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Contributors	Jelle Lever (Eawag) Daniel Odermatt (Eawag) Susanne Thulin (Brockmann Geomatics) Petra Philipson (Brockmann Geomatics) Jorrit Scholze (Brockmann Consult) Carsten Brockmann (Brockmann Consult) Kerstin Stelzer (Brockmann Consult) Miguel Dionisio Pires (Deltares) Tamara Keijzer (PBL)

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1 Background

1.1 Biodiversity at a glance

Biological diversity or biodiversity is the variety of life on Earth and depends on the many different aspects that make organisms and the communities within which they coexist unique. For monitoring biodiversity, a single, objective metric of biodiversity does not exist. It can, however, be determined on different levels of organisation, i.e. varying from genetic diversity within and between populations of the same species, species diversity within and between ecosystems, to the diversity of different ecosystem and/or habitat types on a regional or global scale. In addition to this, species have different roles and functions within ecosystems. In a well-functioning ecosystem, i.e. in which species coexist over longer time periods, there are typically large differences between the number and diversity of species within different functional and/or taxonomic groups. There are, for example, usually few top predators (e.g., bird species) relative to the number of species at lower trophic levels (e.g., insect species).

We may therefore want to determine the biodiversity of different functional or taxonomic groups separately and/or to determine an ecosystem's functional diversity, i.e. the extent to which species are different or fulfil different functions, rather than determining the total species richness of entire ecosystems. To identify the major components of biodiversity, Franklin (1988) recognized three primary attributes in ecosystems: composition, structure, and function (Figure 1). Composition has to do with the identity and variety of elements in a collection of, e.g., genes, species, or landscape types. Structure is the physical organization or pattern of a system, from habitat complexity to patterns in the networks of interactions between species. Function involves ecological and evolutionary processes, including gene flows, disturbances, and nutrient cycling.

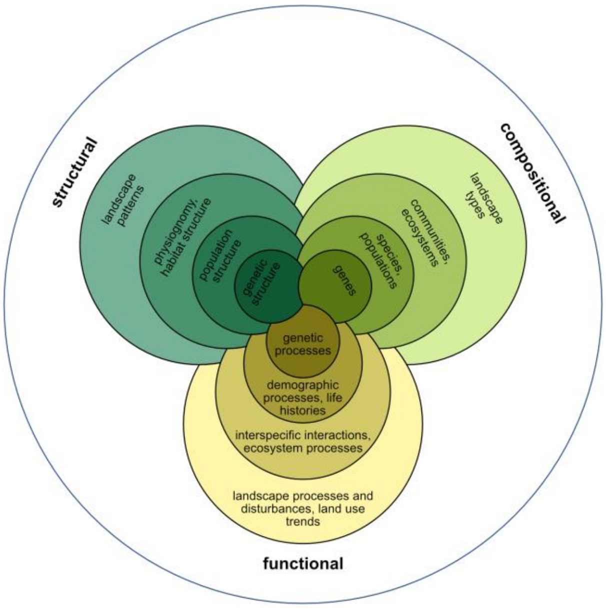

Figure 1: Compositional, structural, and functional biodiversity, shown as interconnected spheres, each encompassing multiple levels of organization. This conceptual framework may facilitate selection of indicators that represent the many aspects of biodiversity that warrant attention in environmental monitoring and assessment programs (redrawn from Noss, 1990).

1.2 International policies and drivers of policy

Global and regional biodiversity and sustainability policies, strategies and assessments comprise a suite of regular updates by different bodies of the United Nations, namely the General Assembly (GA), the United Nations Environment Programme (UNEP), the Secretariat of the Convention on Biological Diversity (CBD), and the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES). The 2030 Biodiversity Strategy of the European Union (EU) is closely linked to these developments. In addition, almost 200 countries have developed National Biodiversity Strategies and Action Plans (NBSAP) in response to these international policies, and the latest versions, due by 2024, will also align with the Kunming-Montreal Global Biodiversity Framework (KM-GBF).

The KM-GBF was adopted in December 2022 at the UN Biodiversity Conference and COP 15. The associated monitoring framework is under development to support the four goals and 23 targets to be reached by 2030. The first eight targets aim to reduce threats to biodiversity. Other effective policies and strategies include the UN GA 2030 Agenda for Sustainable Development (2015) with its Sustainable Development Goals (SDG) and is of key importance for policies and strategies for biodiversity as many of its goals contain aspects that directly relate to biodiversity, ecosystems and their services. In addition, the UN GA has proclaimed the UN Decade 2021-2030 as the Decade for Restoration[1], following a proposal for action by over 70 countries from all latitudes. An overview of the most important documents published within this policy framework is shown in Figure 2. More details on international biodiversity policy frameworks are provided in the BIOMONDO Requirements Baseline document (RB; BIOMONDO, 2022).

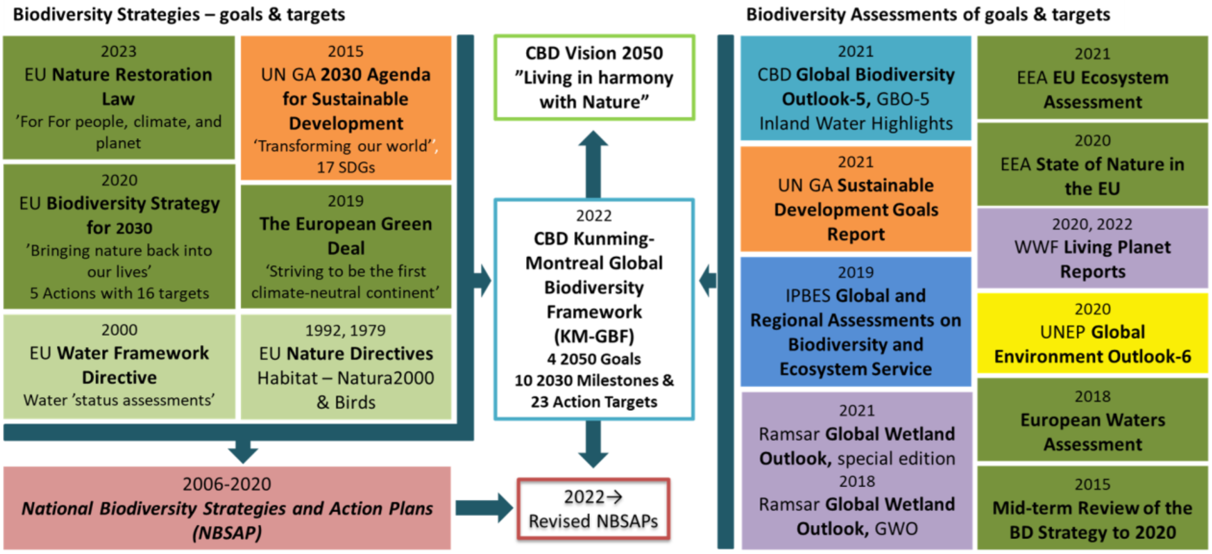

Figure 2: Overview of policy documents released by UN GA (orange), UNEP (yellow), CBD (light blue), IPBES (blue), the EU/EEA (green), individual countries and parties of the CBD (pink) and Ramsar and WWF (purple). The new CBD Vision, the KM-GBF and revised NBSAPs are marked with solid frames in the centre to highlight their global importance.

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[1] https://www.decadeonrestoration.org/

1.3 Multi-dimensional biodiversity monitoring

Measurable, objective metrics of biodiversity cannot capture all different aspects of biodiversity simultaneously, simply because the development of such metrics requires subjective choices on how much we value one aspect of biodiversity relative to the others. Compound metrics of the value or quality of natural areas used in national or regional government policies exist that take a variety of factors into account, but there is no globally accepted metric of biodiversity that can capture the broadness of this concept in a single, measurable value. There are, however, metrics of most of the aforementioned aspects of biodiversity on the level of ecosystem (alpha diversity), between ecosystems (beta diversity), or at a landscape level (gamma diversity; Whittaker, 1972).

When deciding what aspects of biodiversity to monitor, the key question is what aspects we value as most important for nature conservation. This is, ultimately, a question for policy makers. Methodological issues, i.e. some aspects of biodiversity are easier to monitor than others, come second to this. When it comes to policy considerations, we are confronted with the question of whether we want to increase, preserve, or restore biodiversity. To trace an increase in biodiversity, monitoring simple metrics of biodiversity might be sufficient. But environmental policies are more commonly mandates to preserve or restore biodiversity relative to a desired reference state, rather than simply to increase biodiversity. This can mean safeguarding ecosystem services, avoiding biotic homogenization or protecting rare species of specific habitat types that may often have a relatively low biodiversity. So, the reason why we want to monitor biodiversity may influence the way in which we have to do this.

In addition to the previously discussed questions of why and what aspects of biodiversity we want to monitor is what we want to do with the information we obtain when monitoring biodiversity. Usually, this involves mitigation of the effects of changing environmental conditions that are leading to a change in biodiversity, e.g., relative to a reference state. Therefore, global assessments of biodiversity change focus on the impact of these drivers on biodiversity rather than on monitoring a change in biodiversity per se (e.g., IPBES, 2018; Millenium Ecosystem Assessment, 2005). There are also scientific reasons for this approach. On one hand, drivers of global environmental change usually affect most, or all of the above-described aspects of biodiversity simultaneously. As such, they come as close to a compound proxy for change in biodiversity as we can get. On the other hand, a change in environmental drivers may precede biodiversity loss by several decades. Monitoring a change in environmental drivers can thus give us an early outlook on future changes in biodiversity to come.

The key to a biodiversity monitoring system that provides useful scientific and policy output is, consequently, a system that assesses impacts and trends of drivers of global environmental change on biodiversity. BIOMONDO, therefore, takes off from these drivers, and explores how Earth Observation (EO) techniques can be used to assess these drivers and their impacts on freshwater ecosystems (Figure 3). See Section 3.3 for a detailed summary of the potential of EO to support freshwater biodiversity monitoring.

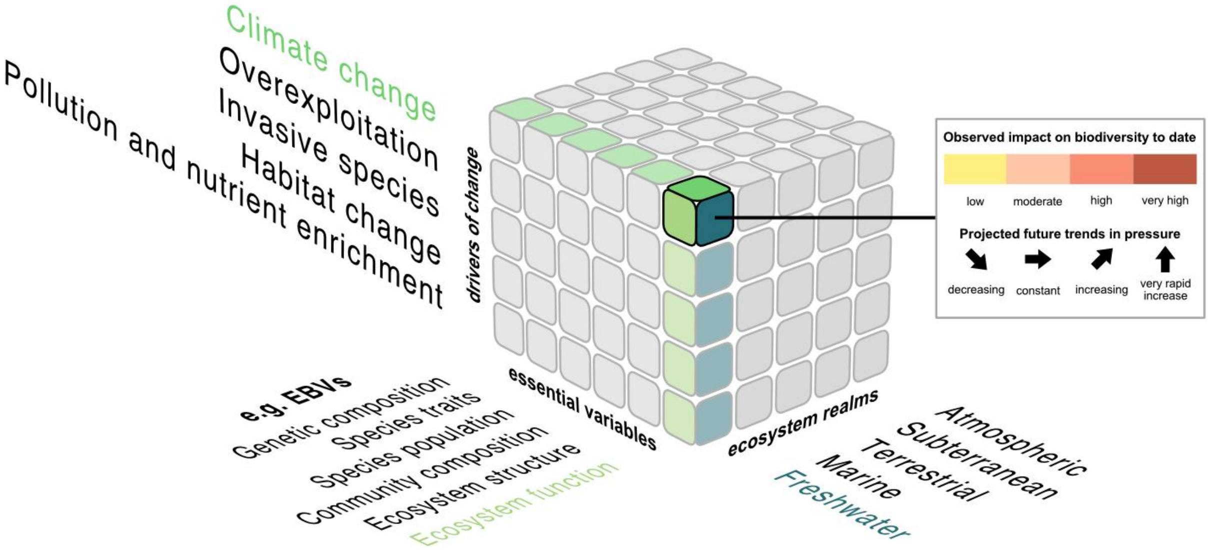

Figure 3: The BIOMONDO cube, representing the multi-dimensional nature of biodiversity monitoring. We propose that monitoring objectives are defined to resolve the effect of driver X on essential variable Y for ecosystem unit Z. Ultimately, these monitoring efforts help to assess observed impacts on ecosystem variables, or to project future trends.

2 Freshwater biodiversity drivers and trends

2.1 Drivers of change in freshwater biodiversity

Freshwater ecosystems, including rivers, lakes, and wetlands, provide home to a rich diversity of species and habitats. Over 125,000 freshwater animal species are described to date, which roughly corresponds to 10% of the number of species described globally (Balian et al., 2008). When considering that rivers and lakes together make up only about 0.01% of the water on Earth and cover approximately 2.3% of the land surface area, it becomes clear that those systems are extremely diverse and of special concern when monitoring biodiversity. In addition, freshwater ecosystems are of key importance for terrestrial biodiversity as a source of freshwater and food; e.g. because terrestrial animals are (indirectly) dependent on fatty acids produced in freshwater ecosystems (Twining et al., 2016). It is perhaps for this reason that wetlands also belong to the world's most biodiverse ecosystem types, and that changes in the diversity and dynamics of freshwater ecosystems are likely to affect global terrestrial biodiversity when cascading through aquatic-terrestrial food webs. Wetlands are estimated to cover approximately 5.4-6.8% of the world's land surface (e.g., Lehner and Döll, 2004; Reid et al., 2019). Definitions of what constitutes a wetland, may however vary, affecting such estimates.

It is impossible to monitor all the different aspects of biodiversity on a global scale directly, for the reasons discussed in Section 1.3. When determining biodiversity, we therefore must rely on estimates and approximations. But facilitating global monitoring of the extent and condition of freshwater ecosystems is a big challenge, even though major drivers affecting their condition are quite clear and often easier to assess and monitor (Revenga et al., 2005). These geospatial indicators are referred to as proxies or surrogates, because they are indicators of current threat and give only indirect information about actual ecological integrity. To monitor freshwater ecosystems, we may thus have to rely on global, relatively easily detectable proxies, 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.

In the sections below, we give a brief overview of the historical assessment of five main drivers of global environmental change to freshwater ecosystems:

- Water pollution and eutrophication
- Habitat change and hydrological disturbance
- Climate change
- Invasive species
- Overexploitation
- (Multiple/unknown drivers)

These drivers are highly akin to the main drivers assessed in global and regional biodiversity assessment reports (e.g., IPBES, 2019; Millenium Ecosystem Assessment, 2005), as well as in scientific reviews of biodiversity change in freshwater systems (Carpenter et al., 2011; Dudgeon et al., 2006; Reid et al., 2019; Revenga et al., 2005).

In addition, Reid et al. (2019) report on 12 emerging threats:

- E-commerce and invasions
- Infectious diseases
- Harmful algal blooms
- Expanding hydropower
- Emerging contaminants
- Engineered nanomaterial
- Microplastic pollution
- Light and noise
- Freshwater salinization
- Declining calcium
- Cumulative stressors

Most of those, however, can be categorized under the five key drivers described below, with the exception of cumulative stressors, which we discuss under a sixth category.

Water pollution and eutrophication

Nutrient concentrations have increased substantially in rivers and lakes throughout the world (Carpenter et al., 2011; Dudgeon et al., 2006; Heathwaite et al., 1996; Reid et al., 2019; Revenga et al., 2005), resulting in eutrophication, harmful algal blooms, loss of submerged macrophytes, biodiversity loss in lakes and rivers, and high levels of nitrate in drinking water. In addition, pollution by hazardous substances has undermined water quality across the world. Of particular concern are pesticides, ammonia, PCBs, polyaromatic hydrocarbons, and metals, while transport is an important source of oil pollution (IUCN, 1992). Newer, emerging substances include microplastics and pharmaceuticals. Diffuse discharges from agriculture are important sources of micro-pollutants for both surface and groundwaters.

Inland water systems are often heavily polluted because they act as accumulators of pollutants from their catchment areas (e.g., Malmqvist and Rundle, 2002; Tockner and Stanford, 2002). For instance, the agricultural sector contributes an average of 50% of the total load of nitrogen and phosphorus to the Danube River in Europe, domestic sources contribute about 25%, and industry or atmospheric deposition 25%.

Habitat change (hydrological disturbance)

Water regimes of inland waters have been modified by humans for centuries, with the last 50 years in particular witnessing largescale changes in many parts of the world, often associated with drainage and infilling activities (Carpenter et al., 2011; Dudgeon et al., 2006; Grill et al., 2019; Malmqvist and Rundle, 2002; Reid et al., 2019; Revenga et al., 2005; Tockner and Stanford, 2002). Modifications include construction of river embankments to improve navigation, drainage of wetlands for agriculture, construction of dams and irrigation channels, and the establishment of inter-basin connections and water transfers. Clearing or drainage for agricultural development is the principal cause for wetland loss worldwide (Millenium Ecosystem Assessment, 2005). By 1985 it was estimated that 56–65% of available wetlands had been drained for intensive agriculture in Europe and North America, 27% in Asia, 6% in South America and 2% in Africa—a total of 26% loss to agriculture worldwide (IPBES, 2019; OECD, 1996).

The most concerned areas include arid regions with naturally limited water availability, and large streams with a large potential for modification. The Aral Sea in Central Asia represents one of the most extreme cases in which water diversion for irrigated agriculture has caused severe and irreversible environmental degradation of an inland water system (Millenium Ecosystem Assessment, 2005). The Mekong catchment on the other hand is one of the world's most important biodiversity hotspots, it provides both ecological and food security for its inhabitants, and its sediments feed the world's third largest delta. The delta has been threatened by climate change and human activities, particularly the proliferation of hydropower development across the Mekong Basin since the 1990s (Li et al., 2017). Other prominent examples of the effects of dam construction include the region downstream of the Aswan High Dam in Egypt (McAllister et al., 1997) and the Indus Delta (Millenium Ecosystem Assessment, 2005).

Climate change

The major impacts of climate change on inland waters include warming of rivers and lakes, which in turn can affect chemical and biological processes, reduce the amount of ice cover, reduce the amount of dissolved oxygen in deep waters, alter the mixing regimes, and affect the growth rates, reproduction, and distribution of organisms and species (IPCC, 2002; Till et al., 2019; Woolway et al., 2021). In addition, sea level rise will affect a range of freshwater systems in low-lying coastal regions. For example, low-lying floodplains and associated swamps in tropical regions could be replaced by salt-water habitats due to the combined actions of sea level rise and extreme sea levels during storm surges or tropical cyclones (Bayliss et al., 1997; Eliot et al., 1999). Plant species not tolerant to increased salinity or inundation could be eliminated, while salt-tolerant mangrove species could expand from nearby coastal habitats. Changes in the vegetation will affect both resident and migratory animals, especially if these result in a major change in the availability of staging, feeding, or breeding grounds for particular species (Boyd and Madsen, 1997; Zöckler and Lysenko, 2000). In addition to this, climate change affects other drivers and can be seen as a threat multiplier. In particular, drought or increased rainfall may lead to habitat change.

The areas most concerned by climate change, apart from coastal areas, are high latitude regions. Largest historical changes in temperature are thus expected in Scandinavia or Canada. Further information on lake heatwaves can be found in Woolway et al. (2021).

Invasive species

The spread of exotic species in inland waters is increasing with the spread of aquaculture, shipping, and global commerce and affecting biodiversity. In general, this driver is, however, considered to be of lesser concern than pollution and eutrophication, habitat change, and climate change (Carpenter et al., 2011; Millenium Ecosystem Assessment, 2005; Revenga et al., 2005).

Examples of concerned areas and species include:

- The South American weeds salvinia *(Salvinia molesta*) and water hyacinth (*Eichhornia crassipes*) are widely distributed across the tropics (Hill and Coetzee, 2017)
- The cane toad (*Bufo marinus*) was introduced to Australia in 1935 and has led to a decline of many large predators (Shine, 2010)
- The American bullfrog (*Rana catesbeiana*) has invaded over 40 countries, where they often outcompete or prey on native amphibians (Ficetola et al., 2007)
- Zebra mussels (*Dreissena polymorpha*) have spread in Eurasia and North America, causing large and sustained changes in physical and chemical attributes that define the habitat for all resident species (Higgins and Vander Zanden, 2010)

Overexploitation

According to FAO's review of inland fisheries (Funge-Smith, 2018) freshwater environments are facing alarming threats and competing demands. Most inland water fisheries rely on natural reproduction of stocks that are overfished or are being fished at their biological limit.

The principal factors threatening inland capture fisheries are:

- Fish habitat loss and environmental degradation
- Loss of lateral and longitudinal connectivity
- Pollution with chemicals, pesticides and fertilizers
- Overfishing, including illegal commercial and recreational fishing
- Climate change

Despite overfishing with negative impacts on fish biodiversity inland fisheries have a key role in providing food security and affordable nutrition, especially to the world's vulnerable populations (Funge-Smith, 2018). Freshwater environments provide important provisioning, regulating, supporting and cultural ecosystem services especially in the lower Mekong basin in Southeast Asia and in the Lake Victoria basin in East Africa.

Asia (including China) and Africa are the two leading regions in inland capture fisheries, accounting for 91% of the global catch in 2015 (Funge-Smith, 2018). The Asian region (excluding China) has the highest inland fishery catch in 2015 representing 46 percent of the global total. China alone provides nearly 20 percent in addition to this.

Multiple/unknown drivers

Drivers may act simultaneously, or drivers may be unknown. Generic patterns, e.g. in spatial or temporal variability, may indicate a loss of resilience regardless of which driver is causing this loss in resilience. Areas of concern may include those approaching a tipping point, i.e. a non-linear shift in ecosystem response. The development of such indicators, however, is still in a preliminary stage, in particular for highly dynamic freshwater ecosystems.

2.2 Global trends assessments

Many of the global reports in Figure 2 describe specific results for freshwaters, which were analysed as a basis for the Requirements Baseline, RB, deliverable (BIOMONDO, 2022) and in particular for the Science Policy Traceability Matrix included therein. The most important trends for freshwater biodiversity are repeated here. In general, the reports indicate that freshwaters are subject to an extraordinarily fast decline in biodiversity, and less studied than other ecosystems.

IPBES Global and Thematic Assessments

The Global Assessment on Biodiversity and Ecosystems Services (IPBES, 2019) is based on 15,000 scientific publications, local and indigenous knowledge as well as feedback on IPBES regional reports (e.g., IPBES, 2018). It was the first global assessment of ecosystems and biodiversity since the Millennium Ecosystem Assessment 2005 (Millenium Ecosystem Assessment, 2005), and it refers to the same direct and indirect drivers (Figure 4). In the case of freshwaters, the impacts of land use changes dominate, followed by direct exploitation and pollution.

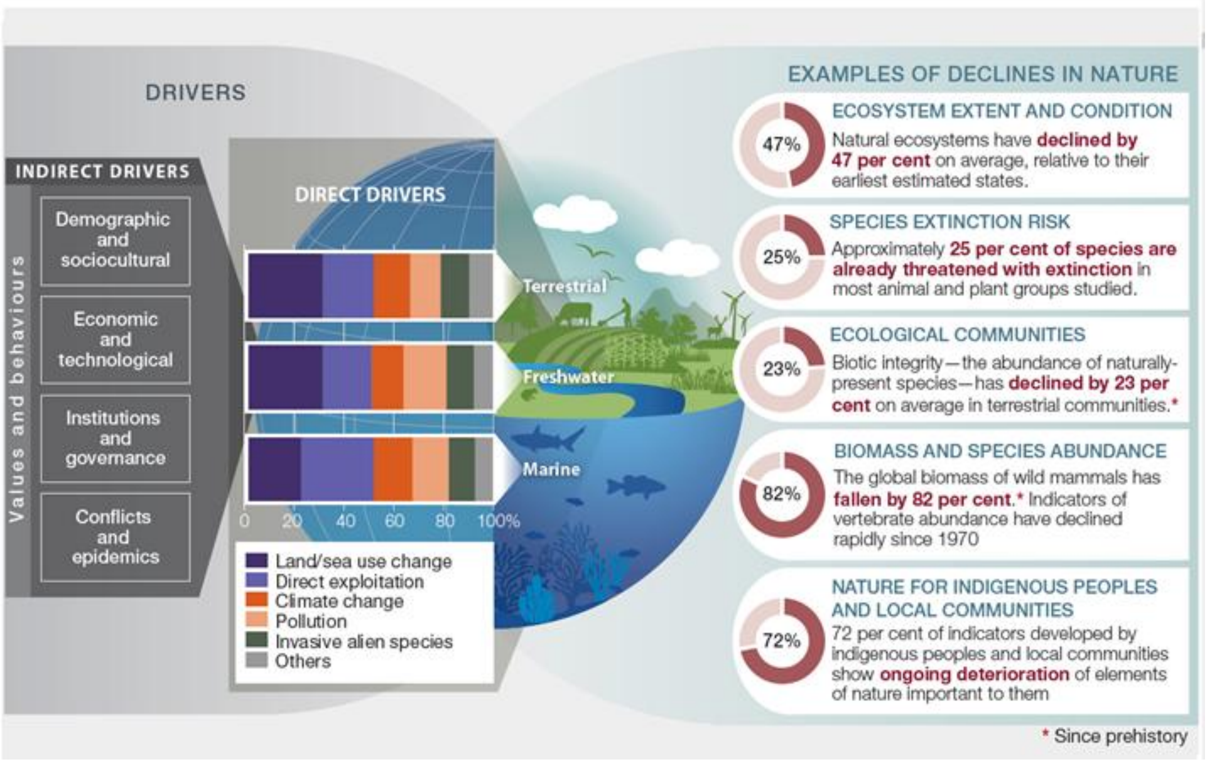

Figure 4: Direct and indirect drivers of change in terrestrial, freshwater and marine ecosystems including examples of declines in nature. Other direct drivers include interactions between drivers (from IPBES, 2019).

The IPBES thematic assessment on Alien Invasive Species and their control (IPBES, 2023) highlights that invasive species are a major and growing threat to nature, with, in some cases, irreversible changes to biodiversity and ecosystems. 25% of documented negative impacts have been reported from the aquatic realm with 14% from freshwater, especially from surface waters with many alien fish species arising from aquaculture. Two additional thematic IPBES assessments were launched in early 2022. One is the Nexus assessment between biodiversity, water, food, energy and health in the context of climate change, and the other aims to assess the causes of biodiversity loss.

CBD Global Biodiversity Outlook 5

The CBD's Global Biodiversity Outlook 5 (GBO-5; CBD, 2020a) is the most recent report on progress towards the Aichi biodiversity targets. It is based on indicators, research studies and assessments, including IPBES' Global (IPBES, 2019) and Regional Assessments on Biodiversity and Ecosystem Service[2], and national implementation reports. It contains a final assessment of the Aichi biodiversity targets for inland and freshwater systems and transitions needed for sustainability. The outcomes are summarised in a separate publication called GBO-5 Inland Waters Highlights (CBD, 2020b). This report proposes a sustainable freshwater transition, whose components are related to the key drivers of biodiversity loss of freshwater ecosystems (Figure 4). They were selected as starting points for the BIOMONDO pilot objectives and are included in the Science and Policy Traceability Matrix SPTM (BIOMONDO, 2022). Difference to note are that climate change effects on freshwater ecosystems is not specifically mentioned in the GBO-5 Inland Water Highlights although integration of environmental flows into water management is included as a key component.

The main findings from GBO-5 indicate:

- A doubling of manmade wetlands at the expense of natural wetlands
- An extensive fragmentation of most of the world's rivers
- A missing protection status for 60% of 15,000 key biodiversity areas
- A faster decline in freshwater species than for all other species

UNEP Global Environment Outlook 6

UNEP's Global Environment Outlook 6 (GEO-6; UN Environment, 2019) provides an assessment of recent scientific information and data, analysing current and past environmental policy, and identifying future options for achieving sustainable development by 2050. It includes specific chapters relating to freshwater, namely Chapter 9: *The Global Environmental State of Freshwater*, and Chapter 16: *Freshwater Policy*.

It is reported that:

- Species extinction rates are increasing
- 34 per cent of freshwater invertebrates are considered at risk of extinction
- Agricultural, urban, infrastructure development and overexploitation of water resources have caused a loss of 40 per cent of all wetlands since 1970
- The loss of wetlands is linked to a likely 81 per cent freshwater species population decline over the same period, the highest for any type of habitat.

UN Sustainable Developments Goals Reports

The UN Sustainable Developments Goals Reports (United Nations, 2023 and previous years) assess the progress towards the SDGs. Specifics for freshwater ecosystems relate

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[2] https://www.ipbes.net/regional-assessments

mainly to SDG 6: *Clean Water and Sanitation* and SDG 15: *Life on Land*. In the scope of SDG 6, there is a focus on the dramatic change in freshwater ecosystems including loss of wetland ecosystems and species. Water-related ecosystems provide clean water, regulate floods and droughts and support biodiversity. But these ecosystems face threats like pollution, climate change and overexploitation. The need for urgent response in the form of upscaling and acceleration of restoration and large-scale protection efforts is highlighted.

The SDG Goals report states that:

- Extents of surface waters are rapidly changing worldwide, with one in five river basins experiencing above-natural extent variations over the past five years
- Wetland ecosystems have suffered an alarming 85 per cent loss in the past three centuries, primarily from drainage and land conversion
- Since 1970, 81 per cent of species dependent on inland wetlands have declined, exceeding declines in other biomes
- 42% of freshwater key biodiversity areas were protected in 2015, with only a 2% increase to 2022
- A majority of key biodiversity areas remain unprotected

Ramsar Global Wetland Outlook

Two recent Ramsar reports, the Global Wetland Outlook (Gardner and Finlayson, 2018) and its 2021 special edition (Ramsar Convention on Wetlands, 2024) highlight that only 13 per cent of the wetland present in 1700 remained by 2000. Today, the Ramsar list of wetlands of international importance comprises 13-18% of the global wetland area, which are under effective protection. But elsewhere, wetland loss continues at a fast pace. They emphasize the need for actions, such as improvement of national wetland inventories, tracking of wetlands' extent and identification of and measurement of drivers of change. These actions can all be supported by approaches integrating remote sensing, field assessments and citizen science. In the Ramsar global guidelines for peatland rewetting and restoration (Ramsar Convention on Wetlands, 2021) it is stated that remote sensing should be developed as a near real-time and cost-effective method for monitoring large-scale restoration projects. In 2024, Ramsar has also released a guide (Ramsar Convention on Wetlands, 2024) on how to include wetlands in National Biodiversity Strategy and Action Plans (NBSAPs) to boost biodiversity and halt wetland loss and degradation with specifics for each target of the KM-GBF.

WWF Living Planet Report

The World Wide Fund for Nature (WWF) published a Deep Dive into Freshwater (WWF, 2020a) as part of its Living Planet Report (WWF, 2020b). The loss of global wetlands lost since 1700 is reported as 90%. Humans have altered millions of kilometres of rivers. For the WWF reports, the abundance of populations is tracked by means of the Living Planet Index (LPI). Between 1970 and 2016, the LPI for freshwaters dropped more steeply than the indices for both marine and terrestrial populations (Collen et al., 2009; Reid et al., 2019). Based on the LPI, the WWF reported a 76% decline in relative abundance of freshwater migratory fish. However, the global LPI does not resolve regionally different declines. The data behind the LPI also show, despite being based on thousands of population time series, a spatial bias towards temperate regions (Proença et al., 2017).

The most recent Living Planet report (WWF, 2022), states that monitored freshwater populations have seen an alarming decline of 83% since 1970, again, more than any other species groups. Habitat loss and barriers to migration routes account for around half the threats to these populations.

2.3 European trends assessments

Several of the assessment reports in Figure 2 contain specific results for freshwaters, including the EU Ecosystem assessment, State of Nature in the EU report and the European Waters assessment. These were not analysed as a basis for the RB (BIOMONDO, 2022) but are included below to provide some information on specific European freshwater issues.

EU Ecosystem Assessment

The EU Ecosystem Assessment (Maes et al., 2021) was performed by a working group for Mapping and Assessment of Ecosystems and their Services. It provides a detailed review of the state of the European ecosystems. It is an analysis of the pressures and the condition of terrestrial, freshwater and marine ecosystems and their services using a single, comparable methodology based on European data relative to the baseline year 2010. The assessment was further enhanced and tested by ESMERALDA, a coordination and support action funded under the Horizon 2020 programme for research and innovation. The five main elements include a conceptual frame to link ecosystems and biodiversity to people via indicators of change and ecosystem services, and ecosystem typology, and indicators to assess ecosystem condition, services and pressures. The EU Ecosystem Assessment includes two separate chapters for freshwater ecosystems, Chapter 3.10: *Wetlands* and Chapter 3.12: *Rivers and Lakes*.

It reports that:

- Wetlands are the ecosystem type with the worst condition in Europe
- 90% of wetlands bad to poor conservation status with small signs of improvement
- Since 2000, domestic pollution and nitrogen atmospheric deposition to rivers and lakes have declined
- Emissions from agricultural land remain high
- Invasive alien species are widespread
- Land take in riparian zones and floodplains remains significant

State of Nature in the EU

The State of Nature in the EU report (European Environment Agency, 2020) evaluates the effects of the EU Nature Directives and reports on how different pressures affect different habitats and species. The results come from Member state reporting under the nature directives 2013-2018. Hydrological flow modifications are reported to be the pressure with the most significant impacts on European freshwaters. This pressure is mostly related to running water and includes modification of flooding regimes or cutting of aquatic and bank vegetation to improve water flow. Physical alterations of water bodies constitute one of the main pressures on freshwater fish. Other major pressures result from the removal of sediments, building of dams and weirs, canalisation, and water deviation. Most figures are reported as parts of overall pressures, which complicates the extraction of precise numbers for freshwater ecosystems.

The assessments of the State of Nature in the EU synthesise the work of the EEA′s European Topic Centre on Biological Diversity and the information reported by EU Member States for the implementation of the Birds Directive (Article 12) and the Habitats Directive

(Article 17). Other information sources include the European Environment Information and Observation Network (EIONET), Corine Landcover and the Natura 2000 database.

European Waters Assessment

The European Waters Assessment (European Environment Agency, 2018) reported that around 40 % of surface waters (rivers, lakes and transitional and coastal waters) are in good ecological status or potential, but only 38 % are in good chemical status. The assessment also 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". This report points out that hydropower must be extended to achieve renewable energy targets, but that it is important for EU policies promoting hydropower to be compatible with the objectives of the WFD and consider impacts on water bodies.

The European Waters Assessment is based on the results reported for the 2nd round of River Basin Management Plans (RBMP; 2013-2018) by the EU Member States. It includes an outline of the pressures that have been causing less than good status as well as the progress that was achieved during the first RBMP cycle (2010-2015). The assessment is based on the Water Information System for Europe (WISE)[3]. WISE provides detailed and continuously updated data on Europe's rivers, lakes, groundwaters, on the pressures affecting them, and on the measures and actions taken to protect them.

The third RMBP cycle (2022-2027) is under way and efforts are being made to improve methods to enhance comparison between countries and RMBP cycles. Lyche Solheim et al. (2020) provide an overview of comparability of ecological status assessments and issues relating to the variability of the use of the quality elements from the previous RMBP cycles and the outputs should give valuable insights for the 3rd RMBP as well as support efforts to streamline biodiversity assessments relevant for the 2030 Biodiversity Strategy.

Overall, the main pressures on surface water bodies are:

- Hydro-morphological pressures (40 %)
- Diffuse sources (38 %), particularly from agriculture, and atmospheric deposition (38 %), particularly of mercury
- Point sources (18 %) and water abstraction (7 %)

3 Monitoring freshwater biodiversity

3.1 Biodiversity observation networks

Over the last decades several biodiversity observation, networks and systems have been developed by different global and regional partners and organisations to try to collate biodiversity related data. An overview of selected examples is provided in Table 1, and an exhaustive list of partnerships is provided in BIOMONDO deliverable D6.1 (BIOMONDO, 2024) including EO relevance. Closely related to these systems are different networks that aim to facilitate sharing of tools and latest scientific results as well as enabling

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[3] https://water.europa.eu/freshwater

communication between different sectors and procure information for policy. Most facilities now operate under the FAIR principle (Findable, Accessible, Interoperable and Reusable).

Table 1: List of selected organizations that promote monitoring of biodiversity or freshwaters in Europe and worldwide. See Table 5 for complementary information on how these organizations use EO to achieve their mandate.

Organization name(s)	Type	Main purpose/contribution	URL
A Long-Term Biodiversity, Ecosystem and Awareness Research Network (ALTER-Net)	Research collaboration/NGO	Science-policy interface mechanism Eklipse	https://alterneteurope.eu/
bioDISCOVERY of Future Earth	Research collaboration	Research programme network	https://biodiscovery.earth/
Biodiversa+	EU collaboration	Science-policy partnership, EU Biodiversity Strategy 2030	https://www.biodiversa.eu/
EEA, EC and the Knowledge Centre for Biodiversity (KCBD)	EU collaboration	Biodiversity Information System Europe (BISE)	https://biodiversity.europa.eu/
EEA and EC	EU collaboration	Water Information System Europe (WISE)	https://water.europa.eu/freshwater
EEA and 400 organisations from 38 countries	EU collaboration	European Environment Information and Observation Network (EIONET)	https://www.eionet.europa.eu/
Freshwater Information Platform (FIP)	Research collaboration	Freshwater Biodiversity Data Portal	http://www.freshwaterplatform.eu/
Global Biodiversity Information Facility (GBIF)	Intergovernmental	International network and data infrastructure	https://www.gbif.org/
Global Lake Ecological Observatory Network (GLEON)	Research collaboration	Lake Data Portal	https://gleon.org/
Group on Earth Observation Biodiversity Observation Network (GEO BON)	Research collaboration	EBV data portal and analyzer, Bon in a Box	https://geobon.org/
International Union for Conservation of Nature (IUCN)	Intergovernmental	Red list, green list and other conservation tools including global ecosystem typology	https://www.iucn.org/
Ramsar Convention on Wetlands	Intergovernmental	Conservation of selected Ramsar sites	https://ramsar-monitoring.org/
UNDP, UNEP-WCMC, CBD	UN collaboration	UN Biodiversity Lab (UNBL), Global Knowledge Support Service for Biodiversity (GKSSB)	https://unbiodiversitylab.org https://gkssb.chm-cbd.net/
World Wildlife Fund for Nature (WWF)	NGO	Global Observation and Biodiversity Information Portal (GLOBIL)	https://globil.panda.org/

Common goals of these biodiversity observation systems are to gather and make accessible species records and derived indices and other spatial and temporal aggregates. Probably the biggest source of original data is the Global Biodiversity Information Facility (GBIF), an international network and data infrastructure funded by the world's governments to provide open access to millions of records of life on Earth, e.g., species occurrence data. However, 79% of GBIF data comes from ten countries, and 37% from USA (Hughes et al., 2021). The authors' analysis represents a comprehensive global analysis of both marine and terrestrial data, their spatial and taxonomic coverage, the biases encountered and the drivers of these biases. Organisations such as GEO BON, UNEP, IUCN, Ramsar and GEO support such observation systems and they also, in their own right, gather data for sharing, assessment, monitoring and reporting.

3.2 From data to actionable information

Effective actions should be based on information that is scientifically valid, based on available data, responsive to change, easily understandable, relevant to users' needs, championed by an institution responsible for its continued production and communication, and used[4]. A lot of dynamic indicators refer to the driver, pressure, state, impact, response (DPSIR) scheme, which link human activities, ecological dynamics, and social goals (Levrel et al., 2009; Smeets and Weterings, 1999). Recent exercises to try to align habitat and classification schemes used at different levels for linking with biodiversity and policy goals have shown that there are many complex issues related to definitions, class hierarchies and descriptions including approaches to overcome problems with inconsistencies and lack of harmonisation.

To complement the chapters on knowledge gaps and research priorities, we give below, a short, non-exhaustive overview of ecosystem and habitat classifications (IUCN, MAES, EUNIS), and essential variables and indicators in use.

IUCN ecosystem typology

A globally consistent ecosystem classification framework has been lacking, which has hampered development of conservation targets and sustainability goals. In 2022, IUCN published a new function-based ecosystem typology and definitive classification scheme, which has been developed by ecologists in response to the demands of the new global biodiversity framework (Keith et al., 2022). It is described as a "conceptually robust, scalable, spatially explicit approach for generalizations and predictions about functions, biota, risks and management remedies across the entire biosphere". It is hoped to facilitate integrated ecosystem assessments by combining ecosystem function and composition with biotic and abiotic drivers. The generic model of ecosystem assembly underlying the Global Ecosystem Typology consists of abiotic (resources, the ambient environment and disturbance regimes) and biotic (biotic interactions and human activity) drivers that filter assemblages and form evolutionary pressures that in turn, shape ecosystem-level properties.

The IUCN ecosystem typology consists of six hierarchical levels (Figure 5), with exploration and analysis of the three upper levels, including maps, available on the IUCN website/portal[5]. The three upper levels are realms (2), functional biomes (2) and ecosystem

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[4] https://www.bipindicators.net/national-indicator-development

[5] https://global-ecosystems.org/

functional groups (3). These levels classify ecosystems based on their functional characteristics (such as structural roles of foundation species, water regime, climatic regime or food web structure) in a top-down approach. The three lower levels are biogeographic ecotypes (4), global ecosystem types (5) and sub-global ecosystem types (6) where the latter two provide nested bottom-up links to level 3 and are often already in use in policy infrastructures at regional or local scales, which is important as it is at these levels ecosystem-specific knowledge and data reside and conservation action takes place.

Freshwater is recognised as a core realm besides marine, terrestrial, subterranean and atmospheric. It consists of 3 biomes (rivers and streams, lakes and artificial wetlands) and 22 functional groups.

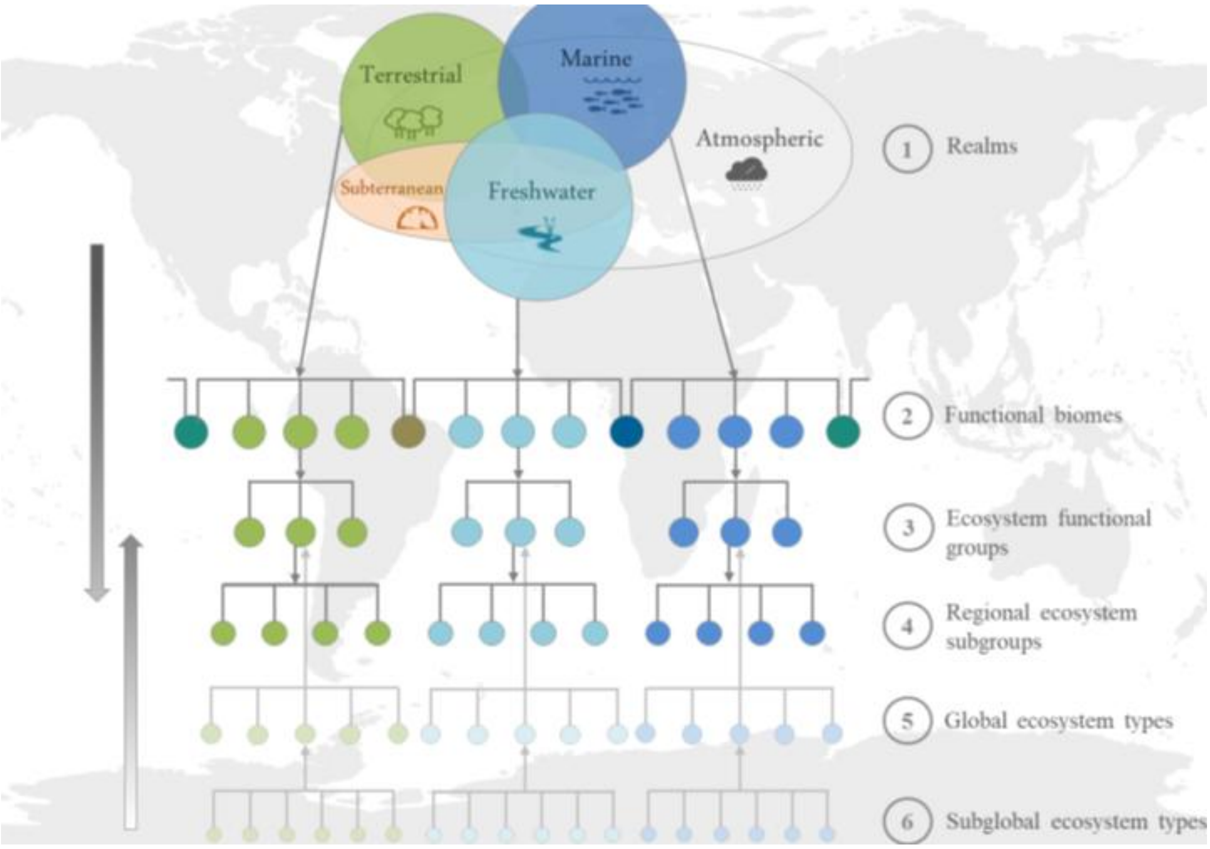

Figure 5: Hierarchical structure of IUCN Global Ecosystem Typology showing a combination of top-down and bottom-up approaches (from Keith et al., 2022).

The functional groups for lakes are: "large permanent freshwater lakes, small permanent freshwater lakes, seasonal freshwater lakes, freeze-thaw freshwater lakes, ephemeral freshwater lakes, permanent salt and soda lakes, ephemeral salt lakes and artesian springs and oases. For rivers and streams the division is based on permanent or ephemeral, upland or lowland, freeze-thaw etc. For each functional group a scheme has been devised showing ecological traits and drivers and interrelationships (see an example in Figure 6 for Large permanent lakes). We think that information for several of the components shown can be derived from EO and provide spatially explicit data over time (see section 5.1.)

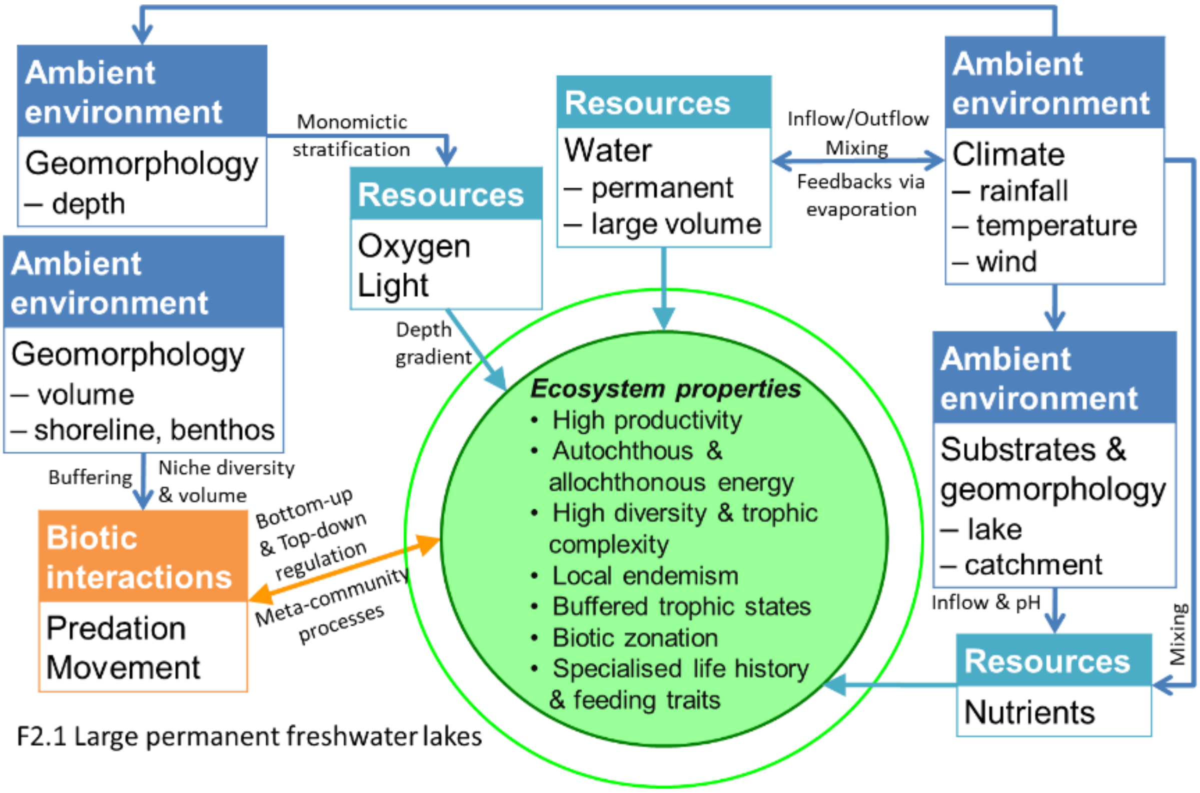

Figure 6: IUCN Ecosystem Typology scheme example for 'F2.1 Large permanent freshwater lakes' with ecological traits and key ecological drivers (from Keith et al., 2022).

In Keith et al. (2022), a review of 23 global ecosystem and habitat classification frameworks were undertaken (their Appendix 1), which concluded that none of them meet the six design principles devised and determined necessary for a stable and scalable global ecosystem typology by IUCN, namely:

1. Representation of ecological processes & ecosystem functions
2. Representation of biota
3. Conceptual consistency throughout the biosphere
4. Scalable structure
5. Spatially explicit units
6. Parsimony & utility

MAES Mapping and Assessment of Ecosystems and their Services

MAES, the European ecosystem typology used for the EU assessment (Maes et al., 2021) was derived from the time series of CORINE Land Cover data (CLC), which constituted a reference dataset for the assessment. It was used to delineate the extent of ecosystems in the EU, to analyse the trends in the extent of ecosystems and as an input layer for the calculation of trends of specific ecosystem condition indicators as well as linking to ecosystem accounting parameters. An Ecosystem map[6] (current version 3.1) was produced by the EEA from a combination and refinement of CLC classes with EUNIS habitat information although it was not used for the ecosystem assessment as it is only available for one point in time (2012). Updates to the ecosystem types should be (will be?) reflected in new versions of the map.

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[6] https://www.eea.europa.eu/data-and-maps/data/ecosystem-types-of-europe-1

IUCN habitat classification

The IUCN 2012 Habitat classification scheme 3.1[7] that underpins the IUCN red list of ecosystems, consists of 3 hierarchical levels where aquatic habitats are included in 5 – Wetlands (i.e. the Ramsar classification scheme) although it is acknowledged that this is not entirely satisfactory, and a review is called for.

EUNIS habitat classification (and WFD typology)

The European Nature Information System (EUNIS) is a reference information system for ecology and conservation[8]. It is a comprehensive pan-European system to facilitate the harmonised description and collection of data across Europe through the use of criteria for habitat identification. It covers all types of habitats from natural to artificial, from terrestrial to freshwater and marine. In EUNIS, a habitat type is defined based on plant and animal communities as the characterising elements of the biotic environment, together with abiotic factors operating together at a particular scale.

EUNIS contributes to the knowledge base for implementing the Biodiversity Strategy 2030 and is used to assist the Natura 2000 process (EU Birds and Habitats Directives) and the development of indicators.

The publicly available data and information in the EUNIS database includes:

- Data on species, habitat types and designated sites compiled in the framework of Natura 2000 (EU Habitats and Birds Directives)
- The EUNIS habitat classification
- The European Red List of habitats
- Data from material compiled by the European Topic Centre of Biological Diversity
- Information on species, habitat types and designated sites mentioned in relevant international conventions and in the IUCN Red Lists
- Specific data collected in the framework of the EEA's reporting activities

The EUNIS classification scheme, first developed in the 1990s, has been revised a couple of times over the years. Figure 7 shows a detailed *Level 2* class hierarchy for surface standing waters (C1) based on biological, hydrological and physical attributes.

More recent revisions propose schemes in which a better comparable level of attribute detail is organised on lower levels. European countries have defined >1000 national river types and >400 national lake types to implement the EU Water Framework Directive (WFD). Common river and lake types have been defined but only a low proportion of national types correspond to intercalibration types which has caused uncertainty concerning whether the classification of ecological status is consistent across countries. Hence, a new typology was devised to reflect the natural variability in the most commonly used environmental type descriptors: altitude, size and geology, as well as mean depth for lakes (ETC/ICM, 2015; Lyche Solheim et al., 2019). In 2022, a revision of the EUNIS inland water habitat group was conducted by ETC BD (Arts et al., 2022). It proposes that *Level 2* separates running from standing waters and provides a finalisation of *Level 3* by accounting for geology, altitude and catchment size attributes with an outlook future development needed for *Level 4* to deal with further habitat attributes including biological information.

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[7] https://www.iucnredlist.org/resources/habitat-classification-scheme

[8] https://eunis.eea.europa.eu/about

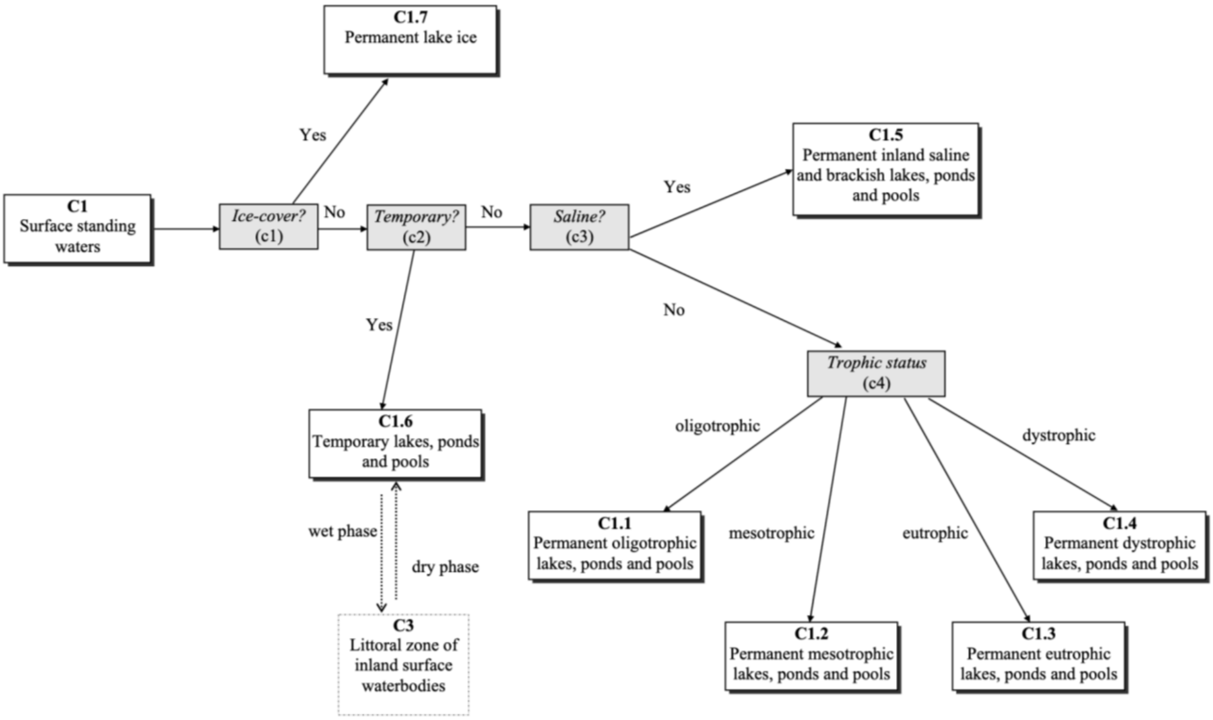

Figure 7: EUNIS habitat classification criteria for 'Surface standing waters' **(type "C1"; from Davies et al., 2004)**. Level C is 'Inland waters', with C2 being 'Surface running waters' and C3 'Littoral zone of inland surface water bodies'.

Essential Biodiversity Variables

Essential Biodiversity Variables (EBVs) were defined to describe the state of genomes, species, populations, or ecosystems that provide a common foundation for trend detection and 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 EBV (Gonzalez et al., 2023b, 2023a). Six general classes of EBV have been defined (see also Appendix A.1).

- Genetic composition
- Species populations
- Species traits
- Community composition
- Ecosystem functioning
- Ecosystem structure

Freshwater BON (FWBON) identified species populations, community composition and ecosystem structure as priority EBV classes identified for action for Freshwater biodiversity (Turak et al., 2017).

However, although the six classes of EBVs have remained stable over the last decade a lack of global consensus on which key aspects of biodiversity to monitor remains, with several EBVs often missing in national or regional monitoring programs. Steps are being undertaken to remedy the situation and a public review of EBVs and drawing on a large body of expert advice was undertaken by EuropaBON (Junker et al., 2023; Lumbierres and Kissling, 2023) resulting in 84 EBVs being identified across terrestrial, marine and freshwater realms. The list and descriptions available on GITHUB[9]. A comparison between GEO BON and Europa BON EBV names for freshwater is included in Appendix A.1.

Essential Ecosystem Services Variables

More recently, the GEO BON Ecosystem Services Working Group has also proposed Essential Ecosystem Services Variables (EESV) that extend the EBV concept to include also social, cultural, economic and knowledge-based systems (Balvanera et al., 2022), which highlight aspects of essential variables that represent nature's contribution to people.

EESVs are grouped into six classes: Ecological supply, Anthropogenic contribution, Demand, Use, Instrumental value, and Relational value. The workflow developments of EESVs have been addressed in recent years (Balvanera et al., 2022) and EESVs are considered ready for monitoring but are perhaps not as far advanced as EBVs, especially not when it comes to realising the potential of Earth observation although work is being carried out to prioritise research in this domain (Cord et al., 2017).

Biodiversity change indicators

Primary observations, model simulations, EBVs and biodiversity change indicators require complex interdisciplinary workflows to ultimately result in actionable information (Figure 8). However, indicators and information obtained in such manner is often specific to regional or national scales, and their translation for global reporting on biodiversity change can be a significant challenge (Bhatt et al., 2020; Guerra et al., 2019).

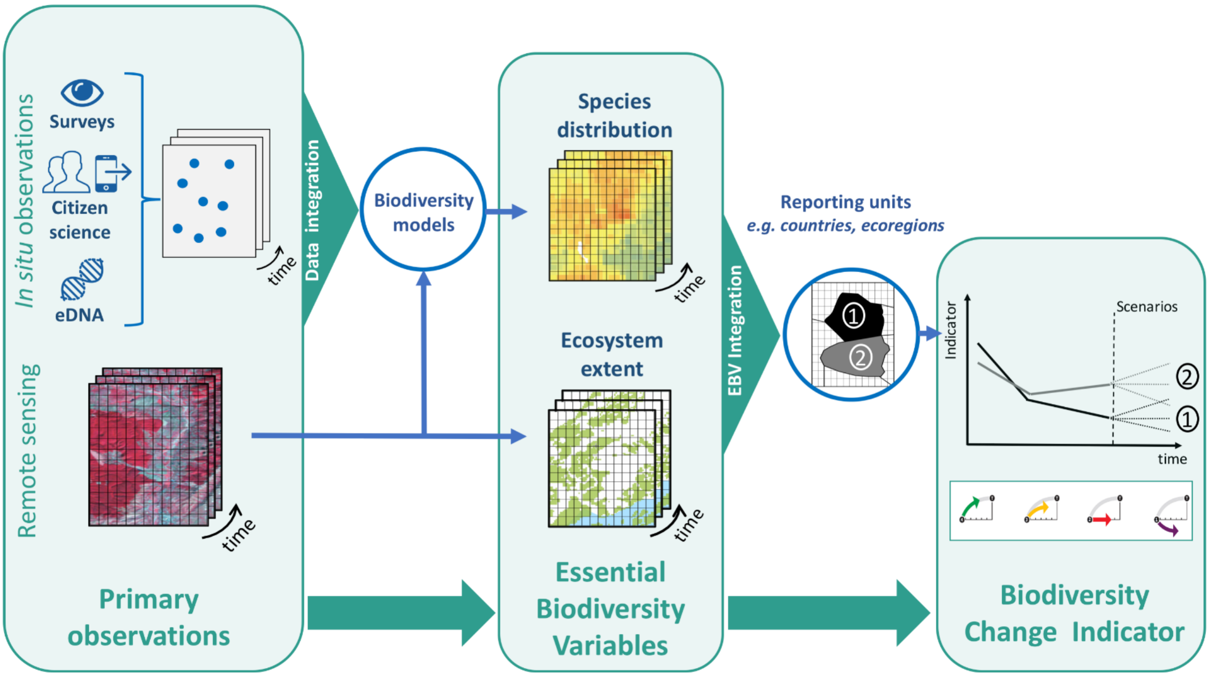

Figure 8: Relationship between primary observations, biodiversity models, EBVs and biodiversity change indicators (from Navarro et al., 2017).

Biodiversity change indicators are needed to assess trends and determine areas of urgent action. They represent a way to simplify the relationship between observations and the

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[9] https://github.com/EuropaBON/EBV-Descriptions

detected changes for policy makers so that appropriate mitigation measures can be implemented with improved chances of meeting set targets.

Examples of indicators for use to monitor biodiversity change include:

- Living Planet Index
- IUCN Red List Index
- Species Habitat Index
- Biodiversity Habitat Index
- Biodiversity Intactness Index
- Mean Species Abundance (MSA; Alkemade et al., 2009)
- Biodiversity Intactness Index (BII; Scholes and Biggs, 2005)
- Change in the extent of water related ecosystems over time

In 2023, the CBD (AHTEG on Indicators for the KM-GBF) developed an updated list of indicators (headline, binary, component and complementary indicators) including information on operationalisation of headline indicators based on the IUCN global ecosystem typology to advance the monitoring framework of the KM-GBF and establish a common basis for reporting for nations worldwide[10]. As mentioned above, the new IUCN Global Ecosystem Typology is “a comprehensive classification framework for Earth’s ecosystems that integrates their functional and compositional features”. The aim is to help identify the ecosystems that are most critical for biodiversity conservation, research, management and human wellbeing into the future. Level 3 is used together with “realm” for possible disaggregation of the headline indicators. Another example of CBD/UNEP WCMC support for sustainable development is the UN Biodiversity Lab[11] that aims to provide access to global data (currently 400 data layers) that can be used to calculate indicators to implement national biodiversity strategies and action plans that are aligned to the GBF. One of the cross-boundary areas featured in the map tool is the Mekong River basin.

3.3 Remote sensing of freshwater biodiversity

EO is the gathering of information about the physical, chemical, and biological systems of the planet Earth through remote sensing. Our analysis of the EO potential for monitoring of the main drivers of global environmental change (BIOMONDO, 2022) demonstrated that satellite observations are increasing our understanding of the dynamics of water systems, their riparian borders and catchments. Satellite remote sensing is crucial for getting long-term global coverage and allows for time series analysis and change detection. It can rapidly reveal where to reverse the loss of biological diversity on a wide range of scales in a consistent, borderless and repeatable manner.

Remote sensing can be done over large areas, including remote areas, and at a relatively high temporal resolution. Remote sensing techniques are thus ideal when monitoring changes in environmental variables (see Table 2) over time and across space, whose signals can be measured in the domains of the electromagnetic spectrum at a relatively large spatial scale (Figure 9). In doing so, EO sensors can resolve processes and objects at meter to kilometre scale, i.e. ecosystem level, and signatures in the optical and thermal domain, e.g. photosynthetic pigments. Therefore, applications are often based on ecosystem-scale estimates of primary production or environmental drivers, from which other parameters

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[10] https://global-ecosystems.org/

[11] https://unbiodiversitylab.org/en/

of interest may be derived. Here we describe in a very abbreviated form the state of the art for the most common applications for freshwater ecosystems.

Table 2: List of lake properties, response variables (modified from Adrian et al., 2006) and related remote sensing indicators (modified from Dörnhöfer and Oppelt, 2016).

Lake properties	Response variables	Remote sensing indicators
Transparency	Dissolved Organic Carbon	Coloured dissolved organic matter
	Turbidity	Suspended particulate matter Turbidity Diffuse attenuation
	Transparency	Secchi depth Euphotic depth
Biota	Algal blooms	Chlorophyll-*a* (phytoplankton) Phycocyanin (cyanobacteria)
	Phenology	Time series analyses of chlorophyll-*a*
	Primary productivity	Trophic state index
	Species composition	Submerged aquatic vegetation
Hydrology	Water level	Bathymetry
Temperature	Epilimnic temperature	Surface temperature

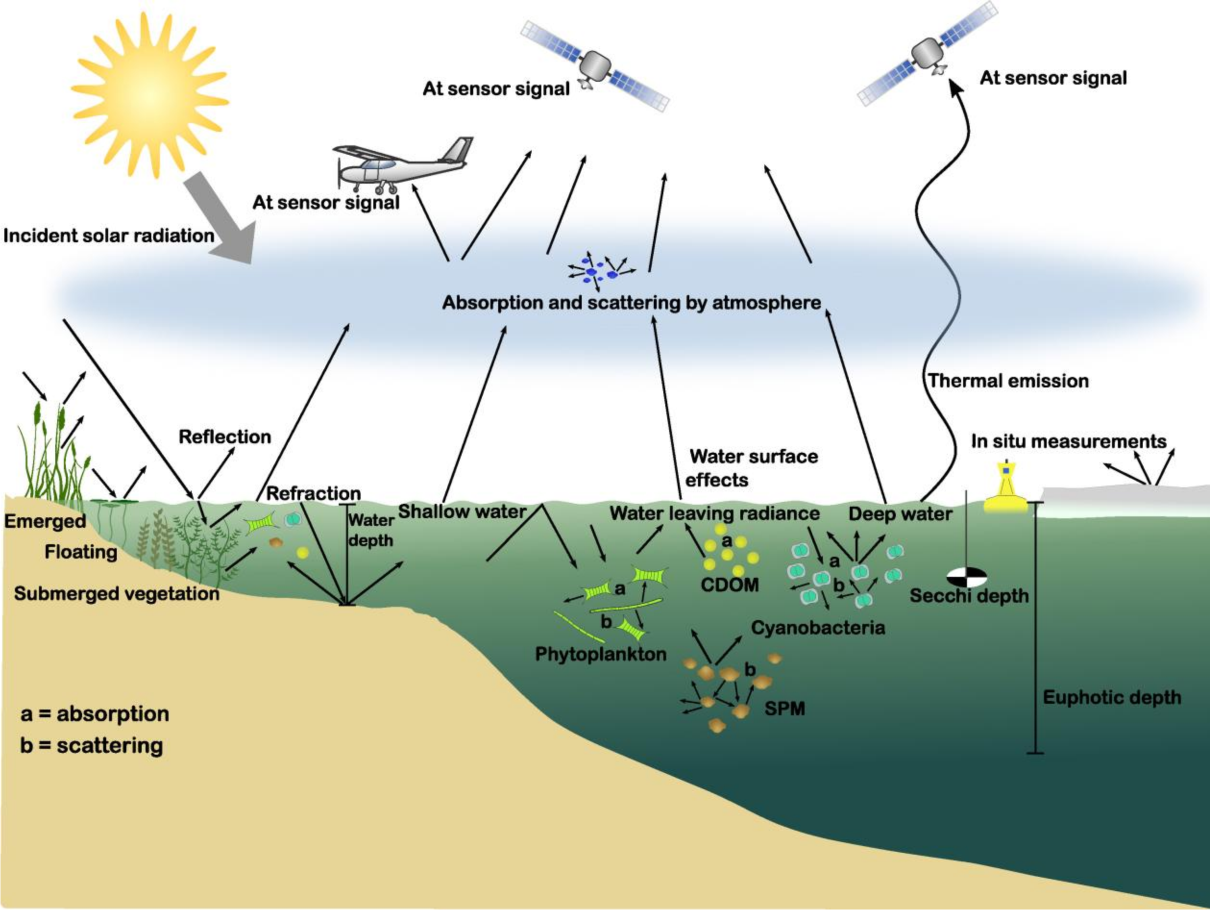

Figure 9: Interaction between radiation, remote sensing indicators of lake ecology, and sensors (from Dörnhöfer and Oppelt, 2016).

Below we summarise currently employed methods for some of the main freshwater applications where EO plays an important role including a list of operational services and products in use and upcoming missions. They describe a state of the art which is later referred to with regards to biodiversity knowledge gaps that EO can fill (section 4.3) and subsequent research priorities (section 5).

Mapping of freshwater ecosystems and habitat types

Remote sensing can be used to understand land use and land cover change in a watershed, habitat connectivity along a water body, water body location and extent, and water quality parameters. EO data, especially optical satellite data (i.e. Landsat suite, Sentinels), from different platforms have for many years been utilised to map land use and land cover (LULC), and changes over time (LULCC). Such data have been used to support delineation and characterization of both terrestrial and freshwater ecosystem and habitat types for various classification schemes depending on the spatial, temporal and radiometric requirements and data availability. Increasingly finer spatial, temporal, radiometric, and spectral resolutions and additional types of data (i.e. radar, lidar, hyperspectral, UAVs/drones), novel pre-processing correction algorithms, modelling and data fusion methods have improved how well different freshwater ecosystems and habitat types can be determined (Kuiper et al., 2023). Methods often include supervised or un-supervised pixel- or object-based classifiers (Maximum likelihood, Random Forest etc.) applied to spectral data or spectral indices using known training data to determine different habitat types together with ancillary data such as elevation and soil types.

Changes in vegetation/land cover spectral response over time are used to assess structures, biomass and productivity, which can be related to many different environmental change aspects including drivers of biodiversity change.

Accurate delineation of water bodies including lakes, ponds, rivers and streams is essential for monitoring freshwater ecosystem condition and changes. The support that EO data can provide to the potential classification of lakes that is required for status assessments and change monitoring is further described in section 4.3. Surface water location, seasonality and long-term changes to large water bodies have been determined using the Landsat archive and these products have been utilized to determine the global data sets using for example the JRC's Global Surface Water (GSW) dataset[12] and for F2.1 Large permanent freshwater lakes, one of the functional groups of the IUCN Global Ecosystem Typology (see section 3.2). Freshwater habitat mapping for specific species or species groups (e.g. fish, macrophytes, aquatic plants, phytoplankton) is still nascent and further characterization is needed to be able to better utilize remote sensing products and guide developments needed (Keith et al. 2022).

For wetlands and flood plain mapping, the increased ability to over time discriminate open water from vegetation growing in the water (including some macrophytes) and floating vegetation has meant that delineation of wetlands has improved. It includes changes to wetland extent, flood plain extent and heterogeneity, and water cycle regimes. Some regional wetland habitat mapping (e.g. tidal flats, mangrove forests, salt marshes) has advanced strongly according to Zhang et al. (2024) even if detailed global wetland habitat coverage is still missing for many inland wetland types (e.g., swamps and marshes). The authors present novel global 30 m annual wetland maps (GWL_FCS30D) with eight wetland subcategories using time-series Landsat imagery on the Google Earth

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[12] https://global-surface-water.appspot.com/

Engine platform. A series of high-resolution global thematic wetland products were generated, including water bodies, tidal flats, mangrove forests, and salt marshes. Most of these products belong to coastal wetlands, and the high-resolution mapping of global inland wetlands (e.g., swamps and marshes) is sparse. As part of the Horizon2020 project SWOS different wetland indicators were developed based on a range of remote sensing analysis methods applied to optical and radar satellite data together with DEM metrics and modelling of stream riparian zones, i.e. a Wetland Extent indicator and its sub-indicators - such as Natural Wetland Extent, Artificial Wetland Extent, Vegetated Wetlands Extent, Open Water Bodies and River Water Bodies, which were integrated to calculate the SDG 6.6.1 indicator (Weise et al., 2020).

Validated LCLU products are now available at different scales and coverage for different time stamps, for example the global LC coverage from Copernicus dynamic LC 'Algorithm'[13], European LCLU coverage from CORINE[14] and Globwetland Africa's wetland example products for some African sites[15]. There is also the Riparian Zones layer of the CLMS Portfolio but only so far for 2012 and 2018, including a change layer. To increase its usability for monitoring of these important freshwater ecosystems repeat mapping is required, i.e. continue the six-year mapping cycle. The CLMS HR layer water and wetness for Europe product (Table 3) "leverages both Sentinel-1 and Sentinel-2 images to enable effective mapping of land cover characteristics such as permanent water bodies, transitional water bodies, and soil wetness".

Phytoplankton diversity, productivity and phenology

The potential for characterizing phytoplankton and its growth in optically complex waters is basically the same as the applications known from Ocean Color remote sensing. However, the larger proportion and greater variability of Coloured Dissolved Organic Matter (CDOM) and Total Suspended Matter (TSM) makes it difficult to determine almost all parameters. Therefore, we currently use a pre-classification of optical water types (Moore et al., 2014; OWT; Spyrakos et al., 2018) for the production of global chlorophyll-*a* (chl-*a*, or, as an aggregate, Trophic State Index TSI) data products, for which various blended band ratio algorithms are applied. Other than that, the optical properties of cyanobacteria are sufficiently different from eucaryotes to facilitate a robust discrimination at moderate and high abundances (Matthews et al., 2012; Simis et al., 2005). The optical properties of many other phytoplankton taxa are well known (Lomas et al., 2024; Xi et al., 2017), but an estimation of their relative abundance is only possible with a high level of previous knowledge of the taxa present (Zheng and DiGiacomo, 2018). Therefore, the great success of remote sensing based marine Phytoplankton Functional Types (PFT), (see roadmap in Bracher et al., 2017) has not yet been transferred to inland waters. However, the increasing availability of hyperspectral data is expected to enable similar developments in the next years.

Phytoplankton phenology retrieval based on MERIS, MODIS or OLCI chl-*a* products were analyzed for many lakes and lake regions (e.g., Benzouaï et al., 2020; Maeda et al., 2019; Palmer et al., 2015; Shi et al., 2019), and a study based on colorimetry rather than chl-*a* even identified phenology shifts across 26'000 lakes (Topp et al., 2021). However, there is no established standard method for lake phenology retrievals yet. This task is complicated by the shorter time scales and less regular seasonal patterns at which phytoplankton abundance varies, in

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[13] https://land.copernicus.eu/en/products/global-dynamic-land-cover/copernicus-global-land-service-land-cover-100m-collection-3-epoch-2019-globe

[14] https://land.copernicus.eu/en/technical-library/clc-2018-technical-guidelines/@@download/file

[15] http://globwetland-africa.org/?page_id=15

comparison to terrestrial vegetation. We are currently investigating adequate methods for phytoplankton phenology retrievals on the basis of chl-*a* products from the ESA CCI processing chain[16].

Primary production can be modeled from a combination of two EO products, namely pigment concentration or absorption, and diffuse absorption or Secchi depth. Together with estimates of downwelling irradiance and a parameterization of photon use efficiency, photosynthetic light availability can then be modeled, in theory, at all depths and wavelengths, allowing for accurate retrievals based on semi-analytical models (Silsbe et al., 2016). In practice, simplified models assuming uniform spectral attenuation, vertical gradients and photon use can be used when previous knowledge of these variables is not available (Sayers et al., 2020). One main limitation for the broad use of such products is however that reference measurements of primary production require incubation of carbon isotopes during long periods, they are hence laborious and scarce, in particular in comparison to chl-*a* measurements. Operational products for lakes are therefore to our knowledge currently not available, not even at the scale of regions or individual lakes.

Lake surface water temperature and thermal structure

Lake Surface Water Temperature (LSWT) is an Essential Climate Variable that can be routinely estimated using surface emitted radiance around 11 and 12 µm (A/ATSR, SLSTR, TIRS). Future satellites will explore also adjacent thermal infrared wavelengths, e.g. 8-9 µm in case of Trishna. Individual retrievals using mono or split window algorithms (Hulley et al., 2011; Oesch et al., 2005) can be tuned further in the temporal domain, e.g. using optimal estimation (MacCallum and Merchant, 2012). Global and regional operational LSWT products are available from a range of sources, most prominently Copernicus and ESA CCI. Their main limitation is a spatial resolution of 1 km, which limits the application potential to the few thousand largest lakes in the world. 100 m resolution LSWT is distributed within Landsat Collection 2 products, but subject to longer revisit times of eight days for Landsat-8 and Landsat-9.

Water temperature largely determines lake water stratification, and stratification is key to near-surface nutrient availability and deep-water oxygen renewal. This is why vertical temperature gradients are a key information in lake research. LSWT represents however only the top micrometres of lake water, which why it was predominantly used for decadal warming trend estimations. But lately, it was reported how seasonal stratification and mixing in large temperate lakes can be estimated by means of a 4° LSWT threshold representing the temperature of maximum density (Fichot et al., 2019). This threshold, occurring as a longitudinal thermal bar in very large lakes, indicates vertical mixing when it passed the entire lake during a given winter. With this approach, 20 lakes that experienced mixing anomalies in the past 20 years (e.g. from dimictic to oligomictic) could be identified from the CCI LSWT products (Calamita et al., in preparation). Further detail on vertical temperature gradients in lakes, e.g. the thermocline depth, requires 1D hydrodynamic models (see BIOMONDO pilot 2, section 4.4). LSWT from EO can make a significant contribution to the calibration and validation of such models.

River connectivity

Remote sensing to determine river connectivity is generally based on mapping obstructions including different infrastructure development to determine stretches that are

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[16] https://www.bgbphenology.com/

impeded or remain un-impeded. Grill et al. (2019) produced a global dataset of the world's remaining free flowing river stretches using data from globally available remote sensing products, other data compilations, or numerical model outputs, such as discharge simulations to calculate six proxy indicators for six pressure factors (river fragmentation, flow regulation, sediment trapping, water consumption and infrastructure developments in riparian and floodplain areas. The remote sensing products used are available from the HydroSHEDS platform[17], e.g. HydroBASINS, HydroFALLS and HydroLAKES) and the determination of the level of free flow/connectivity status was based on calculations of a Connectivity Status Index (CSI) for river segments.

The major structures causing habitat fragmentation and obstructions to species dispersal routes that can be mapped using remote sensing are hydropower reservoirs, where the actual mappable component can be inferred from the change of a stretch of river into a water body and other changes to the catchments. Location of dams can also be determined with high resolution satellite data, at least to some extent. Recent dam inventories using EO data such as the Global Dam Tracker (Zhang and Gu, 2023) now includes 35 000 dams worldwide. It builds upon existing global and regional dam databases such as FAO AQUASTAT[18] and the Global Reservoir and Dam Database (GRanD) (Lehner et al., 2011) in combination with various state-of-the-art satellite data products. An algorithm was developed to obtain reservoir and catchment areas associated with dams in GDAT, which allows for inter-temporal analysis of the impact of dam constructions. Another updated source of dam information is GeoDAR (Wang et al., 2022), who have produced comprehensive updates to the geolocation of global dams and reservoir boundaries with the support of EO data including radar altimetry also aspire to improve future assessments of reservoir dynamics (water storage and surface evaporation) and impacts of human water regulation in light of expanding satellite constellations (e.g., Sentinel-6 or SWOT), see also section 4.4. In addition, the Global Dam Watch (GDW)[19] directory of databases (GDW-d) provides summary information and links to a wide range of global, regional and national dam datasets (Mulligan et al., 2021).

Also changes to river water quality is obtainable by remote sensing, especially turbidity, and such products can be used to infer changes to the hydrodynamics of river systems due to climatic and/or human disturbances (Kuhn et al., 2019). Water consumption and infrastructure development in riparian areas and floodplains, including roads, urbanization and levees, are important drivers of change in rivers where dams are less common (Grill et al. 2019) and some of these can be obtained using remote sensing analysis of multi- and high-resolution optical satellite data.

Operational services and products

Various data sources are already available to support assessments and monitoring of biodiversity or its drivers (Table 3), although they may require further processing for effective utilization. It is crucial that the limitations of these services are considered, such as potential constraints in spatial and temporal resolution, particularly notable for smaller freshwater ecosystems. The parameters available from these services may be limited, requiring their combined use with biological, chemical and physical models. Processing capabilities from service providers becomes instrumental, filling the gap for tailored

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[17] https://www.hydrosheds.org/

[18] https://www.fao.org/aquastat/en/

[19] https://www.globaldamwatch.org/directory

ecosystem research questions. This currently allows a deeper understanding and effective utilization of available EO data sources.

Table 3: Operational EO services and the inland water parameters they provide.

Data Source	Parameters
CLMS PAN LCLU	LULC (Europe only)
CLMS PAN European settlement map	LULC urban class (Europe only)
CLMS PAN HR Water & Wetness	Water area change (Europe only)
CLMS LOCAL Riparian Zones	LULC (Europe only)
CGLOPS Lake Ice Extent	Lake ice
CGLOPS Inland Water Products	TSI, TSM, LSWT
CGLOPS Lake Water Level	Water level
CCI+ Lakes	LSWT, lake ice, water colour, chl-*a*, turbidity, water extent
C3S LC	LULC
JRC Global Surface Water Explorer	Water extent
Global Forest Change Univ. Maryland	LULC
ESA Worldcover	LULC

Future Earth observation missions

Planned EO missions and services are the basis for recommendations for extension of the activities and setting of future research agendas. There are several relevant future data sources which have potential use for biodiversity assessment and monitoring (Table 4). Some potential BD parameters need to be evaluated and determined once the data sources are open to use.

Table 4: New and upcoming EO missions and their main data products.

Mission name	Products
BIOMASS (ESA Earth Explorer)	Biomass, LULC
CHIME	chl-*a*, algal groups, phenology
EnMAP	chl-*a*, TSM, TUR, algal groups, submerged and floating vegetation, LULC
FLEX (ESA Earth Explorer)	Phytoplankton fluorescence
Landsat-9	chl-*a*, TUR, submerged vegetation, floating vegetation, LULC, LSWT
Sentinel-6 (Jason cont.)	Water level (altimetry)
Sentinel-2 Next Generation	chl-*a*, TUR, submerged vegetation, floating vegetation, LULC
SWOT	Water level (interferometry)

Uptake of EO in biodiversity assessment workflows

The aforementioned potential to use EO data for biodiversity assessments is increasingly used by national, international and non-governmental conservation agencies. Table 5 provides an overview of such activities. NGOs like IUCN and WWF are providing operational geoinformation platforms providing access to simple biodiversity metrics, alike the Ramsar Convention, whose data service is based on a detailed technical report. EU policy needs in the biodiversity domain related to EO were analysed by the KCEO deep-dive. It had the aim to verify how and to what extent existing EO products and services meet these needs, to highlight existing gaps and to provide recommendations on future evolution (Camia et al. 2023). In the freshwater environment, key in-situ data are still lacking or too heterogeneous to be efficiently exploited, thereby not being able to calibrate and validate remote sensing products for the assessments of the condition of habitats and ecosystems needed to support targets of the European Biodiversity strategy.

The production of RS enabled EBVs however (O'Connor et al., 2015; Pettorelli et al., 2018; Skidmore et al., 2015), targeted by ESA funded GlobDiversity (2017-2020) and other projects still seems to be lacking. The developments proposed there have focused on terrestrial EBVs, but a similar approach as the one described in the GlobDiversity roadmap[20] could be applied to prioritised freshwater EBVs (see Turak et al., 2017) to ensure a process leading to consistent global datasets. Also, integration of EO in ecosystem services modelling is developing (Ramirez-Reyes et al. 2019). To ensure that EBVs and indicators are aligned appropriately to policy objectives, close communication between policy makers and the scientists is required. Lock et al. (2021) describes the inherent problems in these relationships and ideas for how they can be solved. One such idea is for these communities to agree on what geographic extent (area size and scale) to monitor and which biodiversity attributes should be covered.

Table 5: Non-exhaustive list of recent EO activities by biodiversity organisations and programs, websites accessed 10 July 2024. See Table 1 for more context.

Organisation	Use of EO	Sources
BioDISCOVERY Future Earth	EO experts involved, but no updates since 2022 except EO related workshops at WBF 2024, Davos.	https://biodiscovery.earth/
Biodiversa+	EO mentioned in various reports	https://www.biodiversa.eu/biodiversity-monitoring/
KCEO	Dedicated deep-dive assessment performed in 2020	Camia et al., (2023)
EIONET	Review of satellite-based cyanobacteria monitoring	Rinke et al. (2023)
GLEON	EO working group (Calamita, Woolway)	Pers. comm.
GEO-BON	Remote sensing task force, various projects featured, but no updates since 2021	http://remote-sensing-biodiversity.org
IUCN	Featuring a knowledge lab using EO, most prototypes no longer operational	http://world-heritage-analyses.iucn.org/
Ramsar Convention	Technical guidelines for EO usage, Global Mangrove Watch providing EO data access	Rebelo et al. (2018), https://www.globalmangrovewatch.org/
SEEA EA	GEO EO4EA – 2022 Workshop on Earth Observation for Ecosystem Accounting	https://eo4ea-2022.esa.int
WWF	WWF-Sight platform providing EO data access, various project-level reports on using EO data	https://wwf-sight.org/

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[20] https://eo4society.esa.int/wp-content/uploads/2021/01/GlobDiversity_RS-enabled_EBV_RoadMap.pdf

3.4 Models for freshwater biodiversity

Models are critical tools to generalize, interpret and extrapolate links between drivers of change and the ecological state, including biodiversity composition, of ecosystems (IPBES, 2016). There are basically two types of model approaches to describe this link:

1. Correlative models, linking environmental conditions to species composition and/or abundance based on empirical data; examples are species distribution models (SDMs).
2. Process-based models, based on physiological and ecological mechanisms to understand the way ecosystems and species respond to environmental drivers. Examples are dynamic vegetation models, lake food web models and eco-hydrological models.

Empirical, correlative or data-driven models calculate future species composition and/or abundance directly from measurement and other physical data. There is a large variety of correlative models such as Bayesian networks, regressions (Trifonova et al., 2021).

Process-based models are composed of a set of a priori defined (predictive) mathematical equations of the dynamics of the species of interest. Physical and biological data is used to calibrate and validate the parameters in these equations. Process-based models assess the change in species composition and/or abundance based on internal and external stressors such as physiological preferences, nutrient availability, community competition, hydrodynamics, meteorology and species life cycle characteristics (Rousso et al., 2020).

Some hybrid models also exist that combine the two approaches. Within both types, there are (1) ‘spot models’, describing the relationships in (representative) ecosystems assumed homogeneous; and (2) spatial models, that include the spatial relations between (eco)systems, such as catchment-scale models (Teurlincx et al., 2018) and connectivity models (e.g. meta-community models). Models also differ in the biological levels addressed (from organisms via species and populations to communities) and in complexity.

Earth-system models and integrated assessment models (IAMs) are widely used process-based and spatially explicit models. They serve as ‘background models’ to describe the earth’s environment and may go as far as ecosystem extent (depending on climate, hydrology, land-use, etc.), on which the biotic models are superimposed. In this way they are used for global ecosystem and biodiversity assessments and projections.

All these types of models are useful, and may complement each other (IPBES, 2016). Generally speaking, process-based models cover biota in terms of physiological/functional groups, based on traits of comparable species. Available physiological knowledge often sets a limit to extend to the species level, apart from some well-known examples. These models are in principle better suited for extrapolation. Correlative models can cover the species level if the underlying data are there but are less suitable for extrapolation outside the domain of the data. As ecological knowledge expands, the two types tend to move toward each other; e.g. trait-based models are increasing their number of functional groups. The future is in combination of different modelling approaches, model intercomparison projects and clear communication of uncertainties (IPBES, 2016).

Examples of correlative models are GLOBIO (Alkemade et al., 2009; Janse et al., 2015; Schipper et al., 2020) and PREDICTS (for terrestrial systems). They use a reference-based indicator (MSA or BII) representing biodiversity intactness, based on data on several species groups, but also modules based on the SDM approach are being developed for fish (GLOBIO-Species Aquatic; Barbarossa et al., 2020). This species-specific approach allows for quantifying the effect of different impacts on habitat suitability of a certain species. Impacts currently included are changes in discharge, water temperature and fragmentation by dams (Barbarossa et al., 2020; Keijzer et al., 2024). In BIOMONDO we developed a new method to more accurately quantify the impacts of increases in water temperature which includes the ability to acclimate (Keijzer et al., in prep).

PROTECH (Elliott, 2021), is a well-known, process-based phytoplankton traits model. It has been developed to simulate the in-situ dynamics of phytoplankton in lakes and reservoirs, specializing in predicting phytoplankton species, particularly cyanobacteria. The model has species-specific growth rates that respond to temperature, light and nutrients. The algae library holds more than 100 species and has been applied to different water bodies around the world. The process-based model BLOOM (Los, 2009) covers three phytoplankton groups (cyanobacteria, green algae and diatoms). The cyanobacteria consist of eight genera each divided into different physiological states. It calculates the relative abundance of these phytoplankton groups based on the availability of nutrients and light. BLOOM is part of the Delft3D software suite, which allows it to be connected to the hydrodynamics module (Delft3D-FLOW) so that calculations are done at the level of the entire water system (in 3D). There are also several aquatic macrophyte models. PCLake+ (Janse et al., 2008; Janssen et al., 2019) is a model that combines aquatic and benthic primary producers and their consumers within an ecosystem context. The Madingley model (Harfoot et al., 2014) is a so-called ‘General ecosystem model’ (GEM) based on physiological properties covering many biotic groups but does not yet cover freshwater ecosystems. With respect to fish, besides the empirical models mentioned, there are models for fish production, and habitat connectivity models for specific species (Barbarossa et al., 2020; Keijzer et al., 2024).

In BIOMONDO, we used GLOBIO-Species as an example of the correlative approach (for the fish species indicator), and BLOOM as an example of the process-based model (for the phytoplankton indicator).

4 Challenges and knowledge gaps

Knowledge gaps are just one of many challenges associated with the biodiversity crisis. Many challenges are of an economic, social and political nature, such as the combination of global coordination and local implementation, culturally and religiously ingrained behaviour, the time lag in conservation efforts and the trade-off between short-term benefits and long-term values, weaknesses in governance and enforcement, or economic coercion. This range exceeds the scope of a scientific agenda. However, we would like to do justice to it here by distinguishing between specific gaps in scientific knowledge on the one hand and more general challenges in the utilization of information obtained by means of EO on the other. These general challenges are outlined with focus on potential users, the technical possibilities and their further development (section 4.1).

The challenges and particular knowledge gaps for freshwater biodiversity are reported by several key publications (Harper et al., 2021; IPBES, 2019; Maasri et al., 2022; WWF, 2020a). For BIOMONDO, we also conducted a review of current research results to verify the alignment of current research activities with the identified challenges and knowledge gaps. This literature study is based on a similar clustering as we used in the review by Calamita et al. (2024), but using keywords on biodiversity, freshwater, change drivers and remote sensing. A detailed description of the methodology can be found in Appendix A.5. The knowledge gaps from these different sources are categorised and discussed in section 4.3 and further elaborated in relation to the results of the BIOMONDO Pilots in section 4.4. Together these subsections provide a comprehensive basis to develop suggestions for research priorities ranked by importance and feasibility in section 5.

4.1 Challenges in using Earth observation for biodiversity assessments

Identifying users and user requirements

Since the early 2000s, research increasingly aims to achieve a “public engagement with science and technology” instead of a “public understanding of science” (Schäfer, 2009). Yet, Geller et al. (2022) report that incorporation of stakeholder needs into forecasting tools is lagging behind. This means that the engagement of users is an essential constituent of successful research projects. However, such engagement is a limited resource, and the increasing competition for it causes a shortage of the availability and responsiveness of designated technical beneficiaries, referred to as stakeholder fatigue (Reed, 2008). This is particularly the case in regions and at scales that attract a wide range of research activities, which we experienced in BIOMONDO Pilot 3 for the Mekong catchment (see section 4.4). For Pilot 3 the identification of potential users and their needs was a large and challenging task. On the other hand, smaller-scale and problem specific research, such as the impact assessment of restoration and management measures in Lake Marken (BIOMONDO Pilot 1), involve a limited number of users with clear requirements. This does not completely eliminate the risk of stakeholder fatigue, but it greatly simplifies the clarification of expected stakeholder engagement.

This challenge concerns the development of EO products and services, which often require more in-depth engagement than the evaluation of conventional surveys. It also concerns applications for biodiversity monitoring in a particular manner, whose user groups and requirements currently entail considerable heterogeneity. Therefore, we recommend that future research activities be supplemented by appropriate preparations and requirements concerning user engagement, depending on market maturity and spatial scalability. This means that large-scale, (pre-)operational information services, such as the cross-national derivation of certain EBVs, should be prepared by ESA through strategic alliances with users who utilize the services for periodic surveys. For similar services on a national scale and smaller, or preliminary technical studies, however, the formation of suitable partnerships can certainly be left to the bidders.

In this context, we would like to mention the opportunity to hold interdisciplinary workshops in preparation for collaborations at the International Space Science Institute (ISSI) in Bern, Switzerland. The workshop on tipping points and EO data needs[21] (October 2022)

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[21] https://workshops.issibern.ch/tipmip/participants-and-conveners/

demonstrated how this approach can bring an existing scientific community into contact with Earth observation and successfully initiate joint activities. The time required for this preparation is considerable and, in the case of the ITT tipping point, took more than 1.5 years. But with a time horizon of five years envisioned for our research roadmap (section 6), this measure nevertheless seems promising.

Developing suitable geoinformation solutions

The value of EO products for biodiversity monitoring depends on the user-friendly integration of such data in dedicated workflows. A lot of tools have been made available for such integration; a non-exhaustive list is provided in Appendix A.2 as Table 8. The advantages or matches and the disadvantages or gaps of each technology for the biodiversity community is described in this table's rightmost columns. Further development is needed to rectify existing disadvantages, and to provide tools and services that evolve with the improving EO technology. The main challenges for this evolution are to handle big data processing, to develop interfaces between different data sources, to satisfy heterogeneous user requirement, and to make the transfer of data and information to the users workflows and systems possible and readily available.

Many cloud services listed in Appendix A.2 are capable of accessing and processing large volumes of EO satellite data products, e.g. the Copernicus DIAS, AWS or Google Cloud Platform. However, the capacity to handle large amounts of modelled and in-situ data in such platforms is still limited. Such efforts are however necessary for several EBV workflows. Furthermore, the deployment and operation of services on a cloud infrastructure is associated with significant costs and efforts, which are often hard to estimate. There are the obvious costs for the cloud service provider, and there are personnel costs on the side of the user of the cloud platform. Both can vary greatly, and a comparison of costs and efforts across providers can be very difficult. It is generally safer to pay a higher price for a solid, robust and well tested IT infrastructure than to struggle with an infrastructure which is less mature. But this strategy comes with larger financial risks than a strategy that leans towards cheaper or developing infrastructures. To simplify biodiversity assessments, the market of cloud providers should be consolidated in the future resulting in own costs becoming lower and easier to predict.

Biodiversity assessment and monitoring relies to a large degree on in situ observations, and increasingly on citizen science data. However, accessing complex ecosystem information, or the interpolation of sampled data in space and time may require the use of a wide range of ecosystem models. Future IT solutions for biodiversity stakeholders should therefore put a strong emphasis on integrating different data types, especially raster and vector data. Some IT solutions already cover this requirement. For example, the EuroDataCube has a dedicated component, the so-call geoDB which is designed for handling non-raster data.

The tools and solutions described above are often rather generic in functionality. But the use cases and requirements for biodiversity assessments and monitoring are so heterogeneous that the heterogeneity itself is a key requirement for the design of new tools. IT solutions should, for example, handle small scaled regional to global requests, using various national frameworks and ecosystem-specific metrics. The interface between the processed data, e.g. the EBVs, and the users, needs to address these requests. Ideally numerous EBVs are available and can be retrieved in different spatial and temporal resolutions. Tools that users are already using need to be served by data services (standards) for smooth integration into these existing tools.

In our pursuit to find suitable IT solutions for BIOMONDO, we tested various available options, each designed to meet diverse requirements and objectives. GEOBON developed BON in a Box, which is a prototype of what future IT solutions may look like. It aims to serve as a technology transfer mechanism that allows countries access to the most advanced and effective monitoring protocols, tools and software thereby enhancing or harmonizing a national biodiversity observing system. Nevertheless, Bon in a Box does not cover any freshwater EBVs and the processing of big datasets is not possible with this IT solution. Limitations that we identified with other IT solutions included a lack of open access, absence of visualization tools, missing user administration features, and a lack of thematic overlap.

To address these challenges, 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 laboratory features visualization interfaces and export functions. A dedicated data viewer has been set up to display datasets. Ensuring access to the laboratory is a crucial aspect of the project, and we believe that enabling scientists and other users to access novel EO products and models through this platform is the most effective approach. For this purpose, JupyterLab was employed to facilitate data access, and a Python interfaces in the data viewer allows users to work with the data via an API.

For an effective Biodiversity Lab focused on EO data, key criteria emerge from the BIOMONDO project. Firstly, prioritizing an IT solution with open access and interoperability to encourage collaborative data sharing. Thematic overlap, relevance to biodiversity research, and comprehensive visualization tools are crucial for insightful data analysis. Implementation of state-of-the-art methods like Jupyter Notebooks for flexible and collaborative work is helpful for biodiversity scientists. Visualization interfaces and export functions enhance data presentation and usability. Integration of interfaces ensures compatibility with popular scientific programming languages is key for working with the platform. These criteria collectively form a basis for a robust Biodiversity Lab, addressing challenges encountered in the BIOMONDO project and providing a foundation for advanced EO data analysis and biodiversity research.

Keeping pace with the development of new satellite missions

The last decade has revolutionized satellite EO by implementing established mission concepts and proven sensors (e.g. SAR/ASAR, OLI/ETM+, MERIS) on operational platforms of the Copernicus program (Sentinel-1, Sentinel-2, Sentinel-3, respectively). This has extended the technical potential for operational information services to new application areas. Various public and private actors have used this opportunity to offer such information services on a regional and global scale. This success story can be repeated in the case of thermal remote sensing. The missions and sensors available to date have severe limitations in terms of spatial (e.g. SLSTR, 1 km) or temporal (Landsat TIRS, 16 days revisit per satellite) resolution. Trishna, LSTM and SBG and various private satellite missions will provide high-resolution (50 m) data practically every day in a few years. The resulting opportunities can be exploited to a large extent using established methods, although products from the different missions must be intercalibrated. The utilization of the higher spatial resolution beyond the simple scaling of products (e.g. new structural parameters) and the additional thermal spectral bands (e.g. four thermal bands on Trishna; Buffet et al., 2021), on the other hand, requires further research effort.

The expected increase in the number of spectral bands from optical EO sensors (e.g. PACE, in the future CHIME, SBG and Sentinel-2/3 NG) will also pose various challenges for information retrieval, including parameter retrievals, atmospheric correction and other post-processing techniques. Hyperspectral data will be largely backwards compatible with current algorithms. However, the development of dedicated hyperspectral algorithms has slowed down after the first emergence of this technology (e.g. Hyperion, 2000-2017). The uncertainty regarding data products based on hyperspectral data is correspondingly high, especially regarding robustness for mission processing and global scaling. This is because new data products, for example PFT of optically complex water bodies, are initially documented as feasibility studies (e.g., Xi et al., 2017; Zhu et al., 2019). However, the limits of their transferability, which initially manifest themselves as the failure of a methodology, are naturally communicated much more cautiously. On the one hand, strategies established on multispectral data, such as the pre-classification of optical water types (Moore et al., 2014; Spyrakos et al., 2018), could be further developed into new approaches for hyperspectral data. On the other hand, there is a possibility that they will become technologically obsolete and be replaced by methods adapted to the new data (e.g. machine learning). These considerations should make it clear that the potential and challenges in connection with future EO missions must be considered in a very differentiated manner with regard to downstream applications.

Finally, the predictability associated with data products from future satellite missions must be considered for appropriate expectation management of product users and suitable geoinformation solutions. There are certain foreseeable challenges, such as the ever-increasing data volumes. On the other hand, the ideal implementation of downstream products (e.g., EBVs, resilience indicators) and data platforms depends largely on the quality of basic products, which makes expectation management regarding appropriate requirements very difficult in case of novel data products.

4.2 Challenges to address freshwater biodiversity knowledge gaps

Tickner et al. (2020) outlined an emergency framework with six priority actions for freshwater biodiversity that are needed to bend the curve of biodiversity loss. These actions are closely related to the five main direct drivers of biodiversity change in general (section 2.1) and some of the knowledge gaps described in section 4.3. They are:

- to accelerate the implementation of environmental flows,
- to improve water quality,
- to protect and restore critical habitats,
- to manage exploitation of species and riverine aggregates,
- to prevent and control non-native species invasions and to safeguard, and
- to restore freshwater connectivity.

To accomplish this will require knowledge and information-based actions, but the lack of decision support data in freshwaters is considerable. Most biodiversity observations are discrete points in space and time, are influenced by methods of detection, are scarce and costly to collect and are not spatially comprehensive. Hence, reaching the goal also means establishing relevant EBVs to support the actions and the development of indicators for global, regional and local policies. An additional challenge is then to assess the potential for remote sensing to support the EBV workflow developments.

Based on detected changes and trends in biodiversity, it has in recent years been recognized that there is a need to attribute observed changes in biodiversity with inferred causes of the changes and the resulting ecosystem impacts. This is both of great scientific interest and central to policy efforts aimed at meeting national, regional and global biodiversity targets (Gonzalez et al. 2023a). In its explanation of EBVs, GEO BON also highlights (https://geobon.org/ebvs/what-are-ebvs/) the need to both explain and forecast biodiversity changes to support policies.

Gonzalez et al. (2023a) argue that a formal framework and guidelines for the detection and attribution of biodiversity change is required to support effective policy. An inferential framework to guide detection and attribution analyses needs to be designed explicitly for biodiversity change and its ecosystem impacts and includes five main steps – causal modelling, observation, estimation, detection, and attribution – for robust attribution. Monitoring of biodiversity also needs to be linked to policy indicators to track and report on progress and to determine and guide suitable actions.

Local and regional diversity are affected by humans and natural drivers, together with conservation activities designed to protect and restore. Human drivers interact and influence biodiversity at different spatial scales, and vary geographically, which makes attribution of trends in biodiversity to human causes across scales very challenging. In addition, climate change needs to be considered as one of the drivers of biodiversity change, but knowledge gaps are also related to how other drivers are influenced by it and how such effects can multiply and vary across scales. Specifics challenges also arise for monitoring of freshwater biodiversity that are related to the fact that freshwater ecosystems are located within the terrestrial realm, where changes to the upstream landscape processes, catchments and hydrography can affect extent, structure, function and condition.

As the amount of data needed for comprehensive observations is large, big data processing, remote sensing and Artificial intelligence (AI) are considered to play essential roles in the implementation of frameworks for detection and attribution of biodiversity change. AI can help to support traditional science to understand why and where biodiversity is changing and what can be done to mitigate and reverse the effects.

There is also a need for formal and reproducible statements of confidence on the function of different drivers of biodiversity change. The data and analyses used in framework steps need to follow best practices and EO data and remote sensing analyses can play an important role in providing reliable objective information, which is continuous in space and time. Remote sensing can support harmonization of methods for some EBV measures and thereby contribute to assessments and monitoring of ecosystem and environmental parameters used in a detection and attribution framework.

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), see https://geobon.org/gbios-a-global-observatory-to-monitor-earths-biodiversity/, and the new EU Biodiversity Observation Coordination Centre (EBOCC) proposed by EuropaBON (showcased May 27-28, 2024, at EuropaBON's final stakeholder conference (https://europabon.org/workshop/final-stakeholder/). As mentioned above (section 4.1) other tools or platforms, e.g. GEO BONs BON-in-a-box also need to be investigated in relation to how EO data and remote sensing methods can provide support and/or be integrated in the workflows.

4.3 Knowledge gaps that Earth Observation can fill

The IPBES Global Assessment (2019) and selected scientific publications (e.g. Harper et al., 2021; Maasri et al., 2022) highlight a comprehensive list of knowledge gaps in biodiversity research and conservation (see Appendix A.3). We filtered these knowledge gaps 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 (see section 3.3). Furthermore, we performed a literature analysis to estimate the importance of knowledge gaps based on their prevalence in current research (see section 4.1 and Appendix A.5).

The knowledge gaps identified in such manner are grouped by gaps concerning the monitoring of ecosystem structure and functioning as proposed by GEO BON, and their interlinkages, but we also consider a list of environmental variables, and their interlinkages.

Ecosystem structure

1. *Freshwater habitat types and ecosystem mapping* supported by EO is needed to inform on EBV class ecosystem structure and, more specifically, the abundance, distribution and condition (integrity, connectivity) of freshwater ecosystems and habitats. Existing classification systems (see section 3.2) may not resolve the diversity of freshwater habitats appropriately, in particular when the classification is used as a basis to address other knowledge gaps, e.g. interlinkages between ecosystems and environmental variables or links to biodiversity. Such classifications may, in turn, also be subject to dependency on other knowledge gaps, e.g. net primary productivity, phenology, stratification and mixing regimes, etc (see knowledge gaps 4, 6, and 16).
2. *River delta size* is an important prerequisite for the attribution of changes (see knowledge gap 18), and its extraction from Land Use/Land Cover (LULC) products is straightforward. Accordingly, this is only a small yet important gap.
3. *River habitat connectivity* is a key attribute for riverine biodiversity. On the impairment side, very high resolution EO data can be used to track dam construction. Mitigation measures such as fish ladders may also be identified[22]. Several reservoir and dam databases have been developed on the basis of EO data (see section 3.3), some of which may be subject to further development.

Ecosystem functioning

4. *Lake net primary productivity* is needed to inform on EBV class ecosystem functioning and, more specifically, phytoplankton PP, and harmful and harmless algal blooms. This is a fundamental parameter, although related biomass proxies, namely chl-*a*, are often used as a substitute.

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[22] See e.g. Cascades Island and Bradford Island, north and south of Bonneville Dam, Oregon

5. *Lake phytoplankton taxa*, also referred to as Phytoplankton Functional Types (PFT) in remote sensing, is the only taxonomic, aquatic variable that can be derived from EO data. The feasibility varies strongly among different taxa and with their absolute and relative abundance. Product requirements and feasibility must be clarified.
6. *Lake phytoplankton phenology* is needed to inform on EBV class ecosystem functioning and, when it can be identified per PFT (see knowledge gap 5), to some extent also on EBV species traits. We expect lake chl-*a* based phenology to become available soon. Primary-productivity based phenology and per-taxa phenology requires knowledge gaps 4 and 5 to be addressed.
7. *Regime shift and anomaly detection in lake phytoplankton time series* is important because this informs on EBV class ecosystem functioning (i.e. ecosystem disturbances). There is existing data on regime shifts available (e.g. persistent changes to another trophic state; see Gilarranz et al., 2022) but this can be extended to include the most recent years and other data types. Anomaly (i.e. temporary large-scale deviations) detection requires comparison to a baseline, across at least several years. This can be done using either chl-*a* estimates and/or primary productivity, PFT, and phenology products (see knowledge gaps 4, 5, and 6).
8. *Monitoring of lake resilience using 'resilience indicators'* is important because it is not always easy to determine which environmental driver is undermining ecosystem resilience. In those cases, it might still be possible to monitor changes in, e.g., an ecosystem's capacity to recover from disturbances using time series analysis (i.e. an indicator of resilience). Using EO data, this approach has been applied to terrestrial ecosystems (Bathiany et al., 2024; Forzieri et al., 2022), while some of the first studies using in situ data were on lakes (Carpenter et al., 2011). Resilience indicators are seen as particular important in the context of regime shifts and approaches to derive them have some similarities with anomaly detection (see knowledge gap 7). They inform EBV class ecosystem functioning (i.e. ecosystem disturbances).
9. *Incorporation of EO-derived trophic state or related metrics into food web and hydrological models* is, perhaps, a relatively low hanging fruit as EO-derived trophic state indices are readily available. The challenge is how to incorporate EO-derived trophic state indices into these models as they are usually an output, rather than an input of these models. One solution is to use the EO metrics for model validation, but it might be worthwhile to also explore other possibilities.
10. *Impacts of changes in lake phytoplankton phenology on other biodiversity variables* must be assessed to estimate how changes in phytoplankton phenology cascade through food webs and affect entire ecosystems. This requires in situ data and food web modelling. Food web models usually do not take phenology into account. The most feasible is, perhaps, is to start with impacts on zooplankton phenology and abundances. These assessments may differ per habitat type (knowledge gap 1) and are dependent on knowledge gap 6. This knowledge gap is closely related to knowledge gap 11, but with less sophisticated base products (i.e., chl-*a* rather than PP).

11. *Impacts of changes in net primary productivity on other biodiversity variables* must be assessed to estimate how changes in PP cascade through food webs and affect entire ecosystems. This requires in situ data and food web modelling. Established food web models are available in which PP is a key variable. These assessments may differ per habitat type (knowledge gap 1) and are dependent on knowledge gap 4. This knowledge gap is closely related to knowledge gap 9, but with more sophisticated base products (i.e., PP rather than chl-*a*).
12. *Impacts of anomalies in phenology and net primary productivity on other biodiversity variables* must be assessed because they are likely to be associated with extreme events (e.g. heat waves due to climate change) that may increase in the future (see knowledge gap 22). This requires incorporation of the work on knowledge gap 7 into biodiversity models.

Interlinkages between ecosystem structure and functioning

13. *Monitoring the spread of invasive species* is important because it is an important driver of environmental change affecting biodiversity. It is difficult to monitor many invasive species directly through Earth Observation (although there are a few important exceptions when invasive species cover a large surface area). Earth Observation may, however, contribute to freshwater invasibility assessments, i.e. of water quality and other factors that make water bodies susceptible to invasions (see knowledge gap 1).

Environmental variables

14. *Impacts of changes in the extent to which rivers are free flowing (i.e. hydrological connectivity) on sedimentation processes* must be assessed because it, e.g., affects wetland formation (both in the riparian zone and of river deltas). Human induced changes to river flows may involve, e.g., canalisation and dams. This knowledge gap may be addressed by using EO-derived turbidity indices as an input for hydrological modelling. This knowledge gap can, partially, be addressed simultaneously with knowledge gap 3.
15. *Impacts of land use/land cover on nutrient inflows must be assessed* to better understand how this driver of environmental change affects net primary productivity. Addressing this knowledge gap requires to link EO-derived land use products into hydrological modelling. This can, in turn, be used to assess impacts on net primary productivity (which is quite well understood) and on other biodiversity variables (see, e.g., knowledge gap 11 and 12). Impact assessments may differ per habitat type (knowledge gap 1) and are dependent on precipitation rates which might be influenced by climate change (see knowledge gap 16)
16. *Assessment of the impacts of changes in precipitation and evapotranspiration in watersheds on land use/land cover-mediated nutrient inflows* is needed because this is an important way in which future climatic changes may affect primary productivity and other biodiversity variables. This can be achieved through hydrological modelling and by building on the outcomes of addressing knowledge gap 14. These changes may affect primary productivity and other biodiversity variables (see knowledge gap 11 and 21).

17. *Monitoring changes in thermal stratification and lake mixing regimes* is important because it influences nutrient upwelling, primary productivity, and phytoplankton phenology. As such, it is one of the important ways in which climate change may affect freshwater ecosystems. This requires incorporation of EO obtained surface water temperatures into hydrological models. This can, in turn, be used as an input for the work on knowledge gap 11 and 12 (which can be performed independently). Knowledge gap 1, likely, depends on this work.

Interlinkages between ecosystem and environmental variables

18. *Attribution of changes in wetland formation and river-delta size* is important because it allows us to identify the causes of changes in these crucial areas for biodiversity and food production. This requires disentangling the effects of, e.g., sea level rise (caused by climate change), subsidence, and sedimentation processes. See knowledge gap 14.
19. *Assessment of the impacts of changes in thermal stratification and lake mixing regimes on net primary productivity and related metrics of phytoplankton growth* is important because this is, e.g., one of the important ways in which climatic changes may affect biodiversity (e.g., because phytoplankton growth is dependent on temperature and nutrient upwelling). These changes may, in turn, affect other biodiversity variables (see knowledge gap 11) This requires incorporation in hydrodynamic and food-web models. This can be done, e.g., by building on the work in Janssen et al. (2019) and knowledge gap 16. Causes and consequences may depend on lake habitat type (knowledge gap 1).
20. *Attribution of changes in lake phytoplankton phenology* is important because this may help to identify the causes of such changes which may cascade through entire ecosystems (see knowledge gap 10). This requires bringing information on phytoplankton phenology (knowledge gap 6) together with information on the seasonality of thermal stratification and lake mixing regimes (knowledge gap 16) and nutrient inflows (knowledge gap 14). Causes and consequences may depend on lake habitat type (knowledge gap 1).
21. *Attribution of changes in lake trophic state, a loss of resilience, and regime shifts* is important because such shifts are among the most drastic changes that affect water quality and biodiversity. Global information on lake regime shifts is available (Gilarranz et al., 2022), but see knowledge gap 7) which should be linked with info on e.g. land-use in watersheds and lake temperature/mixing regimes (see knowledge gaps 14 and 16). Impact assessments may differ per habitat type (in particular between deep and shallow lakes, knowledge gap 1).
22. *Assessment of the impacts of extreme weather and climate events, e.g. heatwaves and massive rainfall events, on biodiversity variables* is important because this is one of the key ways in which climate change is expected to affect biodiversity in the future. This challenge can be, e.g., addressed partially by building on the work on knowledge gap 16, but then with a specific focus on anomalies both in environmental (i.e. climate) variables and in biodiversity variables. This knowledge gap can be addressed simultaneously with knowledge gap 12 and requires the incorporation of novel techniques to detect anomalies in time series.

23. *Assessment of the impact of changes in the hydroperiod of wetlands on biodiversity variables* is needed because many species in wetlands are crucially dependant on this period, and because this period might be influenced by a variety of anthropogenic drivers (e.g. the extent to which rivers are free-flowing, see knowledge gap 14, and climatic changes). This requires an incorporation of EO-derived information on the length and timing of this period into biodiversity models. These models of biodiversity should take the phenology of species into account (especially for species that have both aquatic and terrestrial life stages).

4.4 Knowledge gaps addressed by BIOMONDO

In the precursor study BIOMONDO, we focused on a few pilot studies that are of relevance within the context of monitoring the impact of changing environmental conditions on biodiversity, and for which results could be obtained within the two-year time frame of the project. In doing so, we used the following key definitions:

- *Pilot Objectives* comprise potential EO application development targets, which were identified based on commonly known environmental drivers and response variables in aquatic ecosystems that can potentially be observed with EO.
- *Biodiversity Pilots* are studies investigating whether one or more *Pilot Objectives*, as defined in the SPTM (see below and BIOMONDO, 2022), can be reached through the development of novel integrated EO/model/in situ products.
- *Biodiversity Pilot Sites* were chosen for the implementation of *Biodiversity Pilots* based on representativeness, biodiversity expertise and historical in situ data available for validation and impact assessment.

Science Policy Traceability Matrix

The SPTM lists 30 potential *Pilot Objectives*, and the three *Biodiversity Pilots* described below address eight of them. Table 6 lists all of the objectives and specifies the best fits with the knowledge gaps described in section 4.3.

Table 6: The selected *Biodiversity Pilots*, the *Pilot Objectives* they address, and the knowledge gaps they relate to.

Biodiversity Pilots	Pilot objective	Knowledge gaps
1	Monitor and assess impact of changes in water column trophic status	9 11
1	Monitor and assess impact of algae blooms	6
1	Monitor and assess impact of cyanobacteria	5
1 and 2	Monitor and assess changes in seasonal dynamics	6
2	Monitor and assess impact of changes in water temperature on fish occurrence/diversity in lakes	22
3	Monitor and assess impact of river dam construction and removal on habitat fragmentation and species dispersal routes	3
3	Monitor and assess impact of river dam construction and removal on changes in habitat extent	3
3	Monitor and assess impact of river dam construction and removal on habitat/water quality and turbidity	14

Pilot 1: The impact of (reverse) eutrophication and habitat changes on the water quality of shallow lakes

We combined in situ and hydrodynamic-water quality model data to investigate ecosystem functioning of Lake Marken, which is going through the process of oligotrophication after decades of severe eutrophication. We used the three-dimensional Delft3D-Delwaq hydrodynamic-water quality model by Deltares to assess the dependency of primary production and phytoplankton diversity on temperature inputs from EO products (LSWT) and the Dutch met office, KNMI. Using optimal model inputs, we can assess the impact of the nature-based actions that were taken to initiate the oligotrophication process. At current, our water quality model has certain limitations such as a fixed nutrient load and no population dynamics of species at higher trophic levels.

As mentioned above, one of the shortcomings of Delft3D-Delwaq is the capability to model the whole freshwater food web. On the other hand, existing aquatic food web models lack a spatial component as provided by Delft3D. In the past an attempt has been made to couple Delft3D to PCLake (which models the whole food web, except birds). Delft3D provided information on hydrodynamics and water temperature to PCLake, which in turn calculated the development of macrophytes. Future work could retry this exercise and expand it to the entire food web (including fish). This could be done with PCLake or with other food web models.

Follow up studies should focus on the combined effects of eutrophication mitigation measures, land use changes in the catchment area (agricultural activities, urbanisation), and climate change. With such an approach, the relative cost-effectiveness of conservation and management measures in different domains can be compared, and it can be investigated how they strengthen and cancel each other. The three-dimensional model is needed to resolve such effects in a spatio-temporally comprehensive manner, with regards to future scenarios, and across all levels of the food web. EO is the only data source that can inform and calibrate such models in a spatially explicit manner. In particular, Secchi depth products can inform the model on light penetration depth in different parts of a lake, chl-*a*, primary production and LSWT products can be to validate or nudge the model. This fundamental concept can be applied in principle to any lake in the world, although certain parameterization requirements (e.g. in-/outflow, bathymetry etc.) are harder to meet in less studied lakes.

Future Earth observation missions, both optical (e.g., CHIME) and thermal (e.g. LSTM), will strongly improve the potential to derive products for use in model calibration and/or nudging. The spectro-radiometric resolution of optical sensors is critical here, especially in wavelengths representative of cyanobacteria pigment absorption (620 nm; Simis et al., 2007) or chl-*a* fluorescence. Monitoring biotic parameters is therefore still largely limited to the spatial resolution of Sentinel-3A/B and large lakes. This limitation will incrementally decrease as Sentinel-3NG's spatial and Sentinel-2NG's spectral resolutions increase, and with the launch of the CHIME mission. In preparation of these missions, the use of surrogate hyperspectral data from PACE, PRISMA, EnMap or automated in situ radiometers should be considered to test the calibration and nudging of biological model outputs. The improved potential of future thermal missions is further discussed in the context of Pilot 2.

Pilot 2: Impact of changes in water temperature and heat waves on fish diversity

We developed a phylogenetic heat tolerance model for fish, and tried to explain interannual variations in the abundance of heat-sensitive fish species in Lake Mälaren by means of gap-filled LSWT products and a cyanobacteria indicator. The potential of this pilot study should be explored further by improving and assessing the model functionality, validating its applicability at ecosystem scale, and upscaling the approach to many small lakes using the upcoming high-resolution thermal satellite missions.

The first advancement should be to clarify and, as much as possible, rectify current model limitations. These include horizontal gradients in lakes with a complex morphology and vertical gradients in deep lakes. This means that the model should be tested further with respect to whether cold water refugia exist in a given habitat and heat wave period, and whether it is accessible for the given fish species. On the other hand, littoral zones may be subject to amplified temperature increases that are hardly represented in 300 m Earth observation products. Sufficiently large polymictic lakes with a low shoreline development index (i.e. approximately circular shape) are expected to be least susceptible to these limitations. Once such application constraints are clarified, it should be considered how oxygen availability, which is often correlated with water temperature, and other potential stressors interact with LSWT and cyanobacteria dominance. The use of 1D models should be considered to obtain insights in vertical temperature gradients and oxygen availability, both of which cannot be observed using EO (see also 'biodiversity where we cannot yet remotely sense', in Geller et al., 2022).

Second, validation with fish abundance data is required to demonstrate the applicability of this monitoring approach at ecosystem scale. The availability of such data is very scarce, and even scarcer when we consider that geographic limitations of the monitoring approach. As a matter of fact, Lake Mälaren does not seem to be an optimal test site for testing the phylogenetic model, but it was chosen due to the scarcity of fish species abundance data. Consequently, future research should give a strong weight to facilitate optimal reference data in order to indicate the full potential of the approach, rather than its performance under largely uncontrolled boundary conditions.

Finally, the growing potential of Earth observations must be tested and investigated, namely the improving spatial resolution and number of thermal missions, such as Trishna, SBG or LSTM. Here, the extended operating time of ECOSTRESS onboard ISS (2026 or even 2029) can be used to investigate effects that may remain unnoticed at 300 m spatial resolution (e.g., SLSTR). With its relatively high temporal resolution, ECOSTRESS is an ideal surrogate for the upcoming constellation of polar orbiting satellite sensors, and it could inform, for example, more specifically on heat stress in littoral areas and shallow water habitats.

Pilot 3: Monitoring river connectivity/dams, its changes and impact on biodiversity

We utilized a method by Barbarossa et al. (2020) to examine changes in river connectivity across the Mekong basin, assessing the degree of fragmentation for 10,000 fish species using a connectivity index (CI). We specifically analysed the impacts of individual river dams built within the Mekong basin and compared them with energy production gains by each dam placement since the 1960s, potentially guiding future dam placements and removals for optimal outcomes in terms of both connectivity and energy production. Furthermore, we tested suspended sediment retrievals in the Mekong using different algorithms. Sediment transport is a third essential ecosystem service provided by the Mekong, and should hence be added to the assessment of trade-offs related to past and future dam construction.

The planning of future EO research in the Mekong basin must consider that the socio-political research milieu in this region is highly complex and requires dedicated clarifications and stakeholder engagement prior to the planning of further activities. The number of ongoing international (e.g., NASA's SERVIR Mekong project), European (e.g., SOS-Water) or national (e.g., DeltAS by Eawag/SNSF) projects with an EO component is as high as the potential for synergies and redundancy. And the transboundary nature of the Mekong basin further increases the complexity of environmental information supply and needs. Due to these reasons, outlining limited scientific studies in the domain of pilot 3 is not as straightforward as for the other two pilots.

Apart from this general challenge, future research based on EO data of the Mekong basin could address a wide range of technical and scientific domains, including (1) the identification of individual dams and possibly their fish ladders, (2) monitoring whether they are operated in compliance with environmental standards, (3) their local impact on up- and downstream habitat extent and connectivity (e.g., lakes, floodplains, free flowing and dammed river stretches), or (4) a more comprehensive investigation of biodiversity gradients with respect to habitat properties, in the form of a space-for-time analysis. We believe that (2) and (4) have tremendous potential to contribute monitoring and research results to support biodiversity conservation in this extraordinarily species-rich region.

Dam operations are of vital economic and ecological importance, and the availability of data on water levels and runoff is hence subject to sensitive political considerations. They may or may not respect environmental standards or the needs of downstream water usage, and independent information on whether such considerations are respected are crucial. Interferometric radar altimetry can play a vital role here, in particular given that the Mekong basin is very cloudy during half of the year. The SWOT mission by NASA and CNES has strongly improved water level measurements from space in terms of spatial resolution, shifting the bottleneck for dam operation monitoring towards the temporal resolution. Against this background, we think that research should be performed to evaluate the requirements for assessing more and less environmentally friendly dam operations in the Mekong using Earth observation, on the basis of SWOT's KaRIn products and in situ measured water level representing different dam operation approaches.

5 Research priorities

Biodiversity remote sensing research priorities were recently summarized by Geller et al. (2022). To predict changes in biodiversity and ecosystem services and to provide the best possible information to decision makers, they make several recommendations such as improved integration of EO in ecological forecasting, coordination with stakeholders, iterative updating of forecasts, use of multisensor data and increased interaction with social scientists. They also call for the development of a shared, sustainable community infrastructure to facilitate ecological forecasting, which is an urgent action in view of infrastructures from previous projects that are no longer operational (see e.g., some of the examples in Table 5). These recommendations are fully endorsed. However, as they relate to the general, ecosystem-independent combination of EO and biodiversity, they do not envisage any specific research questions or priorities. We fill this gap with the following research priorities for freshwater biodiversity remote sensing, which thematically link the knowledge gaps identified in section 4.3 and identify mutual dependencies that must be considered in the planning of specific research projects.

5.1 Freshwater ecosystems and habitats

Geospatial information about the location, size, and geographic relations like connectivity of freshwater ecosystems and habitats are needed to assess their status and monitor changes with regards to biodiversity policy targets and goals. However, existing classification schemes and typologies have evolved over time with different objectives, and they are neither optimized for linking to global biodiversity assessments, nor suited to take full advantage of developments in remote sensing of recent years (see e.g., the MAES, IUCN and EUNIS classifications in section 3.2). With an increasing emphasis on and need for development of EBVs to inform biodiversity indicators, some of the typologies have recently been revised or are under revision. This will hopefully leverage the use of remote sensing and modelling.

The below listed information and knowledge are needed to monitor freshwater biodiversity in rivers and streams, lakes, reservoirs and ponds, wetlands:

- Time series data/maps of freshwater habitats (with flexible classifications that allow for global and regional/local utility, with appropriate resolution and accuracy/uncertainty estimates) to determine short-term and long-term trends
- Transparent connection between biodiversity (species records, abundance and distribution), habitat requirements (temperature, hydrology, depth etc) and habitat and ecosystem characteristics (e.g. structure, function)
- Scalable connection between habitat types[23] (e.g. EUNIS trophic state and vegetation) and ecosystem types (functional not trophic state)

Here we discuss the role of remote sensing and what opportunities exist and are upcoming for this knowledge gap or rather research area.

Current opportunities

Some of the needed information can be provided by remote sensing, of which some is already in use for determining, e.g. extent of lakes, rivers and streams (especially larger ones), some aspects of water quality (trophic state, LCLU and change, net primary production, turbidity, chl-*a*), hydrographics/physical characteristics from sonar (depth), radar (extent attributes, see also section 3.3).

EO based methods to map and monitor changes in the spatial extent of freshwater bodies are readily available (e.g., Verpoorter et al., 2014) and are highly relevant, in particular in permafrost regions and in arid climate zones where freshwater bodies may appear or disappear due to climate change, as well as in river basins where dams are placed affecting water flows and wetland formation. But there is no global dataset that classifies freshwater bodies according to lower classification levels, such as trophic state and depth, which are required for example in the EUNIS classification scheme.

Habitat and ecosystem classes for the terrestrial realm can partly be informed by land cover and land use data, for which remote sensing is an invaluable source. Together with structural and functional attributes class refinements are possible. For freshwater

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[23] From EEA, https://www.eea.europa.eu/en/topics/in-depth/biodiversity/an-introduction-to-habitats: A habitat or a group of related habitats can be considered an ecosystem. Ecosystems are dynamic complexes of plant, animal and micro-organism communities and their non-living environment, which interact to form functional units.

habitats the situation is inherently more complicated because of the position within the terrestrial realm where changes to the upstream landscape processes, catchments and hydrography can affect extent, structure, function and condition. Hydrography can be derived from spaceborne elevation data (Lehner et al., 2008) but other aspects have not been fully assessed when it comes to the support of EO and remote sensing. In condition assessments both environmental quality (physical and chemical quality) and ecosystem attributes (biological quality) are considered. These aspects also provide an opportunity for the expanded use of EO but may need to be explicitly required by framework guidelines to reach full potential.

To achieve a global coverage that can give comparable results and a better understanding of whether mitigation measures are having desired outcomes, methods employed need to be flexible but transparent and work at different scales (see section 3.2), which are design principles of the new IUCN Ecosystem typology. An important scale aspect is the relationship between habitats and ecosystems where the latter often consists of several habitats and different parameters have been used to characterise them depending both on geographic location but also on the resolution or grain of the input data. For wetland classifications this is especially difficult as many wetland habitats are complex with properties that can be assigned to combinations of terrestrial, freshwater and marine biomes.

As the ability to map the extent of and discriminate between different habitats and ecosystems has improved and emphasis on biodiversity monitoring aspects has increased, the condition of the habitats and ecosystems is receiving growing attention. This is especially important for linking with the expanding field of ecosystem accounting and raises issues relating to the notion of high biodiversity per se as it is not always a good indicator of habitat and ecosystem condition – or how to monitor negative change in ecological status not reflected by biodiversity (number of species).

Upcoming opportunities

The condition or quality of freshwater habitats has traditionally been related to the trophic state and relationship to baseline values (e.g., WFD assessments). The upcoming opportunities that are described in more detail in the following sections, can help derive more consistent freshwater habitat definitions and should be incorporated into future revisions of classification typologies and biodiversity observation platforms and frameworks. They will also allow us to better understand interrelationships between biodiversity and drivers of environmental change which may differ between habitat types.

Hestir et al. (2015) evaluated the contribution of a hyperspectral global mapping satellite mission for measuring freshwater ecosystems. The need for such a mission was demonstrated with show cases and included examination of measurement resolution issues impacting freshwater ecosystem measurements (spatial, temporal, spectral and radiometric) as many are small and spatially complex, requiring high fidelity spectroradiometry, and are best described with biophysical variables derived from high spectral resolution data. Data from the Copernicus CHIME hyperspectral sensor (30 m) planned for launch in 2029 have potential to remedy the gaps and challenges identified for freshwater ecosystem measurements.

5.2 Phytoplankton diversity, phenology, and productivity

Phytoplankton is at the basis of the aquatic food web, and its photosynthetic pigments allow direct retrievals of phytoplankton diversity, phenology and productivity using optical EO data. Therefore, phytoplankton is a key topic in aquatic remote sensing. The knowledge gaps relating to ecosystem functioning address various aspects of this topic, namely knowledge gaps 4-12, described in section 4.3. Knowledge gaps 20 and 21 concern phytoplankton-related links between ecosystem functioning and environmental variables. The dependencies of these knowledge gaps are depicted in Figure 10.

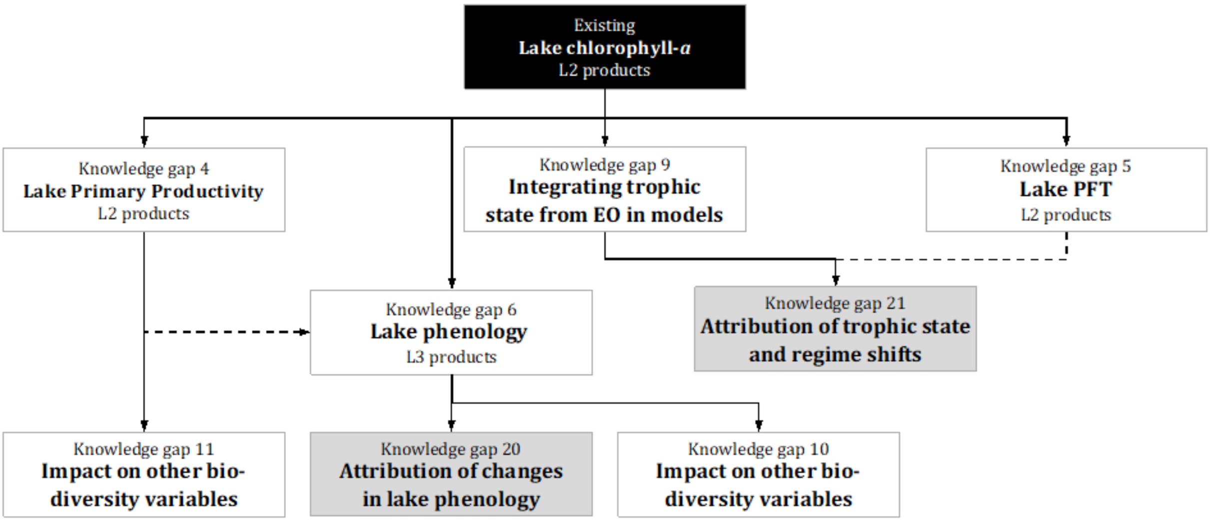

Figure 10: Hierarchy of knowledge gaps (from section 4.3) related to phytoplankton diversity, phenology and productivity. Existing variables are shown in black boxes, ecosystem functioning knowledge gaps are shown in white boxes, and knowledge gaps linking ecosystem to environmental variables are shown in grey.

Current opportunities

Net primary productivity (knowledge gap 4) and phytoplankton phenology (knowledge gap 6, based on chl-*a* products) are proven applications of EO data (see section 3.3). But the comprehensive upscaling of phenology products is limited to, e.g., the US-wide lake browning (Topp et al., 2021), and global, full mission phytoplankton phenology is missing. The upscaling of PP retrievals is limited to a simple, empirical approach for the eleven largest lakes in the world (Sayers et al., 2020). Phytoplankton phenology products are currently in development at Eawag[24], based on chl-*a* products from MERIS and OLCI provided by the Plymouth Marine Laboratory (PML). These products are well validated, which is why only limited validation work is necessary. Contrariwise, PP products from analytical algorithms (e.g., CAFE model; Silsbe et al., 2016) still need comprehensive validation and high-quality PP reference measurements are much scarcer than chl-*a* measurements. However, the EO input products to PP algorithms (phytoplankton absorption, diffuse attenuation, downwelling irradiance) are well established, and operational PP products could be used far beyond the biodiversity community (e.g. in carbon assimilation

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[24] www.bgb-phenology.com

models). Therefore, we think that operational products for both parameters should be developed within the next few years.

Lake PFT (knowledge gap 5) describe highly diverse phytoplankton taxa, which play different roles within ecosystems (e.g. as food for other species) and within the carbon cycle (e.g. the shells of some phytoplankton species may sink to the bottom after death, while others release a larger fraction of carbon back into the atmosphere). Different species may also respond differently to changing environmental conditions, and some species produce toxins that are harmful for ecosystems and water quality (e.g. cyanobacteria). Operational products are until now limited to cyanobacteria (e.g., CyanoAlert and CyanoLakes), which can be identified robustly by means of spectral reflectance features in red wavelengths (Matthews and Odermatt, 2015; Simis et al., 2005; Wynne et al., 2010). The use of cyanobacteria products for a dedicated phenology product is currently considered in ESA Lakes CCI. However, PACE, launched earlier this year, is significantly improving the potential to distinguish PFT in lakes that are sufficiently large for the use of 1 km spatial resolution data (Dierssen et al., 2023). Methods to exploit the potential of the first daily hyperspectral satellite data exist already (e.g., WASI; Gege, 2014), and spectral absorption properties of some common lacustrine and marine algae taxa are available (e.g., Lomas et al., 2024; Soja-Woźniak et al., 2022), although further lab analyses are needed for less common lacustrine taxa and to clarify the sensitivity of spectral absorption properties to environmental conditions (Göritz et al., 2017).

Integrating trophic state from EO in models (knowledge gap 9) is a task that can be implemented on the levels of different parameters that are available from EO and ecosystem (water quality) model parameters, as well as in different work steps. At the current stage, readily available trophic state EO products can be used, and existing assimilation techniques could be used to connect these products with existing model simulations. In the long run, dedicated models should be developed to leverage relatively robust EO products, such as LSWT, trophic state or turbidity, in the estimation of inaccessible variables, such as stratification, grazing or cyanobacteria toxicity. Improved PP (knowledge gap 4) and PFT (knowledge gap 5) products from EO can also feed into this integration framework, but they are not a prerequisite. For more conceptual details, see also the description of BIOMONDO Pilot 1 in section 4.4.

Upcoming opportunities

The attribution of trophic state and regime shifts (knowledge gap 21) can start from the first analyses of lake tipping point signals in the time domain of global EO products (Gilarranz et al., 2022). The potential regime shifts identified in such manner can be investigated across the scientific and non-scientific literature to associate them with drivers such as eutrophication from aquaculture, increased precipitation, glacier melting, soil erosion and pollution, dredging, reduced ice cover, which are altogether more potential drivers than tipping elements. For a systematic attribution of the drivers of regime shifts, dedicated model simulations would be needed, here represented by knowledge gap 9 as a prerequisite. Apart from the clarification of the drivers of historical regime shifts, these models will also enable the development of early warning applications.

The attribution of changes in lake phenology (knowledge gap 20) is necessary because phytoplankton phenology varies much more erratically between subsequent years than terrestrial phenology, and we need to better understand the causes of these variations to understand the range of lake responses and associated risks. The main drivers of phytoplankton growth, i.e. light, nutrients and temperature, are well known, and the seasonal variability of lake temperature and thermal structure can also be estimated from EO (see knowledge gap 17, sections 4.3 and 5.3). This means that the most significant drivers should be available for assessing their impact on phenology.

The impact of changes in lake phenology (knowledge gap 10) and the impact of changes in lake primary productivity (knowledge gap 11) on other biodiversity variables correspond to the propagation of changes in the timing of primary productivity on other trophic levels, including zooplankton, insects, amphibians or fish. This gap is elemental but very large and complex. As soon as the corresponding EO products are available, it can be explored on the basis of empirical coincidence and correlation in the scope of case studies, similar to the way we reported on heat stress, cyanobacteria and fish abundance in BIOMONDO Pilot 2 (see section 4.4). Ultimately, the objective is to develop universal process understanding and modelling capabilities that enable biodiversity risk assessments and warning schemes, but it may take longer than five years to establish such tools.

5.3 Thermal structure

Lake water temperature is linked directly to warming air temperatures, although it was reported that lake surface temperatures warm only at a rate of 0.24° per decade, while surface air temperatures increase at a rate of 0.29° per decade (Tong et al., 2023). The retrieval of LSWT from satellite EO is rather straightforward and accurate with uncertainties in the order of 1°. But LSWT is not an optimal environmental variable for aquatic biodiversity, which requires information on bulk surface (epilimnetic) temperatures or vertical stratification. Both can be achieved through skin-to-bulk conversion (e.g., Wilson et al., 2013) or thermal bar mapping approaches (Fichot et al., 2019), respectively, but further research is needed to make these tasks optimal and operational, and other variables, such as thermocline depth, require complementary model simulations.

Current opportunities

Monitoring changes in thermal stratification and lake mixing regimes (knowledge gap 17) requires gap-filled LSWT products, which were compiled by ESA CCI fellow E. Calamita (Eawag) and used for BIOMONDO Pilot 2. A second, enhanced gap-filled product by the University of Reading will become available through ESA CCI Lakes in the next one to two years. Using our own gap filled data, we applied the thermal bar approach (Fichot et al., 2019) for all 1000 CCI lakes and several decades of LSWT data. Preliminary results show that the mixing in large dimictic lakes can be identified accurately, and years with mixing anomalies can be identified robustly. Furthermore, the risk of mixing anomalies can be estimated during the annual cooling period by means of comparison with multi-annual cooling climatology.

Assessment of impacts of changes in thermal stratification and lake mixing regimes (knowledge gap 19) must address impacts on primary producers as well as impacts on consumers. Concerning the former, it should be investigated how changes in the seasonality of epilimnetic temperature and vertical mixing are related to phytoplankton growth (knowledge gap 16), by contrasting them with currently available TSI, or, preferably, gap filled chl-*a* products prior to temporal aggregation. In doing so, it should be considered that temperature and productivity may be related positively when lake water temperature is limiting, but negative when nutrient availability in the epilimnion is limiting (Bouffard et al., 2018). Furthermore, it must be taken into account that short term weather phenomena related to solar irradiance and wind forcing can cause algae blooms that exceed even the seasonal dynamic range (Irani Rahaghi et al., 2024). These combined effects, and the differences in their relative contributions and temporal and spatial scales, complicate systematic assessments significantly, while antecedent case studies with a focus on individual lakes and events are relatively straightforward.

Assessments of the impacts of extreme climate events, e.g. heatwaves and massive rainfall events, on biodiversity variables (knowledge gap 22), can hence be understood as case studies within knowledge gap 16 if they focus on response variables related to primary producers.

Upcoming opportunities

A large number of future high-resolution (ca. 50-70 m) thermal satellite missions (i.e., Trishna, SBG, LSTM) will enable near daily observations if used as a constellation, and hence extend the use of thermal EO to a huge number of smaller lakes, and even rivers. This leap in spatial resolution is the largest upcoming opportunity, and preparatory research must be carried out to utilize high-resolution TIR data in the same manner as low-resolution TIR data has been used for decades. The ECOSTRESS mission can be considered as a surrogate in the next years. It flies on the ISS' orbit and may, during favourable periods, also provide daily observations.

5.4 River connectivity, sedimentation processes and wetland formation

Obstacles such as dams and other human-made waterworks heavily alter and interrupt dispersal routes for many species including fish (Barbarossa et al., 2020; Duarte et al., 2021), aquatic invertebrates (Grönroos et al., 2013), and plants (Merritt and Wohl, 2006). In addition, river dams and other human-made waterworks change the natural flow regimes, e.g. the quantity, timing, and variability of water flows, which define the habitats of aquatic and semi-aquatic species in rivers, riparian zones, floodplains, estuaries, and other river-associated wetlands (Janse et al., 2015; Kuiper et al., 2014; Poff et al., 2010; Poff and Zimmerman, 2010). In particular, the period during which wetlands are flooded (i.e. the hydroperiod) is important in this context, as this is a crucial period for the development of amphibian and insect larvae and the species that depend on them as a food source. In addition to this, flow alterations affect water quality and sediment transport which is crucial for the formation and maintenance of riverine wetlands and river deltas which may be threatened by future sea level rise despite overall growing deltas (Nienhuis et al., 2020). Because of this mix of negative impacts of human-made waterworks, it is perhaps no surprise that dam removal is an explicit target in the EU Nature Restoration Plan (European Commission, 2021), which aims for the restauration of at least 25,000 km of free-flowing rivers by 2030. River dams, however, are also important in the less developed countries, and are welcomed as a source of renewable energy (i.e. hydropower) when combatting climate change (Winemiller et al., 2016). Dam-building, and potentially other human-made waterworks, thus provides a real challenge when developing environmental and developmental policies which require a careful consideration of pros and cons (e.g. see Schmitt et al. 2019 and Section 4.4).

Knowledge gap 3 and 14 are central to the here discussed research themes, which can partially be addressed simultaneously (see 'current opportunities' below). Dependencies on, and dependencies of other related knowledge gaps are shown in Figure 11.

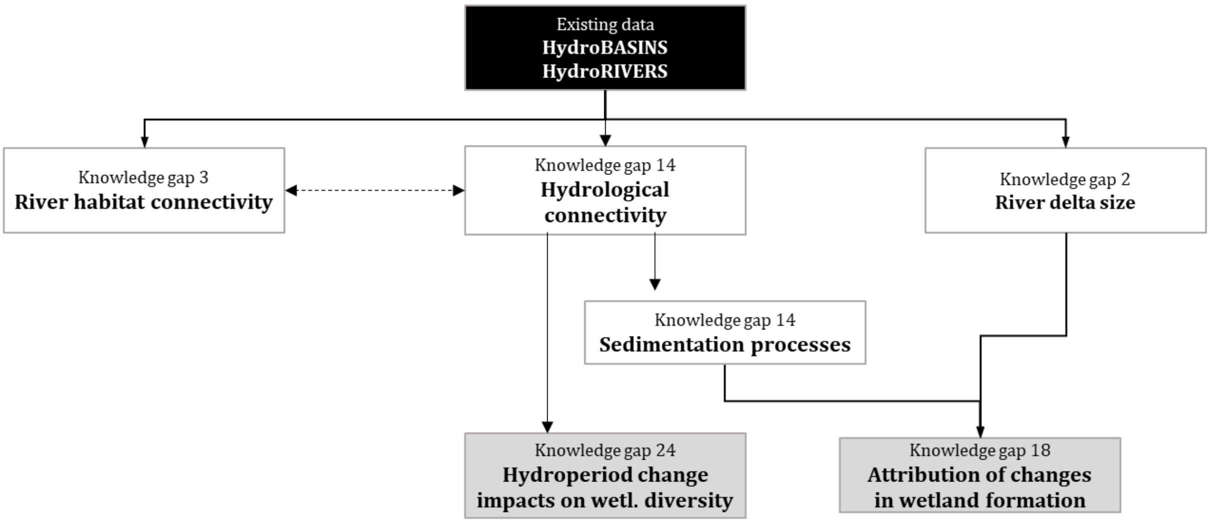


Figure 11: Hierarchy of knowledge gaps (from 4.3) related to river connectivity and sedimentation processes. Existing variables are shown in black boxes, ecosystem functioning knowledge gaps are shown in white boxes, and knowledge gaps linking ecosystem to environmental variables are shown in grey.

Current opportunities

Addressing both knowledge gap 3 and 14 starts with an inquiry of the location of river dams and other human-made waterworks. Waterworks that affect habitat connectivity (i.e. that block migration or dispersal of species – in particular river dams) also affect hydrological connectivity and sedimentation processes, so this is an effort that can be made for both knowledge gaps simultaneously. There are several datasets of global river dams available. These datasets, however, vary in terms of quality, coverage and definitions of dams and in the attributes provided apart from location, such as dam and reservoir dimensions, type of turbines, fish passages, flow management etc. Despite many efforts, there is no globally consistent or complete database on the locations of dams. In particular, the rapid increase in the placement of smaller hydro powerplants (SHPs) may be unaccounted for, even though estimates suggest that there might be approximately 11 SHPs for each larger powerplant (Couto and Olden, 2018). To support the work on knowledge gap 3 and 14 (connectivity) it might be of interest to explore whether it is feasible to develop a global, EO based automatic detection of river dams (e.g. using machine learning). To support the work on knowledge gap 14 (connectivity), it is, in addition to this, of interest to monitor other waterworks that influence river flows, e.g. dykes and channels. This should be an ongoing effort that is made on a regular, e.g. yearly, basis.

To determine habitat connectivity, the information on river-dam locations need to be incorporated into biodiversity models that take the geographical range of species (i.e. their natural habitat) into account. This has been done previously (e.g., Barbarossa et al., 2020), but the approach could benefit from a more exact approach towards determining what constitutes a habitat fragment which can be supported by EO. Such fragments correspond to a stretch of river within which a species can move freely without encountering an obstacle. To monitor this well, a detailed monitoring of river flows along the surface is desirable that, e.g. is capable to determine whether there are side branches that provide a passage around river dams. River dams may also change the shape of river basins (e.g. as in HydroBASINS). Information on this thus may needs to be updated after the placement of a dam. This may also be of importance for biodiversity models that use these basins as a key unit of what constitutes a habitat fragment.

To determine hydrological connectivity, different aspects of this type of connectivity may be considered (Grill et al., 2019); 1) longitudinal (connectivity between up- and downstream), 2) lateral (connectivity to floodplain and riparian areas), 3) vertical (connectivity to groundwater and atmosphere), and 4) temporal (connectivity based on seasonality of flows). EO data could serve as an input for river network routing models (see Lehner and Grill, 2013 for an example of such a modelling approach and its challenges), or might be able to directly inform on the here mentioned aspects 1, 2, and 4. Aspect 4 (i.e. temporal connectivity) is also important to inform on the hydroperiod of wetlands.

To further inform on sedimentation processes EO derived metrics of sediment load (i.e. based on changes in turbidity/surface-water colour) can be incorporated into models of water flows and (changes in) hydrological connectivity. Such models can also be extended to include (human induced) changes in land use/land cover on the watershed that may affect sediment inflows (e.g. deforestation). The results may then, in turn, be used to determine the extent to which a (future) loss of river deltas (i.e. EBV ecosystem distribution) can be attributed to changes in hydrological connectivity and reduced sediment inflows (knowledge gap 18, e.g., as in Schuerch et al., 2018). This may be combined with a direct monitoring of (changes in) the extent of river deltas (knowledge gap 2) using EO (e.g., regular updates according to Donchyts et al., 2016). A similar effort can be made for other types of wetlands (i.e. beyond river deltas), but we consider this more challenging (see upcoming opportunities below).

Even though there are quite a few examples of studies that use EO to monitor changes in the hydroperiod of wetlands (Díaz-Delgado et al., 2016; Murray-Hudson et al., 2015), there is no globally consistent approach or dataset of changes in hydroperiods across the globe. Such methods could have some similarities with approaches towards monitoring phenology which also aim to extract metrics of temporal change from time series (see section 5.2). EO derived metrics of a wetland's hydroperiod (changes in the length and timing) can be used to validate hydrological models of change in hydrological connectivity (see above, i.e. knowledge gap 14a), and as input for biodiversity models as this period is important for (particular life stages/phenology of) many aquatic and terrestrial species (see knowledge gap 23).

Upcoming opportunities

While it is straightforward to monitor changes in the extent of river deltas (i.e. because of their size), it is more difficult to monitor changes in the extent of smaller, riverine wetlands. Work on these wetlands could benefit from a higher spatial resolution.

Future research building on the here described work could focus on (the spread of) invasive, emergent macrophytes and/or other species (knowledge gap 13). This could be combined with efforts to map the vegetation of wetlands using EO (e.g., as in Adam et al., 2010).

5.5 Ecosystem disturbances, regime shifts, anomalies, and resilience indicators

While the focus of section 5.2 is on the production of new time series (i.e. of lake primary productivity and lake PFT) and the extraction of seasonal dynamics (i.e. phenology), this section focusses on the cases in which these time series or dynamics show a substantial change, either in the form of longer-term regime shifts or relatively short-lived but large-scale anomalies. This is important because shallow lakes are known to typically show (at least) two alternative states, i.e. a clear-water state with submerged macrophytes and piscivorous fish, or a turbid state dominated by phytoplankton. Shifts between these states may occur relatively suddenly under the influence of gradual changes in nutrient inflows when ‘tipping points’ are passed (Scheffer et al., 1993). Deeper lakes may, e.g., exhibit shifts in mixing regimes under the influence of climatic changes (Calamita et al., 2024), while the high rates of herbivory in freshwater systems makes them particularly susceptible to regime shifts arising from changes in biotic interactions (which, e.g., are dependent on phenology; Lever et al., 2023). Anomaly detection is important because they are expected to increase in size and frequency under the influence of climatic changes with potentially catastrophic consequences for species and biodiversity. Such extreme events may also trigger regime shifts. At the same time, such anomalies may provide important information about the resilience of ecosystems under the influence of global environmental change. Resilience may be, among other possibilities, defined as the speed at which a system recovers from disturbances (i.e. engineering resilience), or as the amount of change a system can handle without going through a regime shift (i.e., ecological resilience; Holling, 1996). Loss of both types of resilience tends to go hand-in-hand and, therefore, an increasingly slow recovery from disturbances (e.g. after anomalies) can be used as an indicator of the loss of both types of resilience. Changes in the statistical properties of time series (e.g. increased variance and autocorrelation) may provide an indication that the speed of recovery from disturbances is slowing down. Monitoring of lake resilience using such ‘resilience indicators’ is important, in particular because it is not always easy to determine which environmental driver is undermining ecosystem resilience (Scheffer et al., 2009; van Nes and Scheffer, 2007).

Knowledge gaps 7 and 8 are the key knowledge gaps related to the here discussed research themes. Dependencies on, and dependencies of other knowledge gaps are shown in Figure 12. This figure also shows the large number of gaps that may need to be filled to attribute observed regime shifts to environmental changes (i.e. knowledge gap 21). When it is difficult to do attribution (e.g. because there are many drivers of change) direct monitoring of resilience indicators might be a particularly important alternative.

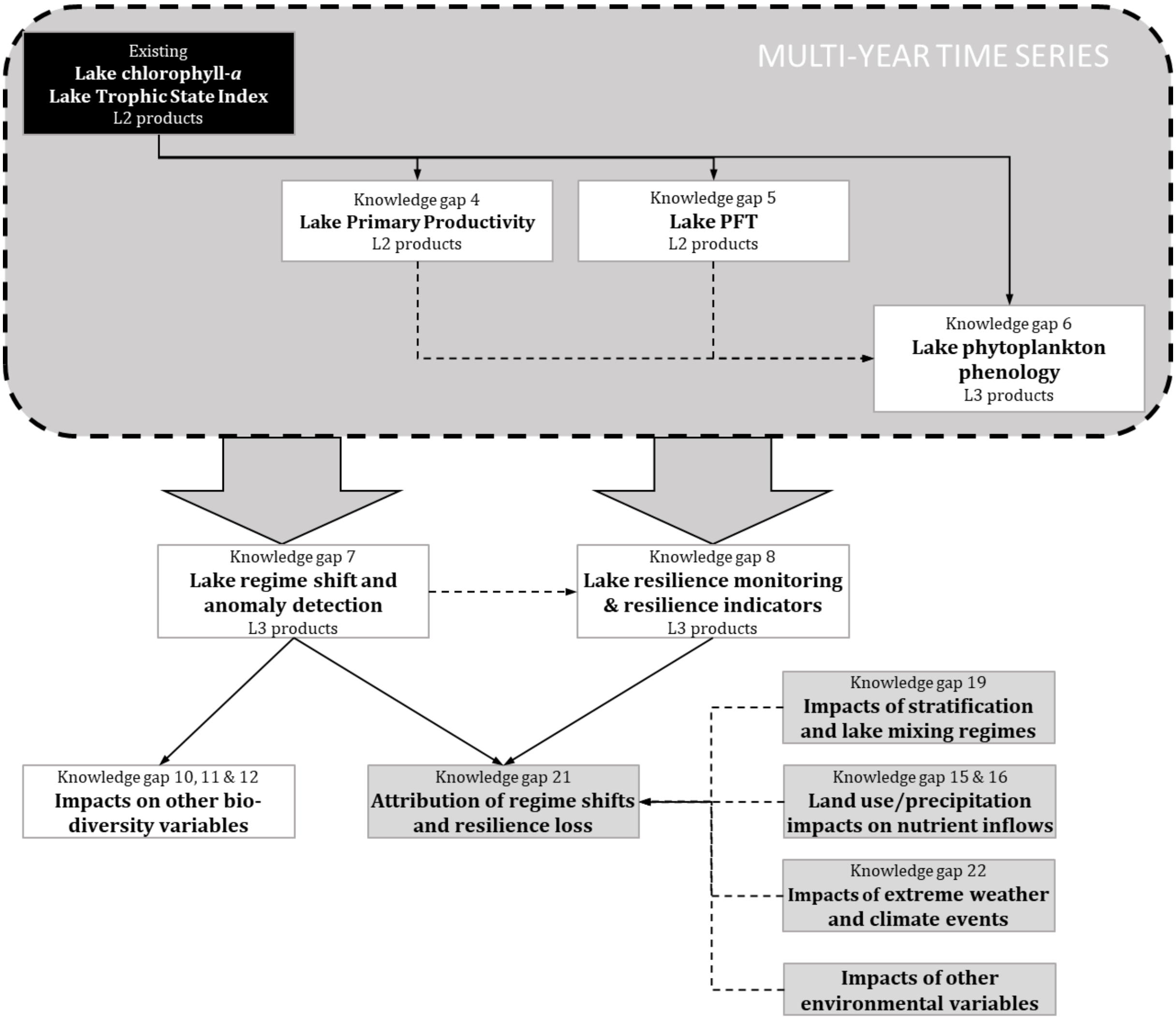


Figure 12: Hierarchy of knowledge gaps (from 4.3) related to lake regime shifts, anomaly detection, and resilience monitoring. In this section we focus on knowledge gaps 7 and 8. Knowledge gaps 4-6 are discussed in section 5.2. Existing variables are shown in black boxes, ecosystem functioning knowledge gaps are shown in white boxes, and knowledge gaps linking ecosystem to environmental variables are shown in grey.

Current opportunities

Studying regime shifts requires knowledge of when and where they may have happened (i.e. knowledge gap 7) which requires data preparation (e.g. gap filling) and decomposition of time series in seasonal, trend, and residual components. A wide variety of methods exist to do this (Bathiany et al., 2024). One of the most commonly applied methods when using satellite data is BFAST (Verbesselt et al., 2010) and the more recent BEAST (Zhao et al., 2019), although the most appropriate method depends on the nature of the data. This, in turn, allows for the detection of so-called ‘change points’, i.e. where a sudden change in the statistical properties of a time series occurs. To do this, classical change-point detection algorithms are increasingly often combined with supervised classification models to filter out false positives (Bathiany et al., 2024). Following earlier work on case studies (e.g., Gsell et al., 2016), a first global dataset of regime shifts, trends, and variability in lakes was produced by Gilarranz et al. (2022). This dataset can, however, be extended to include more recent years (e.g. using OLCI data, the current dataset uses MERIS only), to include more lakes, and to use other time series data (e.g., chl-*a* estimates, instead of TSI, and other spatial or temporal resolutions). When knowledge gaps 4 and 5 are addressed primary productivity and PFT time series may be good candidates as well.

Anomaly detection is typically used to study 'disturbance regimes' in their own right and are often characterized by their size (i.e. the area affected), frequency, and the 'severity' of the anomaly (Senf and Seidl, 2021). It is expected that the values of these anomaly metrics will increase as the frequency and severity of extreme climatic events escalates. There is a wide variety of anomaly detection algorithms available (e.g. k-nearest neighbours mean distance, kernel density estimates, a recurrence approach, and ensemble approaches that combine them). For the detection of anomalies, the method to extract the key features (e.g. the seasonal, trend, and residual components as discussed above) may, however, be more important than the specific anomaly detection method chosen (Flach et al., 2017). (Changes in) anomalies can be studied for all the aforementioned time series as well as for metrics of phenology (after addressing knowledge gap 6)

There is a rapid increase in studies that use of EO to monitor changes in the resilience of terrestrial ecosystems (e.g., Forzieri et al., 2022). For lakes, similar studies rely mostly on in-situ data (Carpenter et al., 2011; Gsell et al., 2016), with few exceptions that use EO (Gilarranz et al., 2022). Extracting resilience indicators from lake phytoplankton time series thus constitutes an important opportunity (i.e. knowledge gap 8). To validate obtained results, known cases with and without regime shifts may be used (i.e. benefitting from the work on knowledge gap 7). It might be more challenging to extract classical indicators of resilience (e.g., as in Scheffer et al., 2009) for lakes, because the seasonal dynamics of lakes are more complicated than those on land. Existing methods might therefore need to be updated to take this into account. Alternative methods could also involve the development of a metric of recovery after anomalies, or machine learning approaches (e.g., as in Bury et al., 2021), to close this gap.

Upcoming opportunities

The above-described analysis can currently be applied only to existing time series of, e.g. TSI and chl-*a* concentrations. When knowledge gap 4, 5, and 6 are addressed this may also be possible for time series of primary production, PFTs, and phenology.

The attribution of regime shifts (knowledge gap 21) can be done in two fundamentally different ways. It might be possible to relate the occurrence of regime shifts with particular land use/land cover properties on a global scale where correlations with human population densities in the catchment area are found, e.g. in Gilarranz et al. (2022). This approach can be extended to include a wider range of potential drivers of environmental change. However, for a more systematic attribution of the drivers of regime shifts, dedicated hydrological model simulations are needed, and, for example information on nutrient inflows and lake mixing regimes obtained when addressing knowledge gaps 15-17. Apart from the clarification of the drivers of historical regime shifts, these models will also enable development policies that may prevent future regime shifts.

6 Roadmap (2024-2028)

The European Space Agency (ESA) activity called Biodiversity+ Precursors is a contribution to the joint EC-ESA Earth System Science Initiative. The freshwater precursor BIOMONDO aimed to support freshwater biodiversity monitoring through Earth Observation (EO), which is the gathering of information about the physical, chemical, and biological systems of the planet Earth through remote sensing and/or ground-based techniques. One of the activities of BIOMONDO was to develop a 5-year roadmap for further research. The development of such a roadmap, however, cannot be done without setting priorities which, in turn, requires a longer-term outlook on what the future of freshwater biodiversity research and monitoring, i.e. beyond those five years, should bring. What the future of freshwater biodiversity monitoring *should* bring can, in turn, not be anything more or less than a matter of opinion. In this chapter, we provide therefore this roadmap as well as the framework we used to develop it. We hope to present a well-founded opinion by building on our view of biodiversity monitoring as a multi-dimensional challenge as outlined in section 1.3. In addition to this, we hope that, by providing the framework we used to set priorities, we provide the opportunity for the reader to develop his or her own opinion and deviate from our proposal where desired.

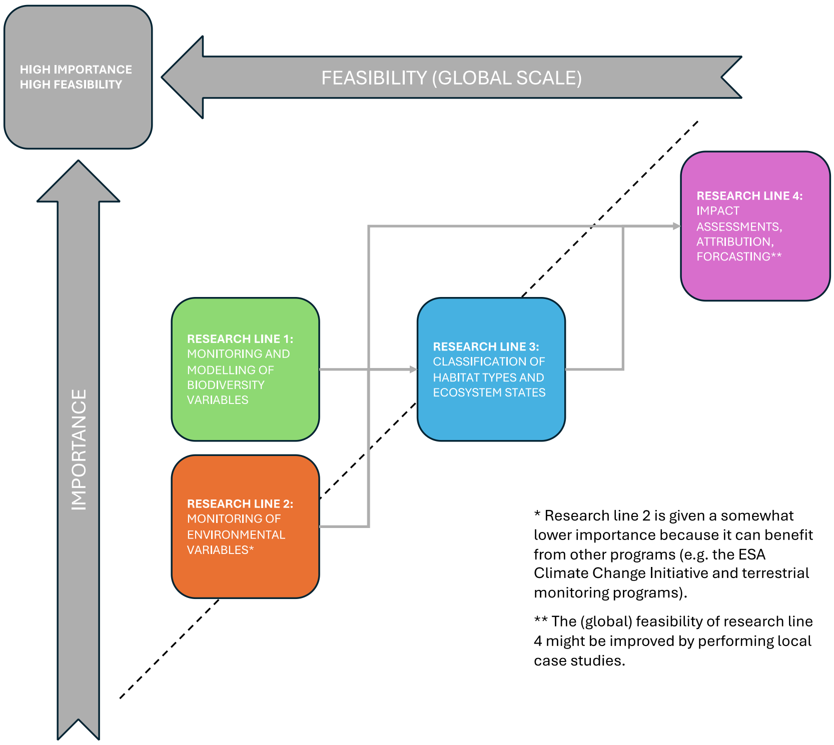
6.1 Setting priorities and the multi-dimensional nature of biodiversity monitoring

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. When reviewing our knowledge gaps in section 4.3, we believe that four different lines of research can be distinguished that link back to our view on biodiversity monitoring as a multi-dimensional challenge as outlined in section 1.3. More specifically, we suggest that the following lines of research can be distinguished:

1. **'Monitoring and modelling biodiversity variables'** which comprises knowledge gaps 4, 5, 6, 7, 8, 9, 10, 11, and 12. These knowledge gaps are all related with the direct monitoring (4 and 5), the extraction of relevant metrics (6, 7, and 8), or the modelling (9, 10, 11, and 12) of the biotic part of ecosystems. The monitoring and modelling of ecosystem services could be part of this research line as well.
2. **'Monitoring and modelling of environmental variables'** which comprises knowledge gaps 2, 3, 13, 14, 15, 16, and 17. These knowledge gaps are all related to the direct monitoring (2, 3, 13) and modelling of drivers of environmental change (14, 15, 16, and 17) and/or abiotic properties that define a system's habitat type.
3. **'Classification of habitat types and ecosystem condition/state'** which comprises knowledge gap 1, in which we classify freshwater ecosystems according to their habitat type (i.e. long-term properties such as lake depth, position in river network, climate zone) and their state (i.e. that can change under the influence of drivers of change such as trophic state and mixing regime).
4. **'Impact assessments, attribution, and forecasting'** which comprises knowledge gaps 18, 19, 20, 21, 22, and 23. This research line brings information from the previous research lines together in which the impacts of drivers of environmental change (research line 2) on biodiversity variables (research line 1) is studied for a particular habitat type and ecosystem state (research line 3).

Research line 1-3 each correspond to a different dimension (or axis) of biodiversity monitoring as outlined in section 1.3 and Figure 3, while research line 4 corresponds to work on the interactions between them. 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 (see section 1.3). It may, however, not be easy to perform this work because the work on this research line 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. If there were no other research programs, we would consider research lines 1-3 to be of equal importance. Part of the work on research line 2 may however be performed by, for example, the ESA Climate Change Initiative and (biodiversity) programs studying the terrestrial realm and climatic changes or nutrient inflows. For this reason, we give the work on research line 2 a somewhat lower importance as a part of program research program on freshwater biodiversity. It is important though, to keep monitoring what is and what is not done as a part of these research programs. Combined, these considerations result in the graph presented in Figure 13. Taking these aspects into account we believe that work on research line 1 scores best in terms of importance and global-scale feasibility to make substantial progress while this score is the worst for research line 4 despite its high importance. In section 0 we elaborate further on what this means for our proposed roadmap towards global monitoring of freshwater biodiversity.

While Figure 13 presents an estimate of the importance and global-scale feasibility of making progress for entire research lines, similar estimates can be made for individual knowledge gaps. The development of novel EO products that are an estimate of the absolute quantity of a key variable (e.g. knowledge gaps 4 and 5) needs to precede the extraction of relevant metrics for phenology and resilience (e.g. knowledge gaps 6, 7, and 8) and the incorporation of these products into modelling efforts (e.g. knowledge gaps 9, 10, 11, and 12). As a rule of thumb, we believe therefore that it is more feasible to just develop a novel EO product than to also extract meaningful metrics from this product (which must come in a second step) and certainly more feasible than the incorporation of such a product into more complex models (which is more complicated than the extraction of metrics). In appendix A.6 we provide draft examples of more detailed schemes for each research line, and we suggest that more detailed schemes can be developed further by the consortium applying additional activities of the Biodiversity Flagship action of the Earth System Science Initiative (e.g. as a part of their proposal) as this may in part also depend on the knowledge and competences of the consortium that is applying.



* Research line 2 is given a somewhat lower importance because it can benefit from other programs (e.g. the ESA Climate Change Initiative and terrestrial monitoring programs).

** The (global) feasibility of research line 4 might be improved by performing local case studies.

RESEARCH LINE 1:
KG 04: Primary productivity
KG 05: Phytoplankton diversity
KG 06: Phytoplankton phenology
KG 07: Phyto. regime shifts and anomalies
KG 08: Monitoring resilience
KG 09: EO-derived phytoplankton in biodiversity and hydrological models
KG 10: Impacts of phenology changes on other biodiversity variables.
KG 11: Impacts of productivity changes on other biodiversity variables.
KG 12: Impacts of phyto. anomalies on other biodiversity variables.

RESEARCH LINE 2:
KG 02: River delta size/habitat loss
KG 03: River habitat connectivity
KG 13: Monitoring the spread of invasive species
KG 14: Impacts of river hydrological connectivity on sedimentation processes
KG 15: Impacts of Land Use Land Cover on nutrient inflows
KG 16: Impact of precipitation and evapotranspiration on nutrient inflows
KG 17: Monitoring thermal stratification and lake mixing regimes.

RESEARCH LINE 3:
KG 01: Freshwater habitat types and ecosystem mapping

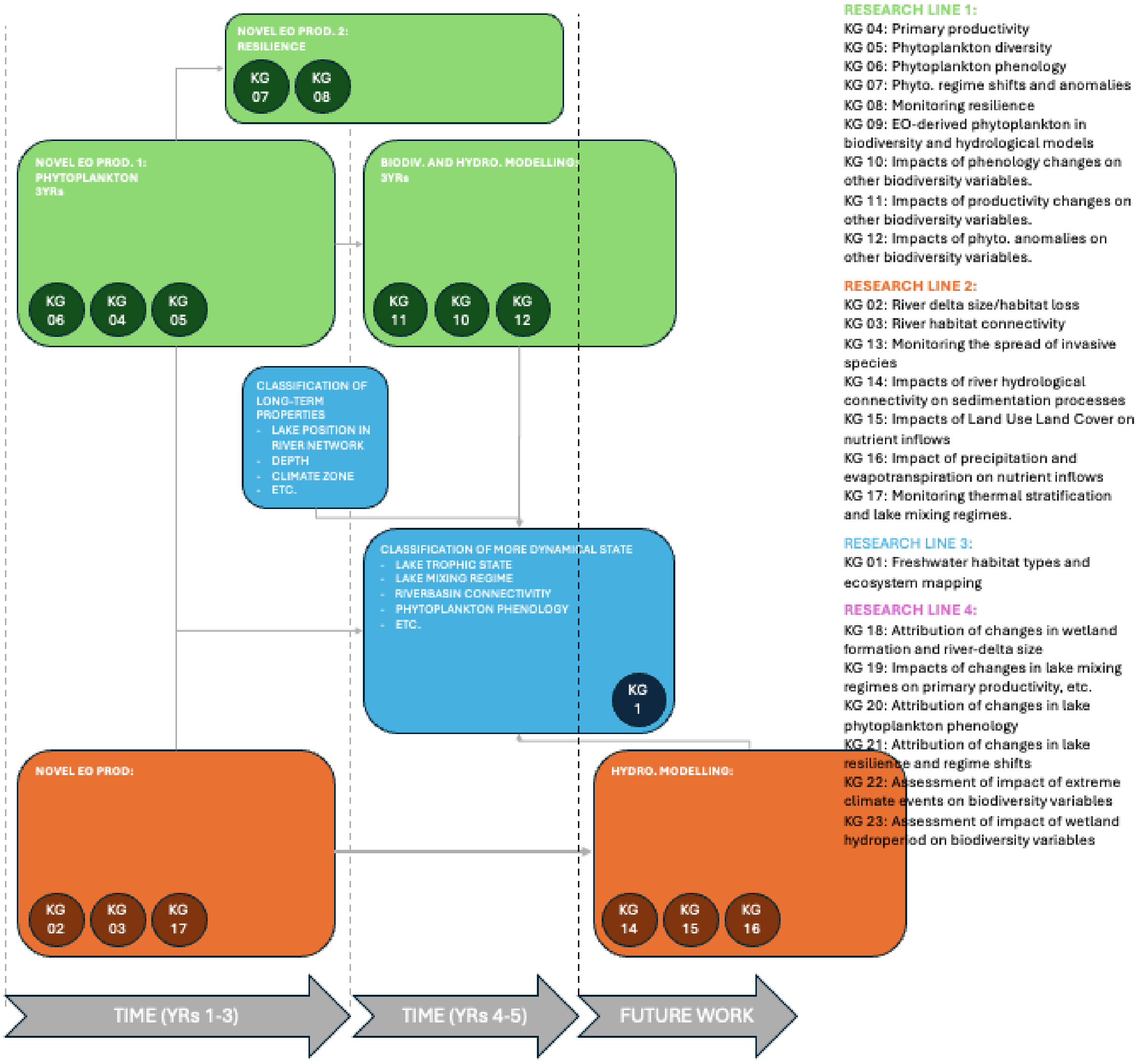
RESEARCH LINE 4:
KG 18: Attribution of changes in wetland formation and river-delta size
KG 19: Impacts of changes in lake mixing regimes on primary productivity, etc.
KG 20: Attribution of changes in lake phytoplankton phenology
KG 21: Attribution of changes in lake resilience and regime shifts
KG 22: Assessment of impact of extreme climate events on biodiversity variables
KG 23: Assessment of impact of wetland hydroperiod on biodiversity variables

Figure 13: Importance and feasibility of making progress across different lines of research on a global scale. Some research lines depend on input from other lines (grey arrows) which lowers their feasibility. Because research line 4 is the final aim to which the here proposed biodiversity monitoring programme should contribute, it is given the highest importance. We gave a somewhat lower importance to the monitoring of environmental variables (research line 2) because this can partially be done by other research programmes (e.g. the ESA Climate Change Initiative and terrestrial monitoring programmes). We consider the combined score in terms of feasibility and importance to be better for research lines that are on the left of the black dashed line when compared to those on the right of this line. Research line 1-3 correspond to different axis of the cube in Figure 3, while research line 4 is looking at the interactions between these different aspects of biodiversity monitoring.

6.2 A two-track approach: global- and local-scale research on a time axis

As suggested by Figure 13, we believe that work on research line 1 (biodiversity variables) scores best in terms of importance and feasibility which should, therefore, 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 (environmental variables), in a way that paves the way for perhaps more preliminary work on research line 3 (habitat types and ecosystem state). In particular, because the work on research line 2 may benefit from work in other research programmes. At the same time, we believe that it is highly important to also perform work on research line 4 (impact assessments, attribution, and forecasting) 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 way that allows for upscaling at a later stage. We thus propose a two-track approach:

- Global-scale research on research lines 1 & 2 in a way that paves the way for work on research line 3 (Figure 14).
- Case studies at well-studied pilot sites that improve the feasibility of future global-scale work on research line 4 (Figure 15).



RESEARCH LINE 1:
KG 04: Primary productivity
KG 05: Phytoplankton diversity
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KG 10: Impacts of phenology changes on other biodiversity variables.
KG 11: Impacts of productivity changes on other biodiversity variables.
KG 12: Impacts of phyto. anomalies on other biodiversity variables.

RESEARCH LINE 2:
KG 02: River delta size/habitat loss
KG 03: River habitat connectivity
KG 13: Monitoring the spread of invasive species
KG 14: Impacts of river hydrological connectivity on sedimentation processes
KG 15: Impacts of Land Use Land Cover on nutrient inflows
KG 16: Impact of precipitation and evapotranspiration on nutrient inflows
KG 17: Monitoring thermal stratification and lake mixing regimes.

RESEARCH LINE 3:
KG 01: Freshwater habitat types and ecosystem mapping

RESEARCH LINE 4:
KG 18: Attribution of changes in wetland formation and river-delta size
KG 19: Impacts of changes in lake mixing regimes on primary productivity, etc.
KG 20: Attribution of changes in lake phytoplankton phenology
KG 21: Attribution of changes in lake resilience and regime shifts
KG 22: Assessment of impact of extreme climate events on biodiversity variables
KG 23: Assessment of impact of wetland hydroperiod on biodiversity variables

Figure 14: 5-year roadmap for global-scale research. The focus during the first three years is on the development of novel EO-products that should become available on a global scale. After three years, the priority should shift towards the incorporation of these products in global biodiversity modelling efforts and support towards the classification of freshwater habitat types and ecosystem states. Novel EO products developed as a part of research line 2 should pave the way for future work on hydrological modelling efforts (that are also a part of research line 2). When part of the work on research line 2 could be performed by other programmes, it might be possible to shorten this timeline.

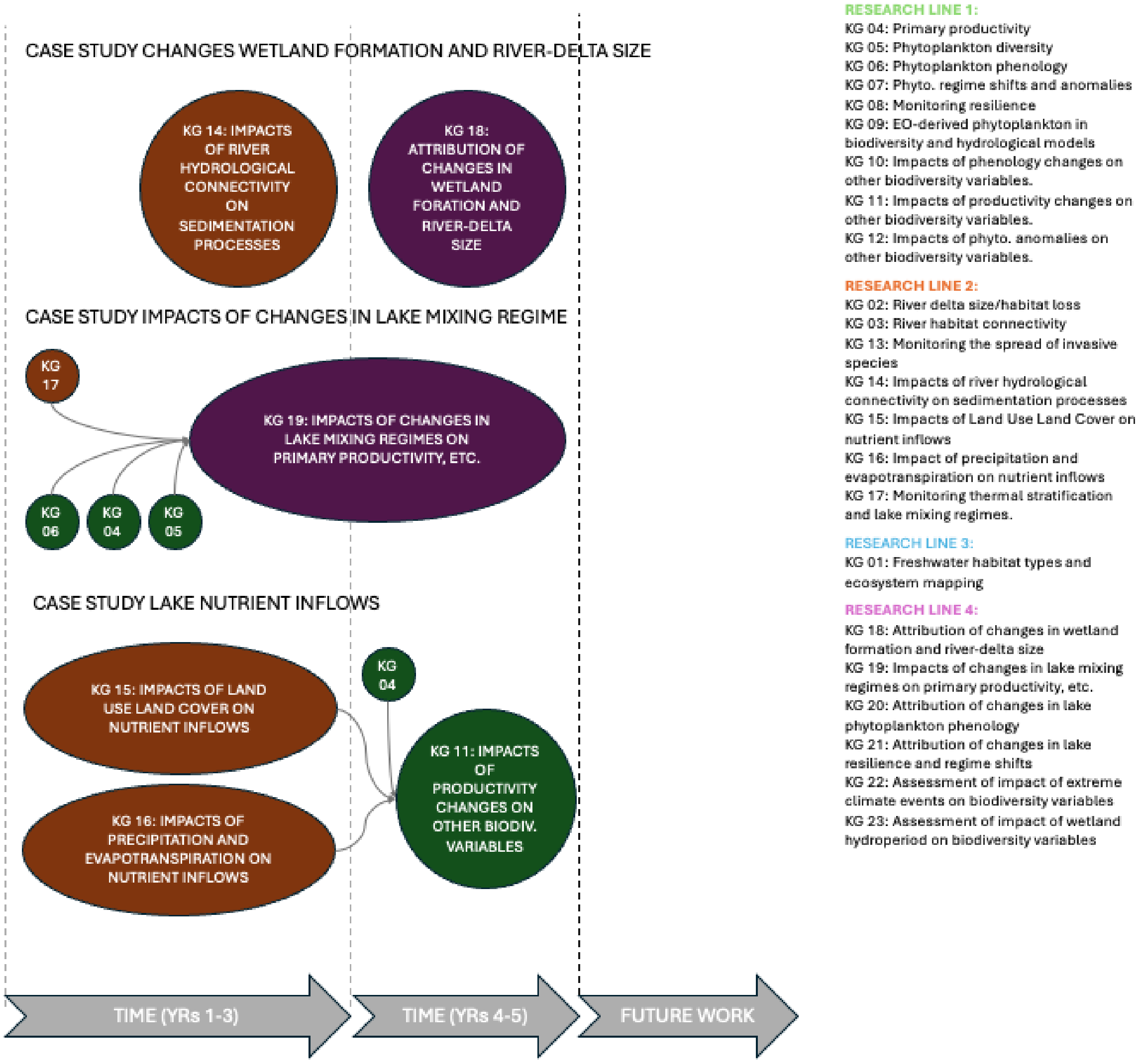

Figure 15: Proposed case studies on a local scale. These local-scale studies should help to improve the feasibility of global-scale research on line 4 (impact assessments, attribution, and forecasting).

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A.1 Essential Biodiversity Variables

Table 7: The six classes of Essential Biodiversity Variables (EBVs) as defined by the Group on Earth Observations Biodiversity Observation Network (GEO BON). EBV class priorities identified by FWBON are indicated with an asterisk (Turak et al. 2017, Pereira et al. 2013). In the third column the names of the freshwater EBVs identified by EuropaBON are listed for comparison. Suboptimal fit between GEO BON EBV and EuropaBON EBV names are highlighted in italics and from the point of view of BIOMONDO, a missing EBV is marked with underline.

EBV class	**EBV name**	**EuropaBON Freshwater EBV names**
Genetic composition	Genetic diversity (richness and heterozygosity)	Genetic diversity of selected freshwater taxa
	Genetic differentiation (number of genetic units and genetic distance)	
	Effective population size	
	Inbreeding	
Species populations*	Species distributions	Species distributions of freshwater fishes Species distributions of amphibians Species distributions of freshwater mammals Species distributions of freshwater invertebrates Species distributions of dragonflies Species distributions of freshwater macrophytes Species distributions of invasive alien freshwater taxa of European concern Species distributions of freshwater reptiles
	Species abundances	Species abundances of selected wetland bird species Species abundances of dragonflies
Species traits	Morphology	
	Physiology	
	Phenology	Phenology of migration of wetland birds Phenology of migration of freshwater fishes
	Movement	
	Reproduction	
Community composition*	Community abundance	*Community composition of phytoplankton* *Community composition of macrophytes* *Community composition of phytobenthos* *Community composition of benthic invertebrates* *Community composition of fishes* *Community composition of zooplankton* *Community composition of aquatic fungi*
	Taxonomic/phylogenetic diversity	
	Trait diversity	
	Interaction diversity	

EBV class	EBV name	EuropaBON Freshwater EBV names
Ecosystem functioning	Primary productivity	Freshwater ecosystem productivity *Rate of decomposition* Harmful and non-harmful freshwater algal blooms
	Ecosystem phenology	Phenology of phytoplankton blooms (listed as an example by GEO BON)
	Ecosystem disturbances	
Ecosystem structure*	Live cover fraction	
	Ecosystem distribution	Ecosystem distribution of freshwater EUNIS Habitats *Structural complexity of riparian habitats* *River Connectivity/Free river flow*
	Ecosystem vertical profile	

A.2 Available EO tools and services

Table 8: List of IT tools and services that facilitate EO data access, analysis and visualization.

Name	Description	Matches for BD community	Gaps for BD community
CEOS COVE	The CEOS COVE is a suite of tools for analyzing satellite sensor coverage for more than 100 Earth-observing satellites.	Quick overview for present and potential EO data.	Processing, management and analysis of EO data not possible.
EuroDataCube	Euro Data Cube is a one-stop-shop for browsing, analysis and processing of EO data, from source up to the final product.	Collection, Processing, management and analysis of raster and vector data possible.	BD models and BD variables have not yet been integrated in workflow.
Thematic Exploitation Platforms	ESA's Earth Observation Thematic Exploitation Platform (TEP) is a browser for satellite imagery and specific products on an environmental topic.	Various BD variables present.	Management and analysis of raster and vector data not possible.
Earth System Data Laboratory	The Earth System Data Lab seeks to be a service to the scientific community to greatly facilitate access and exploitation of multivariate data sets in Earth Sciences.	Various BD variables present. Analysis and management of raster data possible. Will be continued within EuroDataCube.	Management of model and vector data not possible.
Copernicus DIAS	The five DIAS online platforms allow users to discover, manipulate, process and download Copernicus data and information.	Processing of big EO data possible.	Management of raster or vector data not possible.
National Platforms (CODE-DE, THEIA)	National Platforms offer high-performance access to all Copernicus data in corresponding countries.	Processing of big EO data possible.	Management of raster or vector data not possible.
Sentinel Hub	Sentinel Hub makes satellite data easily accessible for browsing or analyzing them, within a cloud GIS or within an own environment.	Easy access to big EO data possible.	Processing, management and analysis of raster or vector data not possible.
ADAM platform	The Advanced geospatial Data Management platform is a tool to access a large variety and volume of global environmental data	Management and analysis of raster data possible. Multiple BD variables.	Management of model and vector data not possible.
Planetary Computer	The Planetary Computer combines a multi-petabyte catalog of global environmental data.	Easy access to big EO data and BD parameters possible.	Management of model and vector data not possible.
GlobWetlandAfrica Toolbox	GlobWetland Africa Toolbox was launched to facilitate the exploitation of satellite observations for the conservation, wise-use and effective management of wetlands in Africa	Toolbox developed for BD analytical purpose. Ready to use.	Toolbox is tailored to study sides in Africa.

Name	Description	Matches for BD community	Gaps for BD community
Ocean Virtual Lab	The Ocean Virtual Laboratory is a virtual platform to discover the existence and then to handle jointly the various co-located EO datasets and related model/in-situ datasets over dedicated regions of interest with a different multifaceted point of view.	Management and analysis of raster and vector data possible.	OVL tailored to ocean applications.
Agriculture Virtual Lab	The Agriculture Virtual Laboratory is an integrated, user-friendly online environment that helps scientists to discover, explore, analyse, and visualize a wide variety of agricultural earth observation data.	Management and analysis of raster and vector data possible.	AVL tailored to agricultural applications.
Rasdaman	Rasdaman is an Array DBMS which adds capabilities for storage and retrieval of massive multi-dimensional arrays, such as sensor, image, simulation, and statistics data.	Tool for managing raster data (model and remote sensing data) and in situ data.	No interface for satellite data processing.
Callisto, DeepCube, GEM, BETTER, CANDELA, EOPEN, openEO, PerceptiveSentinel, RapidAI4EO	European R&D projects conducted under the H2020.	Development of machine learning methods analyzing EO data and other data.	-

A.3 Freshwater biodiversity knowledge gaps

Table 9: Freshwater knowledge gaps collated from IPBES (2019), Maasri et al. (2022) and Harper et al. (2021).

Freshwater Knowledge Gap	Research need/comment	Source
No global dataset on the extent of aquaculture, locations and area of coverage		IPBES (2019), p 206 Ch 2.2 Status and trends in nature
Only few indicators for the structure of freshwater ecosystems, with ecosystem condition less well represented than ecosystem extent.		IPBES (2019), p 233.
No available indicators on interaction among organisms and taxa. Freshwater together with marine assemblages are greatly underrepresented compared to terrestrial.		IPBES (2019), p 238.
No global indicators of biotic homogenization. NOT SPECIFIC FW	But may apply also to FW	IPBES (2019), p 238.
Low degree of confidence related to impact of climate change in freshwater but thought to be dominated by effects on ecosystem function		IPBES (2019), p 254.
Lack of comprehensive global dataset on Protected Area management effectiveness. NOT SPECIFIC FW	But may apply also to FW	IPBES (2019), p 417.
Most scenarios of biodiversity change are terrestrial or marine, while far fewer exist for freshwater. Therefore, most evidence provided for freshwater biomes is based on local and regional studies. Only a few metrics of biodiversity and ecosystem function have been explored deeply enough to draw conclusions on their interactions in a globally changing environment.		IPBES (2019), p 625.

Freshwater Knowledge Gap	Research need/comment	Source
Unknown or uncertain effects of climate change, i.e. projections but changes will occur from change in: temperature, water availability, flow regimes through changes in precipitation and/or temperature.	Includes many more detailed examples of likely changes and interactions. Including Wetland changes and release of carbon that will cause habitat loss and reduced water quality.	IPBES (2019), p 650.
Future impacts of habitat fragmentation on freshwater biodiversity and ecosystem function. Uncertain effects of dam building (e.g. species extinction risks – blocked migrations and/or reduced population size and gene flow) and spiraling interacting changes due to altered flow regimes, more dam building and population increases)		IPBES (2019), p 650, p 652
Unknown effect of competition between non-native and native species leading to (e.g. disease spread, degraded ecosystem services and economies as well as biotic homogenization of aquatic ecosystems)		IPBES (2019), p 653
Inland fisheries are underestimated, including relationship to changes to biodiversity		IPBES (2019), p 654, 4.2.3.6 Future impacts of harvest on freshwater biodiversity and functioning
Understanding of links between biodiversity and ecosystem function on a global level – i.e., global modelling tools to explore in different systems (marine, terrestrial and freshwater) the futures of biodiversity or futures of ecosystem function are disconnected. Gap reflects need for connecting model developments across disciplines.		IPBES, p. 664 4.2.5 Challenges in linking biodiversity and ecosystem functioning at the global level
Overview of data availability is lacking How to access and mobilise analogue freshwater data Lack of databases structured according to the FAIR principle	Data infrastructure – improvements are needed	Maasri et al. (2022)
Knowledge gaps relating to improved/innovative methods for monitoring including monitoring programs	Monitoring	Maasri et al. (2022)

Freshwater Knowledge Gap	**Research need/comment**	**Source**
Lack of understanding of mechanistic relationships btw biodiversity and Ecosystem services Lack of knowledge relating to biodiversity response to different stressors Lack of knowledge relating to ecological and evolutionary responses of organisms, communities and ecosystems to global changes	Ecology	Maasri et al. (2022)
Lack of knowledge from evaluation of restoration activities Lack of knowledge on how to develop NFF type strategies Lack of landscape perspective to make dam construction and operation ecologically sound	Management	Maasri et al. (2022)
Lack of knowledge relating to incorporation of social science into biodiversity research Lack of methods for assessing trade-offs among ecological, economic and social needs Lack of knowledge to systematically develop citizen science and participatory research	Social ecology	Maasri et al. (2022)
Limited understanding of reasons for success or failure of past conservation efforts	1 Learning from successes and failures	Harper et al. (2021)
Limited understanding of the spatial and temporal scales best suited to application of management interventions to benefit freshwater biodiversity	2 Learning from successes and failures	Harper et al. (2021)
Limited understanding of characteristics of current protected areas and networks including what indigenous management lead to improved status of freshwater ecosystems	3 Learning from successes and failures	Harper et al. (2021)
Limited/deficient understanding of use of flagship/umbrella freshwater species for increased restoration and protection of fwbd and public involvement	4 Learning from successes and failures	Harper et al. (2021)
Deficient monitoring metrics to guide restoration, conservation and sustainable management of freshwater biodiversity	5 Learning from successes and failures	Harper et al. (2021)
Limited knowledge relating to prioritisation of KBAs	6 improving current practices	Harper et al. (2021)

Freshwater Knowledge Gap	Research need/comment	Source
Knowledge gap relating to best approaches to pollution reduction and remediation efforts beneficial for fwbd	7 improving current practices	Harper et al. (2021)
Lack of knowledge relating to what research innovations are most needed to help restore fwbd	8 improving current practices	Harper et al. (2021)
Lack of knowledge how to incorporate climate change adaptation (resilience) into fw conservation	9 improving current practices	Harper et al. (2021)
Limited knowledge how to manage fw invasive species for improvement of bd	10 improving current practices	Harper et al. (2021)
Limited knowledge of what the optimal riparian management actions are that best contribute to fwbd	11 improving current practices	Harper et al. (2021)
Deficient knowledge on measures that effectively address synergistic threats to fwbd	12 improving current practices	Harper et al. (2021)
Limited knowledge relating to what priorities are in common for sustainable food production and fwbd conservation	13 balancing resource needs	Harper et al. (2021)
Limited knowledge relating to how needs for dams and ass. Infrastructure can be balanced with connectivity, health and flow requirements of fw ecosystems and bd	14 balancing resource needs	Harper et al. (2021)
Limited knowledge on how to best balance conflicting interests between human demands for natural resources and fwbd	15 balancing resource needs	Harper et al. (2021)
Limited knowledge relating to what policies/programmes/activities can be implemented to turn risks with urbanisation into benefits for fw bd enhancement	16 Rethinking built environments	Harper et al. (2021)
Limited knowledge on how freshwater biodiversity conservation can be better integrated into economic infrastructure planning, implementation and operation	17 Rethinking built environments	Harper et al. (2021)
Limited knowledge on role of novel and designed ecosystems in conservation, and how can these systems be managed to benefit freshwater biodiversity	18 Rethinking built environments	Harper et al. (2021)
Limited knowledge on what public policy measures can most effectively promote conservation and restoration of freshwater biodiversity	19 Reforming policy and investment	Harper et al. (2021)

Freshwater Knowledge Gap	**Research need/comment**	**Source**
Limited knowledge on how to scale up and optimise financial investments from all society sectors to create a step change in funding for fw cons and rest. efforts	20 Reforming policy and investment	Harper et al. (2021)
Limited knowledge relating to what social and natural science investments are needed to implement environmental flows that benefit fwbd	21 Reforming policy and investment	Harper et al. (2021)
Limited knowledge relating to what type of investments in *ex situ* conservation (e.g. captive breeding, reintroduction, managed relocation) are most effective for imperiled biodiversity	22 Reforming policy and investment	Harper et al. (2021)
Limited knowledge relating to how to develop management frameworks and evidence bases that gain greater traction with stakeholders and managers	23 Enabling transformative change	Harper et al. (2021)
Limited knowledge relating to what steps to take to better communicate and share evidence and knowledge about the science of freshwater biodiversity among stakeholders	24 Enabling transformative change	Harper et al. (2021)
Limited knowledge relating to how to increase public engagement to change mindsets and build social license and political will to 'bend the curve' of biodiversity loss	25 Enabling transformative change	Harper et al. (2021)

A.4 Knowledge gaps relevant for the BIOMONDO pilots

Table 10: Knowledge gaps from IPBES Global Assessment (see also Appendix A.3) relevant for BIOMONDO Pilots.

Sector	Knowledge gaps
Data, inventories and monitoring of 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)
	Indicators on the global extent and consequences of biotic homogenization, including genetic homogenization
	Global spatial datasets on key threats, e.g., data on patterns in the intensity of unsustainable exploitation of species and ecosystems
	Understanding of how human-caused changes to any EBV class (e.g., ecosystem structure) have impacts on others (e.g., community composition) and on nature's contributions to people
	Data gaps in key inventories: World Database on Protected Areas, the World Database of Key Biodiversity Areas, red lists of threatened species and ecosystems, and the Global Biodiversity Information Facility
Biomes and units of analysis	Inventories on under-studied ecosystems: freshwater, arctic, marine/ocean, seabed, and wetlands
	Inventories in soil, benthic and freshwater environments, and the implications for ecosystem functions
NCP (ecosystem services)	Data on the status of species and nature's contributions to people linked to specific ecosystem functions
	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 some Sustainable Development Goals and Aichi Biodiversity Targets (e.g., Aichi Biodiversity Target 15 on ecosystem resilience and contribution of biodiversity to carbon stocks and Target 18 on integration of traditional knowledge and effective participation of indigenous and local communities)
	Better quantitative data to assess the Sustainable Development Goals and Aichi Targets where qualitative indicators have been dominant (9 out of 44 targets under the Sustainable Development Goals reviewed)
Potential policy approaches	Data to analyse the effectiveness of many policy options and interventions, including 1) the comparative effectiveness of different area-based conservation mechanisms (e.g., protected areas, other effective area-based conservation measures), and 2) the effectiveness of different restoration methodologies and to assess restoration progress over time (including values)
	Better data to develop biodiversity and environmental quality standards

A.5 Literature analysis to identify 'environmental research themes'

To identify research areas where there might be mismatches between the data collected and research questions addressed by the 'biodiversity community' (of researchers that study biodiversity using a wide range of techniques) and the 'remote sensing community' (of researchers that use remote sensing techniques but not necessarily to study biodiversity) we performed a literature analysis using Web of Science[25]. More specifically, we performed six different searches using the search terms {lake biodiversity}, {river biodiversity}, {wetland biodiversity}, {lake "remote sensing"}, {river "remote sensing"}, and {wetland "remote sensing"}. For the papers resulting from each of these searches, we identified different fields of research by determining whether there are groups of papers of which the 'author keywords', i.e. the words chosen by the authors to summarise the core concepts of their paper, tend to be the same. These groups of papers were identified using network analysis. We assumed papers that have at least one keyword in common to be linked. Groups of papers (i.e. modules) that tend to share more links within them than between them were determined using the method by Newman (2006). We considered the most common author keywords used to describe these groups of papers to represent different research 'themes'. This method follows an approach used in Calamita et al. (2024).

During a first iteration of this approach, we found that clusters were formed around author keywords that were rather generic and difficult to compare between biodiversity and remote sensing research, e.g. 'conservation', 'taxonomy', and 'species richness' for biodiversity, and 'gis', 'modis', and 'landsat' for remote sensing research. We therefore narrowed our study down to author keywords that refer to 'environmental variables', i.e. measurable properties that are abiotic, i.e. that determine the environment on which species depend, and that formed a link between at least 50 papers. Examples of such words are 'climate change', 'eutrophication', 'water quality', 'permafrost', 'hydrology', and 'turbidity'. We also included the keyword 'ecosystem services', i.e. the only common keyword that referred to a property that is dependent on biodiversity. Words that are generic (i.e. unmeasurable), a reference to a particular species group, a measure of biodiversity, a reference to a specific location, or a particular methodology were excluded. Examples of such words are 'conservation', 'zooplankton', 'taxonomy', 'species richness', 'biogeography', 'landsat', 'modis', 'gis', and 'sentinel-2'. Borderline, but included were 'chlorophyll-a' and 'ndvi', which are both metrics of a biotic component but not species specific, and 'invasive species', which is an important known driver of environmental change. Excluded however was 'phytoplankton', which is a species group (e.g. like zooplankton) even though this word is very closely related to estimates of chlorophyll-a concentrations in remote sensing papers, this is not necessarily the case in biodiversity papers.

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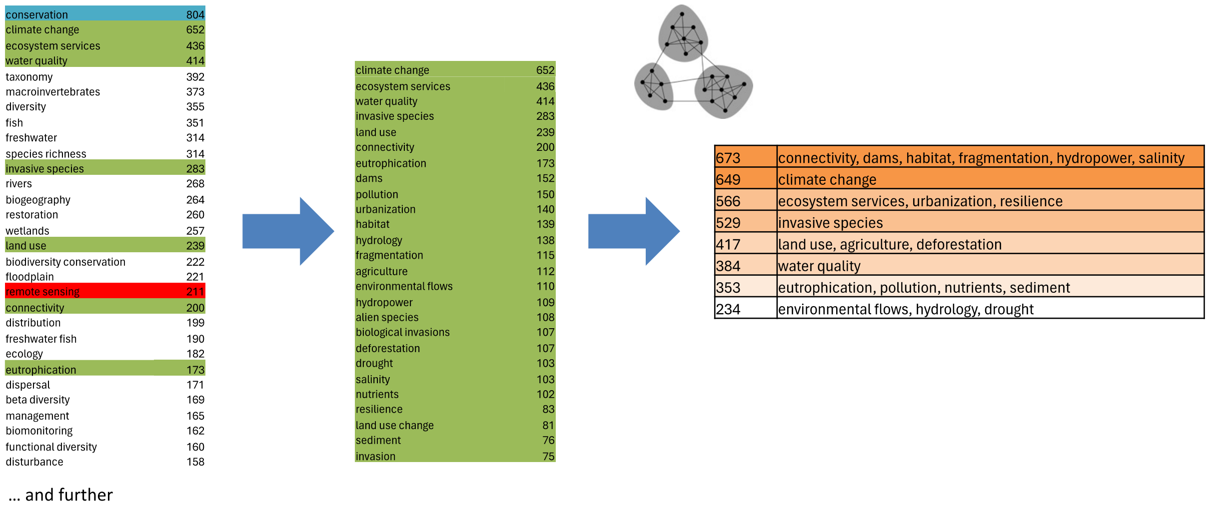
[25] www.webofscience.com



conservation	804
climate change	652
ecosystem services	436
water quality	414
taxonomy	392
macroinvertebrates	373
diversity	355
fish	351
freshwater	314
species richness	314
invasive species	283
rivers	268
biogeography	264
restoration	260
wetlands	257
land use	239
biodiversity conservation	222
floodplain	221
remote sensing	211
connectivity	200
distribution	199
freshwater fish	190
ecology	182
eutrophication	173
dispersal	171
beta diversity	169
management	165
biomonitoring	162
functional diversity	160
disturbance	158

... and further

climate change	652
ecosystem services	436
water quality	414
invasive species	283
land use	239
connectivity	200
eutrophication	173
dams	152
pollution	150
urbanization	140
habitat	139
hydrology	138
fragmentation	115
agriculture	112
environmental flows	110
hydropower	109
alien species	108
biological invasions	107
deforestation	107
drought	103
salinity	103
nutrients	102
resilience	83
land use change	81
sediment	76
invasion	75

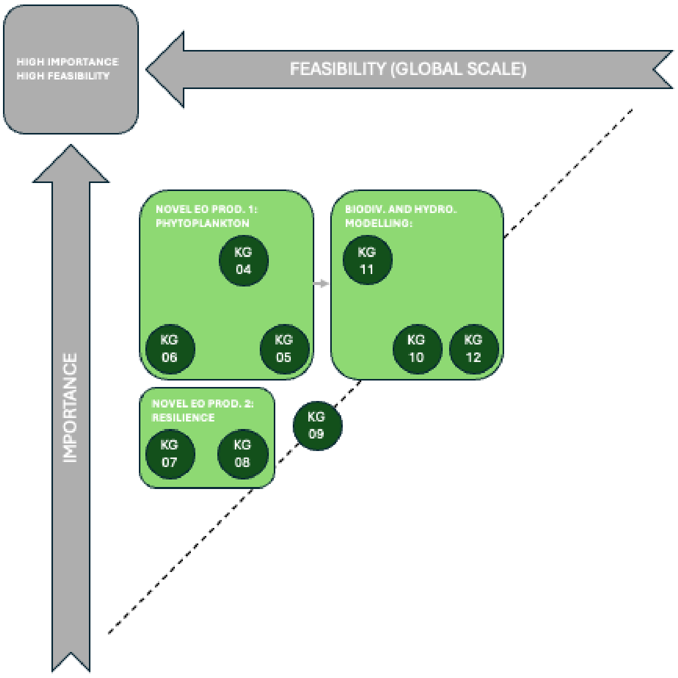
673	connectivity, dams, habitat, fragmentation, hydropower, salinity
649	climate change
566	ecosystem services, urbanization, resilience
529	invasive species
417	land use, agriculture, deforestation
384	water quality
353	eutrophication, pollution, nutrients, sediment
234	environmental flows, hydrology, drought

Figure 16: Schematic representation of how research fields were identified out of a long-list of author keywords. From left to right, the long list of author keywords, the selected keywords that refer to environmental variables and ecosystem services, and the groups of keywords identified through the clustering analysis.

A.6 Detailed schemes for the proposed roadmap

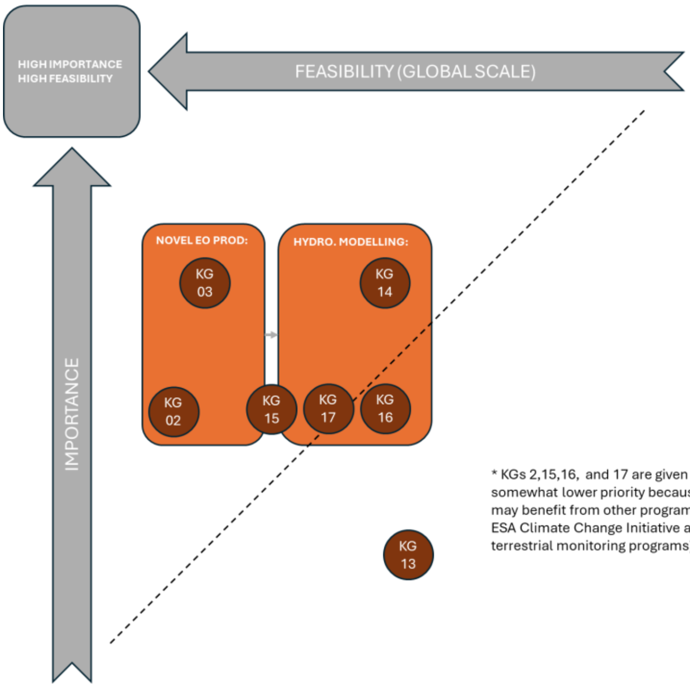
Draft examples of more detailed schemes for each research line, which should be further developed.

Detailed graph of research line 1



RESEARCH LINE 1:
KG 04: Primary productivity
KG 05: Phytoplankton diversity
KG 06: Phytoplankton phenology
KG 07: Phyto. regime shifts and anomalies
KG 08: Monitoring resilience
KG 09: EO-derived phytoplankton in biodiversity and hydrological models
KG 10: Impacts of phenology changes on other biodiversity variables.
KG 11: Impacts of productivity changes on other biodiversity variables.
KG 12: Impacts of phyto. anomalies on other biodiversity variables.

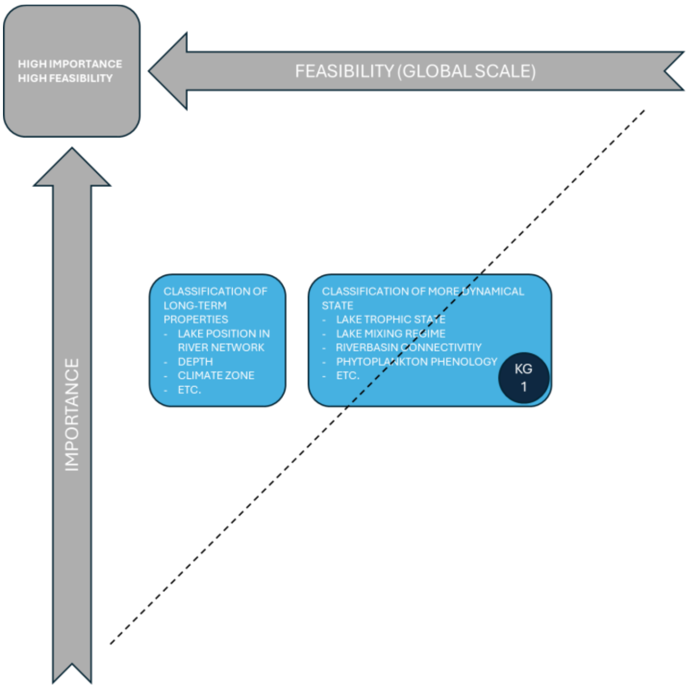
Detailed graph of research line 2



* KGs 2,15,16, and 17 are given a somewhat lower priority because they may benefit from other programs (e.g. the ESA Climate Change Initiative and terrestrial monitoring programs).

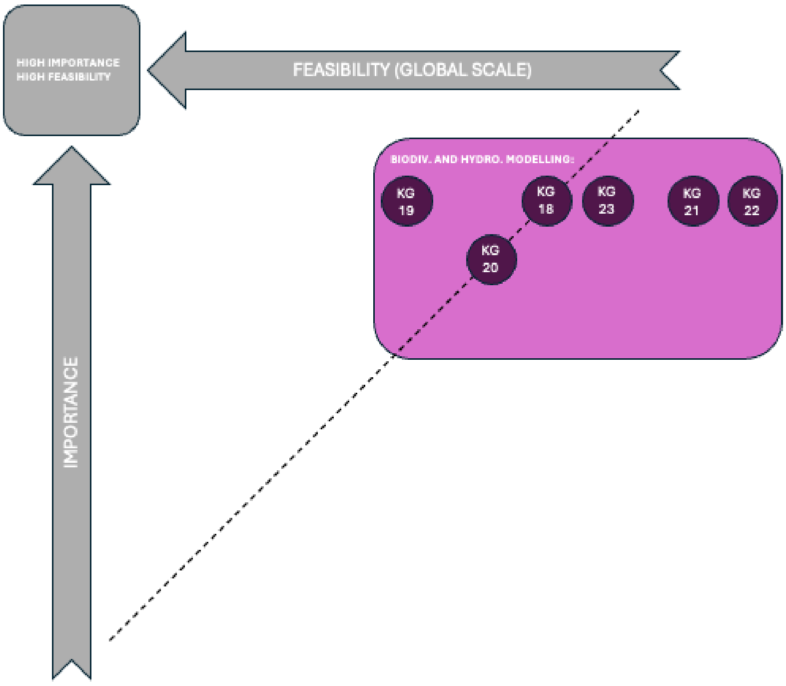
RESEARCH LINE 2:
KG 02: River delta size/habitat loss
KG 03: River habitat connectivity
KG 13: Monitoring the spread of invasive species
KG 14: Impacts of river hydrological connectivity on sedimentation processes
KG 15: Impacts of Land Use Land Cover on nutrient inflows
KG 16: Impact of precipitation and evapotranspiration on nutrient inflows
KG 17: Monitoring thermal stratification and lake mixing regimes.

Detailed graph of research line 3



RESEARCH LINE 3:
KG 01: Freshwater habitat types and ecosystem mapping

Detailed graph of research line 4



RESEARCH LINE 4:
KG 18: Attribution of changes in wetland formation and river-delta size
KG 19: Impacts of changes in lake mixing regimes on primary productivity, etc.
KG 20: Attribution of changes in lake phytoplankton phenology
KG 21: Attribution of changes in lake resilience and regime shifts
KG 22: Assessment of impact of extreme climate events on biodiversity variables
KG 23: Assessment of impact of wetland hydroperiod on biodiversity variables