOMONDO TECIs are based on the Experimental Datasets and are designed to capture changes in water quality, habitat conditions of fish or land cover that are associated with specific ecosystem processes, including eutrophication or urbanization. TECIs can provide valuable information for understanding the drivers and impacts of ecosystem change, as well as for monitoring progress towards biodiversity, conservation, and sustainable development goals.

The Experimental Datasets were gathered in the BIOMONDO Freshwater Laboratory. Central to this Lab is federation of all data on common grids (a data cube). Analysis and processing functions for state-of-the-art methods, as well as visualisation interfaces and export functions are available in the Lab. The central part of the BIOMONDO Freshwater Laboratory is the BIOMONDO Viewer and its functionalities. It is used to access and work with the Experimental Datasets. The BIOMONDO Freshwater Lab allows the user to combine different information sources to analyse and compare the model output with observations made in-situ or by Earth Observation. For access to the BIOMONDO viewer, please visit www.biomondo.info and the Results & Resources section.

The external Biodiversity Experts, Early Adopters and the Advisory Board were given access to the novel Earth Observation products and model results through the Lab and supported the validation and evaluation of scientific impact and benefit of the developments. The Early Adopters also used the produced results for the selected sites and explored their utility in relevant policy processes. Finally, the analysis and assessment of the results, including the feedback from the external expertise, have been summarize in a Science Agenda and a scientific roadmap, where present opportunities have been identified together with requirements that need further research and development to support the monitoring of status and trends related to declining global diversity.

1 WP1 - Analysis of Scientific and Policy Priorities

1.1 Objectives

The objectives of WP1 were to review and analyse the scientific and policy priorities in Earth Observation (EO) for biodiversity and to develop a scientific requirement baseline for the BIOMONDO innovative integrated Earth Systems Science (ESS) pilots for freshwater ecosystems.

In addition to the review of reports, policies, and observation systems relevant to biodiversity of freshwater ecosystems, the defined tasks included both an analysis of the potential for EO and an analysis of IT solutions to improve monitoring aspects important for freshwater biodiversity. These activities also included the preparation of a Science and Policy Traceability Matrix (SPTM), to be used as a basis for specification of candidate ESS Freshwater Biodiversity Pilots. The purpose the SPTM was to relate the candidate pilots (and associated products) to key biodiversity questions and policy priorities in a tabular form. Hence, the SPTM should include rows and columns addressing relevant science questions, drivers of biodiversity change, knowledge gaps and policy priorities. It should also define input datasets and models, including an assessment of their maturity and suitability, needed for the pilot studies. Finally, the tasks included specification of policy relevant showcases to demonstrate how the novel EO and biodiversity modelling products could be integrated to provide or enhance decision support systems for biodiversity monitoring and address policy priorities of European and global biodiversity strategies. A link to the WP1 deliverable (D1.1) can be found in section 1.2.1 below. D1.1 also includes comprehensive references to relevant scientific papers and policy documents.

1.2 Summary of results

The main international biodiversity policies, strategies and assessments of progress towards set targets were reviewed and described with focus on their relevance for freshwater ecosystems and biodiversity. In general, the review concluded that there has been a failure to halt the negative trend of biodiversity loss and that different approaches that includes transformative change are needed to reverse the situation. This includes revision of targets and the indicators that inform the targets and greater emphasis on the links between biodiversity, ecosystems and their services and people.

Despite the detailed goals of the biodiversity policies and strategies for the last 25 years, the negative trends have continued in response to direct human-caused drivers. The reasons are many and interlinked, but the main areas that have been highlighted are a lack of legally binding agreements and conservation legislation, especially on national and local levels where implementations of actions to protect and restore biodiversity take place.

There is general agreement on the five drivers of environmental change (Figure 1) although a better understanding of their interaction is required to be able to develop improved mitigation measures. Intense work has been directed towards the development of the new CBD Post-2020 Global Biodiversity Framework (GBF) – the Kunming-Montreal Global Biodiversity Framework was adopted in 2022 – to try to ensure that it can facilitate radical change and really lead to "bending the curve" of biodiversity loss.

Although the knowledge gaps that need to be filled to revert the negative trend of global biodiversity loss are common to all ecosystem groups, such as data gaps and effects of interacting drivers, there are specific needs pertaining to freshwater biodiversity. The needs are different mainly because freshwater ecosystems link land and sea and supply ecosystem services that sometimes are in conflict, for example establishment of hydropower dams that negatively affect river connectivity and sedimentation processes but provide green energy. The main knowledge gaps relate to uneven biodiversity data coverage (spatial, temporal and for different organism groups) and structure of freshwater ecosystems, with ecosystem condition less well represented than ecosystem extent. Also, better overview of- and access to data are called for, including better methods for monitoring freshwater biodiversity.

The main knowledge gaps highlighted by the IPBES 2019 assessment, for which EO data can be of support, are for example missing information on ecosystem extent and condition that require continuity in space and time. This is especially important for freshwater ecosystems that compared to terrestrial are considered under-studied.

Policy goals and targets need to have a sound scientific base with possibilities for simple tracking of progress. Essential biodiversity variables (EBVs) have been developed to support the link between primary observations, including remote sensing, and in situ data and indicators of biodiversity change used for monitoring of achievements. In recent years efforts have been made to identifying those EBVs for which satellite data and remote sensing can enable improved information that is consistent, scalable and continual, and that addresses key knowledge gaps, the so-called remote sensing-enabled EBVs.

The same goes for Essential Ecosystem Services variables (EESVs) where EO has potential to support modelling and assessments. Initiatives focusing on EESV developments include among others the Group on Earth Observation (GEO), Servir Global and Servir-Mekong, Earh Observation for ecosystem valuation (ESA) and Earth Observation for Ecosystem Accounting (EO4EA).

The value of EO data for biodiversity assessment and monitoring is generally recognised. However, beside gaps in algorithm suitability and quality there are also barriers for stakeholders to practically use the EO based products in the daily work. These barriers are due to technical challenges related to

- data assessment
- identification of most suitable data sources
- combination of satellite measurements with other data types (e.g. models, insitu, air-borne, drone)
- synthesisation of biodiversity relevant information
- and coping with the shear amount of data.

Therefore, the future of EO supported biodiversity assessment and monitoring partly relies on an extensive development of IT solutions covering diverse requirements and objectives. The main challenges of this evolution are to process big data and to develop interfaces between different data sources and satisfy various user requirement.

Several international biodiversity networks (e.g. GEO BON, bioDISCOVERY, Biodiversa+) are now operating and try to bring the work of the different science communities closer to the priorities of the policy sectors. The systems for monitoring, modelling and assessing biodiversity are creating a multitude of data, but there is substantial difference in coverage across the globe with a bias towards temperate regions. The challenges facing the networks, and the development of information systems are several: Access to appropriate biodiversity data (spatial coverage, consistency, etc), difficulties in translating raw observation data into EBVs that can facilitate indicator development to support monitoring of progress towards policy targets, and difficulty in improving communication between the science and policy sectors.

Models are critical tools to generalize, interpret and extrapolate links between drivers of change and the ecological state, including biodiversity composition of ecosystems. There are basically two modelling approaches to describe this link: correlative models linking environmental conditions to species composition and/or abundance based on empirical data, and process-based models based on physiological and ecological mechanisms. We believe the future is in a combination of different modelling approaches, model intercomparison projects and clear communication of uncertainties. In BIOMONDO, we used a part of the PBL GLOBIO model suite as an example of the empirical approach (for the fish species indicator), and the Deltares Delft3D modelling suite as an example of the process-based model (for the phytoplankton indicator).

In practice, it is difficult or even impossible to obtain the information needed to determine biodiversity on a global or even regional scale through field work, because it requires large and costly sampling efforts, and it is difficult to investigate some regions and ecosystem types and because there simply are too many species. Therefore, upscaling could include remote sensing enabled proxies that are more easily detectable on a global scale, and biodiversity models to extrapolate from field observations at point locations to a regional or global scale. For many metrics of biodiversity (including EBVs) it is not clear how this should be done, highlighting huge knowledge gaps. In BIOMONDO WP1, we made a start at assessing the potential to transfer the results of the planned pilots to other areas and upscaling to a large-scale regional or global monitoring system.

The starting point in BIOMONDO was the five main threats of global environmental change related to freshwater ecosystems, i.e. ‘Water pollution and eutrophication’, ‘Habitat change (hydrological disturbance)’, ‘Invasive species’, ‘Climate change’, and ‘Overexploitation’. The key to a biodiversity monitoring system that provides useful scientific and policy output is, in our view, a system that assesses impacts and trends of drivers of global environmental change on (different aspects of) biodiversity. BIOMONDO, therefore, has taken off from these drivers, and explored how different variables based on EO techniques can be used to assess these drivers and their impacts on freshwater ecosystems (Figure 1).

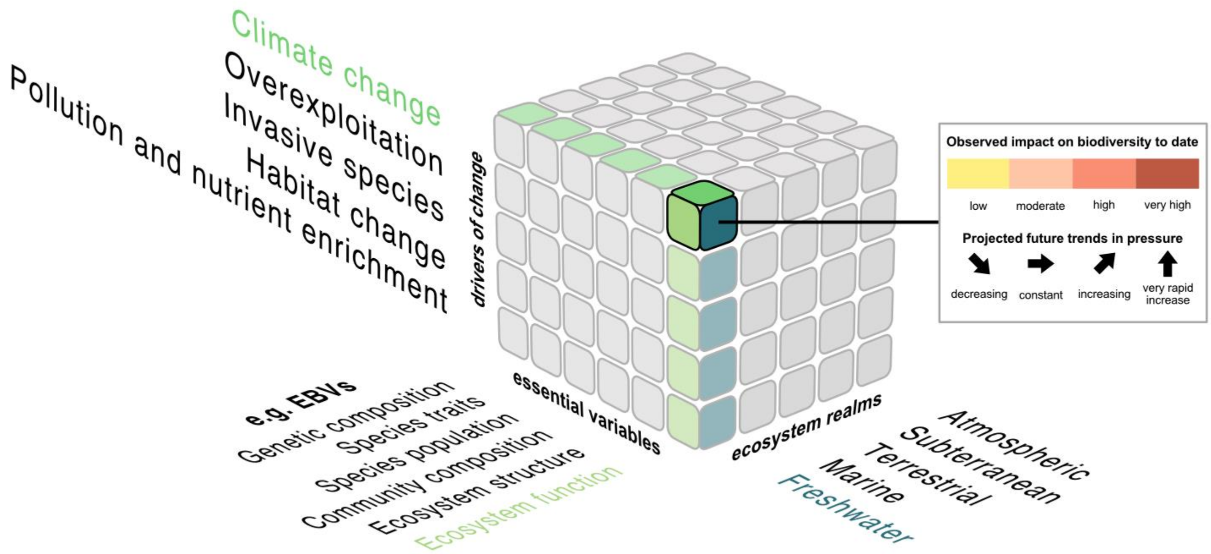

Figure 1 The BIOMONDO cube, representing the multi-dimensional nature of biodiversity monitoring. We propose that monitoring objectives are defined to resolve the effect of driver X on essential variable Y for ecosystem unit Z. Ultimately, these monitoring efforts help to assess observed impacts on ecosystem variables, or to project future trends.

Considering the findings of the review and analysis of scientific and policy priorities, several science questions were identified as having high priority to close knowledge gaps for freshwater ecosystems, and candidate ESS Pilots were determined. Each of the potential pilot objectives and associated pilot sites were described in the SPTM (see Sec. 1.1) that enabled evaluation and determination of the final selection of three pilots and corresponding pilot sites.

The three pilots selected, developed, and demonstrated were:

- Pilot 1 – The impact of (reverse) eutrophication and habitat changes on the water quality of shallow lakes.
- Pilot 2 – The impact of changes in water temperature and heat waves on freshwater fish diversity
- Pilot 3 – The impact of dam construction and removal on biodiversity

The outlined data requirements of the pilot studies supported the development of a suitable data repository (BIOMONDO data cube) and visualisation tool (BIOMONDO Viewer) in WP2.

In addition to the specification of the scientific scope and data needs for the different pilots, several BIOMONDO Freshwater showcases were outlined. The aim was to demonstrate how novel EO and biodiversity modelling products can be integrated to enhance decision support systems for biodiversity monitoring and address the policy priorities. The showcases were to be based on the three selected pilots and developed to demonstrate and assess the policy utility and impact of the results from these pilots. The assessments were a task in WP4 (Ch. 0) and made together with the Early Adopters, who also had access to the BIOMODO data cube of data and results via the BIOMONDO Viewer. Each show case addressed specific biodiversity policy goals by presenting information that is easy to act on and has clear potential to lead to enhanced biodiversity management. The showcases were created as stories with clear illustrations to make sure the key points can be easily understood and adopted. The key points were summarised in a BIOMONDO Policy Brief for each pilot (see section 7.2.5).

The results of WP1 are described in further detail in deliverable D1.1 BIOMONDO Requirements Baseline Report (see 1.2.1 WP1 Deliverables). The requirements derived from the review and analyses to support the approach in BIOMONDO are outlined there in the following separate sections:

- International policies and assessments
- Scientific frameworks and challenges
- EO for freshwater biodiversity monitoring – SPTM
- IT solutions for improving biodiversity monitoring
- ESS Pilot studies for freshwater ecosystems
- Freshwater biodiversity policy show cases

1.2.1 WP1 Deliverables

- D1.1 Requirement Baseline (RB) – BIOMONDO_D1.1_RequirementsBaseline_v2.1.pdf

1.2.2 WP1 Conclusion

In conclusion, WP1 developed the requirements for the work in WP2 for the three pilot studies as well as provided the basis for the impact and utility assessments of the results in WP3 and WP4. This included identifying key science questions and policy priorities, that existing and novel EO data and modelling products together with sound IT solutions could address. The potential for these approaches to enhance decision support systems for biodiversity monitoring were outlined in showcases to be further developed in WP4. As mentioned, quite a few developments relating to policies and assessments of biodiversity (including EO aspects) have been undertaken since the start of BIOMONDO. In addition to the ones included in the RB, several new developments are described in the Science Agenda in WP5, which contains relevant updates.

2 WP2 - Development of Earth System Science Pilots

2.1 Objectives

The objective of WP2 was to address how recent and future EO systems can support scientific challenges in freshwater biodiversity knowledge and assessments. The objectives included exploring, analysing, developing, and testing the methods (i.e., the EO algorithms and the models) to derive the required products, as well as identifying solutions for implementation of the ESS Pilots for Biodiversity defined in WP1, which integrate satellite observations, biodiversity modelling, and information technology into innovative integrated scientific solutions for biodiversity monitoring.

This involved gathering and processing a comprehensive set of data, including EO data, in-situ data and model outputs for the pilot sites. All input data needed to be strictly quality controlled and validated. The methodological and algorithmic basis for the Experimental Datasets is reported in D2.2 Algorithm Theoretical Baseline Document (ATBD) and the validation of the datasets in D2.3 Project Validation Report (PVR). Links to the deliverables can be found in section 2.2.1 below and these documents also include comprehensive references to relevant scientific papers.

A common shared BIOMONDO Freshwater Lab was planned for organising, visualising, and sharing the Experimental Datasets, ensuring usability and suitability for biodiversity monitoring. The database should be maintained and updated as appropriate, even post-project, and support provided to the external experts.

For understanding and quantifying the drivers and impacts of ecosystem change, as well as for monitoring progress towards biodiversity, conservation, and sustainable development goals, a machine learning based method called Thematic Ecosystem Change Index (TECI) was included in the tasks of WP2.

2.2 Summary of results

Data gathering and processing played an important role in WP2. A key aspect of this effort was the collection and processing of the Experimental Datasets, which demonstrated a wide range of information for understanding ecosystem dynamics. These datasets included outputs from various models, EO data on water quality, land cover, and water availability, among others. In total, over 15 datasets were collected or processed to provide input into the BIOMONDO pilots. The datasets are described in detail in D2.4 Experimental Datasets. To facilitate the demonstration of the developed novel methods and identify knowledge gaps, Lake Marken (Pilot 1 & 2), Lake Mälaren (Pilot 2), Lake Balaton (Pilot 2), and the Mekong Basin (Pilot 3) were selected as study areas to showcase the developments. Additionally, WP2 of BIOMONDO introduces several novel methods to advance freshwater biodiversity monitoring:

Heat Tolerance Model

This model estimates the physiological tolerance of freshwater fish species to water temperature variations, providing insights into their distribution and survival. By incorporating species-specific data and a phylogenetic regression model, BIOMONDO enhances our understanding of the thermal resilience of fish populations.

Integration of Models and EO Data

BIOMONDO integrated remote sensing data with models to comprehensively analyze biodiversity patterns and trends. This integration enables the identification of drivers of biodiversity change, prediction of future trends, and assessment of management strategies' effectiveness, supporting evidence-based conservation efforts. The integration of EO data was performed for the Delft3D and the Heat Tolerance model.

Thematic Ecosystem Change Indices

TECIs quantify changes and point out anomalies in freshwater ecosystems, capturing variations in water quality, habitat conditions, and land cover associated with specific ecosystem processes. By analyzing diverse data sources, including EO data and models, TECIs offer information for understanding ecosystem dynamics and could support decision-making for conservation and sustainable development. TECIs are derived with machine learning techniques, overcoming challenges such as temporal and spatial data gaps. By analyzing these TECIs, BIOMONDO enhances the characterization of freshwater ecosystems and provides a comprehensive assessment of ecosystem anomalies.

Furthermore, WP2 included the development and implementation of the technical framework called the BIOMONDO Laboratory for freshwater biodiversity. This laboratory became the central hub for integrating diverse data sources and methodologies, enabling the synthesis and analysis of complex data related to freshwater biodiversity. Key components of the BIOMONDO Freshwater Laboratory include EO-based inputs, non-raster data sources, ecosystem and biodiversity models, user interfaces, and data analysis APIs. The BIOMONDO Freshwater Laboratory facilitates the integration and analysis of diverse data sources, enabling users to combine information from various sources and derive biodiversity products. The processing of data was carried out using the BC in-house Calvalus processing system and Deltares in-house processing system. A HTTP file server served as the database for distributing Experimental Datasets and facilitating collaboration among project partners. Furthermore, xcube was utilized to generate data cubes, and the xcube server was employed for running the viewer and accessing APIs, ensuring efficient data management and analysis. The lab's central component, the BIOMONDO Viewer, provides intuitive tools for monitoring and analyzing Experimental Datasets from freshwater pilot sites. Additionally, the xcube Python package allows users to access and analyze datasets within a Python environment, offering extensive processing capabilities and cloud-based processing. Figure 2demonstrates the setup of the individual components of the technical framework for WP2.

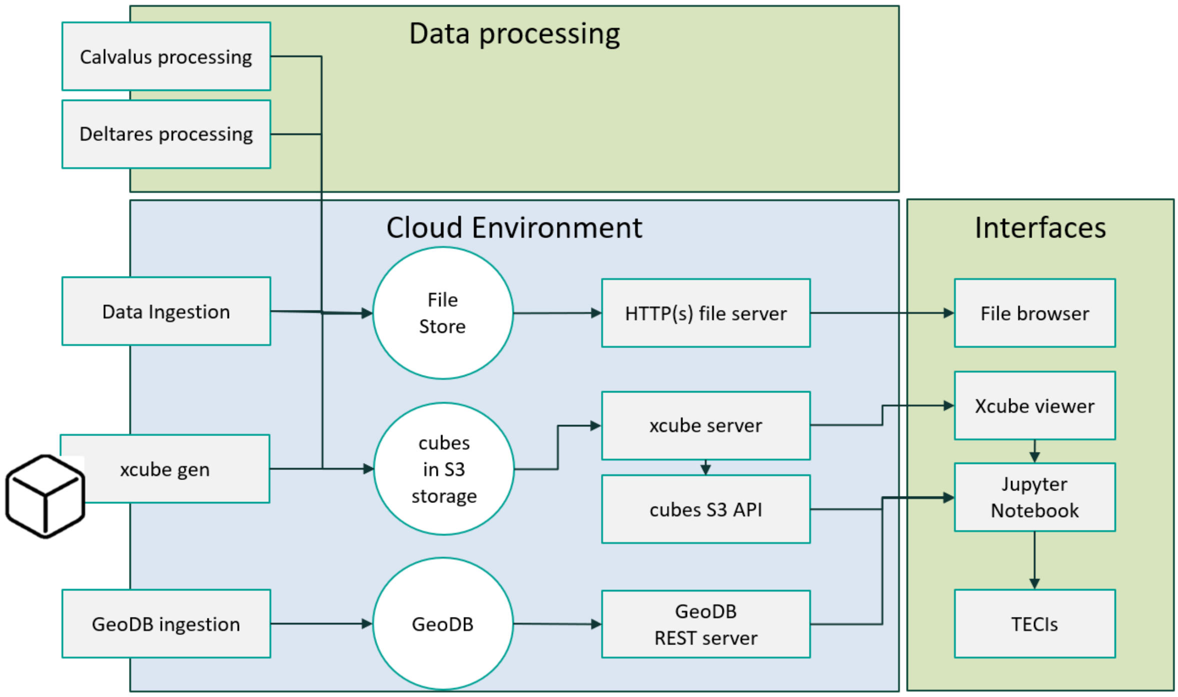

Figure 2 Technical framework of WP2.

2.2.1 WP2 Deliverables

- D2.1 Biodiversity+ Development Database – available on request
- D2.2 Algorithm Theoretical Baseline Documents (ATBDs) - BIO-MONDO_D2.2_ATBD_v2.1.pdf
- D2.3 Product Validation Reports (PVRs) -
- D2.4 Experimental Datasets -

2.2.2 WP2 Conclusion

In conclusion, WP2 of BIOMONDO built the methodological and technical framework for the subsequent work packages through the development and implementation of novel methods and the BIOMONDO Laboratory for freshwater biodiversity. The Lab served as a central hub for data access, demonstration and analysis for the team, the early adopters, and the biodiversity experts, providing them with the tools and resources needed.

3 WP3 - Scientific Utility & Impact Assessment

3.1 Objectives

The objective of WP3 was to assess the scientific utility and impact of the validated results from the ESS Pilot studies, the corresponding Experimental Datasets (D2.4) and the associated documents (D2.2 ATBD, D2.3 PVR) in the framework of the SPTM (D1.1 RB). Following the cross-cutting design of the SPTM, this scientific assessment was combined with the policy impact assessment from WP4 in one Impact Assessment Report (IAR) for each of the three pilot studies. The IAR of pilot 1 focuses on eutrophication assessment in Lake Marken using primary production models. The IAR of pilot 2 focuses on heat stress and heat tolerance of different fish species in Lake Mälaren and Lake Marken. The IAR of pilot 3 focuses on impacts of hydropower production on connectivity and sediment transport in the Mekong River. For each pilot, we organized consultation meetings with scientists performing research related to the pilot topics and test sites, in which we presented and discussed our results, the use of the BIOMONDO Viewer as a visualization tool, and the interpretation of TECI products in view of known anomalies. Links to the WP3 deliverables can be found in section 3.2.4 below. These documents also include comprehensive references to relevant scientific papers and policy documents.

3.2 Summary of results

3.2.1 Pilot 1: Eutrophication

Lake Marken (NL) is a Heavily Modified Water Body according to the Water Framework Directive and faces biodiversity challenges caused by its separation from Lake IJsselmeer in 1976 and high nutrient levels. Despite phosphorous reduction since the 1980s, biodiversity has not improved. The lake is characterized by high turbidity and the suspended particles reduce light penetration, impact the underwater vegetation growth, and simplifies the food web. Measures such as creating the Marker Wadden islands aim to enhance habitat diversity and improve light conditions and are monitored by Rijkswaterstaat under EU directives like Natura 2000 and the Water Framework Directive. In BIOMONDO we developed and evaluated EO products that can aid in assessing the islands' impact on wind fetch and light conditions that are crucial for Lake Marken's ecosystem restoration and aligned with EU biodiversity goals.
We also used the Delft3D model by Deltares to estimate chlorophyll-a and primary production for 2016, 2020, and 2021 and compared the results with EO data products of chlorophyll-a, and in situ data of both chlorophyll-a and primary production. In addition, we used EO-based Lake Surface Water Temperature (LSWT) data as input data to the model instead of in situ air temperature and compared the different model outputs with each other and to in situ data of primary production. For this purpose, we compiled gap-filled LSWT products from the CCI Lakes data set using DINEOF. We reviewed these results with

experts from Rijkswaterstaat (Marcel van den Berg), Deltares (Ruurd Noordhuis, Lièn Klugkist) and members of the BIOMONDO Advisory Board.
The main scientific impacts of pilot 1 concern the use of Data Interpolating Empirical Orthogonal Functions (DINEOF) in operational EO product pipelines, the parameterization of aquatic ecosystem models using EO products, and the use of such models for simulating the effects of ecosystem restoration (or amelioration) scenarios. DINEOF reconstructs missing information in geophysical data sets, such as satellite imagery or time series. Such gap-filling is a very important postprocessing step for various EO data use cases. In BIOMONDO, we adopted LSWT products that were gap-filled for the use of identifying thermal barriers in lakes, which were compiled for the ESA CCI Fellowship LakeCREST. They were successfully validated and adopted for pilot 1 in BIOMONDO. However, we also identified several shortcomings of our approach, and reported them to the Lake CCI team, which is developing a more widely applicable gap-filling workflow in the next stage and for future product versions. Aquatic ecosystem models and dedicated process models can reproduce and even forecast many physical, chemical and biological processes in lakes, and a list of relevant models is given in the IAR of pilot 1. But their practical utilization and robustness is strongly limited by the availability of input data for parameterization. BIOMONDO demonstrated how EO satellite data can improve the parameterization of a primary production model, which is pivotal for the coupling of models on higher trophic levels. Complementary results concerning the parameterization of physical processes in Delft3D are available from the ESA AlpLakes project (2021-2024), both advancing the combined use of satellite EO data and models. Ultimately, this combination could be used in impact assessments to monitor the ecological effects of the newly created islands in Lake Marken.

3.2.2 Pilot 2: Heat tolerance

Heatwaves in lakes are characterized by prolonged periods of exceptionally high water temperatures. Despite a slight decreasing trend in the 20th century, climate projections foresee a significant increase in both intensity and duration of lake heatwaves during the 21st century, posing risks to ecosystems through multiple direct and indirect consequences, such as oxygen depletion and altered stratification. In BIOMONDO we combined EO data with a phylogenetic model for contrasting the heat tolerance of different fish species with satellite-observed variations in LSWT, chlorophyll-a and cyanobacteria abundance.
A novel phylogenetic heat tolerance model created by PBL as part of the GLOBIO model suite was used in BIOMONDO pilot 2. It integrates species-specific heat tolerance data to determine warming tolerance across space and time, enabling assessment of fish susceptibility to heatwaves and exploration of the spatial and temporal variability and its effects. For the task we used the same DINEOF-interpolated CCI LSWT products as in pilot 1, the chlorophyll-a concentration and cyanobacteria indicators available from the operational CyanoAlert service, and detailed fish abundance data from Lake Mälaren. We reviewed our results with experts from SLU (Thomas Axenroth, Caroline Ek, Helena Strömberg, Björn Rogell), Rijkswaterstaat (Joep de Leeuw) and members of the BIOMONDO Advisory Board.
The main scientific impact of pilot 2 concerns the possibility to investigate temporally resolved fish species abundance with high temporal resolution and full spatial coverage EO

and model-based heat stress, chlorophyll-a concentration and cyanobacteria abundance. The information provides a better basis for understanding the extent of heat waves in time and space and when the impact, in combination with other water quality variables, creates an environment in a critical state for different fish species. Oxygen concentration and vertical temperature distribution was not generated as a part of the Experimental Dataset but could be included to improve the analysis. This was identified as the main limitation of the pilot study and could be resolved by using 1D hydrodynamic models. The future deployment of high-resolution thermal missions is anticipated to address current limitations in EO data resolution and coverage, facilitating advanced ecosystem studies also in smaller water bodies. Upscaling efforts should prioritize the development and validation of integrated approaches for different lake types, leveraging high-resolution EO data to expand understanding of temperature impacts on freshwater biodiversity.

3.2.3 Pilot 3: River connectivity and sediment transport

River dams disrupt aquatic biodiversity by fragmenting habitats and altering flow regimes, impacting species dispersal and sediment transport. Despite restoration efforts, decisions on dam construction or removal involve weighing multiple impacts, including energy production and habitat connectivity. BIOMONDO pilot 3 combines EO data and biodiversity modelling to assess dam impacts on fish habitat connectivity, water quality, and sedimentation, aiding in optimal dam placement decisions, for the Mekong catchment. In doing so, we focused on one hand on the adaptation of a catchment-wide connectivity model to assess the impact at the scale of individual dams, on the other hand we investigated the feasibility of suspended sediment estimates before and after dam constructions.

We utilized a published method (see pilot 3 IAR, section 3.2.3 for details) to examine changes in river connectivity across the Mekong basin, assessing the degree of fragmentation for fish species using a Connectivity Index (CI). Unlike metrics focused on free-flowing rivers, this approach emphasizes biodiversity by evaluating species geographic range fragmentation. We specifically analysed the impacts of individual river dams within the Mekong basin and compared the change in connectivity by dam building throughout the years to energy production gains associated with dam placement since the 1960s, potentially guiding future dam placements and removals for optimal outcomes in terms of both connectivity and energy production. To explore sediment transport in the Mekong, suspended sediment concentrations were estimated from EO data using the C2RCC algorithm and the Forel-Ule (FU) colour scale algorithm. C2RCC features robust performance under various conditions, although the representativeness of its training data for rivers like the Mekong is not optimal. The FU colour index was utilized to assess water colour changes in the Mekong due to dam construction, with shifts from brownish to green-blueish water colours indicating a drop in sediment transport due to the decreased flow velocities. We reviewed our results with experts from Deltares (Arjen Haag), Wageningen University (Philip Minderhoud), Stanford University (Rafael Schmitt), the (Vietnamese) Southern Institute of Water Resource Planning (SIWRP, Nam Nguyen Trung, Lam Dang Thanh), and members of the BIOMONDO Advisory Board.

Historic analysis revealed large reductions in habitat connectivity around 1994 and 2019, with less optimal dam placement in terms of energy production gains. Diadromous and non-diadromous fish species showed varying impacts from individual dam removal, with the Don-Sahong and Xayaburi dams having notable effects despite differences in electricity production, emphasizing the importance of balancing connectivity and energy production in decision-making processes. The before-after dam construction comparison of seasonal suspended sediment concentrations in the Mekong revealed striking shifts from brown to blueish water (Lower Se San 2, 2016-2020), and the time series validation with in situ measurements indicate a very high robustness of these findings. Effects could be seen both upstream and downstream of the dam. However, we also identified the Monsoon season's cloud coverage as a major challenge for comprehensive sediment transport assessments, which can be mitigated to some degree by incorporating a larger number of optical satellite missions. The BIOMONDO viewer presented various metrics aiding decision-making, though experts suggested simplifying its presentation and integrating it with existing decision support tools for the Mekong.

3.2.4 WP3 Deliverables

- D3.1 Impact Assessment Reports / Science Chapter (Pilot 1) – BIOMONDO_D3.1_D4.1_IAR_Pilot_1_v2.1.pdf
- D3.1 Impact Assessment Reports / Science Chapter (Pilot 2) – BIOMONDO_D3.1_D4.1_IAR_Pilot_2_v2.1.pdf
- D3.1 Impact Assessment Reports / Science Chapter (Pilot 3) – BIOMONDO_D3.1_D4.1_IAR_Pilot_3_v2.1.pdf

3.2.5 WP3 Conclusion

In conclusion, WP3 of BIOMONDO demonstrated and assessed the scientific utility and impact of the selected pilot studies in different sites. The assessment was made together with external experts with thematic and/or site knowledge. The advantages of adding EO data to the analysis have been defined and the limitations of the developed setup discussed.

4 WP4 - Policy Utility & Impact Assessment

4.1 Objectives

The objective of WP 4 was to assess the policy utility and impact of the validated results from the ESS Pilot studies, the corresponding Experimental Datasets (D2.4) and the associated documents (D2.2 ATBD; D2.3 PVR) in the framework of the SPTM (D1.1 RB). Following the cross-cutting design of the SPTM, these policy assessments were combined with the science impact assessments from WP3 in one Impact Assessment Report (IAR) for each of the three pilot studies. The IAR of pilot 1 focuses on eutrophication assessment in Lake Marken using primary production models. The IAR of pilot 2 focuses on heat stress and heat tolerance of different fish species in Lake Mälaren and Lake Marken. The IAR of pilot 3 focuses on impacts of hydropower production on connectivity and sediment transport in the Mekong River. For each pilot, we organized consultation meetings with scientists performing research related to the pilot topics and test sites. In some of the meetings experts involved in policy or policy guideline development participated. At those meetings we presented and discussed our results and asked for ideas of the usefulness related to current and projected policy needs and utility in decision making processes. Links to the WP4 deliverables can be found in section 4.2.4 below. These documents also include comprehensive references to relevant scientific papers and policy documents.

4.2 Summary of results

4.2.1 Pilot 1: Eutrophication

Lake Marken (NL) is a Heavily Modified Water Body according to the Water Framework Directive and faces biodiversity challenges caused by its separation from Lake IJsselmeer in 1976 and high nutrient levels. Despite phosphorous reduction since the 1980s, biodiversity has not improved. The lake is characterized by high turbidity and the suspended particles reduce light penetration, impact the underwater vegetation growth, and simplifies the food web. Measures like creating Marker Wadden islands aim to enhance habitat diversity and improve light conditions and are monitored by Rijkswaterstaat under EU directives like Natura 2000 and the Water Framework Directive. In BIOMONDO we developed and evaluated EO products that can aid in assessing the islands' impact on wind fetch and lighting conditions, crucial for Lake Marken's ecosystem restoration and alignment with EU 2030 Biodiversity Strategy goals, the binding restoration targets of the new Nature Restoration law as well as providing input to national restoration plans.

In addition to the EU directives and Biodiversity Strategy the main relevant global policies include Ramsar, which calls for monitoring of the status of its designated wetland sites.

In the pilot 1 policy show case – Monitoring effects of mitigation measures, we showed how specific EO-based timeseries of turbidity can be used to monitor the effects of the mitigation efforts from the establishment of the Marker Wadden Islands in Lake Marken and provide important information for other projects of similar nature.

To support water quality mitigation projects and ongoing monitoring relevant to Natura2000 (and Ramsar) as well as the WFD status assessments, spatially and temporally continuous EO based products, derived for pilot 1 can provide valuable and useful information. They also have potential to aid in the development of indicators of biodiversity change related to climate change impacts on habitats that are relevant for the European and global monitoring frameworks such as EU 2030 Biodiversity Strategy and the Kunming-Montreal Global Biodiversity Framework and its developing monitoring framework with targets for restoration of 30% of the freshwater realm by 2030.

4.2.2 Pilot 2: Heat tolerance

Heatwaves in lakes are characterized by prolonged periods of exceptionally high water temperatures. Despite a slight decreasing trend in the 20th century, climate projections foresee a significant increase in both intensity and duration of lake heatwaves during the 21st century, posing risks to ecosystems through multiple direct and indirect consequences, such as oxygen depletion and altered stratification. In BIOMONDO we combined EO data with a phylogenetic model for contrasting the heat tolerance of different fish species with satellite-observed variations in LSWT, chlorophyll-a and cyanobacteria abundance.

Validated EO data LSWT products, in combination with models and in situ data, were used to demonstrate how this type of data can be used to quantify the impacts of increases in temperature and heat waves on freshwater fish diversity. It can support research and decision making for managers and increase knowledge regarding how changes in temperature and other parameters affects different species addressed in the WFD.

The pilot 2 policy show case – Towards an EO based climate index for fish in freshwater ecosystems, addressed the development of indices based on EO derived temperature products that could provide a better link to effects of climate change and that can complement the current list of metrics need for assessment of freshwater ecosystem condition and changes. The starting point was the heat tolerance of different species. When estimating the warming tolerance for species occurring in Lake Mälaren, the two species European Smelt (*Osmerous operlanus*) and Vendace (*Coregonus Albula*) stood out from the other species by exhibiting a lower warming tolerance. Smelt and Vendace are cold water species and can serve as indicator species for this functional group. Smelt plays a key role in the food webs of the Swedish great lakes and are a prerequisite for other highly valued fish species. They are among the most sensitive species in a warming climate, most likely to be affected first, and should therefore be prioritised for monitoring and restoration actions required by both international and European biodiversity frameworks.

The pilot 2 information could also be useful to support prioritisation of lakes and freshwater ecosystems in need of restoration and thereby support restoration targets of the EU 2030 Biodiversity strategy. There is a knowledge gap relating to which lakes or lake basins have experienced heatwaves in the past and which fish species are most at risk of being seriously affected by increases in temperature that threaten existing biodiversity.

Resource managers might also need to consider additional management tools and strategies in combination with area protections to mitigate the effect of warming on aquatic communities.

It was pointed out in the policy discussions that these data may contribute also to global goals such as the SDGs, and for example Target 10 of the KM-GBF, which is related to sustainable management of fisheries, and should therefore be considered important for any biodiversity strategy or policy including the nexus assessments involving water, food, climate and biodiversity. An important contribution from pilot 2 considered by the Early Adopters, was the provision of input data to support a range of ecological investigations, especially in the light of changing climatic conditions. The availability of these spatially and temporally continuous data can lead to economic savings and more efficient use of resources compared to field sampling and can reduce usage of experimental/laboratory animals (fishing) and perhaps provide appropriate proxies.

4.2.3 Pilot 3: River connectivity and sediment transport

River dams disrupt aquatic biodiversity by fragmenting habitats and altering flow regimes, impacting species dispersal and sediment transport. Despite restoration efforts, decisions on dam construction or removal involve weighing multiple impacts, including energy production and habitat connectivity. BIOMONDO pilot 3 combines EO data and biodiversity modelling to assess dam impacts on fish habitat connectivity, water quality, and sedimentation, aiding in optimal dam placement decisions, for the example in the Mekong catchment. In doing so, we focused on one hand on the adaptation of a catchment-wide connectivity model to assess the impact at the scale of individual dams, on the other hand we investigated the feasibility of suspended sediment estimates before and after dam constructions.

The biodiversity strategies and policies most relevant to pilot 3 for the assessment of impact and utility were determined to be the EU 2030 Biodiversity Strategy and targets of the new Nature Restoration Plan, the Water Framework Directive, the 2030 Agenda for Sustainable Development (UN GA, 2015) and Kunming-Montreal Global Biodiversity Framework (KM-GBF). The EU Biodiversity Strategy calls for restoration of all degraded ecosystems, with 30% of degraded ecosystems restored by 2030 including specific restoration of 25,000 kilometres of degraded rivers to free flowing. The two global sustainability and biodiversity frameworks also include goals and targets for which the availability of consistent information of connectivity and water quality of rivers is highly pertinent. With the adoption of the KM-GBF in 2022 most policies now include specifics for the freshwater realm, recognising that the availability and quality of inland surface waters are key to most other issues related to the health of ecosystems, provision of ecosystem services and biodiversity in all realms.

In the pilot 3 policy show case we demonstrated and exemplified the usefulness of the BIOMONDO Experimental Datasets from three different perspectives related to monitoring of water quality in rivers and reservoirs in connection with dam constructions, i.e., identifying habitat changes, analysis of sediment transport and anomaly detection in big datasets. This in turn has potential to improve understanding of the drivers involved and impacts on ecosystem and biodiversity changes.

The results from pilot 3 were presented to the Early Adopters but only limited feedback regarding the utility and potential policy impact could be solicited as the experts were mainly involved with scientific issues. However, it was suggested that the results could provide additional information to existing decision support systems used by natural resources managers operating in the Mekong basin and that the BIOMONDO Viewer, if kept simple and adapted to user needs, could be used as a decision support system in its own right.

Improved knowledge of historical and current sediment fluxes up- and downstream of reservoirs including unexpected events such as dam breaks can be used by both catchment managers and policymakers. Innovative combinations of time series of EO data with hydrological and connectivity modelling can provide explicit spatial information of differences throughout a river basin and its subbasins including changes over time. This type of information can be used to compare and mitigate impacts of existing hydropower structures and reservoirs, support planning and prioritisation of new establishments, and provide input to the development of indicators for policy targets and goals. The results of plot 3 also have potential to support resource managers working to preserve biodiversity. It provides spatially explicit information on connectivity needed to identify the extent of free-flowing river stretches and prioritise restoration of degraded river sections. Furthermore, time series of EO based sediment estimates can help monitor the impact of mitigation actions on sediment loads.

4.2.4 WP4 Deliverables

- D4.1 Impact Assessment Reports / Policy Chapter (Pilot 1) – BIOMONDO_D3.1_D4.1_IAR_Pilot_1_v2.1.pdf
- D4.1 Impact Assessment Reports / Policy Chapter (Pilot 2) – BIOMONDO_D3.1_D4.1_IAR_Pilot_2_v2.1.pdf
- D4.1 Impact Assessment Reports / Policy Chapter (Pilot 3) – BIOMONDO_D3.1_D4.1_IAR_Pilot_3_v2.1.pdf

4.2.5 WP4 Conclusion

In conclusion, WP4 of BIOMONDO demonstrated and assessed the policy utility and impact of the selected pilot studies in different sites. The assessment was made together with external experts and stakeholders with thematic and/or site knowledge. The advantages and opportunities of adding EO based information to the management process and decision support systems, and how it can aid assessments related to different strategies and policies, has been demonstrated and limitations have been discussed.

5 WP5 - Science Agenda and Scientific Roadmap

5.1 Objectives

The objective of WP5 was to define a Science Agenda and associated Scientific Roadmap for freshwater ecosystems, with recommendations on how to further advance the use of EO technology to address the main knowledge gaps and scientific challenges in Biodiversity research and science-policy integration. The specific objective of the Science Agenda was to identify the key Research and Development (R&D) activities to be conducted to advance the integration of EO technology into biodiversity research, biodiversity observation networks and biodiversity policy implementation, and ultimately better respond to the priority goals of the overarching science and policy frameworks on biodiversity. The specific objective of the Scientific Roadmap was to outline a 5-year research plan, with the major scientific and technical activities to be conducted and associated timelines.

The Science Agenda and Scientific Roadmap (D5.1) is the main deliverable of WP5, and an effort has been made to streamline the contents and structure of the science agenda and roadmap for all three Biodiversity+ Precursors. In addition, a White Paper on EO-based ESS Approaches to Biodiversity (D5.2) is being written as a common effort between the three Precursors. The work with the common paper will continue during autumn 2024.

5.2 Summary of results

The importance of freshwater ecosystems cannot be exaggerated. Not only as a unique realm on its own with a vast number of species, but also of key importance for terrestrial and coastal ecosystems. The target for the Science Agenda was to identify research priorities and a timeline for these efforts for freshwaters. The five drivers of change; water pollution and eutrophication, habitat change (e.g. hydrological disturbance), climate change, invasive species and overexploitation, served as the basis for the work in WP5. To put these efforts into context, the agenda also includes a description of policies, monitoring systems, drivers of change, global and European trends, and the specific challenges related to freshwaters.

As the main part of the species and biodiversity related to freshwater exists subsurface, we must rely on relatively easily detectable proxies and indicators, particularly those measuring changes of environmental conditions, and biodiversity models that use these proxies to extrapolate from local field observations to a regional or global scale.

Essential Biodiversity Variables (EBVs) have been defined to describe the state of genomes, species, populations, or ecosystems and provide a common foundation for trend detection and change indicators tracking. Different actors including the Group on Earth Observations Biodiversity Observation Network (GEO BON) and its thematic working groups work on a detection and attribution framework across the full set of EBVs. The EBVs species populations, community composition and ecosystem structure have been identified as priority EBV classes for action for freshwater biodiversity by Freshwater BON (FW BON). More recently, complementary EESVs that extend the EBV concept to include also social, cultural, economic and knowledge-based systems have been proposed. From the proposed indicators some are so called remote sensing enabled indicators, for which improved information that is consistent, scalable and continual with sound scientific basis, and that addresses key knowledge gaps can be derived. Satellite remote sensing is crucial for getting long-term global coverage and allows for time series analysis and change detection. In BIOMONDO, as part of the development of the Science and Policy traceability Matrix (SPTM) and the three pilot studies, the EBVs were reviewed to ensure that the products developed provide information that has potential to close knowledge gaps in EBV workflows. With an increasing emphasis on and need for development of EBVs to inform biodiversity indicators, some of the ecosystem and habitat typologies have recently been revised or are under revision.

Knowledge gaps are just one of many challenges associated with the biodiversity crisis. The range of other challenges is large, and in D5.1 we have divided them into two sections describing those specific to using EO for biodiversity assessments, e.g. identifying users and user requirements, developing suitable geoinformation solutions and keeping pace with the development of new satellite missions, and those that relate to addressing freshwater biodiversity knowledge gaps, e.g. lack of spatially comprehensive decision support data for freshwaters including the need to attribute observed changes in biodiversity with inferred causes of the changes and the resulting ecosystem impacts. The latter is both of great scientific interest and central to policy efforts aimed at meeting national, regional and global biodiversity targets. Coordination systems under development that can provide detection and attribution frameworks to support and transform our capacity to monitor biodiversity and guide action include the Global Biodiversity Observation System (GBIOS) and the new EU Biodiversity Observation Coordination Centre (EBOCC) proposed by EuropaBON.

The knowledge gaps were also described in two different sections; those that EO can fill and in more detail, those that were addressed in BIOMONDO. We filtered the knowledge gaps identified by IPBES and others with the observation potential of passive EO satellite sensors, namely the sampling of primary production and environmental variables at ecosystem scale, and derivatives of such observations. They were grouped into issues relating to monitoring of ecosystem structure and functioning as proposed by GEO BON, but also environmental variables and interlinkages were considered. The knowledge gaps addressed by the BIOMONDO Pilot Studies (see also section 4.2) were complemented with suggestions for improvements and advancements not addressed within the project and constitute input to the research priorities outlined in D5.1 Ch. 5 and summarized below.

Published recommendations for biodiversity remote sensing research priorities include improved integration of EO in ecological forecasting, coordination with stakeholders, iterative updating of forecasts, use of multisensor data and increased interaction with social scientists, which we fully endorse. However, the generality of these priorities require filling with specifics that link to the identified knowledge gaps including consideration of mutual dependencies, which is needed for planning of specific research projects. The specifics, including current and upcoming opportunities for EO to support monitoring of freshwater biodiversity, were divided into five different themes in D5.1:

- freshwater ecosystems and habitats
- phytoplankton diversity, phenology and productivity
- thermal structure

- river connectivity, sedimentation processes and wetland formation
- ecosystem disturbances, regime shifts, anomalies, and resilience indicators

To provide an overview of each theme and aid interpretation, graphical representations of the hierarchy of the knowledge gaps were constructed and included in the deliverable. The figures show the relationship between existing variables, ecosystem functioning knowledge gaps and knowledge gaps linking ecosystem to environmental variables.

Setting priorities requires, in our view, an estimate of the importance as well as of the feasibility of making substantial progress towards filling the key knowledge gaps associated with different lines of research.

To device a 5-year Roadmap with timelines and interdependencies, the research priorities for the knowledge gaps were divided into four research lines:

1. Monitoring and modelling biodiversity variables
2. Monitoring and modelling of environmental variables
3. Classification of habitat types and ecosystem condition/state
4. Impact assessments, attribution, and forecasting

These different lines of research link back to our view on biodiversity monitoring as a multi-dimensional challenge as outlined in section 1.2. Their prioritisation forms the basis for the framework used to develop the roadmap.

To set priorities, we believe that the highest importance should be given to work on research line 4 because this should, in our view, be the ultimate goal of a biodiversity monitoring system that provides useful scientific and policy output. However, research line 4 depends on the outcomes of work on research lines 1-3, in particular when this work needs to be done on a global scale. Similarly, the work on research line 3 depends on inputs from research line 1 and 2, which makes it less feasible to make considerable progress (within a fixed time period on a global scale) when working on this research line.

In our assessment, work on research line 1 scores best in terms of importance and feasibility, which therefore should get the highest priority when performing global-scale research. We believe, however, that - in a 5-year research programme - there will be sufficient time left to also make considerable progress on research line 2 in a way that paves the way for more preliminary work on research line 3, as the work on research line 2 may benefit from work in other research programmes. However, we believe that it is very also important to perform work on research line 4 even though this might not be feasible on a global scale. For this research line, an important objective might be to improve the feasibility of global-scale work with the help of more local-scale research at well-studied pilot sites (i.e. case studies). This more local-scale work should be performed in a way that allows for upscaling at a later stage. We thus propose a two-track approach in D5.1:

- Global-scale research on research lines 1 & 2 in a way that paves the way for work on research line 3 (5-year Global-scale Road Map)
- Case studies at well-studied pilot sites that improve the feasibility of future global-scale work on research line 4 (5 year Local-scale Road Map)

Both these tracks are illustrated graphically in the Science Agenda to provide overview and aid interpretation. In addition, detailed graphs for each research line are provided in Appendix 6.

Various data sources are already available to support assessments and monitoring of biodiversity or its drivers, although they may require further processing for effective utilization. It is crucial that the limitations of these services are considered. In this context there are many sources of data, but not all fulfill all needs. Future Earth Observation missions can improve the spatial and temporal resolution and increase discrimination possibilities with hyperspectral information. D5.1 describes aspects of remote sensing with an analysis of the potential to fill knowledge gaps that relate to different themes, e.g. mapping of freshwater ecosystems and habitat types, phytoplankton diversity and phenology, lake surface water temperature, thermal structure and river connectivity. Operational services and products are reviewed together with outlines of future EO missions and potential for uptake of EO in freshwater biodiversity assessment workflows.

Models are critical tools to link drivers of change and the ecological state, and the main objective of the Precursors was to develop pilot studies that integrate Earth Observation data in biodiversity modelling. Two basic types of models exist and in BIOMONDO we have explored integration of EO based information into the process-based model BLOOM (Delft3D software suite) and into an empirical Heat Tolerance model by PBL (GLOBIO model suite), with possibilities demonstrated and new knowledge gained. Important opportunities can be perceived in this area of data and model combination.

The value, usability and thereby impact of EO products for biodiversity monitoring depends on the user-friendly integration of such data in dedicated workflows. The main challenges of this evolution are to handle big data processing, to develop interfaces between different data sources, and to satisfy heterogeneous user requirement. These issues are further discussed in D5.1. In BIOMONDO, we tested various available options, and finally, we took the initiative to establish our own framework called the BIOMONDO Freshwater Laboratory. This solution acts as a federation of all the project's data, providing accessibility through state-of-the-art methods such as Jupyter Notebooks and the xcube Viewer. The BIOMONDO Freshwater Laboratory enhances the project's capabilities to view and access the biodiversity datasets.

The Scientific Agenda also summarizes available reports and assessments related to the most important trends for freshwater biodiversity and in general, all reports indicate that freshwaters are subject to an extraordinarily fast decline in biodiversity, and that this realm is less studied than other ecosystems. On the global level, UNEP's Global Environment Outlook 6 reports that species extinction rates are increasing in freshwaters. Agricultural, urban and infrastructure development and overexploitation of water resources have caused a loss of 40 per cent of all wetlands since 1970 and the loss of wetlands is linked to a likely 81% freshwater species population decline over the same period, the highest for any type of habitat. The Ramsar Global Wetland Outlook, the WWF Living Planet Report and UN SDG Goals reports confirm but mention a significantly higher and alarming 85% loss of wetland ecosystems or more if a longer time period is considered. In Europe, the EU Ecosystem Assessment states that this is true also for Europe and that wetlands are the ecosystem type in worst condition in Europe, with very small signs of improvement. In addition, it is concluded that emissions from agricultural land remain high, and that invasive alien species are widespread. In the EEA State of Nature report hydrological flow modifications are reported to be the pressure with the most significant impacts on European freshwaters, and the EEA European Waters Assessment identified that the more than 25 000 hydropower plants in Europe were "one of the main drivers affecting status of rivers and resulting in loss of connectivity, altered water flow and sediment transport".

Finally, in BIOMONDO we also conducted a review of current research literature using relevant author key words to search the Web of Science to verify the alignment of current research activities with the identified challenges and knowledge gaps. The analysis is presented in D5.1.

5.2.1 WP5 Deliverables

- D5.1 Science Agenda and Scientific Roadmap BIOMONDO_ScienceAgenda_v2.5.docx
- D5.2 White Paper on EO-based ESS Approaches to Biodiversity (work in progress, will be finalised autumn 2024)

5.2.2 WP5 Conclusion

In conclusion, WP5 of BIOMONDO has elaborated a Science Agenda and an associated 5-yr Scientific Roadmap, with recommendations on how to further advance the use of EO technology for freshwater ecosystems. Challenges were defined and divided in two sections describing those specific to using EO for biodiversity assessments, and those that relate to addressing freshwater biodiversity knowledge gaps. The knowledge gaps were also divided and described in two sections; those that EO can fill and in more detail, those that were addressed in BIOMONDO. For prioritisation of activities, an estimate of the importance as well as of the feasibility of making substantial progress towards filling the key knowledge gaps associated with different lines of research within the next 5 years, were taken into account.

6 WP6 - Networking and Partnerships

6.1 Objectives

The objectives of BIOMONDO WP6 were to coordinate the efforts with the other Biodiversity+ Precursor projects and to explore synergies with the European Commission's work programme on biodiversity and international observation and research networks on biodiversity.

Besides close interaction with ESA and the Biodiversity+ Precursor family, the included tasks comprised interaction and communication with the BIOMONDO scientific Advisory Board, the science-oriented Biodiversity Experts, and the policy oriented Early Adopters identified for each BIOMONDO pilot. In addition, an effort to interact with European and international research networks projects and initiatives was included.

6.2 Summary of results

Several coordination meetings with the Biodiversity+ Precursor projects were arranged during the lifetime of the project. Besides initial preparation discussions, the interactions were intensified when the preparation for and development of the Science Agenda and Scientific Roadmap became main project tasks. One of the main events where all Precursor projects attended, presented and discussed the results was at the joint EC-ESA Earth System Science workshop in Frascati, Italy, 22-24 November 2023. The workshop was an invitation to scientists, research institutions, policy makers, innovators, industry, ESA activities and Horizon Europe projects to participate and contribute to advance science for a green and sustainable society. Latest advances in EO and ESS across domains and especially presentations of the latest ESA and EC funded results, projects and initiatives was in focus. Writing of the common White Paper with the tentative title "Biodiversity in a changing environment: the need for a unifying perspective from EO", will finalise the collaborative effort. As a positive side effect, the interaction with EO4Diversity led to the development, application, and approval of the EU HORIZON-RIA project OBSGESSION, Observation of ecosystem changes for action, where e.g. the TECI developments initiated in BIOMONDO will continue. OBSGESSION had its kick-off meeting in January 2024.

The BIOMONDO Advisory Board was stablished in the very beginning of the project, and the members were Prof. Dr. Ole Seehausen, Eawag, Ass Prof. Dr. Erin Hestir, University of California, Dr. Petteri Vihervaara, SYKE, Ass. Prof. Dr. Maria Vallejos, University of Buenos Aires, Dr. Lisa Maria Rebelo, Int. Water Management Institute & DE Africa and Dr. Victor Martinez-Vicente, Plymouth Marine Laboratory. Drs. Vihervaara and Martinez-Vicente have also served as important contacts for the two other Precursor projects on terrestrial (EO4Diversity) and coastal (BiCOME) ecosystems respectively. Project deliverables and results, primarily related to the Requirements Baseline and the pilot developments and their assessments, have been sent to the Advisory Board members for comment prior to submission to ESA and presented during dedicated consultation meetings.

The interactions with the external Biodiversity Experts and Early Adopters also started at the beginning of the project, but was much intensified when the Experimental Datasets had been generated and the scientific and policy assessments in WP3 and WP4 started. Several consultation meetings were conducted as the pilot developments progressed and the assessments became in focus. It can be noted that several experts acted both as scientific and policy experts, due to their involvement in national monitoring and management developments. The involved experts and their affiliations are listed in Table 1 for each of the pilots.

Table 1 BIOMONDO external experts supporting the developments and assessment of results.

	Name	Institution
Pilot 1	Marcel van den Berg	Rijkswaterstaat
	Ruurd Noordhuis	Deltares
	Lièn Klugkist	Deltares
Pilot 2	Thomas Axenroth	SLU
	Caroline Ek	SLU
	Helena Strömberg	SLU
	Björn Rogell	SLU
	Joep de Leeuw	Wageningen Marine Research / RWS
Pilot 3	Arjen Haag	Deltares
	Rafael Schmitt	Stanford University
	Philip Minderhoud	Wageningen University
	Nam Nguyen Trung	SIWRP
	Lam Dang Thanh	SIWRP

Interactions with European and international research networks and projects have mainly constituted in participating in workshops and webinars organised by the main organisations involved for both science and policy developments. These workshops span a wide range of topics relevant to monitoring of freshwater ecosystems and how to support development of EBVs and indicators for tracking progress against the goals and targets of different multi-lateral environmental agreements. Examples of subjects are action plan developments for different GEO BON Working Groups, webinars explaining new tools, discussions on how to advance the role of EO for biodiversity monitoring and importance of attempts at mainstreaming issues related to freshwater biodiversity.

The events attended include:

- Action plan development workshops, GEO BON Ecosystem services Working group and Ecosystem Function Working group, both in 2022.
- GEO EO4EA – 2022 Workshop on Earth Observation for Ecosystem Accounting, ESA, UNSD – SEEA EA and EO4EA, 2022.
- “Bon in a Box” goes interactive, GEO BON Webinar, 2023.

- Ecosystem Services, Biodiversity and the Nature Positive Journey, GEO BON Webinar, 2024.
- GEO Wetlands Ideation, renewal of GEO Wetlands Initiative, on-line workshop, GEO, GEO Wetlands and Ramsar, 2022.
- GEOAquaWatch Meeting, Water Quality Information for the Benefit of Society, 2022.
- “AI for Good” talk – AI in monitoring biodiversity change, A. Gonzalez, GEO BON, 2023.
- Un Water International Day for Biological Diversity – Celebration event – From Agreement to Action: The Central Role of Water to Build Back Biodiversity, UN Water and CBD, 2023.
- Biodiversity in Coastal ecosystems, workshop outlining what the Copernicus services can offer, DG DEFIS/EUSPA, 2022.
- KCEO First Stakeholder Workshop, EU Knowledge Centre for Earth Observation, 2022.
- EuropaBON Hybrid conference – Shaping the future European biodiversity monitoring framework, EuropaBON and Biodiversa+, 2022.
- EuropaBON 3-day virtual Stakeholder Workshop, EBV Workflows, 2023.

Most of the events that the partners of BIOMONDO have participated in and contributed to are described in deliverable D6.1 (see 6.2.1). The main biodiversity partnerships, networks and projects are described in detail in deliverable D6.1. The document contains a list of major European and International initiatives, networks, organisations and projects on biodiversity, which are active in advancing the uptake of EO in biodiversity and ecosystem services research and implementation, with their points of contact and strategic areas of influence. The document describes some of the recent developments of the organisations and the content has been revised based on information received and solicited via regular searches during the lifetime of the project. D6.1 has been updated five times during the lifetime of BIOMONDO. Where appropriate, description of webinars and meetings attended have been added as well as information of recent publications by several of the organisations. The references to workshops and links to organisations and project websites will become outdated with time. Therefore, D6.1 v5 should be seen as reflecting the status at the start of 2024.

The main biodiversity partnerships are presented in separate sections and also summarised in tables at the end of the document:

- International initiatives and networks
- Organisations with Biodiversity-EO links
- Biodiversity Information Services and Networks
- Biodiversity projects advancing EO

6.2.1 WP6 Deliverables

- D6.1 Directory of Biodiversity Partnership on EO – Available on request

6.2.2 WP6 Conclusion

In WP6 the BIOMONDO developments were coordinated with the other Biodiversity+ Precursor projects and synergies with the European Commission's work programme on biodiversity and the international observation and research networks on biodiversity were explored. Many meetings and workshops were attended and actively contributed to, to keep the work in BIOMONDO updated and in line with other efforts.

7 WP7 - Scientific and Policy Outreach

7.1 Objectives

The objectives of WP7 were to perform outreach activities within both the biodiversity scientific community and towards policy stakeholders. The effort included promotion and awareness activities, outreach activities with key biodiversity research and observation networks (engaged in WP6), and dissemination of project results, both in terms of scientific advances and policy relevance. The tasks identified to reach the objectives included generation of promotion materials and project promotion actions, engaging with the biodiversity community, preparing scientific publications, and set up of a project portal.

7.2 Summary of results

Outreach activities have been conducted from the beginning of the project and the effort and activities were slightly overlapping with the actions and results of WP6. We have decided to collect and report on the more interactive outreach activities in Ch. 6 and have focused on conference presentations, publications, and web portal in this chapter.

7.2.1 Project promotion activities

BIOMONDO partners visited several events and conferences, and presented the project and the project results with the aim to showcase the potential for EO to support freshwater biodiversity monitoring activities. Promotion material in the form of presentations and posters were prepared for each event, building on a Biodiversity+ Precursor unified graphical layout provided by the ESA graphical bureau. The events vary from local meetings to international world congresses and online webinars:

World Biodiversity Forum 2024

- Conference poster, June 16-21 2024, Davos, Switzerland
- Title: BIOMONDO - Earth Observation supported monitoring of freshwater biodiversity
- URL: https://worldbiodiversityforum2024.org/

EC-ESA JOINT EARTH SYSTEM SCIENCE INITIATIVE

- Oral presentations of project and workshop contributions, Nov 22 – 24th, 2023, ESA, ESRIN, Frascati, Italy
- Titles: ESA / EC Biodiversity Projects/ ESA BIOMONDO, The ESA Biodiversity+ Precursor for freshwaters and BIOMONDO Science agenda
- URL: https://essi2023.esa.int/

GEO BON Global Conference: Monitoring Biodiversity for Action

- Oral presentation, Oct 10-13th, 2023, Montreal, Canada
- Title: Monitoring and assessment of effects by drivers of biodiversity changes in freshwater ecosystems
- URL: https://event.fourwaves.com/geobon-2023/

6th Sentinel-2 Validation Team meeting

- Poster, Sep 12-14th 2023, ESA, Frascati, Italy
- Title: Validation of Sediment and Turbidity Products in the Mekong River System
- URL: https://nikal.eventsair.com/6s2vtm/

GEO AquaWatch Webinar

- Online Webinar, Feb 2nd, 2023
- Title: BIOMONDO, BiCOME and BOOMS – Towards Earth Observation supported monitoring of freshwater and marine biodiversity
- URL: https://www.geoaquawatch.org/geo-aquawatch-webinar-series/
  video - https://www.youtube.com/watch?v=c14yhPL4S9A

Miljöövervakningsdagarna 2022 (Swedish Annual Environmental Monitoring Conference)

- Conference exhibition and presentation, Sep 13-15th, 2022, Umeå, Sweden
- Title: BIOMONDO - Towards Earth Observation supported monitoring of freshwater biodiversity
- URL: Not available

World Biodiversity Forum

- Conference presentation, June 26-July 1, 2022, Davos, Switzerland
- Title: BIOMONDO - Towards Earth Observation supported monitoring of freshwater biodiversity
- URL: https://www.worldbiodiversityforum.org

ESA Living Planet Symposium

- Conference presentation, May 23-27, 2022, Bonn, Germany
- Title: BIOMONDO - The ESA Biodiversity+ Precursor for freshwaters
- URL: https://lps22.esa.int

NWO Life2022: Resilience (Dutch Research Council annual scientific conference)

- Conference presentation, May 24-25, 2022, Egmond aan Zee, Netherlands
- Title: Impacts of heat waves on freshwater fish
- URL: NWO Life2022: A great breeding place for wild ideas | NWO Life

7.2.2 Scientific publications

The following scientific publications have been or will be submitted by BIOMONDO partners.

Title: Detecting climate-related shifts in lakes: a review of the use of satellite Earth Observation

- Authors: Calamita, E., Lever, J., Woolway, R. I., Albergel, C. and Odermatt, D.
- Status: Published 2024
- Journal: Limnology and Oceanography
- https://doi.org/10.1002/lno.12498

Title: The mitigating effect of acclimation on climate change impacts on freshwater fish species

- Authors: Keijzer, T., Verberk, W.C.E.P., Barbarossa. V., Marques, A., Huijbregts, M.A.J. and Schipper, A.
- Status: In preparation

Title: Towards a global remotely sensed phytoplankton phenology product

- Authors: Lever, J., Odermatt, D. and TBD
- Status: In preparation

7.2.3 Project portal

The Project Portal was developed in the beginning of the project and has been regularly updated (Figure 3). During the development phase of the Project Portal several discussions took place between representatives from ESA and the three precursors, focusing on harmonization. This resulted in harmonized domain names (biomondo.info, eo4diversity.info and bicome.info), a harmonized web structure (same first level, similar second level) and a harmonized graphical layout. Thanks to the Earth Observation Graphic Bureau all three precursors received harmonized colour codes and key visuals. All this initial work resulted in a professional graphical collection that were used on the Project Portal, in presentations and in promotional materials, etc.

The Portal includes information on the Biodiversity+ Precursors, the BIOMONDO objectives, the pilot studies, the consortium and the Advisory Board, as well as News and Events, which varies from local meetings to international world congresses). In the portal one can also find all deliverables and papers, and information on how to get access to the BIOMONDO viewer.

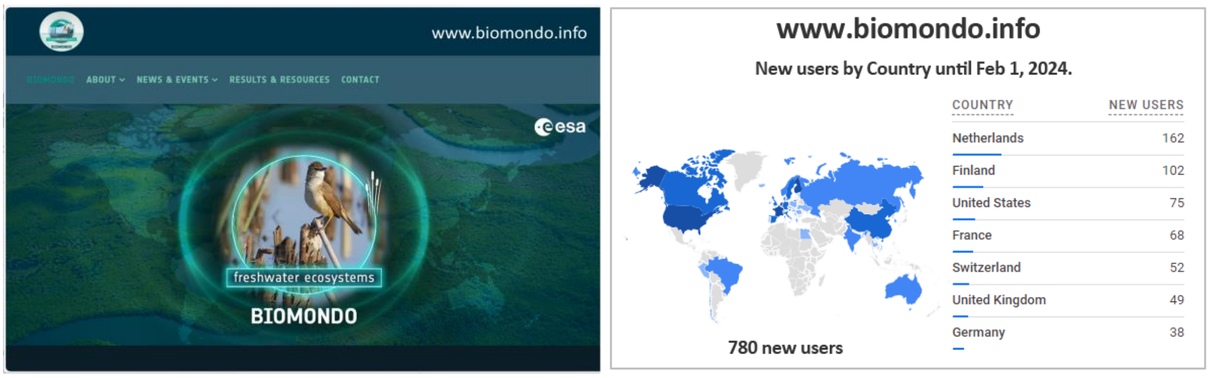

Figure 3 The BIOMONDO portal, www.biomondo.info (left) and the geographic extent of www.biomondo.info website users, showing the number of new users per country, about 780 in total until 2024-02-01.

The Project Portal will be maintained at least 2 years after the end of the project. Geographic extent of www.biomondo.info website users, showing the number of new users per country, about 780 in total until 2024-02-01, is shown in Figure 3.

7.2.4 Science & Policy briefs

Science and policy briefs were created to highlight and showcase the major findings of the different pilots. Each science brief is a one-page summary of the scientific goals of the pilots and scientific results achieved. The policy briefs build on the science and showcase their relevance for biodiversity policies, biodiversity conservation and management purposes to policy makers. All six briefs have been published on the project portal and links are provided in section 7.2.5 below.

7.2.5 WP7 Deliverables

- D7.1 Project Portal – http://biomondo.info/
- D7.2 Promotion material – several oral and poster presentations are published through the relevant conference sites
- D7.3 Scientific Briefs – http://biomondo.info/results-and-resources#scientific
- D7.4 Policy Briefs – http://biomondo.info/results-and-resources#policy
- D7.5 Peer-reviewed scientific publications

7.2.6 WP7 Conclusion

In WP6 outreach activities addressing both the biodiversity scientific community and policy stakeholders have been conducted. Conferences and workshops have been attended, scientific papers prepared, and a project portal created and maintained.

8 WP8 - Project Management

8.1 Objectives

The main objectives of WP8 were to manage the administrative, financial, and technical elements of the project including:

- Organization of meetings with the project team and ESA
- Handle milestone payments
- Quality control and submission of deliverables and monthly progress reports
- Create and maintain the project internal online working environment

8.2 Summary of results

The main administrative change was that the duration of the project was extended six months from October 2023 to April 2024. This was initially done to encompass the collaborative effort between the Biodiversity+ Precursors related to WP5 and the Science Agendas and White Paper. In April 2024, it turned out the finalisation of the Scientific Agenda required more time than initially planned and the project duration was further extended. Table 2 shows the implemented meeting schedule for the project. In addition to these official progress-, review- and co-location meetings the team held internal working and planning telecons at least once per month. Additional meetings with Biodiversity Experts, Early Adopters and members of the Advisory Board were organized particularly in the beginning and demonstration phases of the project. See WP1, WP4 and WP5 chapters for more details.

Table 2 BIOMONDO meeting schedule

Meeting	Date
KO - Online	2021-10-11
Co-location 1a - Online	2021-11-23
PM1 - Online	2021-12-15
Co-location 1b - Online	2022-01-10
Requirement Review (M1) - Online	2022-03-04
PM2 - Online	2022-04-07
PM3 - Online	2022-07-08
PM4 - Online	2022-09-21
D&V Review 1 (M2) - Online	2022-11-17
PM5 - Online	2023-01-30
D&V Review 2 (M3) - Online	2023-03-24
Co-location 2 (20-24m) - Online	2023-05-30
PM6 - Online	2023-06-12

Assessment Review (M4) - Online	2023-08-23
PM7 - Online	2023-10-23
Co-location SA (20-24m) - Online	2024-01-11
Final Review (M5) - ESRIN	2024-02-12

The project deliverables are presented in the respective WP chapters. A majority of the deliverables are available for the public via the project portal.

8.2.1 W8 Deliverables

- D8.1 Final Report (This document)
- D8.2 Contract Closure Document