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Towards Earth Observation supported monitoring of freshwater biodiversity	

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1 Description of ESS pilot

1.1 Scientific case

Heatwaves in lakes are prolonged periods of extraordinarily high water temperatures. A retrospective analyses of satellite Earth observation data suggests that between 1970 and 1999, average lake heatwaves had an average intensity of 3.7° (above the climatological mean) and lasted on average 7.7 days. The average intensity of heatwaves had a slightly decreasing trend in the 20th century; however, climate projections suggest that heatwaves will strongly increase in intensity and duration during the 21st century (Woolway et al., 2021). Lake ecosystems are vulnerable to these temperature changes: directly by pushing to or exceeding species and ecosystems limits of resilience, and indirectly through decreasing amounts of oxygen in the water, altered stratification or cyanobacteria. Accurate data on surface water temperature is therefore crucial for estimating impacts on biodiversity. According to the BIOMONDO Requirements Baseline analysis (BIOMONDO_D1.1_RequirementsBaseline_v2.1.pdf), Earth Observation (EO) data can complement or replace (incomplete, point based) in situ water temperature measurements, or give more spatially and temporally detailed estimates compared to modelling products.

In the scope of BIOMONDO pilot 2, we investigate the impact of rising temperatures and heatwaves on freshwater fish diversity by combining Earth observation data on surface water temperature with thermal tolerance information of freshwater fish species. The project involved the development of a novel phylogenetic regression model incorporating data from various sources such as existing databases and literature reviews, to predict the physiological tolerance of freshwater fish species to maximum water temperature. In doing so, it considers morphological, ecological, phylogenetic, and acclimation-related factors. Validation through cross-validation ensures robustness. Remotely sensed surface water temperature data for this task is available from the Copernicus Land service and ESA Climate Change Initiative, which cover a relatively large number of lakes and temporal range. However, their spatial resolutions' suitability for the selected test sites and the given case study must be evaluated, as well as the representativity of satellite-observed skin temperature for heatwave assessments. If existing EO products fall short in these regards, a combination with modelled water temperature or air temperature (e.g. ERA5) or the use of higher resolution EO data (Landsat) could be considered.

The Early Adopters for this pilot study are the Institute of Freshwater Research at the Swedish University of Agricultural Sciences, where a detailed assessment of results for Lake Mälaren was performed, and Rijkswaterstaat, a part of the Dutch Ministry of Infrastructure and Water Management, responsible for monitoring of Lake Marken. The main policy framework is the European Water Framework Directive (WFD).

1.2 Science/Policy Traceability Matrix

The Science/Policy Traceability Matrix (SPTM, Figure 1) compiled for BIOMONDO lists six major drivers related to the decline of freshwater biodiversity, including pollution and eutrophication, habitat changes, invasive species, climate change impact, overexploitation, and effects of driver interaction or unknown drivers. Pilot 2 aims to explore one of five objectives that aim to assess climate change related impacts.

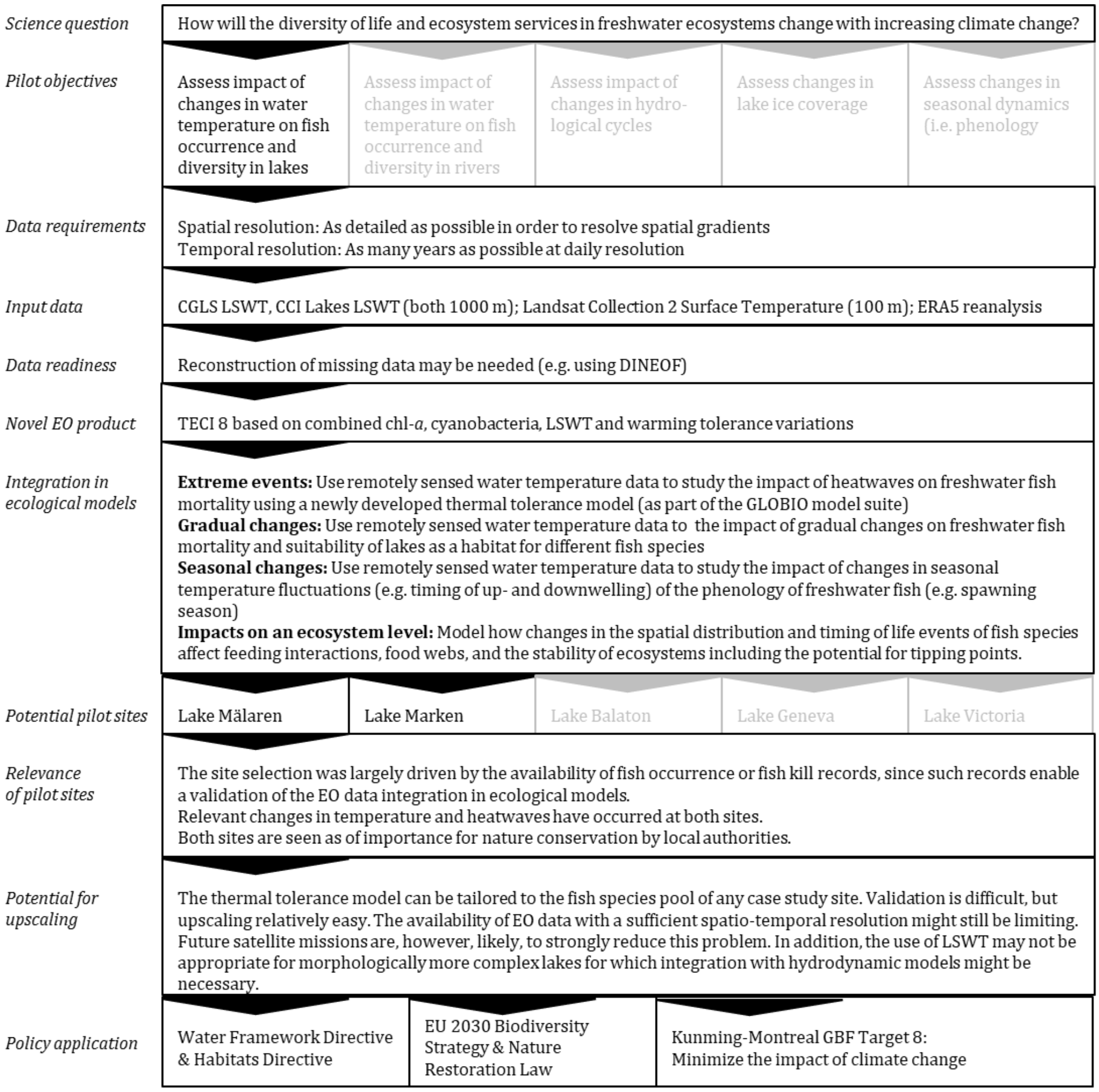

Figure 1 Graphical summary of the Science/Policy Traceability Matrix for pilot study 2 (modified from BIOMONDO WP1 SPTM).

1.3 Test sites

In total five test sites were considered for this pilot study, namely Lake Balaton, Lake Geneva, Lake Mälaren, Lake Victoria, and Lake Marken. The focus for the scientific analyses, and scientific and policy impact assessments is on Lake Mälaren and Lake Marken. The description here is compiled from the BIOMONDO Requirements Baseline (BIOMONDO_D1.1_RequirementsBaseline_v2.1.pdf) and Experimental Dataset (BIOMONDO_D2.4_ExperimentalDatasets_v1.0.docx) reports. In the case of Lake Marken, the same description is repeated in the IAR for Pilot 1.

1.3.1 Lake Mälaren

Lake Mälaren is Sweden's third largest lake (1,122 km², Figure 2). It has an average depth of 12.8 meters and a maximum depth of 66 meters. Several larger rivers flow into Lake Mälaren. Its catchment area includes Lake Hjälmaren, which is Sweden's fourth largest lake, as well as several smaller lakes. Lake Mälaren is regulated and its main outlet, which has an average water flow of over 160 m³/s, is through Stockholm into the Baltic Sea. Lake Mälaren is a typical plains lake with over 8,000 islands, islets and skerries. Its catchment area is 22,650 km², which corresponds to about 5% of Sweden's area.

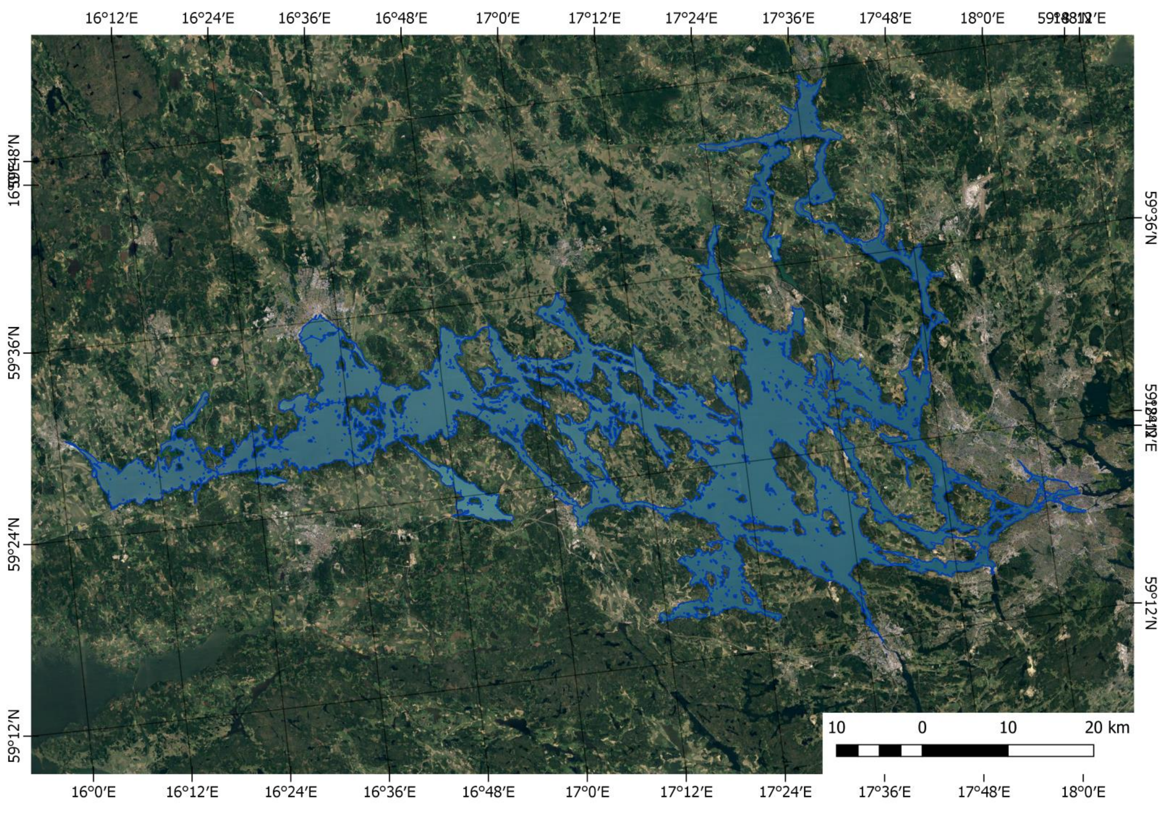

Figure 2 Pilot site Lake Mälaren.

There are about eighty nature reserves around Lake Mälaren and over forty Natura 2000 areas. In addition to these, there are areas that have been pointed out as national interests by the Swedish regional County Administrative Boards. The area is diverse with agricultural landscapes, forested mountain areas and the archipelago. The water in Lake Mälaren is naturally nutrient-rich, which makes it sensitive to eutrophication. High levels of phytoplankton biomass have been measured, and cyanobacteria are common.

During the 1960s, Lake Mälaren was heavily eutrophicated, but thanks to improved treatment plants and agricultural measures, the situation has improved. Lake Mälaren's water is very heterogeneous, and the lake is divided into several administrative basins, as the conditions vary from one part to another. The lake is used for a large number of different activities, such as shipping, commercial fishing, agriculture, drinking water production and tourism.

Mälaren has 34 naturally occurring fish species. The most common species are smelt, perch, roach, birch, bream and pikeperch. Smelt, which dominates the pelagic waters, plays an important role in the ecosystem as prey fish. It is anticipated that climate change will change the water level and water flows in Lake Mälaren. Climate change will also mean increasing water temperature, reduced ice cover and sea level rise which has consequences for different interests around the lakes (Eklund et. al, 2018).

We collected warming tolerance data for 10 fish species and Lake Surface Water Temperature data for Lake Mälaren, for the period of September 1999 to September 2020. From the CyanoAlert project, we obtained Chlorophyll-a concentration and cyanobacteria abundance data in 2016-2022, and the Copernicus service's Riparian Zone dataset, available for 2012 and 2018, was used for demonstration and further analyses (see BIOMONDO_D2.4_ExperimentalDatasets_v1.0.pdf for more details).

1.3.2 Lake Marken

Lake Marken, or Markermeer, is a 680 km^2 large lake in the Netherlands. It is second in size to Lake Ijssel, which lies between Lake Marken and the North Sea, and is separated from them only by dams. Lake Marken has an average depth of 3.6 meters and a maximum depth of 5 meters. It has an open connection to Lake Gooi and Lake Eem in the south, and it is connected by sluices to Lake IJssel and its main tributary, the IJssel, which is a distributary of the Rhine River (Figure 3). Lake Marken and Lake IJssel are artificial freshwater lakes, which were created in a shallow bay of the North Sea, the Zuiderzee. Plans to turn Lake Marken into the Markerwaard polder were abandoned in 2003, and it has now become an ecological and recreational site on its own.

Lake Marken, Lake Ijssel and their border lakes are all Ramsar and Natura 2000 sites. Owing to the way they were constructed, the lakes are "heavily modified" according to the definition of the Water Framework Directive (WFD). As with many freshwater lakes, the Markermeer-IJsselmeer system has unique biochemical properties that influence its ecological health and sustainability. The lakes are characterized by relatively high turbidity, high nutrient concentrations, and a complex food web that supports a diverse range of plant and animal species. While Markermeer and IJsselmeer share many similarities in terms of their physical and chemical properties, there are some notable biological differences between them. One key difference is in the composition of the plankton community. Markermeer has been shown to have a higher abundance of small-sized phytoplankton compared to IJsselmeer, which tends to have a higher proportion of larger phytoplankton species.

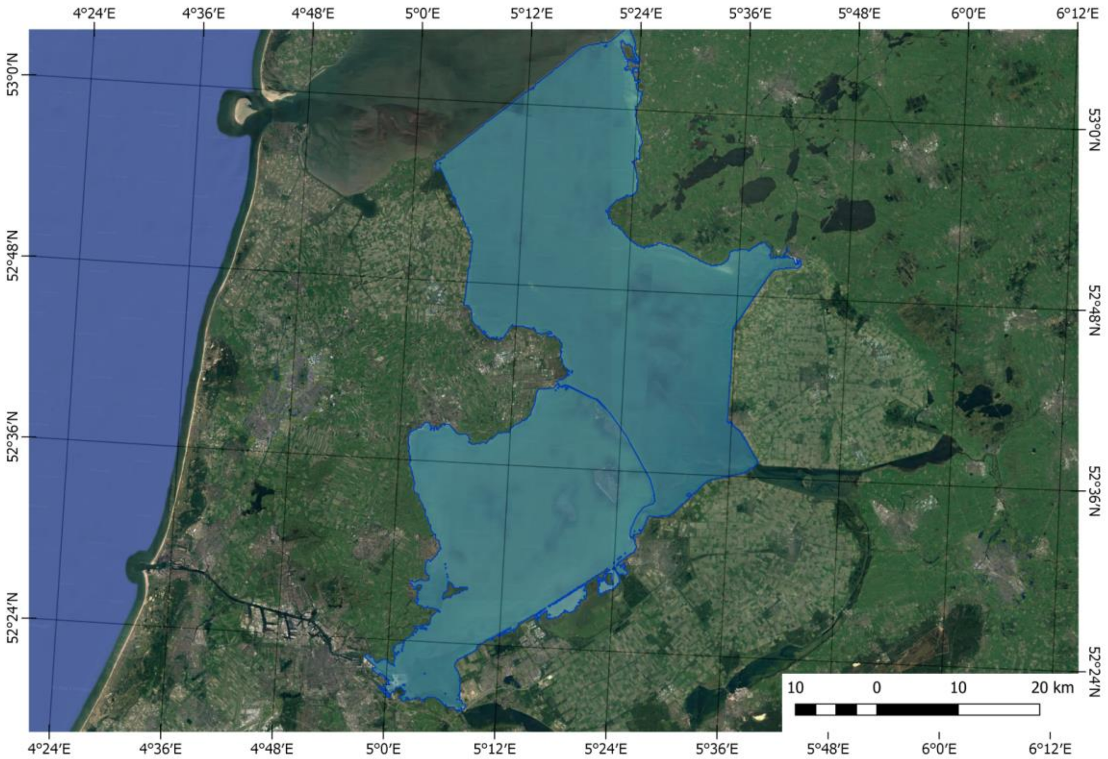

Figure 3 Pilot Site Lake Marken (bottom) and Lake Ijssel (top).

We collected warming tolerance data for 28 fish species and EO based Lake Surface Water Temperature data for Lake Marken, for the period of September 1999 to September 2020. The most common species are smelt, roach, rudd, perch, bream, carp, tench, pike and ruffe. We also obtained various biological parameters sampled in 2016, such as Chlorophyll-*a*, NPP, and counts of seven phytoplankton species.

1.4 Methods

The developed heat tolerance model required continuous Lake Surface Water Temperature (LSWT) products, which none of the ready to use data sources mentioned in the SPTM provide. Therefore, we ran DINEOF (Data Interpolating Empirical Orthogonal Functions (Alvera-Azcárate et al., 2011) for all lakes available in the CCI Lakes dataset, using quality levels 4 and 5 only and generated gap-filled daily LSWT products. Matchup comparison of DINEOF interpolated CCI LSWT with in situ bulk temperature measurements taken at max. 0.5 m depth in Lakes Mälaren and Marken agreed with biases < 0.5 ° and RMSEs between 1.14 and 1.29° (BIOMONDO_D2.3_PVR_v2.0.pdf). Given the selected test sites' size and dynamic range of more than 20°, we expect these product specifications to be fit for purpose. A submission of the gap-filled daily LSWT products to the Pangaea data repository is in progress.

Ecological models are needed to interpret variations in LSWT with reference to the thermal tolerance of fishes. The novel phylogenetic heat tolerance model, created by PBL as part of the GLOBIO model suite (globio.info), facilitates this task. It uses species-specific heat tolerance data from various sources and phylogenetic regression (BIOMONDO D2.2 ATBD v2.1.pdf). For BIOMONDO, we use the model with an acclimation period of 14 days and determine the warming tolerance of each species across space and time. The warming tolerance is defined as the difference between the LSWT and the upper thermal limit (heat tolerance) of a fish. The warming tolerance shows whether the LSWT exceeds (negative values) or approaches (low values) the heat tolerance, i.e., how close current conditions are to their thermal limits. A species' thermal limit is exceeded when LSWT is larger than its heat tolerance on a given date. Results can indicate which species are more susceptible to heat (waves) and enables to explore the spatial and temporal variability of heat (waves) as a threat to fish species.

1.5 Expert consultations

The main findings of BIOMONDO pilot 2 were discussed with various scientific and policy experts. Table 1 provides an overview of the consultation meetings held for the assessment of the main findings.

Table 1: List of experts providing feedback on the main findings of pilot 2.

Name	**Institution**	**Meeting dates**
Thomas Axenroth	SLU	8 May 2023
Caroline Ek	SLU	8, 25 May 2023
Helena Strömberg	SLU	8 May 2023
Björn Rogell	SLU	8 May 2023
Joep de Leeuw	Wageningen Marine Research / RWS	5 Sept 2023
Advisory Board • María Vallejos • Erin Hestir • Lisa Rebelo • Ole Seehausen	 Univ. Buenos Aires UC California, Merced IWMI /DE Africa Univ. Bern	 Maternity leave 30 Aug 2023 30 Aug 2023 7 Sept 2023

2 Scientific impact

2.1 Main findings and contribution to current knowledge level

The EO products generated for and used in Pilot 2 comprise Lake Surface Water Temperature, Chlorophyll-a concentration and cyanobacteria indicator products. In general, all three parameters are of vital importance for any ecological study of lakes and can all be strong indicators of lake status. The fact that the data is spatially and temporally continuous is also a strong improvement and complement to sparse in situ monitoring data and many more lakes can be covered. EO products, tailored to fit user needs and provided in analysis ready data format, have the potential to contribute to many research fields. In combination with a set of tools for easy access and visualisation of data, the scientific contribution and impact potential becomes impressive.

The full extent of spatio-temporal variations in EO products and model simulations for both test sites of pilot 2 is visualized in the BIOMONDO Viewer (see section 3.3). An example of the generated gap-filled LSWT products for Lake Mälaren is shown in Figure 4. The image (left) shows the surface temperature on the 16 July 2018, exhibiting the highest temperature during the warm summer of 2018. The plot (right) shows two years of the 1999-2020 time series for a selected point in the lake.

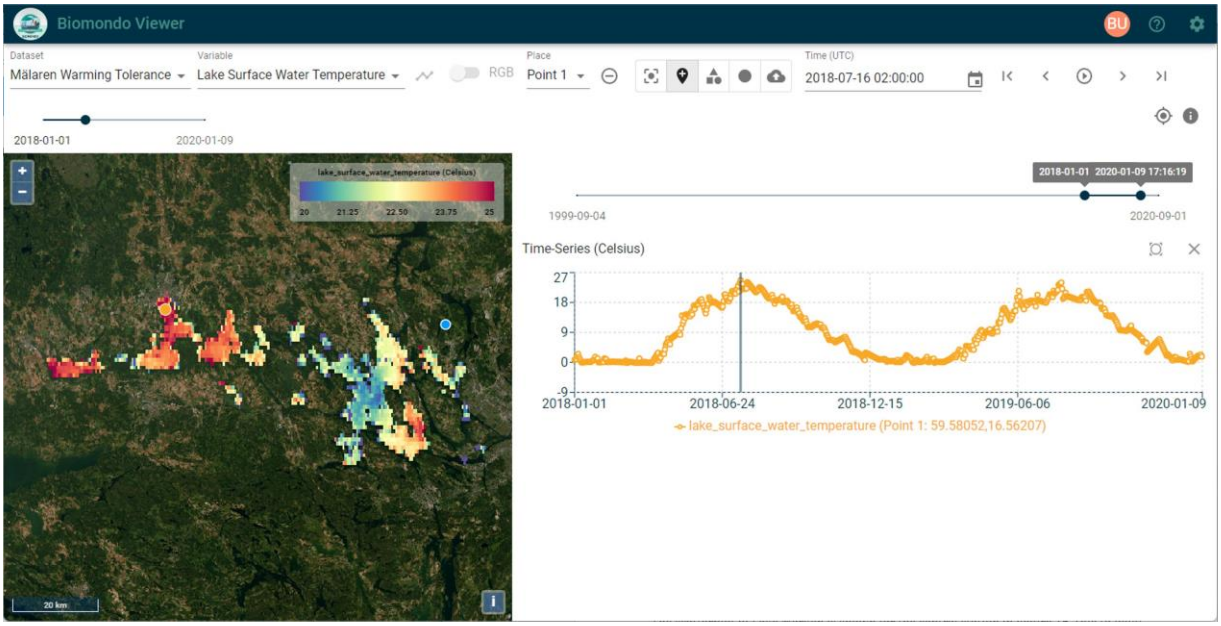

Figure 4 Lake Surface Water Temperature in Lake Mälaren, 16 July 2018.

Fish species' warming tolerance indicates how close instantaneous temperature conditions are to that species heat tolerance limit. Figure 5 shows species warming tolerances experienced in (central) Lake Mälaren from September 1999 to October 2020. According to local experts smelt (Osmerus eperlanus), vendace (Coregons Albula) and perch (Perca fluviatilis) would be most susceptible to high temperatures (Axenrot & Sandström, 2022). Vendace and smelt also show the lowest warming tolerance in our results. The heat tolerance was not exceeded by the LSWT for any fish species in this example but approaching "0" for vendace and smelt. When water temperatures approach a fish's heat tolerance, this can affect growth, reproduction, immunity, and the ability of an individual to cope with additional stressors.

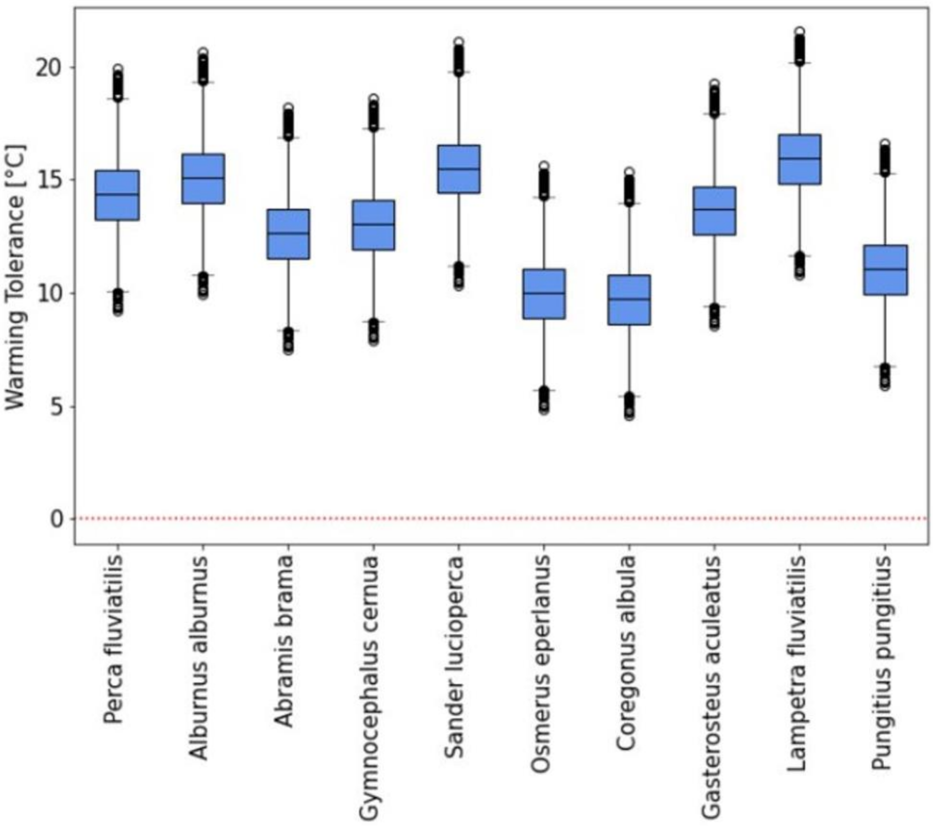

Figure 5 Warming tolerance of different fish species in central Lake Mälaren in the years 1999-2020.

In the summer of 2018 massive fish-death occurred across Swedish lakes, including Lake Mälaren (Mitt i, 2018; Axenrot & Sandström, 2022), in periods of very high water temperatures. We calculated average monthly warming tolerance for smelt across the whole lake for all included years to contrast variations in temperature stress in 2018 with other years. This analysis indicated that the warming tolerance is generally lowest in summer months, i.e., June and July, and the threat of high temperatures highest. 2018 showed high temperatures with relatively low warming tolerance values but did not stand out compared to other summers. A potential explanation is that the fish kill may be an indirect consequence of the heat wave, e.g., due to the lack of oxygen.

When the fish get stressed, the metabolism goes up and the fish want to consume more oxygen than is available (Mikael Svensson, SLU). Though the fish deaths may not be directly caused by an exceedance of the heat tolerance, the water temperatures approaching a fish's heat tolerance will cause stress and affect the ability of an individual to cope with additional stressors (Alfonso et al, 2021). This is probably what occurred in 2018, with the lower oxygen levels as additional stressor. Causality effects on different species accounting for several parameters such as temperature, cyanobacteria presence and reduction in oxygen levels are not well analysed and understood. Here EO data could have a large scientific impact given the incomparable temporal and spatial coverage and resolution. It was also pointed out that research regarding mechanistic explanations is missing for the different parameters that could cause declines in fish abundance, including parameter interaction, lagged effects and feedback loops, e.g., rise in temperature causing cyanobacteria bloom that both cause reduction in oxygen. The experimental data produced in BIOMONDO could significantly contribute to such research initiatives.

For Lake Mälaren there are no continuous, official records of fish kills, but species abundance information from hydroacoustic in situ measurements are available for several years and was prepared and provided by SLU. EO and model data from four years (2017-2020) were analysed and compared to abundance data collected in basin Granfjärden (the relatively shallow western part of the lake) in October each year for smelt. To facilitate the interpretation and support the scientific and policy discussions the generated datasets were compiled in graphical form. Figure 6 exhibits Chlorophyll-a, cyanobacteria abundance, fish abundance of smelt and warming tolerance of smelt at the Granfjärden transect for the summers of 2017, 2018, 2019 and 2020. Fish abundance data boxplots show measurements across the available transects in September of the specified year. Warming tolerance (in red) and Chlorophyll-a concentrations (in green) are given per observation (average across the transect, plus symbol) and as a weekly average (line). The occurrence of a cyanobacteria abundance is indicated with diamonds. A significant reduction in abundance (primarily for juvenile smelt) can be noted for 2018 and 2020. Based on EO data and model results, the summers of 2018 and 2020 were characterized by many alerts of cyanobacteria, relatively low values of warming tolerance during large periods of the summer, and high concentrations of Chlorophyll-a compared to the summers of 2017 and 2019.

The results may indicate an influence of temperature dependent threats (i.e., absolute water temperature and oxygen depletion) on species abundance.

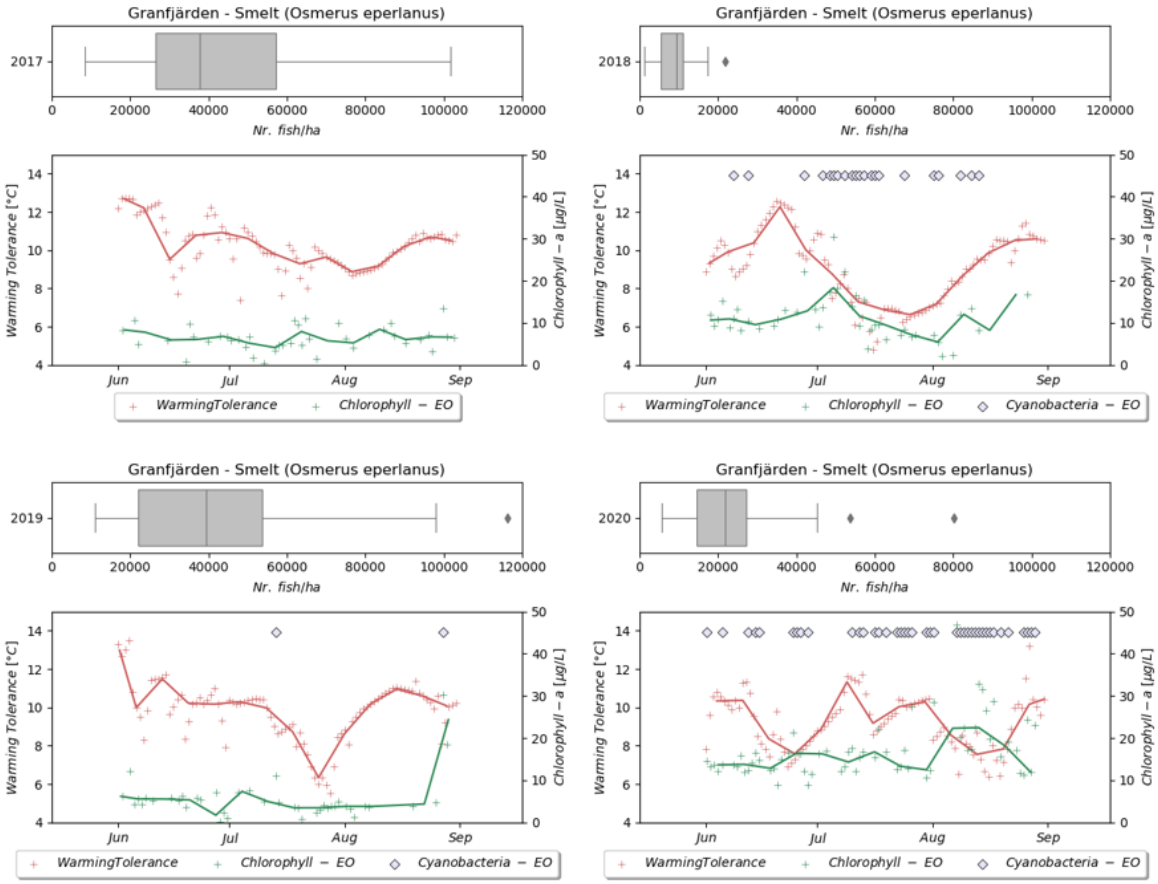

Figure 6 Summary plots for Lake Mälaren experimental datasets.

Validation of warming tolerance using fish abundance data is not straightforward, but still relevant and the data available in Lake Mälaren is better than what is available for most lakes. As discussed below, Lake Mälaren is a large lake and it is possible for fish to move, which makes it more difficult to interpret reasons for increases and decreases in abundance values. In addition, Mälaren has many different basins, some with thresholds that stop some fish species from migrating if conditions deteriorate. The investigated basin Granfjärden commonly hosts quite a high number of juvenile smelt, as this is a breeding area, which probably cannot move. Juvenile smelt also stay in the surface waters, which means that they will have more contact to cyanobacteria when present. Cyanobacteria is a known stressor, but it cannot be determined if it was cyanobacteria, temperature, oxygen depletion or a combination that killed the juvenile smelt in 2018 and 2020. More research is needed and EO based results could have a large impact on the validity of the results.

In response to a request by Prof. Erin Hestir, we investigated specifically the temporal dynamics of warming tolerance for all fish species and lakes, with a particular focus on potential trends in lower warming tolerance towards earlier months of the year. However, we could not find any significant trends.

2.2 Potential for large-scale application

The large-scale application of LSWT products to study the impact of changes in water temperature and heat waves on freshwater fish as demonstrated in BIOMONDO pilot 2 is constrained first by the availability of adequate satellite Earth observation data and their spatio-temporal resolution. Second, the use of LSWT is maybe appropriate for shallow non-stratifying lake but is less suitable for deep and morphologically complex lake with temperature refugia. Third, we found that the interpretation of temperature as a driver of physiological stress is complicated by indirect effects of temperature increase, such as oxygen depletion and cyanobacteria abundance, which must be estimated using hydrodynamic models. Fourth, the current approach may not be able to fully grasp the effect of high water temperatures on freshwater fish.

In the past decades, thermal satellite Earth observation data have been limited to low resolution sensors (e.g., AATSR, ATSR, AVHRR, MODIS, SLSTR, VIIRS) with around 1 km spatial resolution, and Landsat thermal sensors (i.e., ETM on L-4/5, ETM+ on L-7, TIRS on L-8/9) with around 60-120 m spatial resolution. Both data types have been used in large-scale LSWT productions in the past. For example, Riffler et al. (2015) provide 24 years of AVHRR products for 25 lakes in Central Europe, while Prats et al. (2018) provide 17 years of L-5 and L-7 products for 442 inland water bodies in France. The use e.g. of ATSR-2 and AATSR data is limited to the world's largest 3000-4000 lakes (Politi et al., 2016), while there are about 117 million lakes larger than 0.02 km^2 (Verpoorter et al., 2014). On the other hand, individual Landsat sensors have a temporal revisit time of 16 days, which means many heat waves are missed even when using the L-8/9 tandem constellation with 8 days revisit time.

In the near future several thermal missions with high spatial resolution are planned for launch, e.g., Trishna, the NASA Surface Biology and Geology Mission (SBG) and the Copernicus Land Surface Temperature Monitoring Mission (LSTM). All of them are expected to enable LSWT retrievals at an accuracy around 1-2°. Therefore, combining observations from these missions will enable daily high-resolution LSWT products after 2028 (Table 2). It should however be considered that the overpass times of Earth observation satellites typically vary between morning and noon and will not resolve diel maximum temperatures. Near-surface water temperature can vary by 4-7° throughout the day, depending on lake size, and peaks only in the late afternoon (Woolway et al., 2016).

Table 2: List of upcoming high-resolution thermal missions. The revisit time and launch date indicated in brackets represent the second satellite, LSTM-B.

Abbreviation	Revisit [d]	Sampling [m]	Launch date	Reference
LSTM	4 (2)	50	2028 (2030)	Koetz et al. (2018)
Trishna	2-3	50	2025	Buffet et al. (2021)
SBG	2-3	60	2026	Basilio et al. (2022)

Hydrodynamic models of lakes simulate physical processes based on partial differential equations that describe the motion of incompressible, viscous fluids, the so-called Navier-Stokes equations. By describing how wind, air temperature, irradiance, bathymetry and inflow and outflow affect water circulation and stratification patterns, they allow simulations and predictions of water temperature and density gradients, and nutrient or contaminant transport. 1D hydrodynamic models (e.g., ALBM, CLM, GLM, GOTM, LAKE, Simstrat) were implemented for hundreds of lakes worldwide (e.g. Woolway et al., 2021), and they are intensively used in climate impact assessments such as the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP project, 2022; Golub et al., 2022). They were successfully used to model heatwaves, but faster warming and stratification in shallow areas can lead to horizontal heterogeneity, which generally cannot be resolved in such models (Mesman et al., 2020). 3D hydrodynamic models (e.g., Delft3D, MITgcm) can account for such features, but their implementation is much more laborious. Operational 3D models are sparse, for example the NOAA Great Lakes Operational Forecast System (GLOFS; Anderson et al., 2018) or Meteolakes (Meteolakes project, 2018; Baracchini et al., 2020). Meteolakes was initially developed for Lake Geneva, but similar models are in development for several perialpine lakes in Italy and Switzerland, in the scope of the ESA project AlpLakes (AlpLakes project, 2023; see also up-scaling of 3D models in BIOMONDO_IAR_Pilot_1_v2.1.docx).

The combined use of hydrodynamic models and Earth observation products is highly synergistic. On one hand, LSWT can be assimilated in hydrodynamic models (Safin et al., 2022) and remotely sensed aquatic attenuation can be used to parameterise vertical gradients of incident radiant energy in the model (AlpLakes, in work). On the other hand, hydrodynamic simulations can be used to complement LSWT products with depth gradients, to fill gaps during cloudy periods or to estimate diel LSWT maxima from morning observations. Furthermore, lake modelling frameworks can be expanded to variables like oxygen or phytoplankton growth, offering a strong explanatory potential for Earth observations. It is thus vital that the growing number of thermal satellite missions is supported by research on the integration of Earth observation data and lake models in order to maximise the information gain for advanced ecosystem studies as attempted in BIOMONDO pilot 2. The heat tolerance model can be applied to ~11,000 fish species and is widely applicable if a continuous time series of water temperature is available. The current application in Pilot 2 only considers surface water temperatures, giving 2 dimensional products appropriate to use for shallow non-stratifying lakes. For deeper (stratifying) lakes the fish can move to colder zones at larger depths, which would require 3D temperature products derived from hydrodynamic models as mentioned above. The heat tolerance model in this pilot can also be applied in this extra dimension. In lakes with several basins, the fish can also move in the lateral direction to colder areas, complicating the interpretation and validation of results as fish may escape from threatening conditions in one part of the lake. More limited shallow lakes e.g., Balaton, Peipsi (smelt population crash observed) could therefore be interesting validation sites. Some Norwegian and North American lakes are other potential lakes to investigate where hydroacoustic measurements also are performed. In Lake Mälaren, basins Galten and Blacken also warm up and are examples of such basins that could be used for analysis to limit multifactorial complications.

Furthermore, the warming tolerance reflects how close current conditions are to a species thermal limit which can be dangerous by affecting growth, reproduction, immunity, and the ability of an individual to cope with additional stressors (Sadoul & Vijayan, 2016; McArley et al., 2017; Alfonso et al., 2021), but the exact influence on abundance and the interacting influence of simultaneous oxygen decrease by high temperature is unknown. Furthermore, these effects may be lagged. In this pilot we now used cyanobacteria and chlorophyll-*a* presence as a proxy of algae blooms and oxygen decrease. When there is a lot of algae, and decomposition at the lake bottom gets more intensive, fish have to move up to shallower areas with more oxygen. Additionally, water temperature itself also affects the amount of oxygen which can be present in the water. These interactions make both the modelling and validation of effect of high temperatures in lakes on fish challenging.

To tackle this challenge, temporal- and spatial continuous data as created in this pilot on the multiple stressors in lake environments on fish are helpful for future research linking these factors to changes in biodiversity. Further, the use of proxies of oxygen depletion may be replaced in the future by estimated oxygen concentration with the further use of integrated Earth observation data and lake models as mentioned above. Furthermore, a similar model (like the heat tolerance model) regarding oxygen needs is planned to be developed at Radboud University (under supervision of Aafke Schipper). Currently, a threshold of 3.0 mg/L is used in many studies, but the threshold of tolerance can vary with e.g., species, length, water temperature, salinity, and CO_2 concentration, and fish may be able to acclimate to low levels of oxygen (FAO, 1970; Verberk et al., 2022). A novel model including these factors, and data on oxygen concentration in the lakes can further aid in studying the effect of temperature maxima in freshwaters.

In summary, we recommend an upscaling approach in which first interfaces between low resolution EO products, physical and biological models are developed for lake types with increasing complexity. Second, the integrated use of these tools is validated with dedicated ground reference measurements, and third the upcoming suite of high-resolution thermal missions is used to deploy such approaches for many smaller lakes.

3 Policy impact

3.1 Relevant policy goals and targets

Water is essential for natural ecosystems and climate regulation. Hence, the intrinsic two-way links between the extent and condition of freshwater ecosystems and climate change are reflected in most policies on sustainability and biodiversity as well as in recent calls and research funding opportunities that stress the links between climate, water and biodiversity.

As stated by EEA (2022), "Mitigation of and adaptation to climate change are also key EU policy objectives and central to, for instance, the European Green Deal through the EU Adaptation Strategy, Biodiversity Strategy 2030 (EC, 2020) and Farm-to-Fork strategies, as well as the Marine Strategy Framework Directive (MSFD) and the Water Framework Directive (WFD)." The MSFD criterion "good environmental status" includes direct descriptors for biodiversity and states that a rich ecosystem has many available habitat niches, and many different organisms, and that such a system containing a wide variety of life-forms generally is more resilient to environmental change. For freshwaters this is addressed more indirectly in the WFD, but the overarching objective is still to *measure the ecosystem's ability to maintain a balanced, integrated and adapted community of organisms with a species composition, diversity and functional organization typical of natural habitats in the region.*

Policy aspects of biodiversity change, and the relationship with global warming/climate change are highlighted by several initiatives and organisations, for example EuropaBON, KCEO and IUCN. According to the User Needs and Policy Assessment of EuropaBON (Moersberger et al., 2022), improved biodiversity data and information products that are related to drivers of biodiversity change are needed to ensure integrated cross-sectoral policies and evidence for policies for agriculture, climate change, infrastructure, freshwater, and nature-health linkages. Comprehensive, objective, continuous in space and time and scale independent information to support monitoring progress towards targets and goals are lacking in many areas (BIOMONDO_D1.1_RequirementsBaseline_v2.1.pdf).

The results of Pilot 2 show that work related to investigations of impacts of changes in water temperature and effects on fish abundance/biodiversity is important as the links are not straightforward and many different parameters play a role in how ecosystems are affected. As pointed out by Joep de Leeuw, (Wageningen Marine Research/RWS) in one of the consultation meetings, many different events in the past decade have affected Lake Marken so it is hard to pinpoint a cause for changing fish abundance. If not all influencing factors are taken into account, the temperature signal may be obscured.

Most policies stipulate that the driver "climate change" is important to consider when it comes to monitoring of biodiversity change and deciding on adaptation and mitigation efforts. We have found that this requires careful consideration of all input data, EO based, in situ and modelling as well as the relationships between different direct and indirect drivers. The understanding of the dynamic relationship between human actions and effects on biodiversity requires regular observations of nature, as well as information about human activities, which, in turn, require new approaches for the integration of Earth observations also with socioeconomic data (Geller et al. 2022, National Academy of Sciences, 2019).

The SPTM for Pilot 2 focused on one of the five main drivers of biodiversity loss/change, i.e., climate change. The main focus of Pilot 2 has been to derive results and EO based products that can help assessing possible effects on fish biodiversity from fluctuations (increases) in water temperature by analysing EO based products, in situ data and modelled fish warming tolerance for the two test sites (section 1.3).

Pilot 2 results and products show potential to provide needed inputs to several strategies and frameworks, including climate policies and biodiversity strategies with climate related goals, as they include EO based products and modelled information that are continuous in space and time in contrast to currently used sparse in situ data (section 2.1). Specifically, the variation in temperature over time, i.e., seasonal and over the years, for different areas of interest provide important information that can be related to real world observations and trends in fish abundance and diversity (Caroline Ek, SLU, pers. Comm., 2023).

The Water Framework Directive (European Commission, 2014), the Habitats Directive (Council Directive 92/43/EEC) and the EU 2030 Biodiversity Strategy (with the Nature Restoration Law), as well as the Kunming-Montreal Global Biodiversity Framework (CBD, 2022a and b) have been in focus for this policy utility and impact assessment. These policies and directives have been confirmed as being the most relevant in discussions and feedback from consultations with biodiversity experts and members of the advisory board. In addition, reflections on the relevance of the EU Climate Adaptation Strategy and how different Nexus initiatives could benefit from the results are also discussed in this final version of the report.

In the following sections (3.1.1 to 3.1.5) the main policies and strategies relevant to Pilot 2 are summarised and can be viewed as an update to the descriptions in the BIOMONDO Requirements baseline document (BIOMONDO RequirementsBaseline v2.1.docx). Section 3.3 outlines a policy relevant show case with examples of Pilot 2 results and ideas of how these results can be used in practice to support management decisions and inform policy. The BIOMONDO Experimental datasets are described in 3.2 for context. In section 3.4 the potential policy utility and impact of the Pilot 2 results are assessed and described in relation to the added value for related biodiversity strategies and monitoring frameworks. It focuses on the usefulness for current policies and how the results respond to biodiversity policy priorities. We also describe how the products and results could be used for decision support, development of indicators and revision of monitoring guidelines.

3.1.1 Water Framework Directive (WFD)

Waters must achieve good ecological and chemical status, to protect human health, water supply, natural ecosystems and biodiversity (European Commission, 2014).

The Water Framework Directive (WFD), adopted and implemented in 2000, is the main EU directive for member states reporting on the ecological condition of European surface and ground waters. It is based on the natural river basin approach to manage water and to improve the chemical and ecological status. The abundance of aquatic flora and fish fauna, the availability of nutrients, and aspects like salinity and pollution by chemical pollutants defines the ecological status together with temperature as part of the thermal conditions. Morphological features, such as quantity, water flow, water depths and structures of the riverbeds, are also considered. Surface water status is assessed using the following biological quality factors:

- Composition, abundance and biomass of phytoplankton
- Composition and abundance of other aquatic flora
- Composition and abundance of benthic invertebrate fauna
- Composition, abundance and age structure of fish fauna

Chlorophyll-a is one of the parameters used to assess the status related to 'Phytoplankton' and EO based products are already used in several countries to support the classification. Chlorophyll-a is also included in the EO product suite of BIOMONDO for Pilot 2. 'Fish' as a biological quality factor is assessed in Sweden using an index called EQR8, in which eight parameters developed based on fish catches are incorporated, for example, the number of species in the catch, their weight and quotes of different fish groups. The EQR8 index cannot be directly addressed with EO data, but new EO based metrics and indices, including ones related to climate, could be developed and enhance the interpretation and analyses of fish monitoring data from lakes. Different indices are used in different countries, and many were initially developed to reflect effects of eutrophication. This is further discussed in section 3.4 below, including feedback from the expert consultations.

In addition to the biological quality factors, the following general physico-chemical quality factors are included in the WFD assessment:

- Transparency
- Thermal conditions
- Oxygenation conditions
- Salinity
- Acidification status
- Nutrient conditions

Secchi Disk Depth is used to assess the status related to 'Water transparency' and EO based products are already used in several countries to support the classification. For some parameters, for example oxygen, the water temperature is used in the estimation.

Currently, temperature, as part of thermal conditions, are only referenced in the WFD together with oxygen balance and transparency for physico-chemical quality elements and "High status" is when *temperature, oxygen balance and transparency do not show signs of anthropogenic disturbance and remain within the ranges normally associated with undisturbed conditions.* And "Good status" is when *temperature, oxygenation conditions and transparency do not reach levels outside the ranges established to ensure the functioning of the ecosystem and the achievement of the values specified.* Hence, temperature is not included in the WFD to assess status or condition of surface waters. In Sweden, temperature is only used as a determinant to decide when to sample for autumn circulation (i.e. 8 degrees or less). However, there is research showing that temperature variations can affect WFD assessment results (Haubrock et al., 2020), which means that changing thermal conditions need to be taken into account in a different way in the WFD in the future.

3.1.2 Nature Directives – Habitat (and Birds) directives, N2000

The Habitats Directive (Council Directive 92/43/EEC), adopted in 1992, "aims to protect over a thousand species, including mammals, reptiles, amphibians, fish invertebrates, and plants, and 230 characteristic habitat types". Every six years, Member States must report to the Commission on the conservation status of species and habitat types protected under the Habitats Directive that are present on their territory (Article 17). It requires Member States to monitor the habitats and species listed in the annexes. The assessment is made based on information on status and trends of species populations or habitats and on information on main pressures and threats. In the interpretation manual of EU habitats (EC, 2013a, Annex I) there is a section describing freshwater habitats (standing and running waters). The latest conservation assessments, "State of the Nature in EU", were published in 2020 (EEA, 2020) and the next report is due in 2025.

In 2015, the Commission carried out a 'Fitness Check' of the EU Nature Directives (EC, 2020). to see whether they are 'fit for purpose'. They found that there needs to be a substantial improvement in their implementation if they are to achieve their objectives.

"*The Directives have stimulated a significant increase in research and monitoring activities, essential for efficient implementation, in particular in relation to the Natura 2000 network. However, in most, if not all Member States, there are significant data and knowledge gaps that constrain efficient and effective implementation. The most frequently mentioned gaps relate to the distribution and precise location of protected habitats and species."*

In 2017, the Commission therefore launched a new action plan (European Commission, 2017) to rapidly improve the practical implementation of the Habitats and Birds Directives and accelerate progress towards the EU 2020 goal of halting and reversing the loss of biodiversity and ecosystem services. As these goals have not been reached, there is work going on to revise the action plan to better align with the 2030 Biodiversity Strategy goals. It might therefore be reasonable/possible/desirable that the EC's next fitness check is carried out with lake-specific EO and heat tolerance data.

The IUCN Red List covers a wider set of habitats than those legally protected under the Habitats Directive. It therefore complements the data collected on Annex I habitat types through Article 17 reporting. It was pointed out in the report by the EC (2016) that some of the northern European (Swedish) oligotrophic and dystrophic waters are habitats that can be considered especially vulnerable to fluctuations in water temperature (climate change). Pilot 2 results can support future assessments of how cold- and warm water fish species in different types of lakes respond to changes in thermal conditions.

The Natura 2000 network of protected areas are designated under the Habitats and Birds Directive with the purpose of halting biodiversity loss and restore and protect habitats. It is of relevance for Pilot 2, for both Lake Mälaren and Lake Marken, as both contain and are surrounded by N2000 sites. This is the case especially for the test site Lake Marken as the two separate Ramsar Sites "IJmeer" and "Markermeer" were merged into a single site and aligned with the Natura 2000 boundary in 2007 (Ramsar, 2022).

Guidelines on Climate Change and Natura 2000 were published in 2013 (EC, 2013b) and are primarily aimed at Natura 2000 site managers and policy makers. The purpose is to underline benefits from Natura 2000 sites in mitigating the impacts of climate change, reducing vulnerability and increasing resilience, and how adaptation of management for species and habitats protected by Natura 2000 can be used to tackle the effects of climate change.

3.1.3 EU 2030 Biodiversity strategy & EU Nature Restoration Law, EU Climate Adaptation strategy

The EU 2030 Biodiversity Strategy (EC, 2021) & EU Nature Restoration Law will contribute to achieving the EU's climate mitigation and climate adaptation objectives of the EU Climate Adaptation Strategy, that in turn is a key priority under the European Green Deal. However, the Adaptation Strategy has been criticised for lacking targets, enforcement measures and a timeline (EEB, 2021). However, it stresses four key problems for which actions need to be stepped up and one of these is the data and methodology gaps that underpin decision making. This is due to insufficient knowledge and awareness on climate change adaptation, risk, vulnerability and resilience.

EU policy needs in the biodiversity domain were analysed by the KCEO Deep dive called Earth Observation in Support of EU Policies for Biodiversity with the aim to verify how and to what extent existing EO products and services meet these needs, highlight existing gaps and provide recommendations on future evolution (Camia et al., 2023). Suggested improvements included more regular and frequent updates of existing products, longer and consistent time series, and refining of aggregated land cover classes for the mapping of ecosystem types to be able to drive the assessment of habitats and ecosystem condition. Satellite observation requirements and current availability of dataset and future needs to address the targets and indicators of the EU Biodiversity Strategy are provided in a list in an Excel-file annexed to the report (JRC, 2022). The work of Pilot 2 aimed to provide a long and consistent time series of variables that have potential to complement this list and support the needs of the EU Biodiversity Strategy targets.

In a similar way to the targets of the Kunming-Montreal Global Biodiversity Framework (see 3.1.4), the EU BD strategy also has targets to legally protect 30 % of EU's land and sea areas, and for at least 30% of EU habitats to reach favourable conservation status by 2030 (Target 1 and Target 4). Target 12 aims at a 50% reduction in the number of Red List species threatened by invasive alien species. Freshwater ecosystems fall under land areas and are not targeted in a separate category, i.e. n km of protected rivers/freshwaters.

However, several specific missions are planned as part of the Green Deal to support the EU BD Strategy, e.g. Mission Starfish (EC, 2020), which "provides a systemic approach to reducing human pressures, including pollution and climate change, on oceans, seas, coastal and inland waters and a significant step towards restoring their ecosystem functions" (Bieroza et al., 2021). It includes five objectives and 17 measurable targets to be achieved by 2030 of which freshwater quality is covered by target 3 (30% of EU waters are fully protected), target 5 (re-naturalise rivers and waters) and targets 7–9 (zero plastic litter, zero eutrophication and zero spill).

3.1.4 Kunming-Montreal Global Biodiversity Framework (KM-GBF)

The aim of the Kunming-Montreal Global Biodiversity Framework (KM-GBF), with its developing monitoring framework of targets and indicators, is halting and reversing the loss of biodiversity, sustaining water-related ecosystem services, and supporting SDG 6 and the other Sustainable Development Goals. The KM-GBF is recognising inland water / freshwater ecosystems as a realm of its own in addition to terrestrial, coastal and marine ecosystems. The final KM-GBF includes four goals for 2050 that are supported by 23 targets, which aim to be completed by 2030 (CBD, 2022a and 2022b).

The aim of Goal A and some of its targets and headline indicators are of most relevance to Pilot 2. The first eight targets aim specifically at reducing threats to biodiversity. Target 2 stipulates that by 2030, 30% of degraded ecosystems in each realm are under effective restoration and Target 3 that by 2030, at least 30% of all ecosystems in each realm are effectively conserved and managed. Target 8 specifies that the impacts of climate change on biodiversity should be minimised, and resilience increased through mitigation, adaptation and disaster risk reduction action. In addition, Target 10 ensures that areas under agriculture, aquaculture, fisheries and forestry are managed sustainably. In addition, Target 6 - Reduce rates of introduction and establishment of invasive alien species by 50 per cent has strong links to Target 8. Examples of headline indicators for Goal A include A.1 Red List of Ecosystems and A.2 Extent of natural ecosystems.

In August 2023, Guidance notes for each of the 2030 Targets were published (CBD, 2023), that will be updated periodically. The main purpose of the material is to provide an overview of each target and to serve as a resource for national target setting exercises and highlighting implications as well as identifying adopted indicators to monitor progress.

3.1.5 Nexus

Several so-called Nexuses, i.e. connections of several different disciplines to serve as focal points, have been developed that include Biodiversity. Already in 2013 Ramsar released a report highlighting the importance of the role of wetlands in the water-energy-food nexus and for ecosystem services (Russi et al., 2013). Other examples include the ongoing work of IPBES on its Nexus assessment (interlinkages among biodiversity, water, food and health, IPBES, 2022), the Water-Biodiversity Nexus, the Biodiversity-Climate Nexus and the Climate-Biodiversity-Health Nexus (CBH). The CBH frameworks is a goal-oriented attempt to integrate approaches to planning and policy and support monitoring and development of indicators (Newell, 2023). The Water-Biodiversity Nexus, discussed at the UN Water conference 2023, is an important concept that highlights the intrinsic links between sound water management (e.g., in terms of domestic- or industrial use and flood protection) and nature protection and restoration to reduce loss of biodiversity. The Biodiversity-Climate Nexus supported by the CBD and UNFCC constitutes an attempt to integrate biodiversity and climate change issues and work on filling the knowledge gaps in this area. The importance of the interdependency between climate change and biodiversity loss is highlighted by a recent EC DG Env Call (EC, 2023) for project proposals. Other strategies and assessments highlight the importance of looking at climate change and biodiversity. For example, in the EU ecosystem assessment (Maes et al., 2021) it is pointed out that “The challenges of climate change and continued biodiversity loss call for an in-depth rethinking of the current models of managing natural resources or natural capital, in order to increase nature's resilience by both scaling up protection and restoration efforts and by curbing pressures across ecosystems." The interdependence of the two areas is also discussed from a few different angles by ISSD (2022), including the Paris agreement, the KM-GBF and Nature based Solutions (NbS).

IPBES, as part of its work programme, is currently working on a thematic assessment of the interlinkages among biodiversity, water, food and health (Nexus assessment, IPBES 2022). The aim is to examine the interlinkages among the SDGs related to food and water security, health for all, protecting biodiversity on land and in the oceans and combating climate change.

According to Newell (2023), other nexus, e.g. the Water-Energy-Food (WEF), which is not directly linked to biodiversity, have been criticised for lack of clarity in how to apply its framework and that the CBH is an attempt to remedy such shortfalls. In Switzerland and in other countries lake water is used for cooling and heating buildings with heat exchanging devices and cold lake water from ca. 30 m depth. Hydropower production also affects lake/reservoir temperature, and restoration/protection measures include building shaded fish refugia in rivers, where fish could survive during heat waves. In this sense the WEF nexus, despite application problems, will most likely stay relevant for the foreseeable future. However, the Horizon 2020 GoNEXUS project (2022) includes also ecosystems linking the different nexus components Water-Energy-Food-Ecosystems (WEFE) more strongly to human pressures and biodiversity.

All these nexuses emphasise the relevance of the Pilot 2 results, and how the WFD in addition to water and biodiversity, ultimately also links to fisheries-food and energy industries and shows how monitoring, modelling and policy guidelines can influence real world decisions affecting freshwater biodiversity.

3.2 BIOMONDO Experimental dataset

The datasets available for building show cases and methods for viewing the data and products stored in the BIOMONDO Freshwater Laboratory are introduced below and in BIOMONDO_D2.4_ExperimentalDatasets_v1.0.pdf.

For Lake Mälaren, the experimental datasets presented and discussed with the Early Adopters for Pilot 2 consisted of:

- Lake Surface Water Temperature from EO
- Chlorophyll-a concentration from EO
- Cyanobacteria Abundance indicator from EO
- Modelled warming tolerance for occurring species per lake
- Fish abundance from hydroacoustic in situ measurements

For Lake Marken, the experimental datasets presented and discussed with the Early Adopters for Pilot 2 consisted of:

- Lake Surface Water Temperature from EO
- Chlorophyll-a concentration from EO

- Modelled warming tolerance of occurring species per lake
- Fish abundance from in situ net fishing

All produced EO based and modelled datasets have been included in the BIOMONDO Freshwater Lab. The lab allows the user to work with and combine different information sources to analyse and compare model output with observations made in situ or by Earth Observation. The central part of the BIOMONDO Freshwater Laboratory is the BIOMONDO Viewer and its functionalities. The Viewer enables easy access, visualization of and to work with the experimental datasets, and it was essential for the demonstration and consultation sessions. The Viewer also serves as good demonstration and showcase how the results and outputs of the ESS Pilots could be integrated into decision systems on the management side, either as external web-based tool or by integrating data in the organisations existing systems. Figure 7 shows the Viewer and gives an example of the warming tolerance data for Lake Mälaren. Such time series can be generated and analysed for any location or region defined by the user.

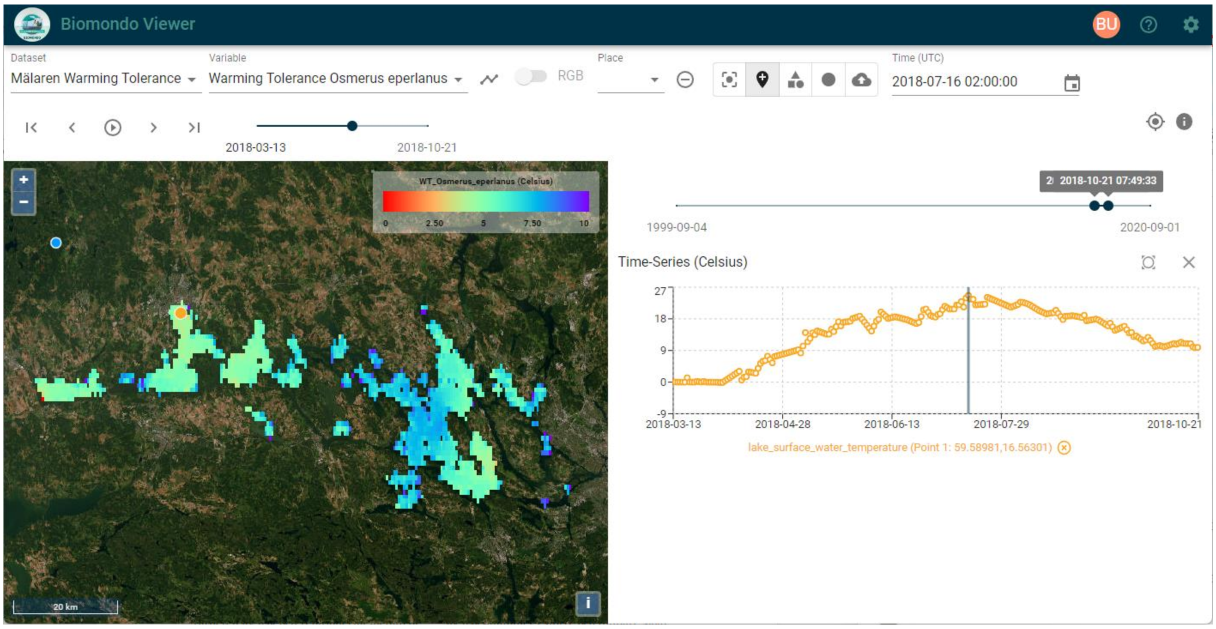

Figure 7 BIOMONDO Viewer showing warming tolerance for Osmerus eperlanus in Lake Mälaren on the 16th July 2018.

To facilitate the interpretation and support the scientific and policy discussions, the generated datasets were compiled in graphical form. An example for Lake Mälaren is shown in Figure 6 and exhibits Chlorophyll-a, cyanobacteria abundance, fish abundance of smelt and warming tolerance of smelt at the Granfjärden transect for the summers of 2017, 2018, 2019 and 2020. The scientific assessment related to these results are presented in section 2.1 above.

As mentioned earlier, a significant reduction in abundance (primarily for juvenile smelt) was noted for 2018 and 2020. EO data and model results show that the summers of 2018 and 2020 were characterized by many alerts of cyanobacteria, relatively low values of warming tolerance during large periods of the summer, and high concentrations of Chlorophyll-a compared to the summers of 2017 and 2019. The plot in Figure 6 was created to summarise and showcase how the experimental datasets can be presented, aggregated, and visualised. The final format and data selection is then dependant on the research question or management needs.

In addition, thematic ecosystem change indices (TECIs) that provide information on the extent and intensity of changes in ecosystems have been developed and demonstrated to the Early Adopters. The developed TECIs for Pilot 2 are based on the analysis of the EO and model datasets listed per lake above and are designed to capture changes in the habitat conditions of fish. TECIs can support the interpretation of big datasets and provide valuable information for understanding the drivers and impacts of ecosystem change. Figure 8 shows an example for the Lake Mälaren data described above. The summers of 2018 and 2020 corresponds to higher TECI scores compared to the other years, indicating high probabilities that these years have higher certainties of anomalies and also that the Chlorophyll-a concentration and cyanobacteria abundance contribute the most to this higher TECI score.

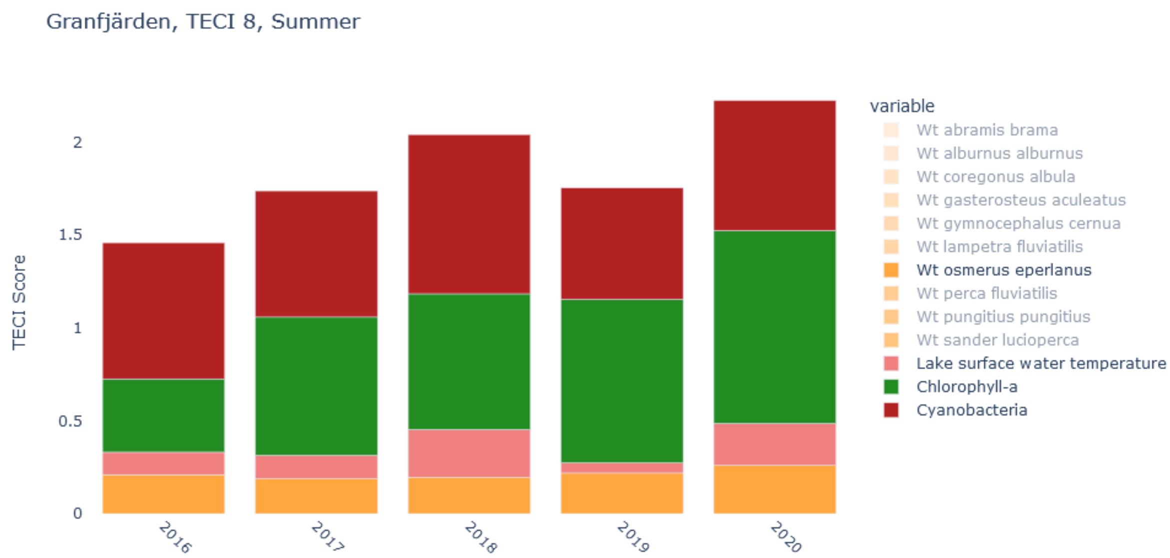

Figure 8 TECI results at Granfjärden for the summers of 2016, 2017, 2018, 2019 and 2020. Shown are the stacked TECI results of Cyanobacteria (red), Chlorophyll-a (green), warming tolerance of smelt (orange) and LSWT itself (pink).

The experimental datasets, the summary plots and TECI examples were presented to the Early Adopters to discuss and assess the impact and utility for policy in general and to form the showcase presented in in section 3.3 below.

3.3 Pilot 2 Show case – Towards an EO based climate index for fish in freshwater ecosystems

The show case described below exploits the potential of experimental datasets developed for Pilot 2 and the ability to address policy priorities related to drivers of biodiversity change. The show case has been developed in close collaboration with the Early Adopters from the Swedish University of Agricultural Sciences (SLU) and included a detailed presentation of the pilot results and discussions about how these products can support relevant policy priorities and be integrated in decision support systems.

Climate change is one of the main direct drivers of biodiversity loss and interacts with other drivers in ways still partly unknown (IPBES, 2019). Information about fish abundance and diversity in a changing climate requires mapping of the habitat of the most sensitive species that will be affected first. For the pilot development, we integrated EO Lake Surface Water Temperature (LSWT) products in a heat tolerance model developed by PBL (BIOMONDO D2.2 ATBD v2.1.pdf) to produce fish species' warming tolerance, which indicates how close instantaneous temperature conditions are to a species heat tolerance limit. The pilot addressed short term heat waves, for which intensity and duration are expected to increase with future climate change. In this show case we have used the same LSWT data but addressed more long-term climate effects and monitoring needs related to the WFD instead.

3.3.1 Policy context and information needs

As described in section 3.1, the Pilot 2 results are relevant for several policy targets and goals, but the focus during the collaboration with the Early Adopters has been on the EU Water Framework Directive and linked aspects of the Habitats Directive. In general, the aim of the WFD is to measure "the ecosystem's ability to maintain a balanced, integrated and adapted community of organisms with a species composition, diversity and functional organization that is typical of natural habitats in the region".

The Water Framework Directive mandates three monitoring programs:

- **Surveillance monitoring** – Aimed to supplement and validate an impact analysis, support efficient and effective design of future monitoring programs and assess long-term changes in natural conditions and changes resulting from anthropogenic activity. Monitoring is performed at least once every management cycle (usually every 6 years).
- **Operational monitoring** – Aimed to establish the status of water bodies identified as being at risk of failing to meet the WFD environmental objectives and assess any changes in the status resulting from the program of measures.
- **Investigative monitoring** – Aimed to determine reasons for exceedances or predicted failure to achieve environmental objectives if the reasons are not already known and to determine the magnitude and impacts of accidental pollution.

All three monitoring programs includes assessment and monitoring of the status of several biological and physical-chemical quality elements for all water bodies (section 3.1.1). For the biological quality element "Fish", monitoring in Sweden is based on three parameters, which consists of three different indexes; EQR8, which address general impacts, AindexW5 addressing acidification and EindexW5 addressing the impact of nutrients. Presently, available EO products have no direct connection to what is needed for the listed quality elements but could, and should, be considered for coming index developments, which currently is one of the tasks for Caroline Ek at SLU. New indicators are needed for several reasons:

- Various metrics that link to eutrophication, connectivity and hydromorphology are being explored but more direct metrics related to climate change should also be included.

- It is not sustainable to continue catching "test animals" to respond to directive requirements, instead the 3R = replace, reduce and refine principle needs to be considered and alternative indexes developed.

The principles of the 3Rs were first described by William Russell and Rex Burch in 1959. Today, they constitute the guiding principles for best practice and humane animal experimentation. Replace means achieving objective by avoiding or replacing the use of animals. Reduce means to include as many experiments as necessary, but as few animals as possible. Refine means to minimize potential suffering and stress of animals.

3.3.2 EO based climate index

The show case addresses development of indices based on EO derived temperature products that could provide a better link to effects of climate change and that can complement the current list of metrics. The starting point was the heat tolerance of different species. When estimating the warming tolerance for species occurring in Lake Mälaren, the two species European Smelt (Osmerous operlanus) and Vendace (Coregonus Albula) stood out from the other species exhibiting a lower warming tolerance during the investigated time period (Figure 9). Smelt and Vendace are cold water species and can serve as indicator species for this functional group. Smelt plays a key role in the food webs of the Swedish great lakes and are a prerequisite for other highly valued fish species. They are among the most sensitive species in a warming climate and most likely to be affected first and should therefore be prioritised for monitoring actions.

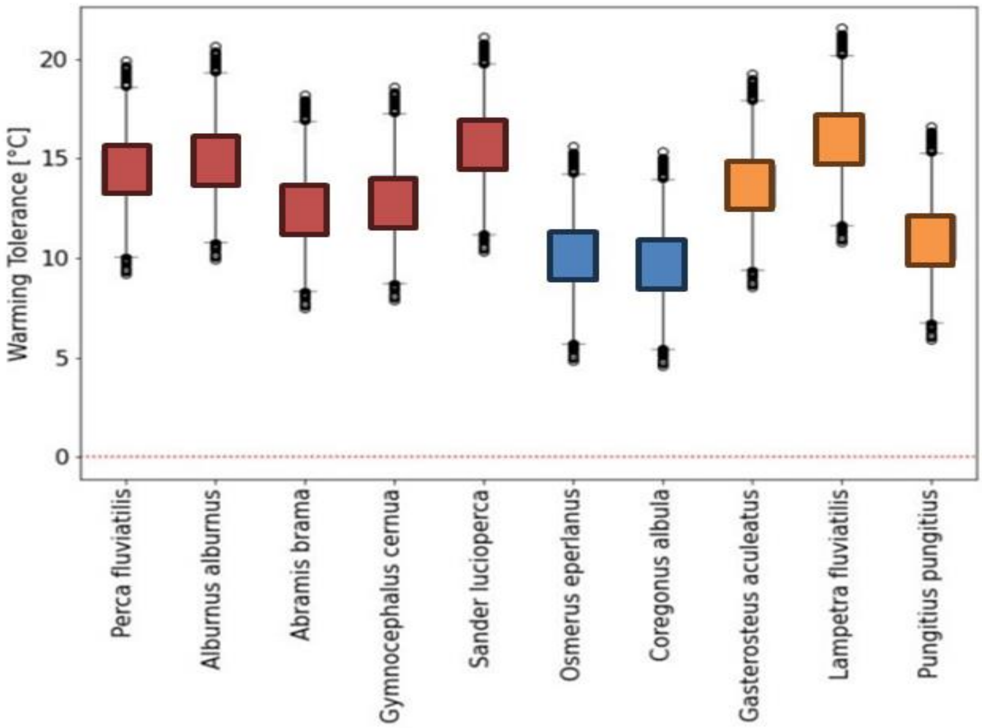

Figure 9 Warming tolerance in the summer months 2000 – 2020 (June, July, August) for species abundant in Lake Mälaren, indicating how close the current conditions are to the thermal limits of the species. Fish species marked with blue colour are cold water species (European smelt and Vendace), in red warm water species and those in orange are unknown.

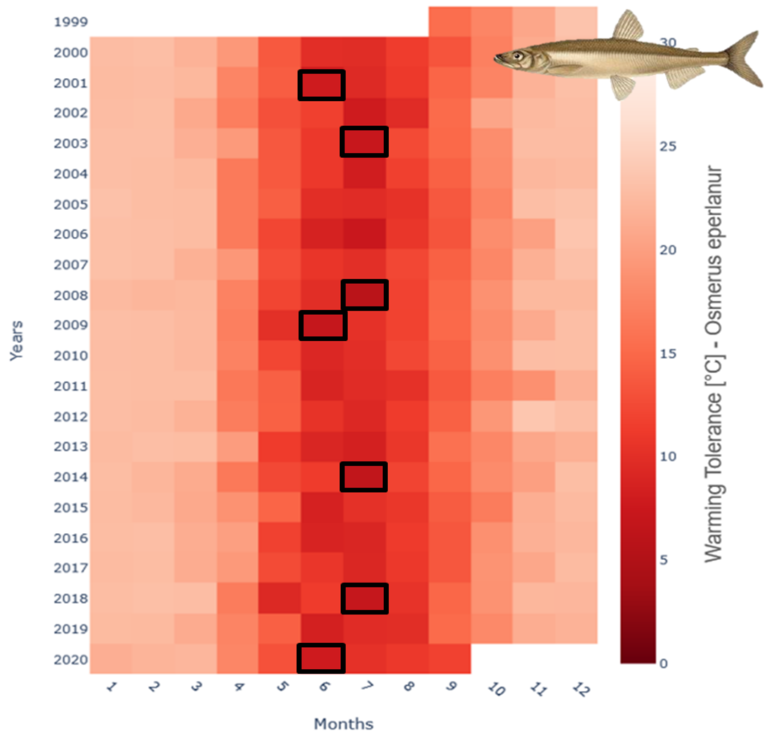

Figure 10 Average monthly warming tolerance (average across the lake) for Osmerus eperlanus (European Smelt) in Lake Mälaren. The dark red months marked with a black box indicates months when the warming tolerance was close to 0, i.e. when the state can cause death or affect growth, reproduction, immunity, and the ability to cope with additional stressors.

Using EO based temperature products it would be possible to investigate different regions of a lake or water body with high temporal resolution. In Figure 10, the average monthly warming tolerance for Smelt in Lake Mälaren and for all investigated years has been visualised. Dark red months marked with a black box indicates months when the warming tolerance was close to 0, i.e. when the state can cause death or affect growth, reproduction, immunity, and the ability to cope with additional stressors.

Based on selected regions, variations within longer time series can be analysed and trends for specific months or seasons of importance for a fish species, e.g., spawning or hatching periods can be analysed. Information essential to understand fluctuations in abundance and distribution of different fish species can be provided and improve status related knowledge. In Figure 11 LSWT data from April has been extracted for all years (2000-2020) from the experimental dataset and plotted in a boxplot graph (left) and showing all single observations (right). In addition, the trend for the investigated time period has been overlaid. Spring months are potentially very important for the Smelt as both spawning and hatching takes place during spring and temperature is an important factor controlling the process. Each data point corresponds to an average of all EO observations within a region where field-based hydro-acoustic measurements of fish abundance is available and has been performed during several years. For the investigated region a temperature increase of about 1.2 degrees C is observed in April. The same increase was observed for May, while October data does not exhibit any trend for the same period. In addition, the data indicate that April 2018 was unusually cold and that May the same year was unusually warm. This could potentially be factors leading to measured low abundance of Smelt the same year.

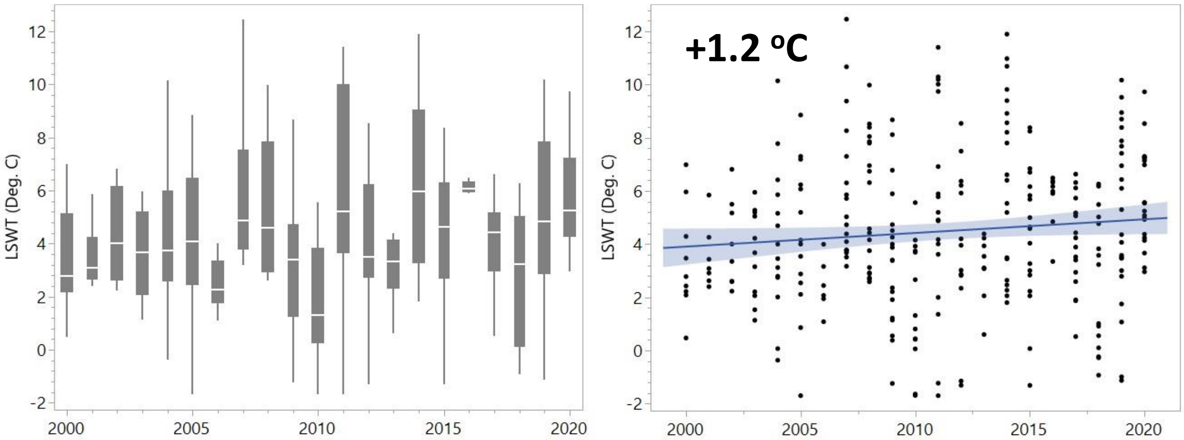

Figure 11 An EO based climate index can be based on longer time series of LSWT variation (left) for a user defined region of interest and trends in large data sets can be identified (right).

3.4 Assessment of policy utility and impact

The results and products as described in Chapter 1 and section 3.2, and exemplified in the show case can contribute to decision making, biodiversity management and conservation by integration in such processes and to future development of monitoring guidelines and target indicators as highlighted by feedback from consultations with experts.

Managers of freshwater ecosystems, tasked with ecological restoration and fish monitoring related to biodiversity and inland fisheries, need to make informed decisions to promote sustainable management. A fundamental part of such work is to monitor temporal variation to assure a satisfactory status of water bodies and to assess the spatial distribution of the most sensitive and essential habitats requiring long-term protection (Sandström et al. 2016).

EO based time series of LSWT products and modelled warming tolerance as well as TECIs from Pilot 2 can support resource managers working to preserve biodiversity in a changing climate by helping to determine risks for, and vulnerability and resilience of different fish species. For Pilot 2, thermal conditions, i.e. lake water temperature including spatial variation and temporal trends are in focus for analysis of fish abundance and distribution. Variations in temperature over the years and the seasons are an important parameter as fluctuations can have strong effects on fish spawning and then hatching success because of timing and survival rates of hatchlings related to availability of phyto- and zooplankton. This could in a subsequent step have an impact on the status of the water body and be important for surveillance monitoring that take changing conditions into account.

Validated EO data LSWT products, in combination with models and in situ data, were used to demonstrate how this type of data can be used to quantify the impacts of increases in temperature and heat waves on freshwater fish diversity, and how it can support research and decision making by managers and how changes in temperature and other parameters affects different species addressed in **WFD**. The first consultation with the Swedish Agricultural University was focused on presenting the scientific results and the outcome is presented in chapter 0 above. A second meeting was conducted with

Caroline Ek, SLU, who works with the development of assessments criteria and indicators for the WFD. According to Caroline, the WFD is the most important policy for reporting when it comes to fish abundance and parameters affecting it. From a national perspective fish distribution and fish abundance data are also important as many fish species can be considered as a food sources (e.g. Vendace).

As mentioned in section 3.1.2, the **Habitat directive** requires 6-yearly national reporting on extent and status of habitat types and species listed in its annexes and requires information on trends including main pressures and threats. Oligotrophic and eutrophic lakes constitute habitats included in the directive and for example, suitable smelt habitats could be quantified based EO derived products such as those demonstrated in Pilot 2, i.e. Lake Surface Water Temperature, chlorophyll-a concentration, Cyanobacteria Abundance indicator from EO and modelled fish warming tolerance. The fish species Aspen (Aspius aspius), which is a protected fish species listed in the Habitat directive and on the Swedish red list ("Near threatened") and known to be sensitive to connectivity issues, was discussed. It occurs in Lake Mälaren but was not included in the hydroacoustic dataset. Further work focusing on the habitat properties for Aspen and utilising net fishing data could be of interest.

The Pilot 2 information should also be useful to support prioritisation of lakes and freshwater ecosystems in need of restoration and thereby support restoration targets of the **EU 2030 Biodiversity strategy** (EC 2020). There is a knowledge gap relating to what lakes or lake basins experienced heatwaves in the past and which fish species are most at risk of being seriously affected by increases in temperature that threaten existing biodiversity. Resource managers might also need to consider additional management tools and strategies in combination with area protections to mitigate the effect of warming on aquatic communities (IUCN Issues Brief, 2021).

It was pointed out in the discussions that these data may contribute also to global goals such as the **SDGs,** and for example Target 10 of the **KM-GBF** (see section 3.1.4 and 3.1.5), which is related to sustainable management of fisheries and should therefore be considered important for any biodiversity strategy or policy including the **nexus** assessments involving water, food, climate and biodiversity. A majority of existing fish abundance data comes from test fishing. However, it is becoming increasingly important to reduce usage of live fish for monitoring purposes or as laboratory animals to support reporting requirements of the directives. The 3R principle, i.e. reduce, refine and replace existing methods (Hubrecht and Carter, 2019), was discussed and is important. Methods that can provide information for identification of suitable fish habitats including changes to these and related abundances would have potential to significantly support a reduction of test fishing. In the paper by Sandström et al. (2016), it was shown that remote sensing has the potential to facilitate several analyses on fish in large lakes. Access to remote sensing data can improve analyses on the distribution of individual fish species and assemblages and since remote sensing variables often are available as continuous map layers, they can be used to model the distribution of the most important habitats, particularly for pelagic species.

An important contribution from Pilot 2 considered by the Early Adopters, was the provision of input data to support a range of ecological investigations, especially in the light of changing climatic conditions. The availability of these spatially and temporally continuous data can lead to economic savings and more efficient use of resources compared to field sampling and can reduce usage of experimental/laboratory animals (fishing) and perhaps provide appropriate proxies.

To achieve the **KM-GBF** goals GEO BON (Gonzalez et al., 2023) has proposed the establishment of global biodiversity observing system (GBIOS) and identified four key components that are needed to bridge the main science-policy gaps:

1. biodiversity observations guided by policy needs;
2. observations coordinated to form monitoring programmes designed to rapidly detect change and attribute causes for biodiversity change;
3. observations that inform models to project biodiversity change and the loss of ecological and evolutionary resilience; and
4. frequent assessments derived from monitoring to provide policy options to guide action.

The Pilot 2 products should be able to support these components and KM-GBF targets. Target 8 specifies that the impacts of climate change should be minimized and resilience increased through mitigation, adaptation and disaster risk reduction action. Target 10 ensures that areas under agriculture, aquaculture, fisheries and forestry are managed sustainably. To achieve these, there is a need for better information on climate change effects over time on water temperature that is specific to freshwater species and their habitats, including species used as food sources. As mentioned above, EO based products show potential to provide essential information on the temperature environments needed to attribute causes for biodiversity changes.

In addition, the Early Adopters gave other examples where temperature is essential in monitoring changes to aid policy making and inform goals and targets. Specifically, information related to invasive alien species (IAS) and effects on their spread with increase in temperature was highlighted by SLU as being of interest as more research on this topic becomes available. The Habitat Directive covers habitat types and priority species connected to these, but only includes specified habitats which must be identified, and the status assessed and reported. Several biodiversity policies and strategies contain specific goals and targets related IAS. For example, the EU Biodiversity Strategy Target 12 - a 50% reduction in the number of Red List species threatened by invasive alien species, and the KM-GBF Target 6 - Reduce rates of introduction and establishment of invasive alien species by 50 per cent. The work conducted with the fish species in Pilot 2 could potentially be applied also to IAS if required species parameters can be made available.

For future assessment of habitat suitability for fish, the use of “umbrella” species such as salmon, which indicate favourable conditions for other species making up the ecological community, could be an option. Other species linked to salmon are trout and river pearl mussel as they have similar ecological and environmental requirements. This approach can support estimates on size and type of area needed to preserve salmon. Hence there is potential to use salmon as proxy for “favourable reference areas” (for reporting under the Nature directives), when it comes to monitoring of freshwater ecosystems and their fish diversity. Favourable reference area is the surface area in a given biogeographical region considered the minimum necessary to ensure the long-term viability of the habitat type (CIRCAB, 2017).

Changes in the land cover and land use around lakes, especially relating to wetlands and reedbeds, and their effects over time on water bodies would be valuable to be able to assess better. The Copernicus high resolution Riparian Zones layer (covering a unique combination of aquatic and terrestrial habitats) could have potential to provide complementary information if the time series is continued (currently 2012, 2018 and a change layer is available). This product offers users standardized, accurate land cover and land use maps which highlight riparian zones that serve as buffer zones between land and waterways across the European continent. The applications include monitoring floodplain characteristics, monitoring sensitive ecosystems, and informing policy decisions related to European waterways and restoration of freshwater ecosystems.

The analysis of the different EO based parameters together with the modelled warming tolerance can provide valuable information on differences between species, changes over time and spatial variability for Lake Mälaren and Lake Marken. It can potentially be used to support the work by researchers analysing fish distribution data and the relationship to temperature, oxygen and other environmental parameters. The results could facilitate reporting to the EU Nature Directives for managers. The spatially and temporally continuous EO based products also have potential to aid in the development of indicators of biodiversity change related to climate change impacts on habitats that are relevant for the European and global monitoring frameworks such as EU 2030 Biodiversity Strategy and KM-GBF.

In summary the contributions to improved decision making, biodiversity management and conservation lies in the integration of EO based products in such processes. Validated EO LSWT products, in combination with models and in situ data, were used to demonstrate that these data and methods can:

- be used to quantify the impacts of increases in temperature and heat waves on freshwater fish diversity -> support to ecological investigations considering changing climatic conditions (EU Biodiversity Strategy, KM-GBF)
- support research and if/how temperature fluctuations affect different species and water status addressed in the WFD
- help reduce information gaps and determine risk, vulnerability and resilience of freshwater fish species (EU Climate Adaptations Strategy)
- provide economic savings and efficiency gains to managers working with monitoring and will be achieved through reduced usage of experimental/test fishing
- support prioritisation of lakes and freshwater ecosystems in need of restoration and thereby support restoration targets of the EU 2030 Biodiversity Strategy
- potentially be applied to determination of risk for spread of invasive alien species
- provide data and information to GBIOS and support the achievement of the KM-GBF targets

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