Claudia Giardino

Inland waters

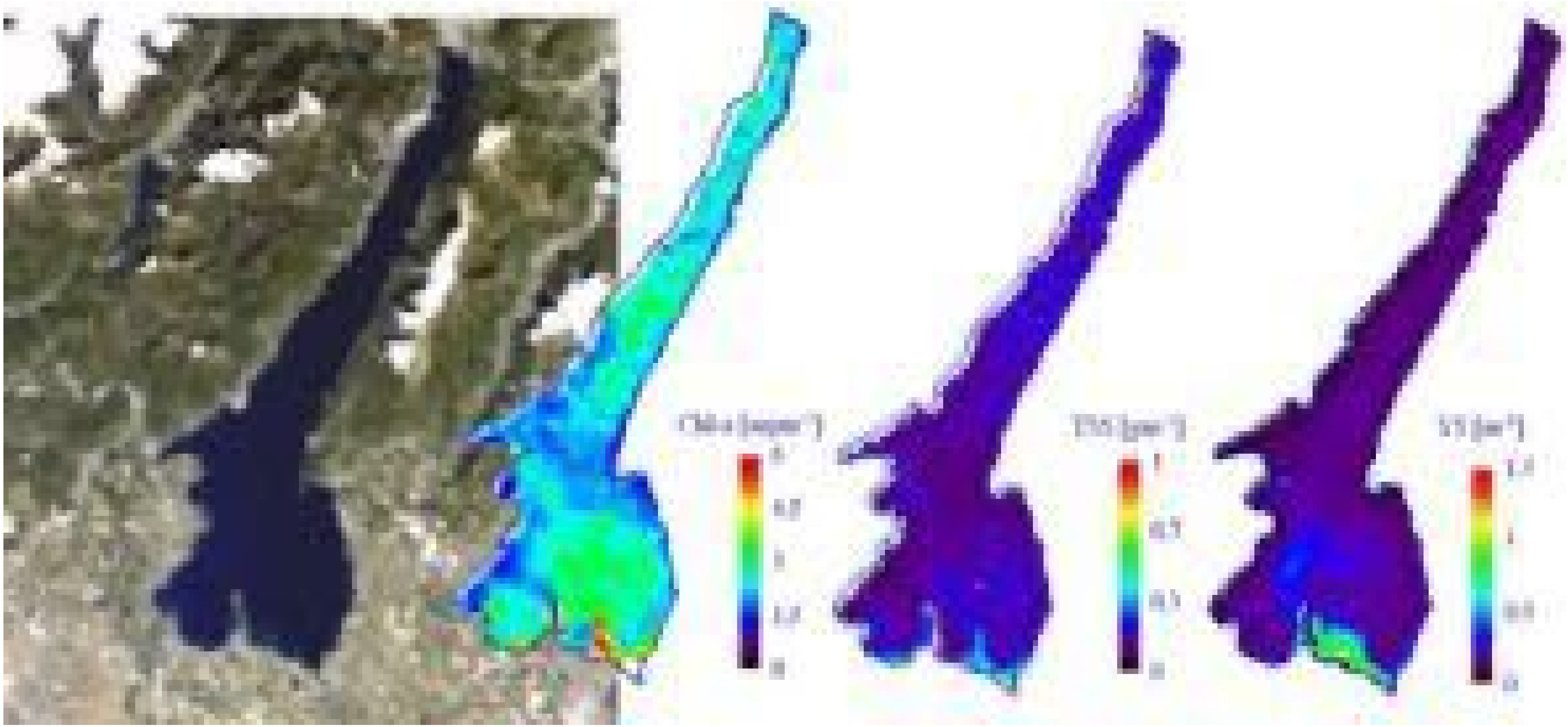
Italian National Research Council

2026 IOCCG Summer Lecture Series

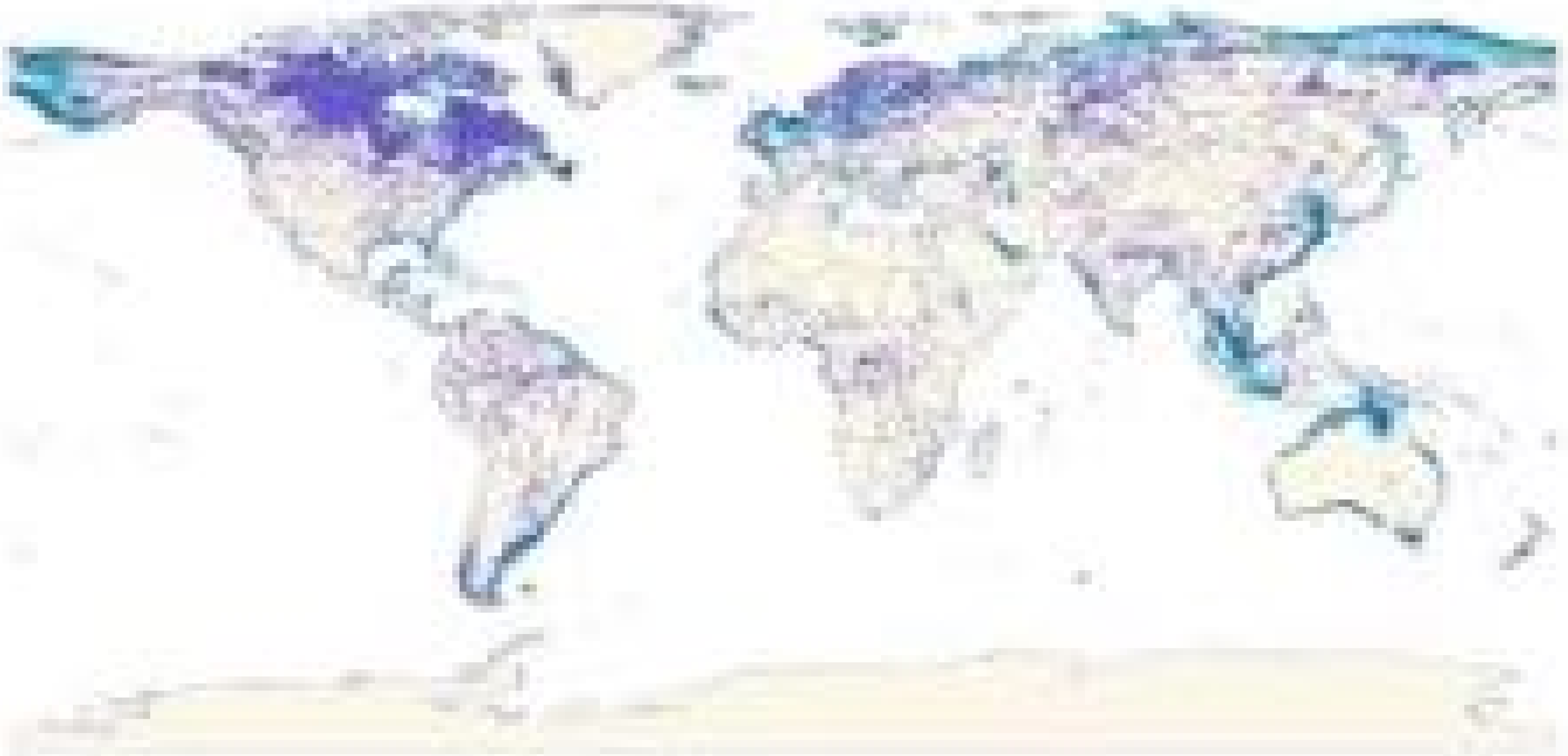
Frontiers in Ocean Optics and Ocean Colour Science: 5 – 19 July 2026

Presentation Outline

From satellite images to quantitative information on aquatic ecosytems

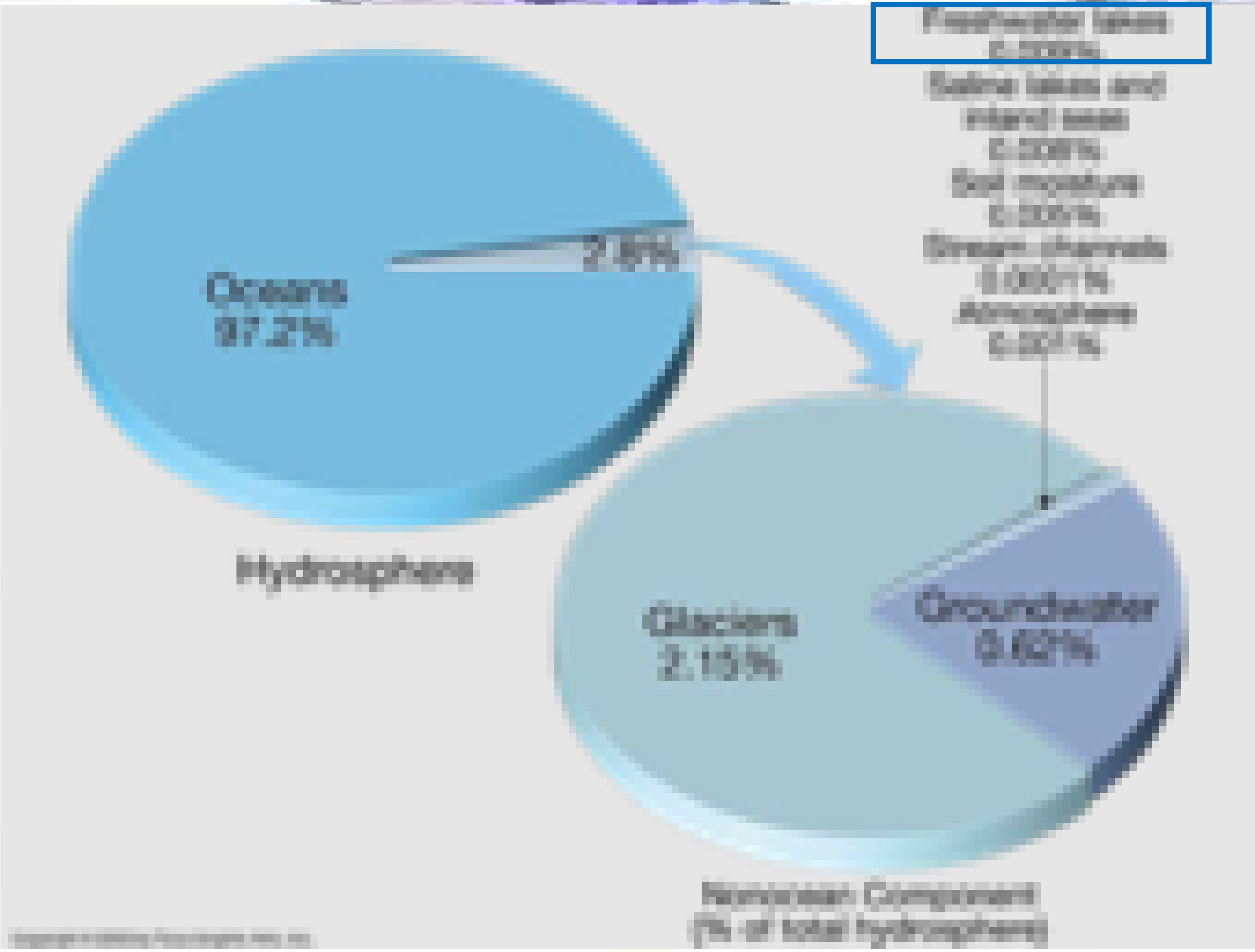


Global relevance



Inland water ecosystems addedd (e.g. lakes, rivers, ponds, streams, wetlands) Data source: GLWD-1 and GLWD-2

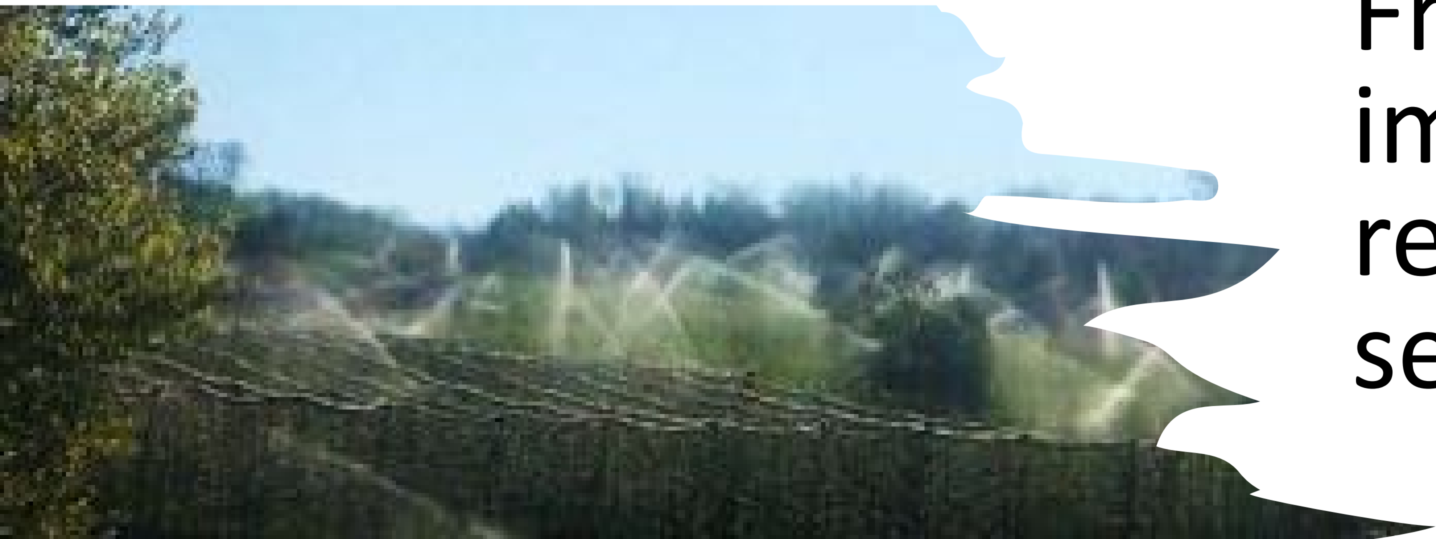
Global relevance



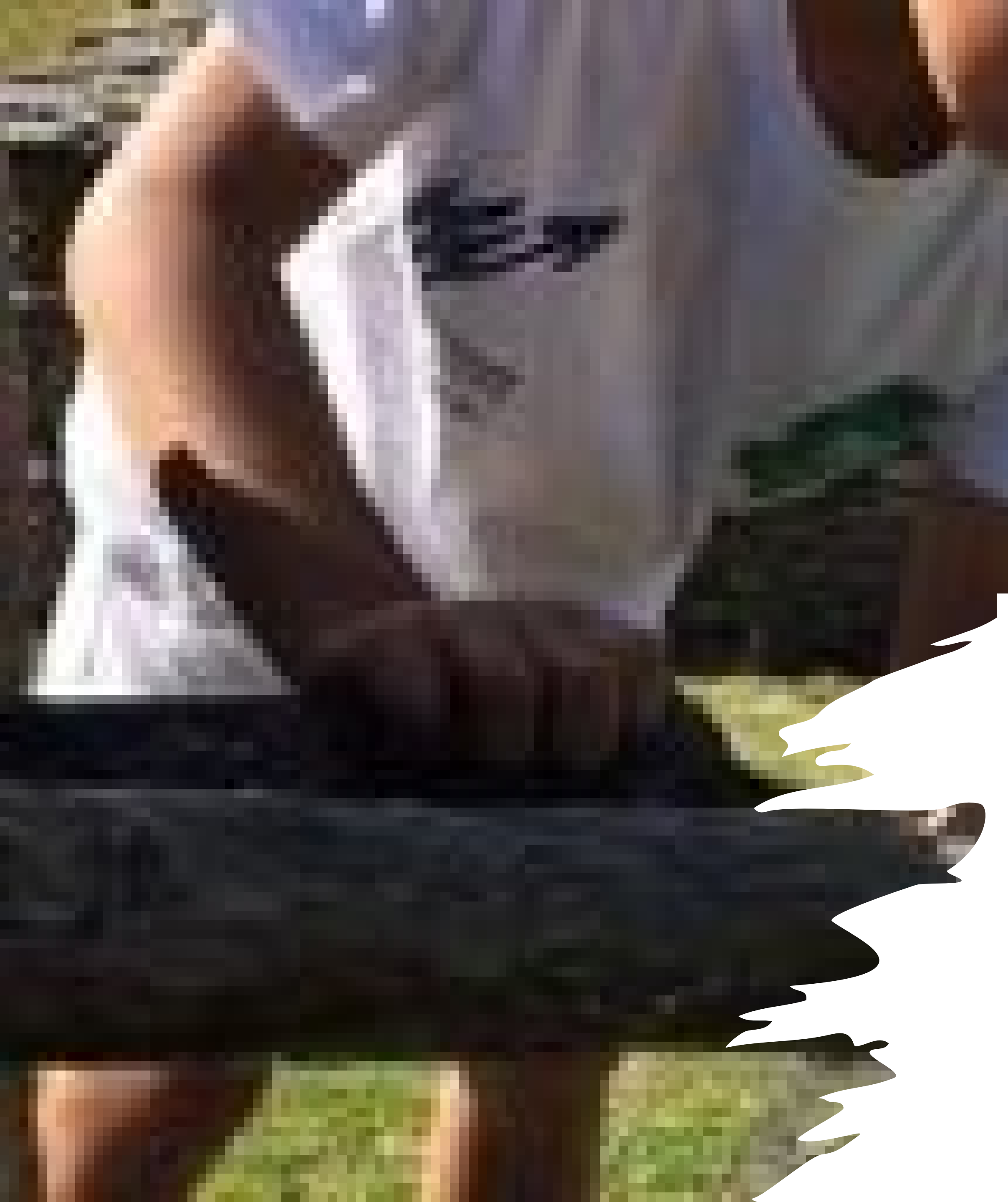
wetlands) Data source: GLWD-1 and GLWD-2

Freshwater ecosystems sustain the world's biodiversity





Freshwater is an important economic resource for many sectors



The life on Earth depends on freshwater supply and healthy freshwater ecosystems

Ecosystems goods and services

- Biodiversity
- Water supply
- Food
- Energy
- Flood control
- Climate regulators
- Recreation
- Tourism
- Aesthetic and cultural

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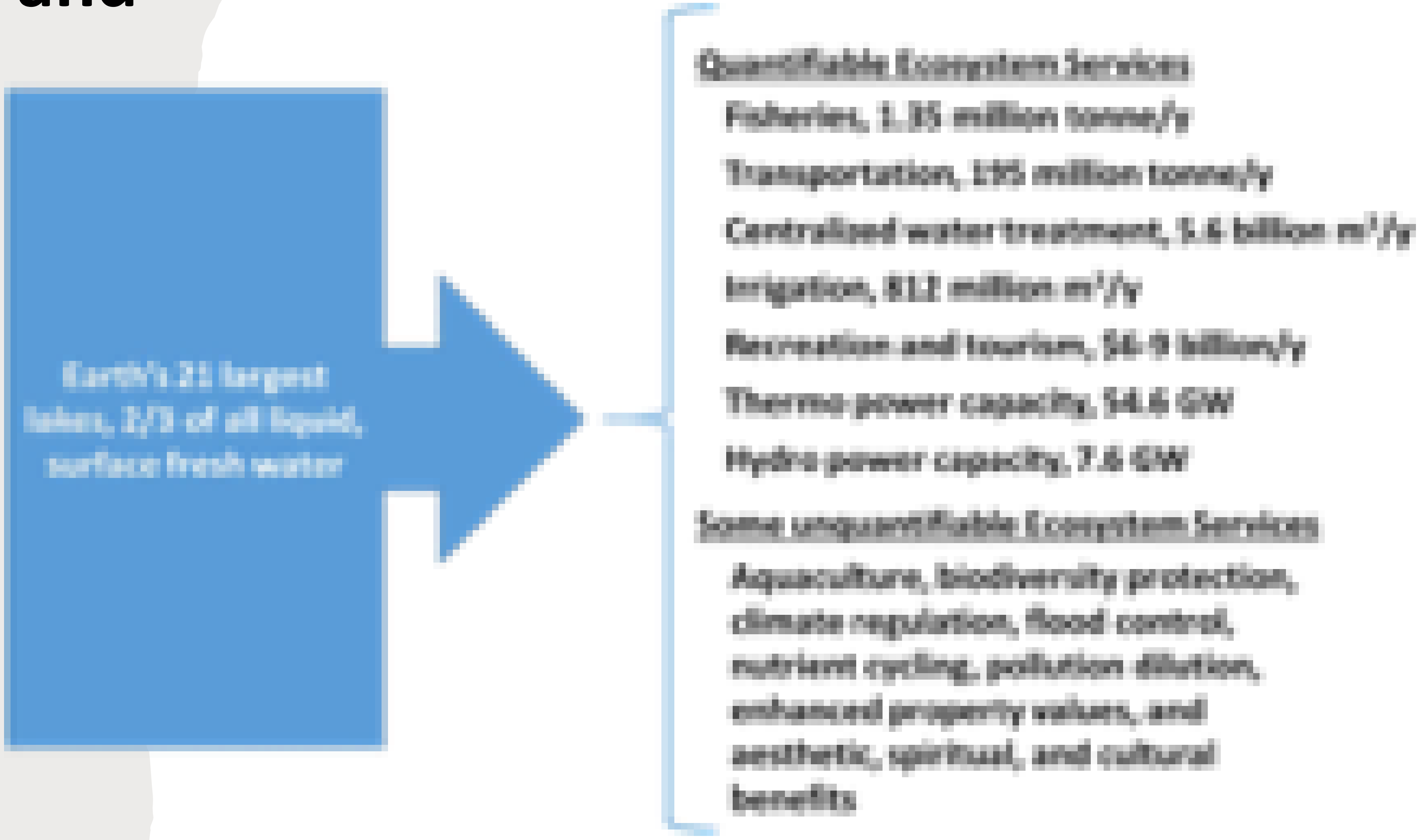
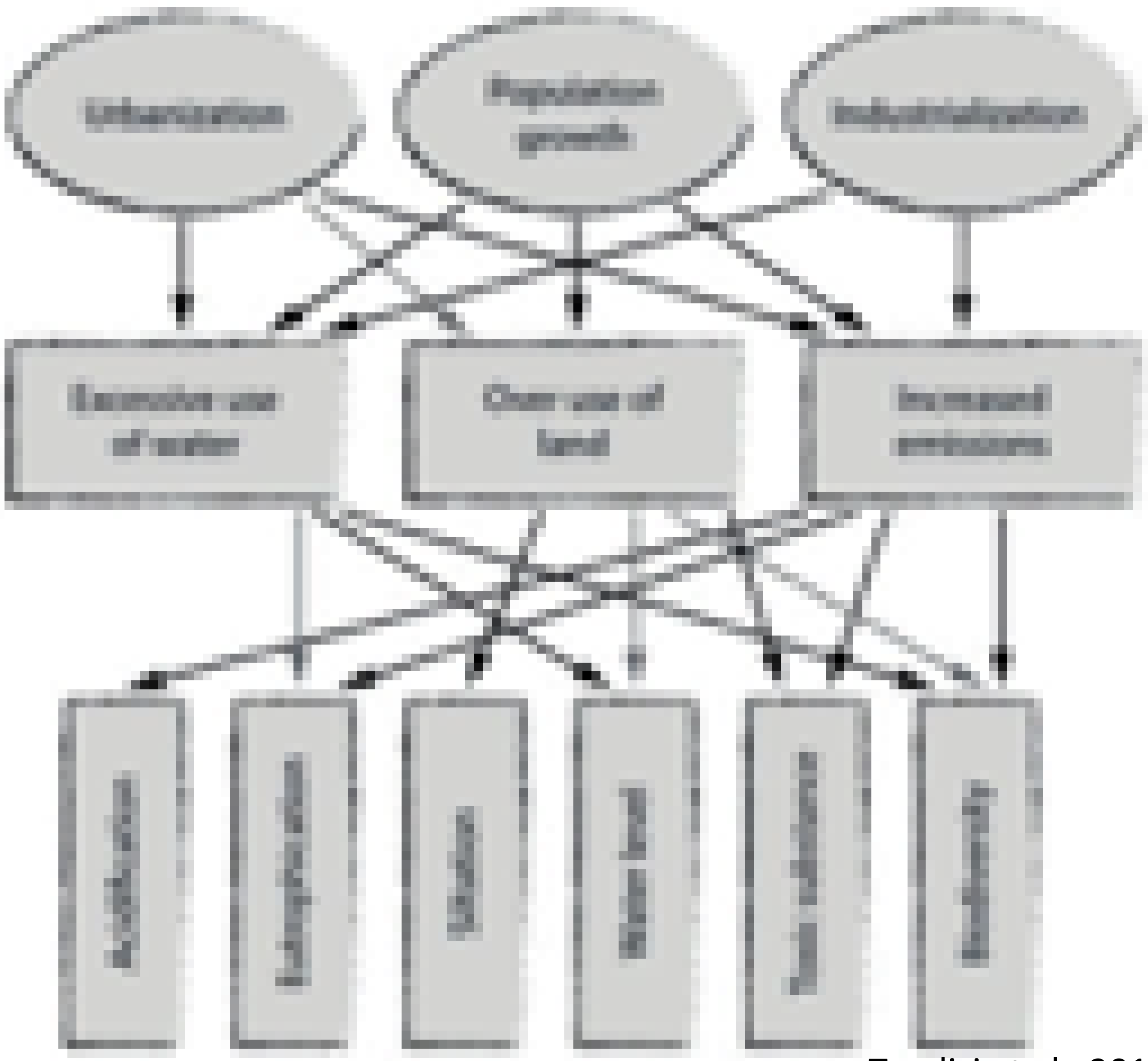


Sterner et al., 2020

Some of the major concerns

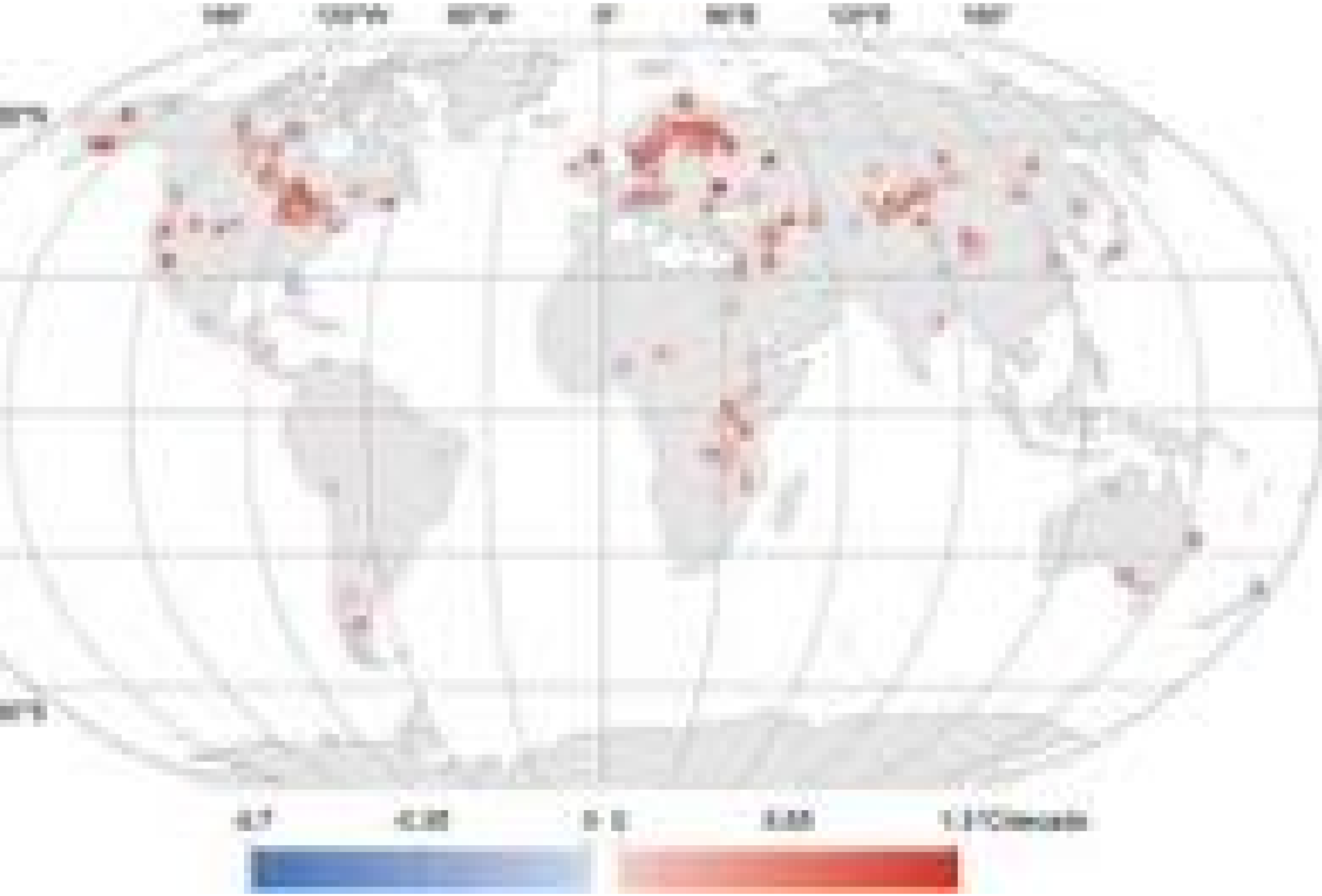
Climate change and the impacts of human activities are affecting these valuable ecosystems in several models such as (e.g. Cantonati et al 2020)



Tundisi et al., 2015

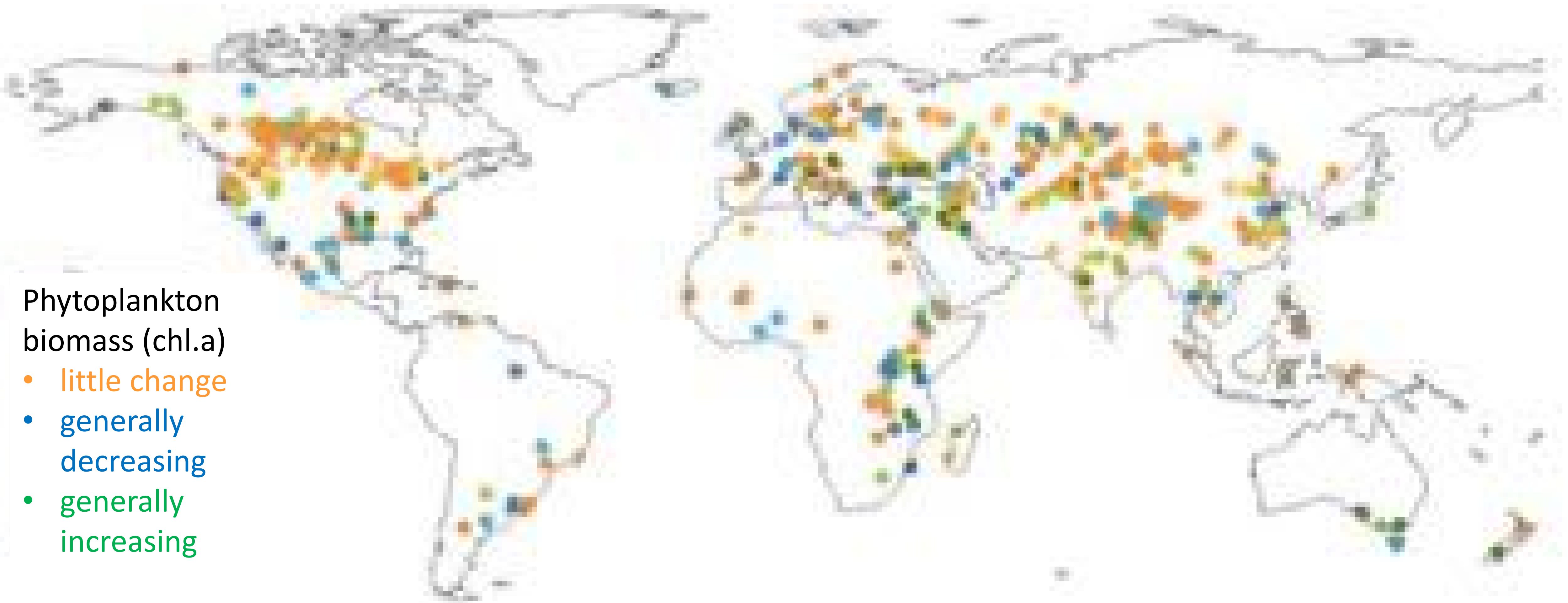
Global concerns

Warming the world lakes (O'Reilly et al. 2016)



Rapid and highly variable warming of lake surface waters around the globe, from satellite times series from thermal infrared sensors

Global concerns



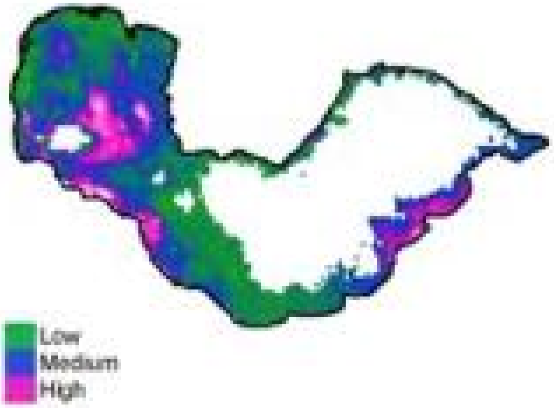
Phytoplankton biomass (chl.a)

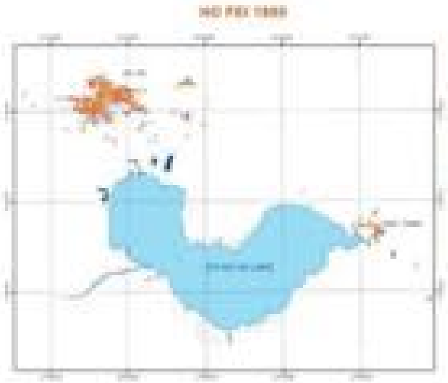
- little change
- generally decreasing
- generally increasing

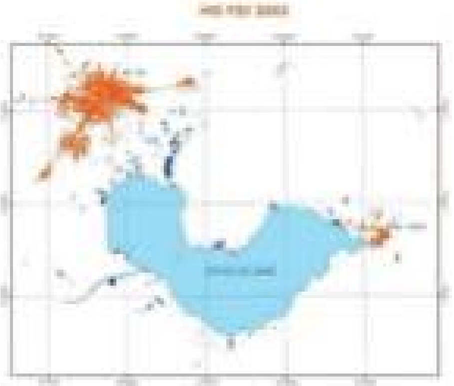
Trends in chl-a concentrations from 2002 to 2012

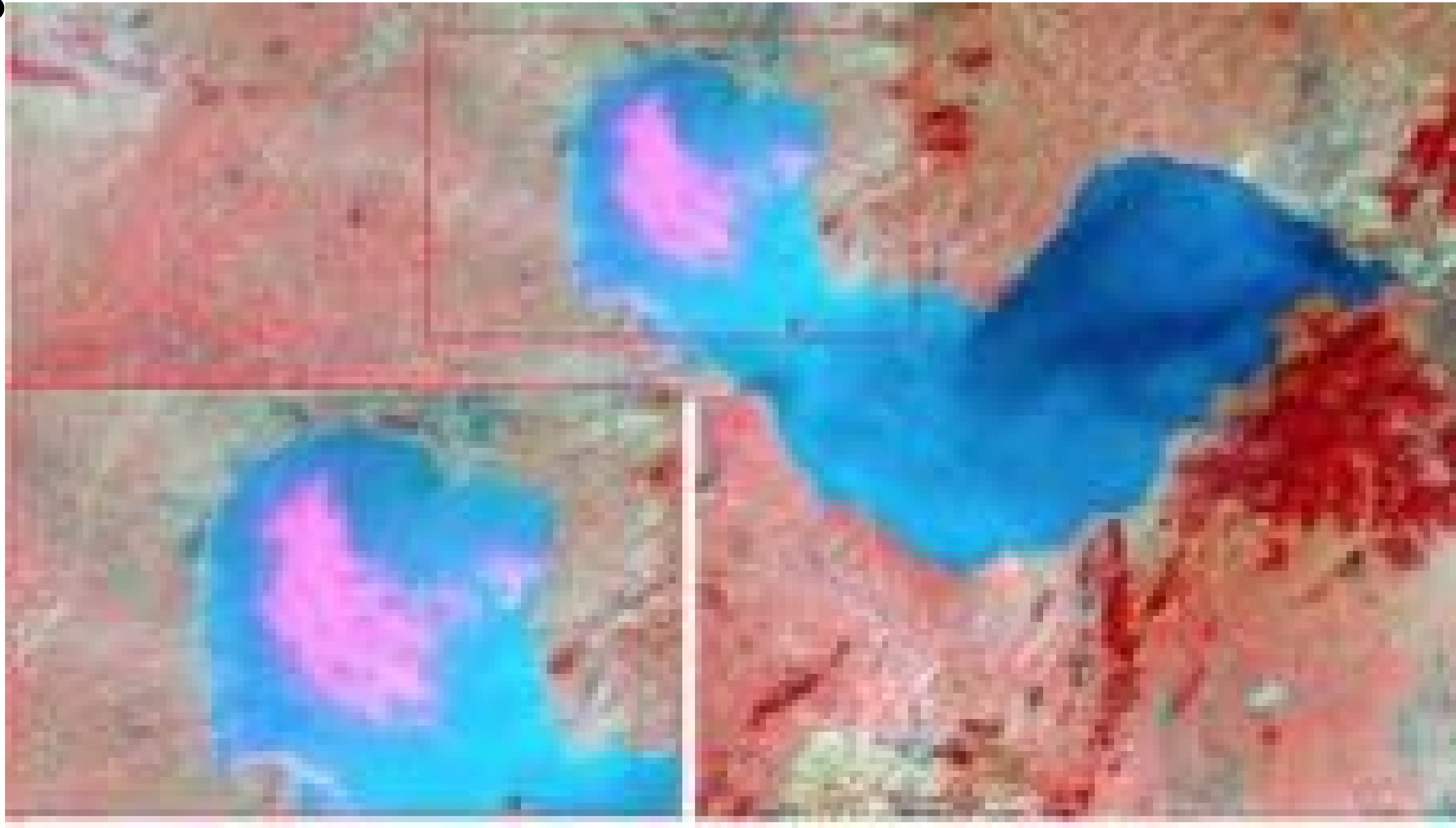
Trophic status in major world lakes (A. Tyler courtesy)

Local concerns

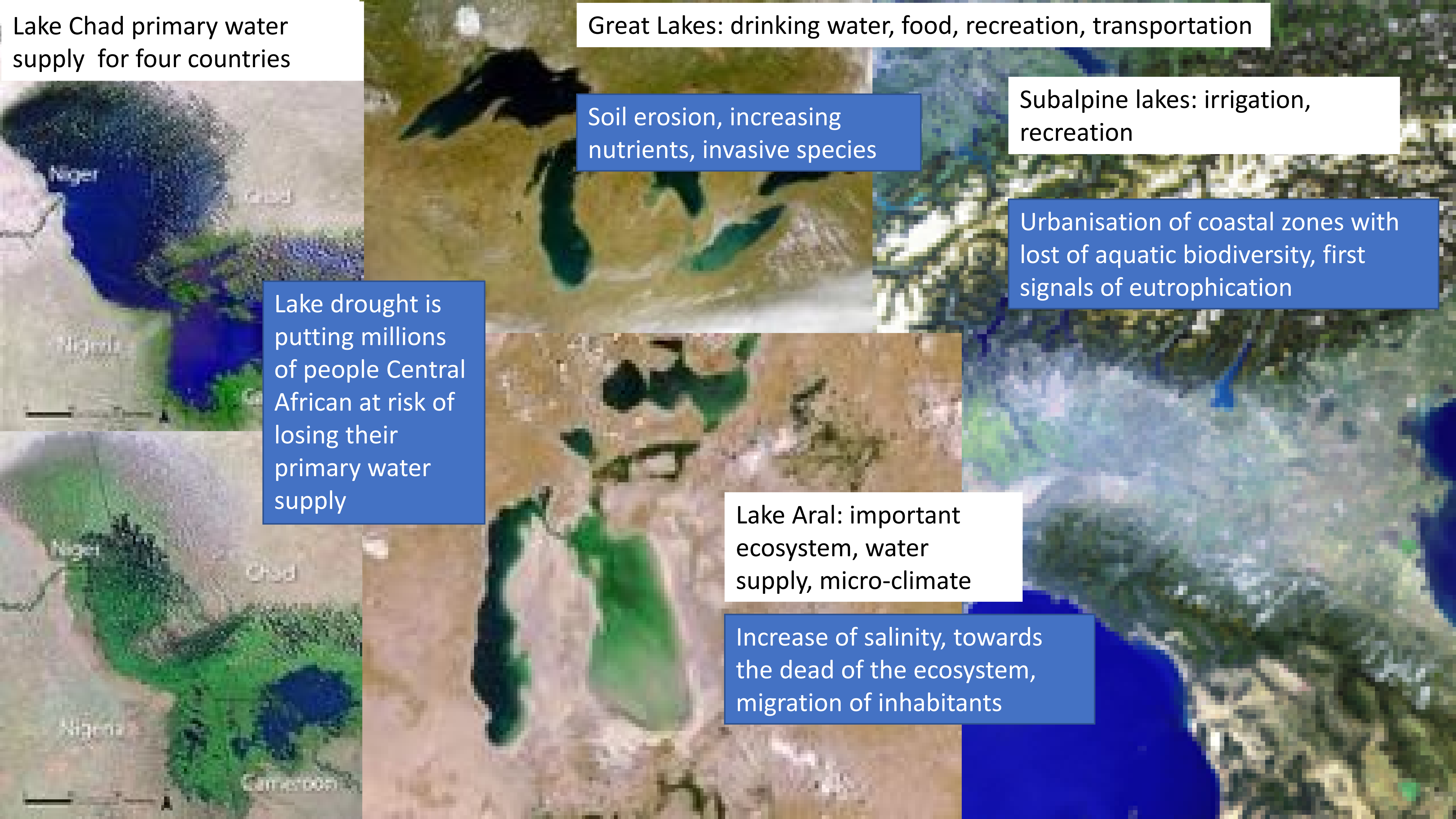








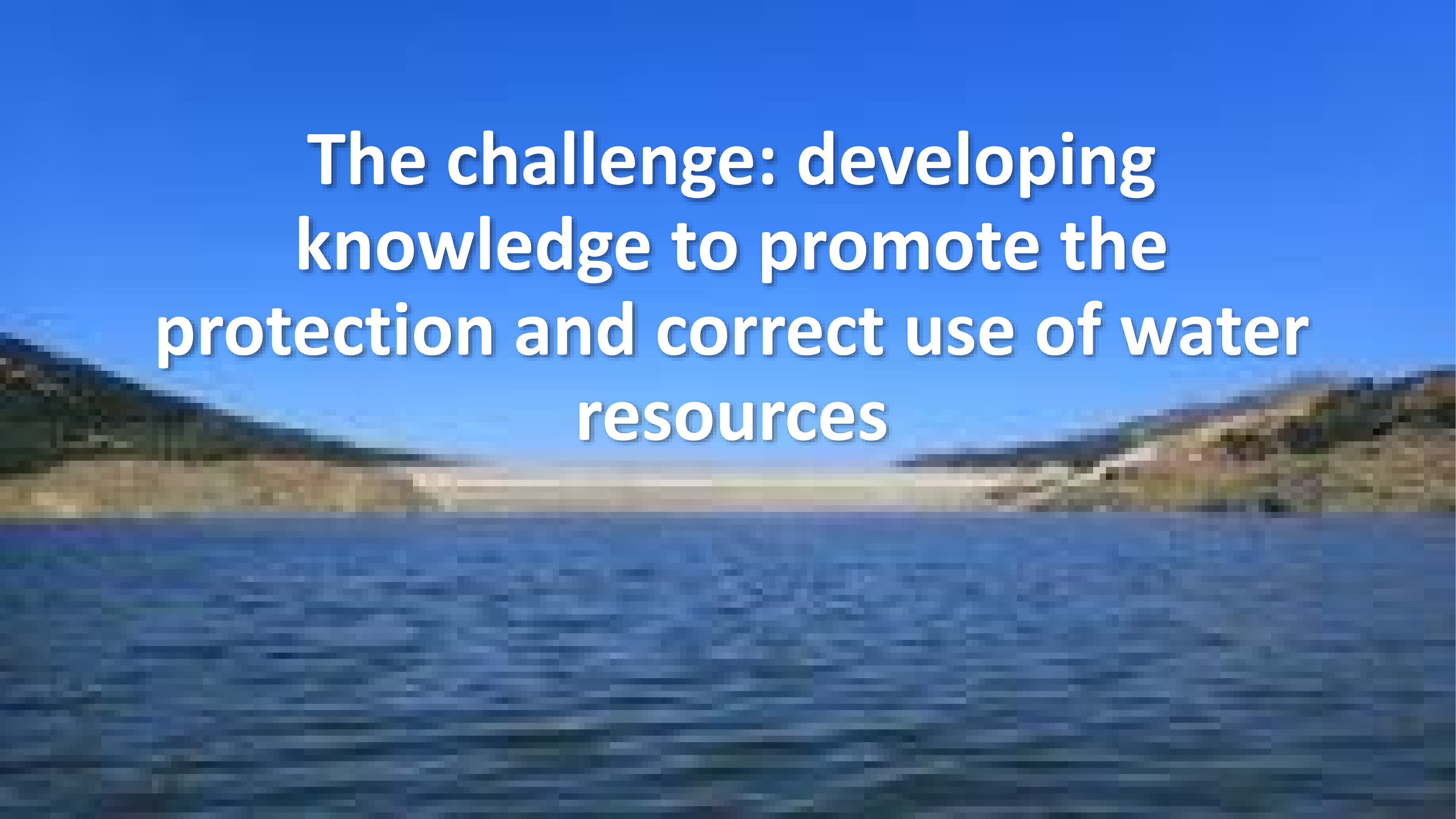
Chao Lake (China): increasing eutrophication (high chl-a and of cyanobacteria) in the northern bay, near HoFei an area signed by a marked urban expansion (Mezzanotte et al., 2011)


Lake Chad primary water supply for four countries
Lake drought is putting millions of people Central African at risk of losing their primary water supply
Niger
Chad
Nigeria
Cameroon
Great Lakes: drinking water, food, recreation, transportation
Soil erosion, increasing nutrients, invasive species
Subalpine lakes: irrigation, recreation
Urbanisation of coastal zones with lost of aquatic biodiversity, first signals of eutrophication
Lake Aral: important ecosystem, water supply, micro-climate
Increase of salinity, towards the dead of the ecosystem, migration of inhabitants

Allarme acqua, da Nord a Sud la situazione siccità regione per regione

di Redazione Cronache

L'emergenza idrica che ha colpito il Nord sta interessando sempre di più anche il Centro e il Sud. Ecco cosa succede nei laghi, nei fiumi e negli altri bacini idrici del nostro Paese



The challenge: developing knowledge to promote the protection and correct use of water resources

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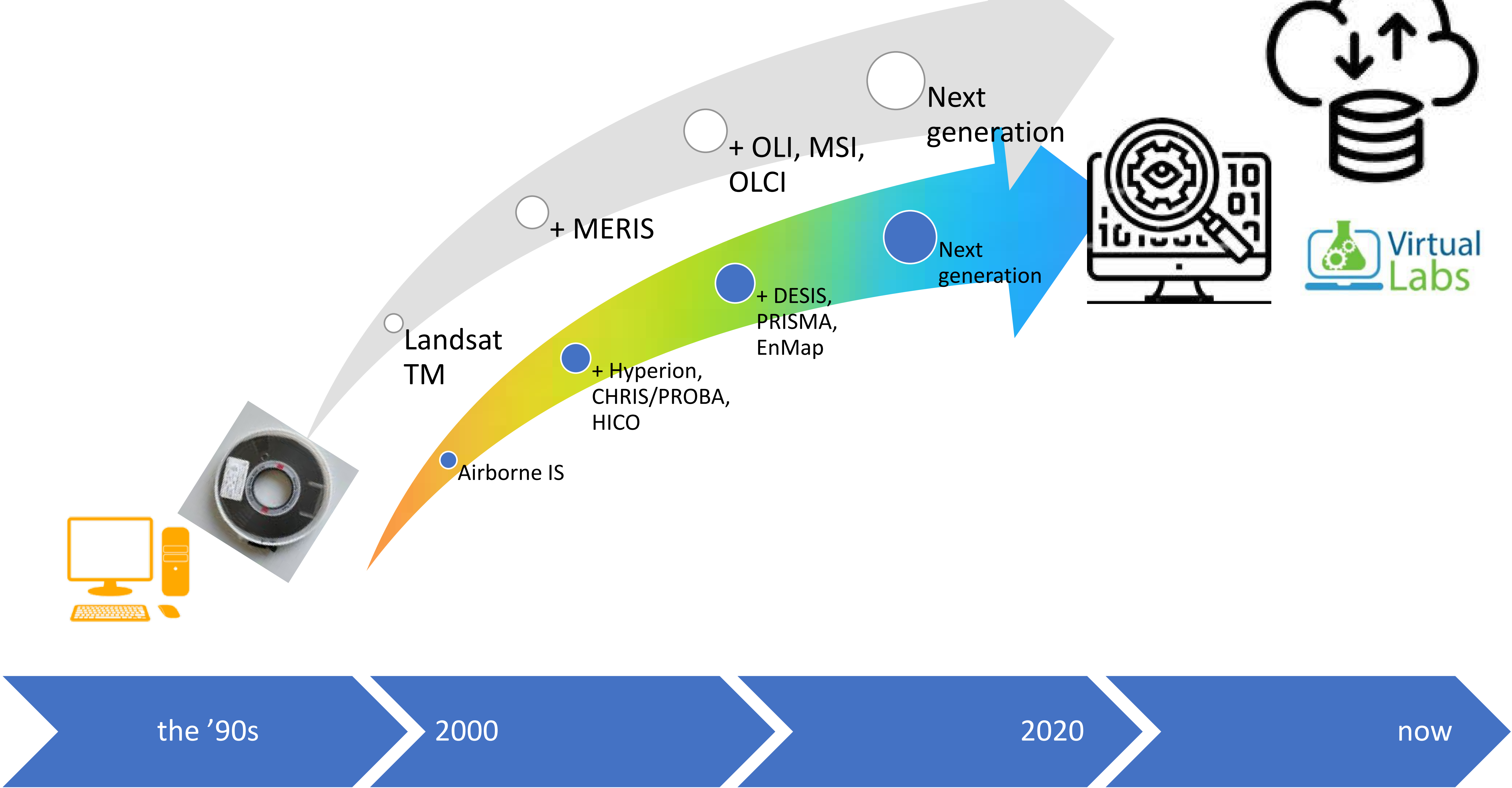
Earth observation technologies represent a useful investigative tool

Global problems force researchers, managers and policy makers to perform environmental assessments at temporal and spatial scales that can be difficult to achieve with traditional methods and there exists a gap in scale and time that can be filled by using remote sensing

Since ∽50 years remote sensing is providing a valuable tool for monitoring and studying aquatic ecosystems

A bit of history



A bit of history

Landsat-TM

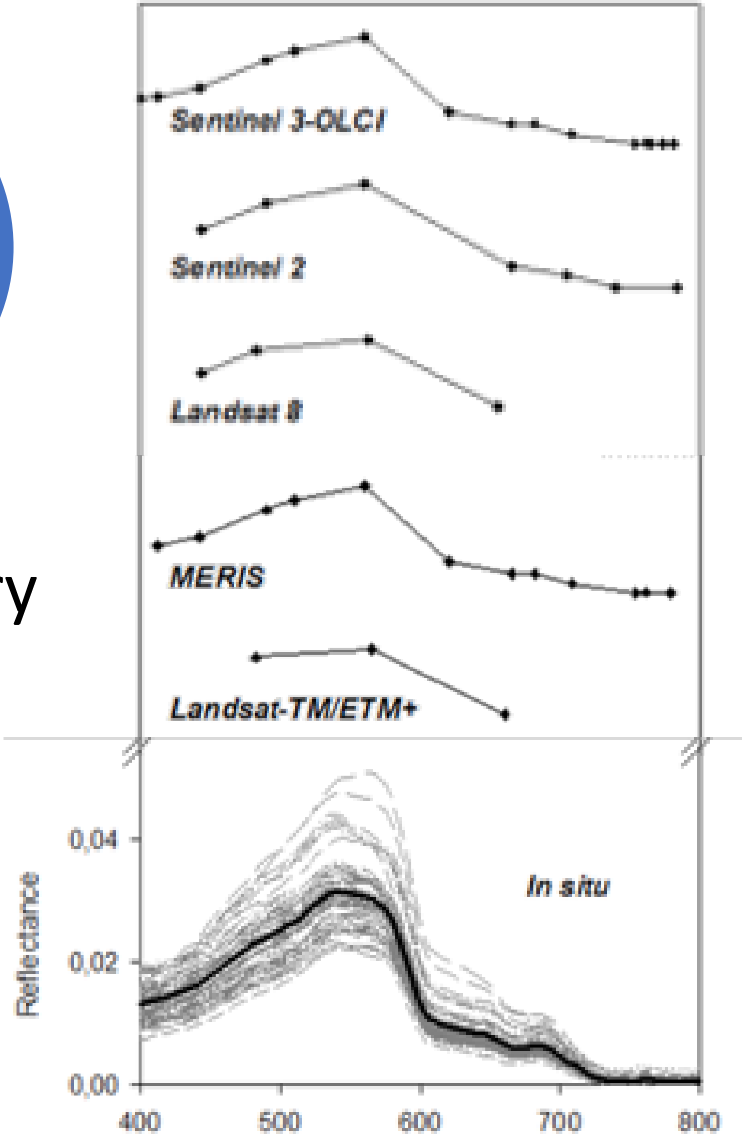
- Blue band
- 30 m

MERIS

- Improved radiometry
- Suitable bands in the red-edge for productive turbid waters
- Increased frequency
- Free/open data policy

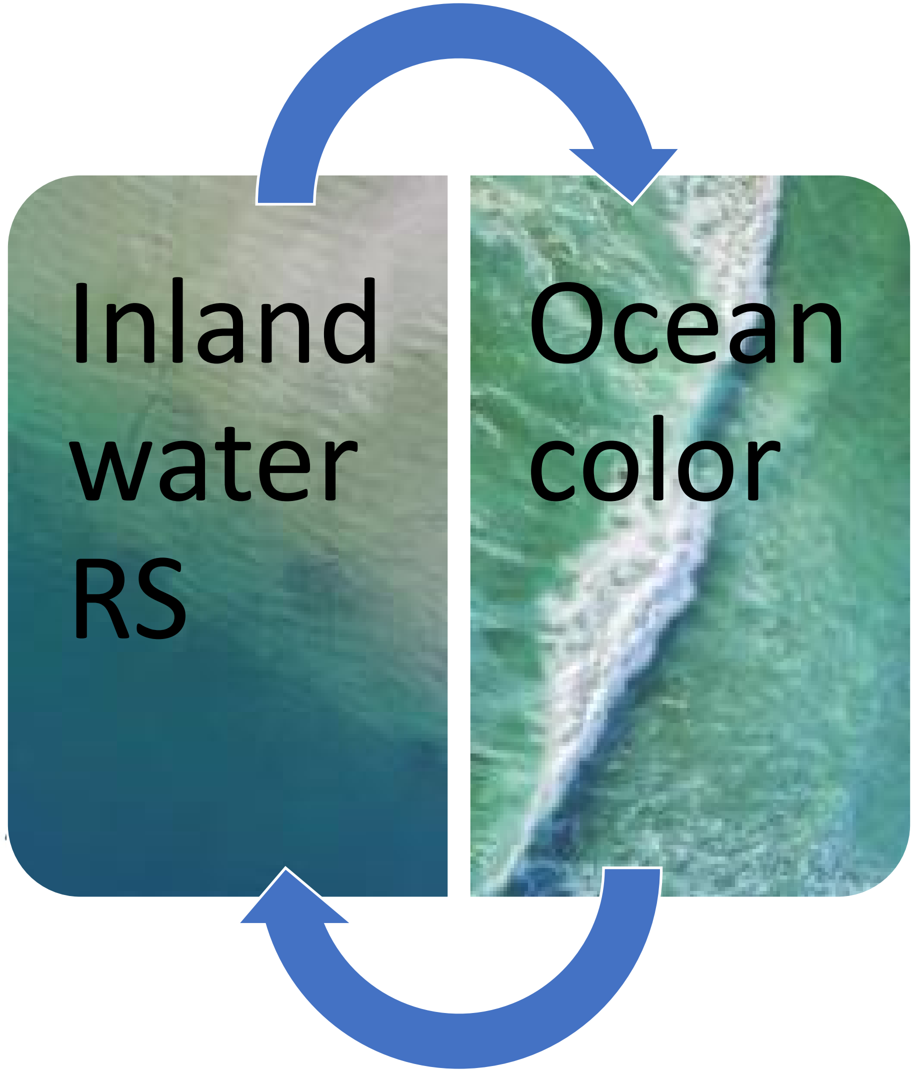
Landsat-OLI, Sentinel-2 & 3

Improved radiometry for finer scale mapping



the ’90s → 2000 → 2020 → now

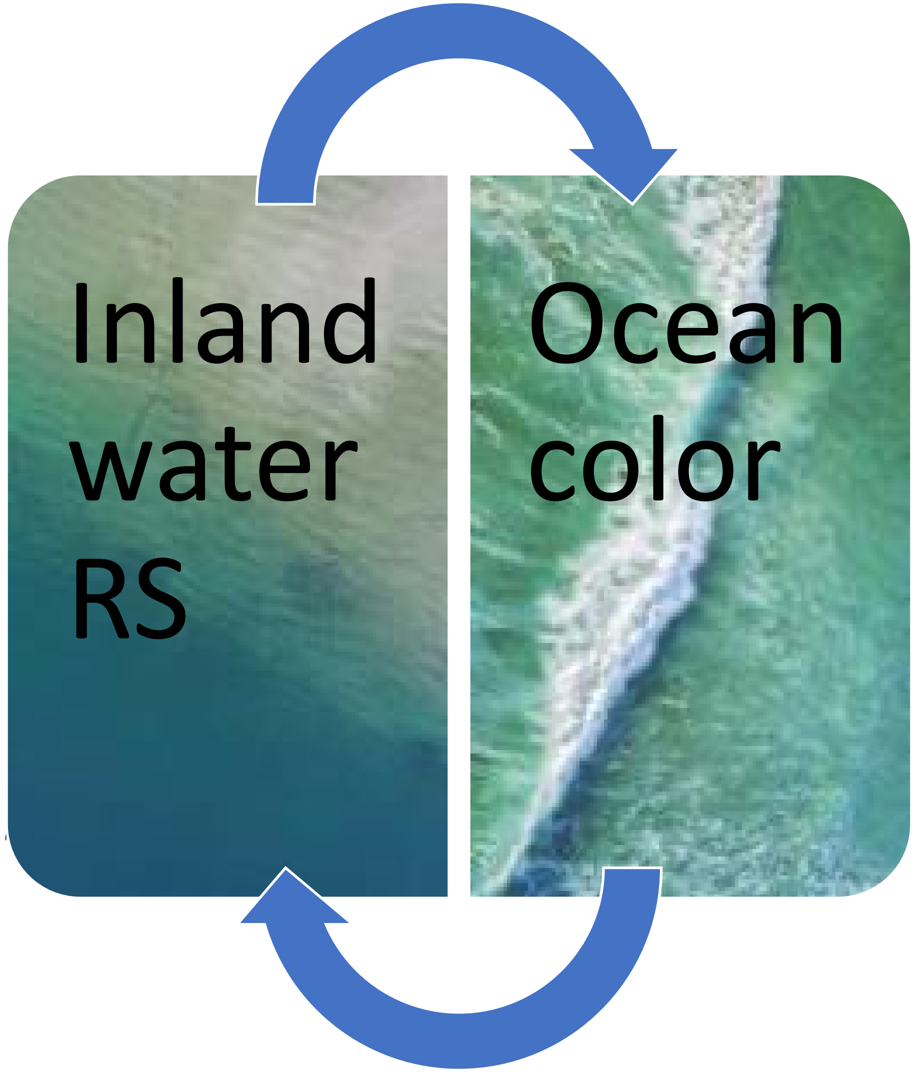
A bit of history



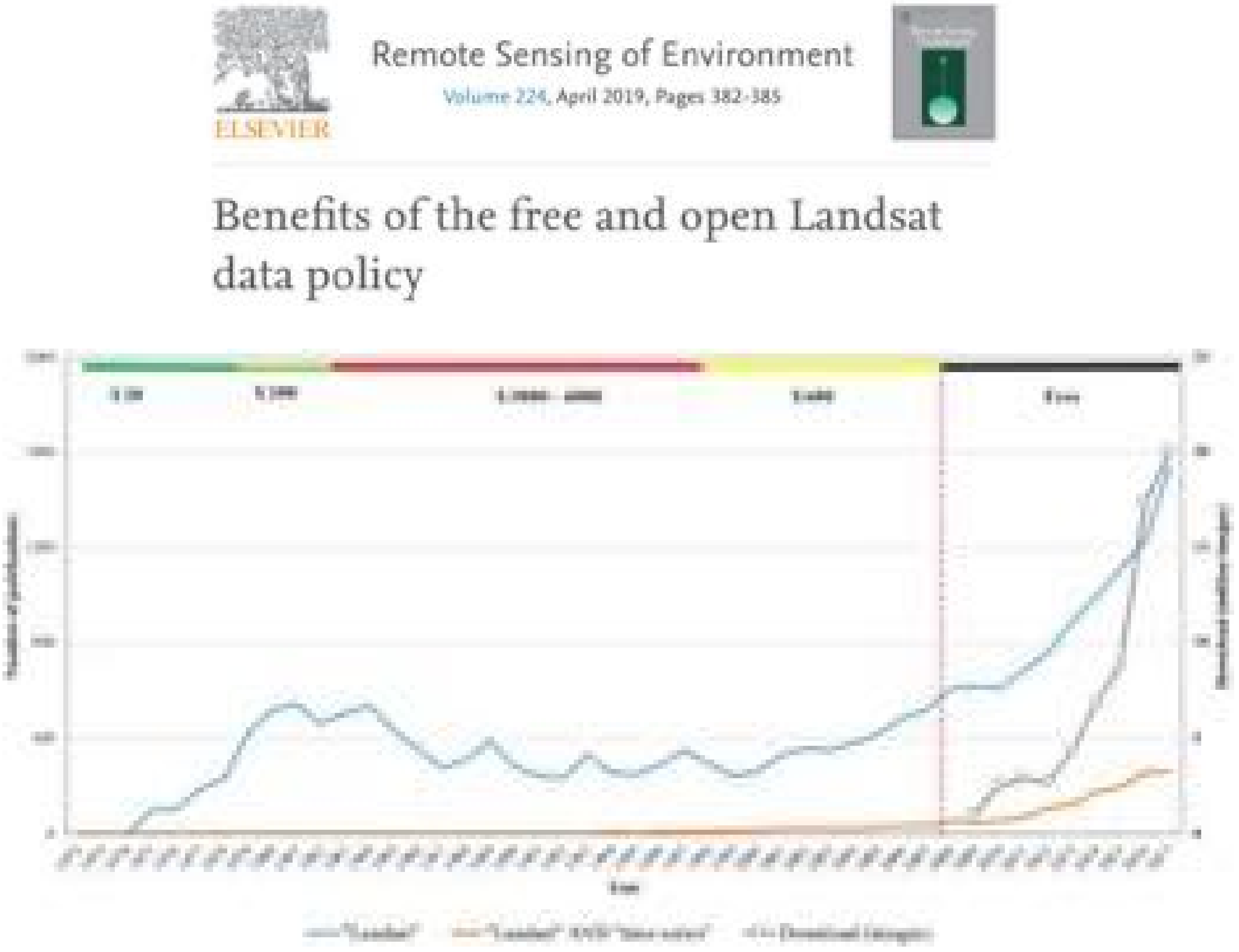
MERIS Workshop

the ’90s → 2000 → 2020 → now

A bit of history



MERIS Workshop



Landsat cost, number of downloads of images from the U.S. Landsat archive (gray line), and the number of annual publications from 1972 to 2017 (Zhu et al., 2020)

the ’90s → 2000 → 2020 → now

A bit of history

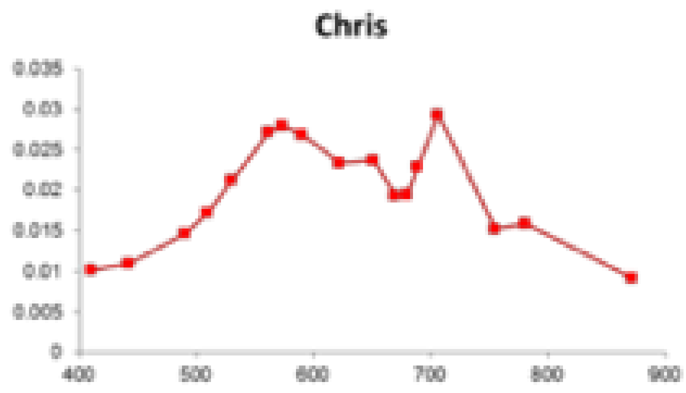
Ariborne IS

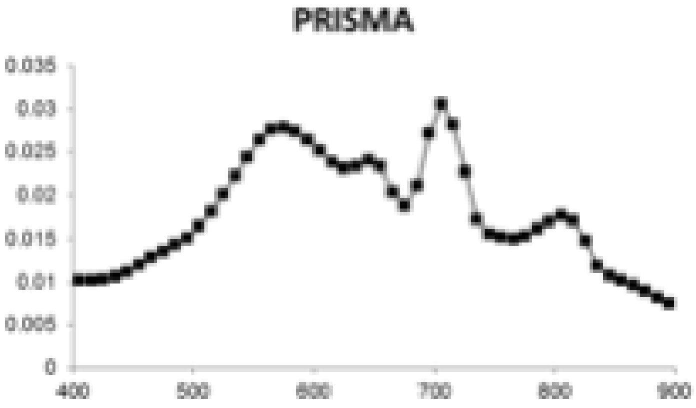
Hyperion, CHRIS-PROBA

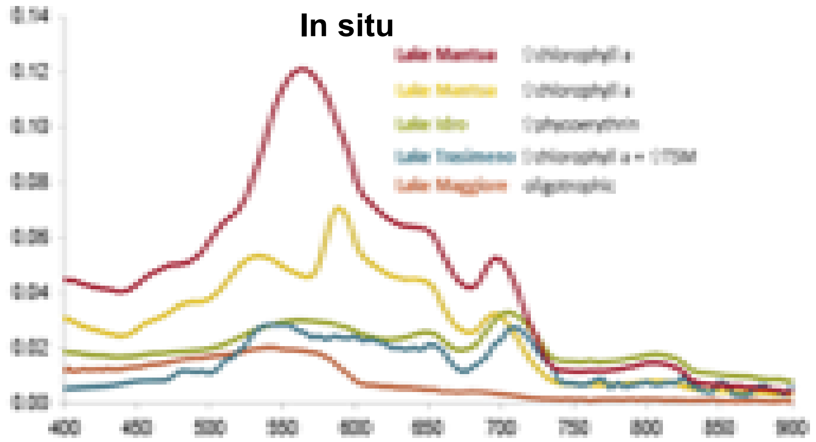
HICO, DESIS, PRISMA, EnMap

- High spectral information and spatial details (e.g., AISA, AVIRIS, APEX, CASI, HYMAP, MIVIS)

Spaceborne Imaging spectrocopy







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2000

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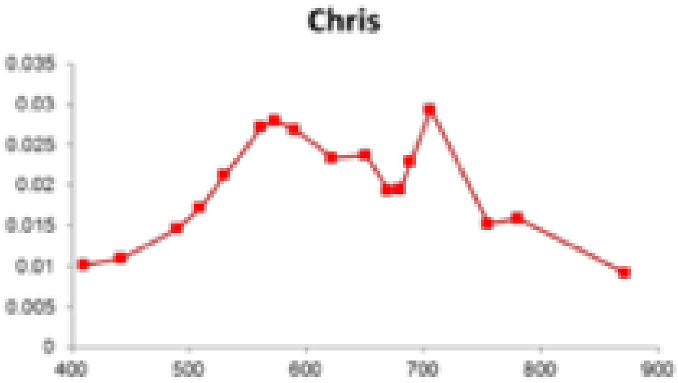
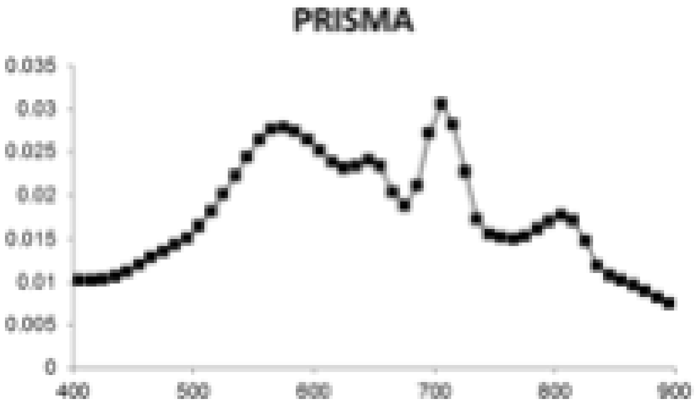
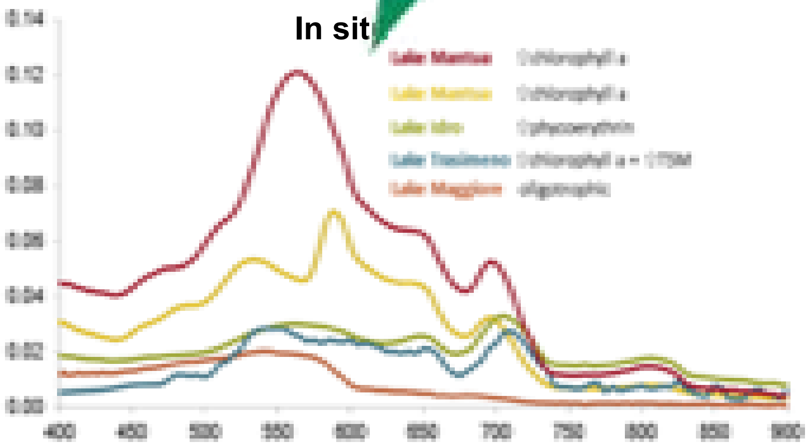






the '90s

2000

2020

now

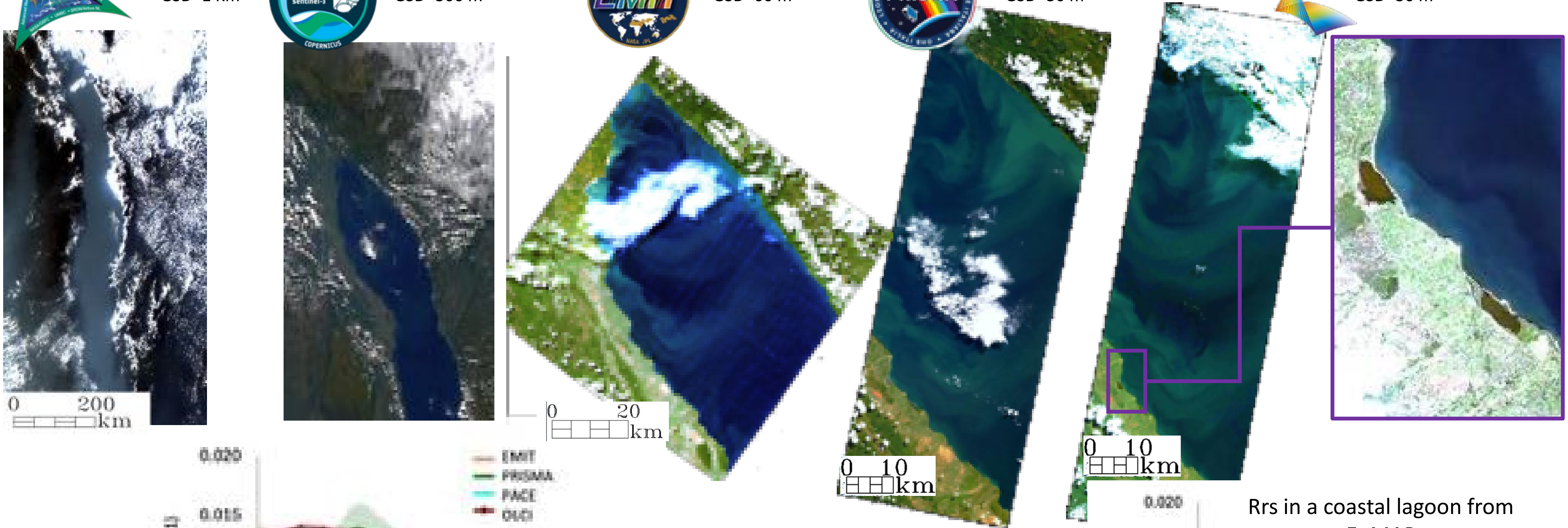
10:26 UTC
GSD=1 Km

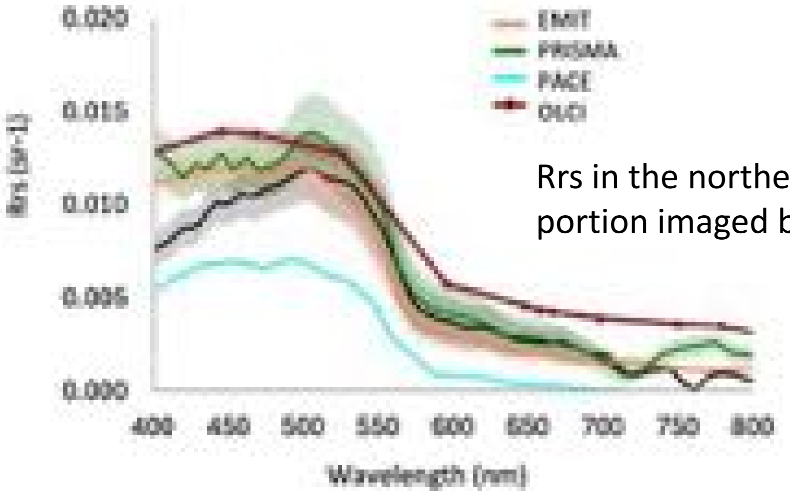
07:06 UTC
GSD=300 m

10:32 UTC
GSD=60 m

08:08 UTC
GSD=30 m

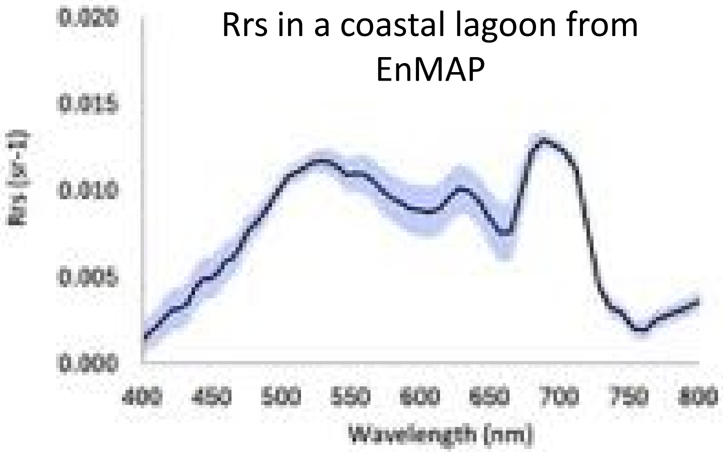
08:41 UTC
GSD=30 m





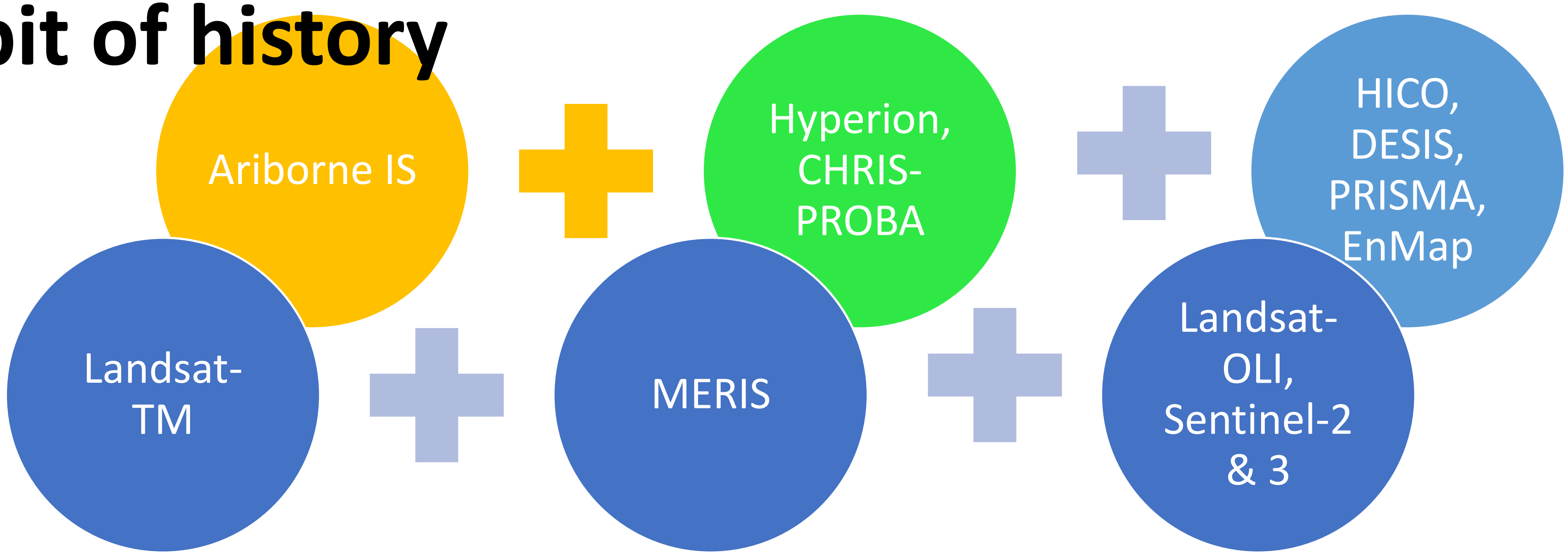
Rrs in the northern bay portion imaged by all sensors

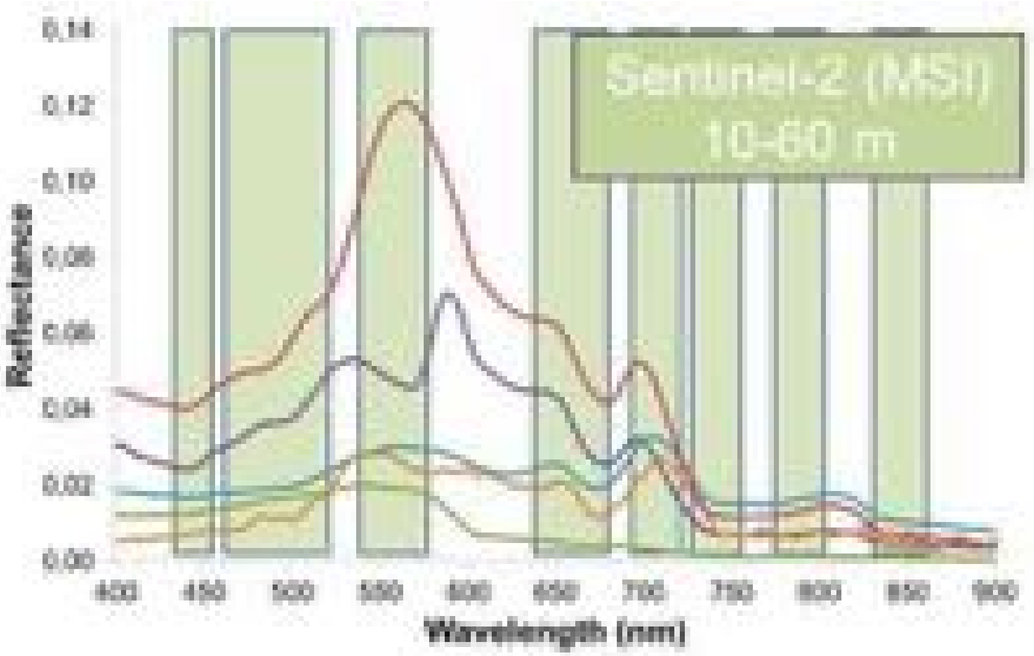
Rrs in a coastal lagoon from EnMAP

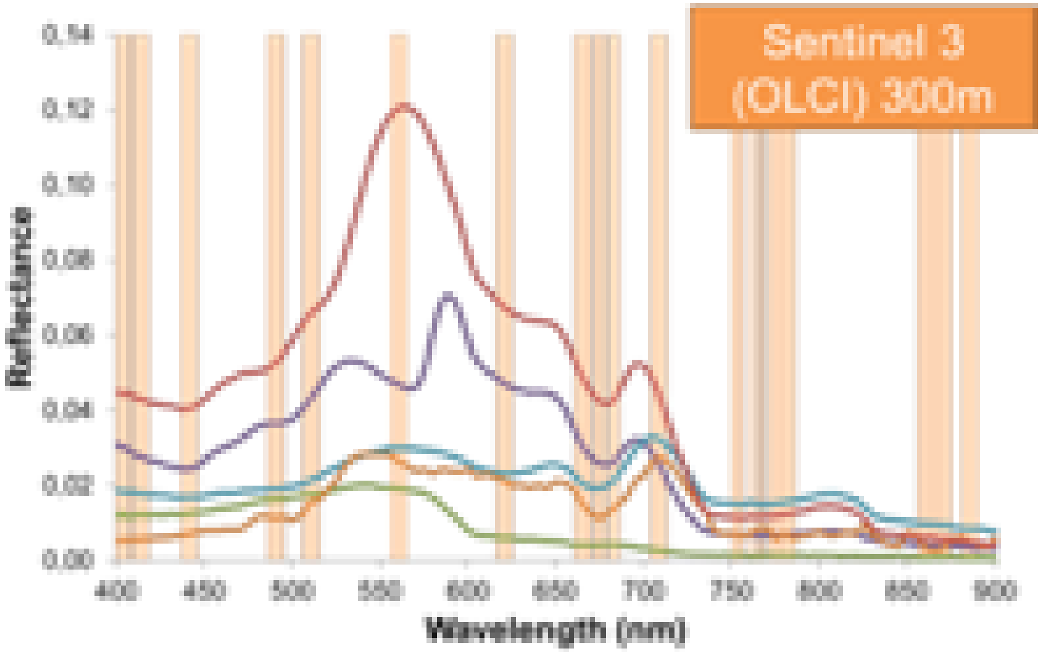


Bracher et al., (2026) – IOCCG

A bit of history





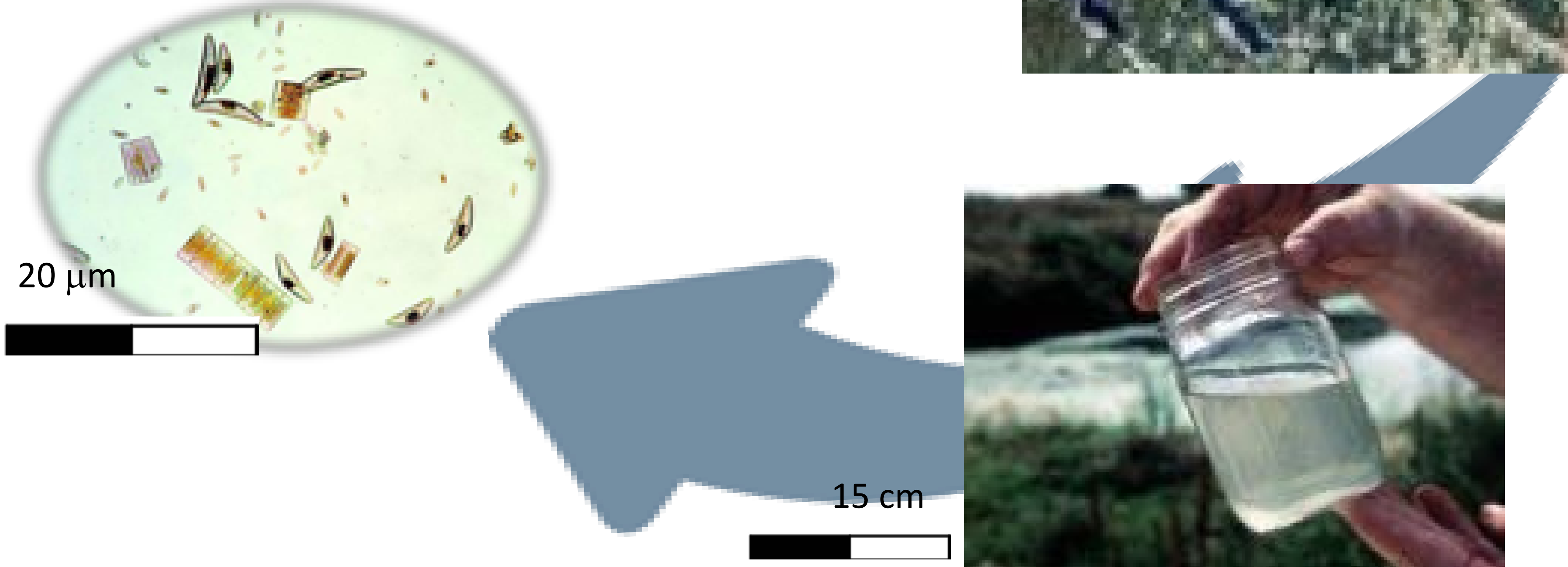


A bit of the approach

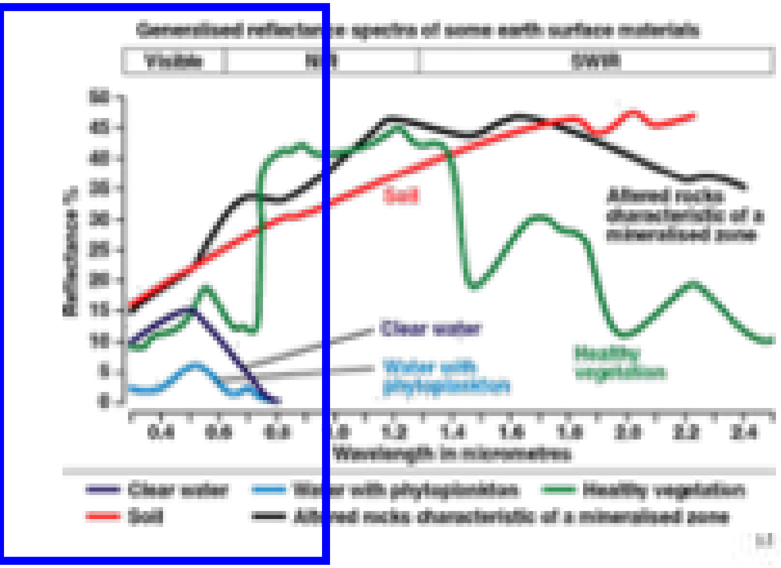
A bit of the approach

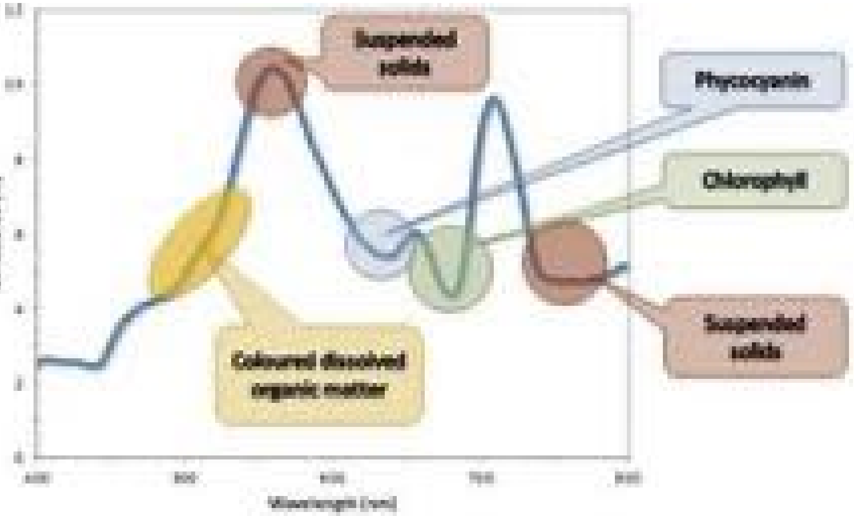

Clear, open water
Algae bloom
Shallow, turbid area
Mouth of a river

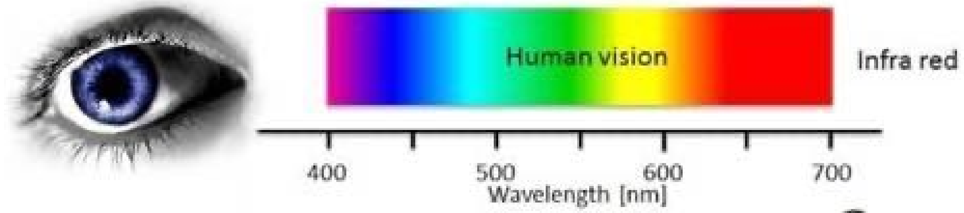
A bit of the approach



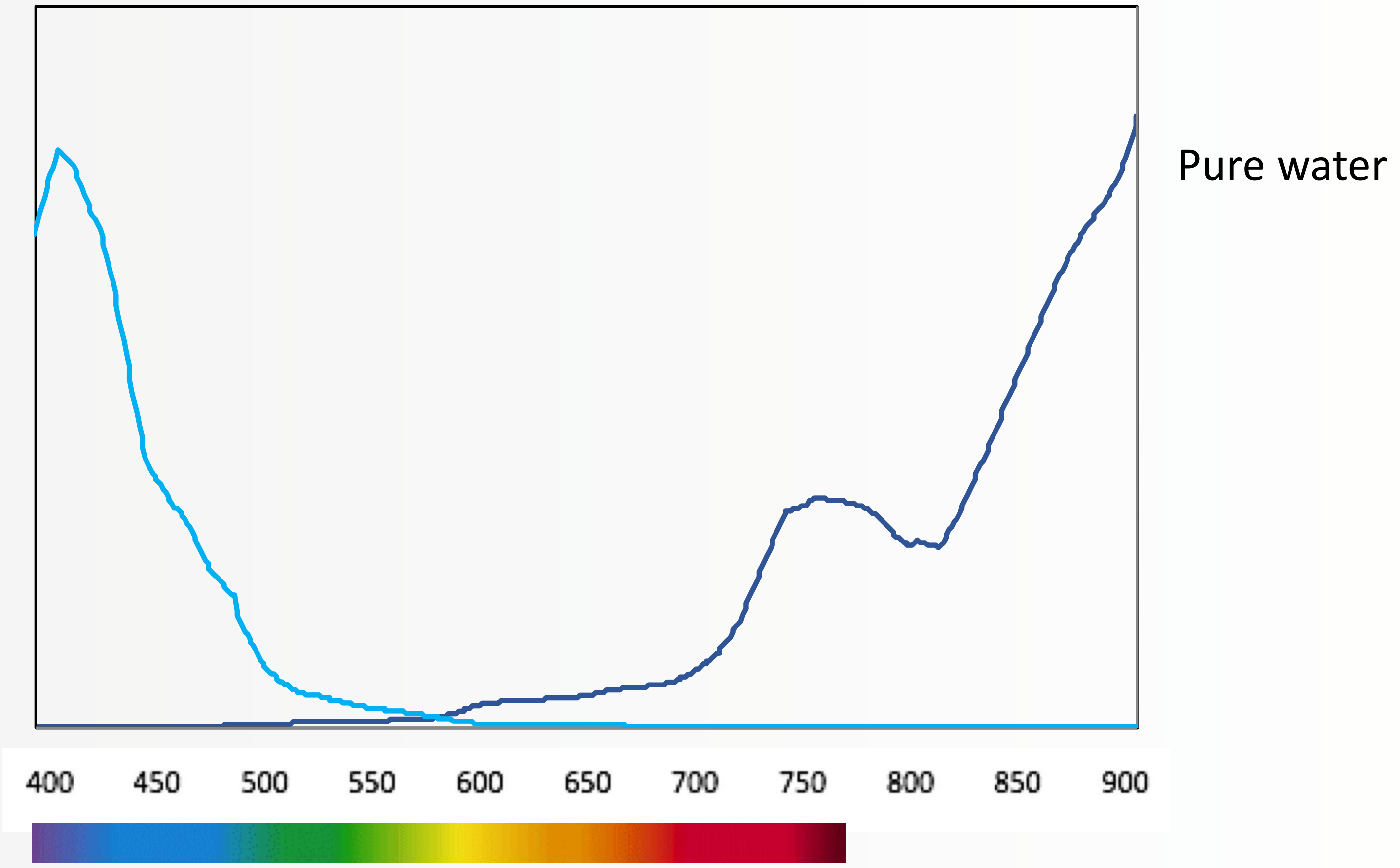
A bit of the approach: water colour



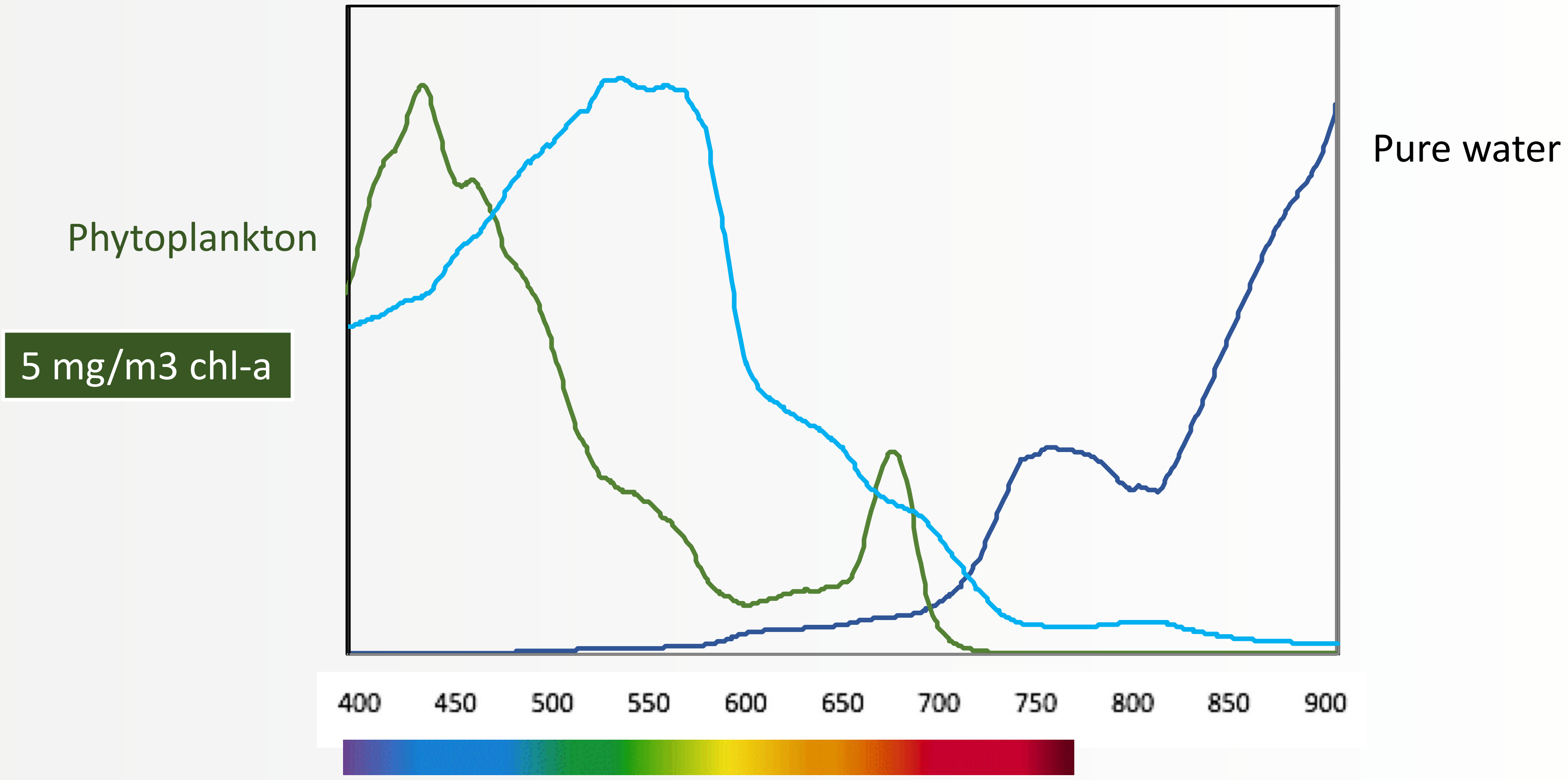




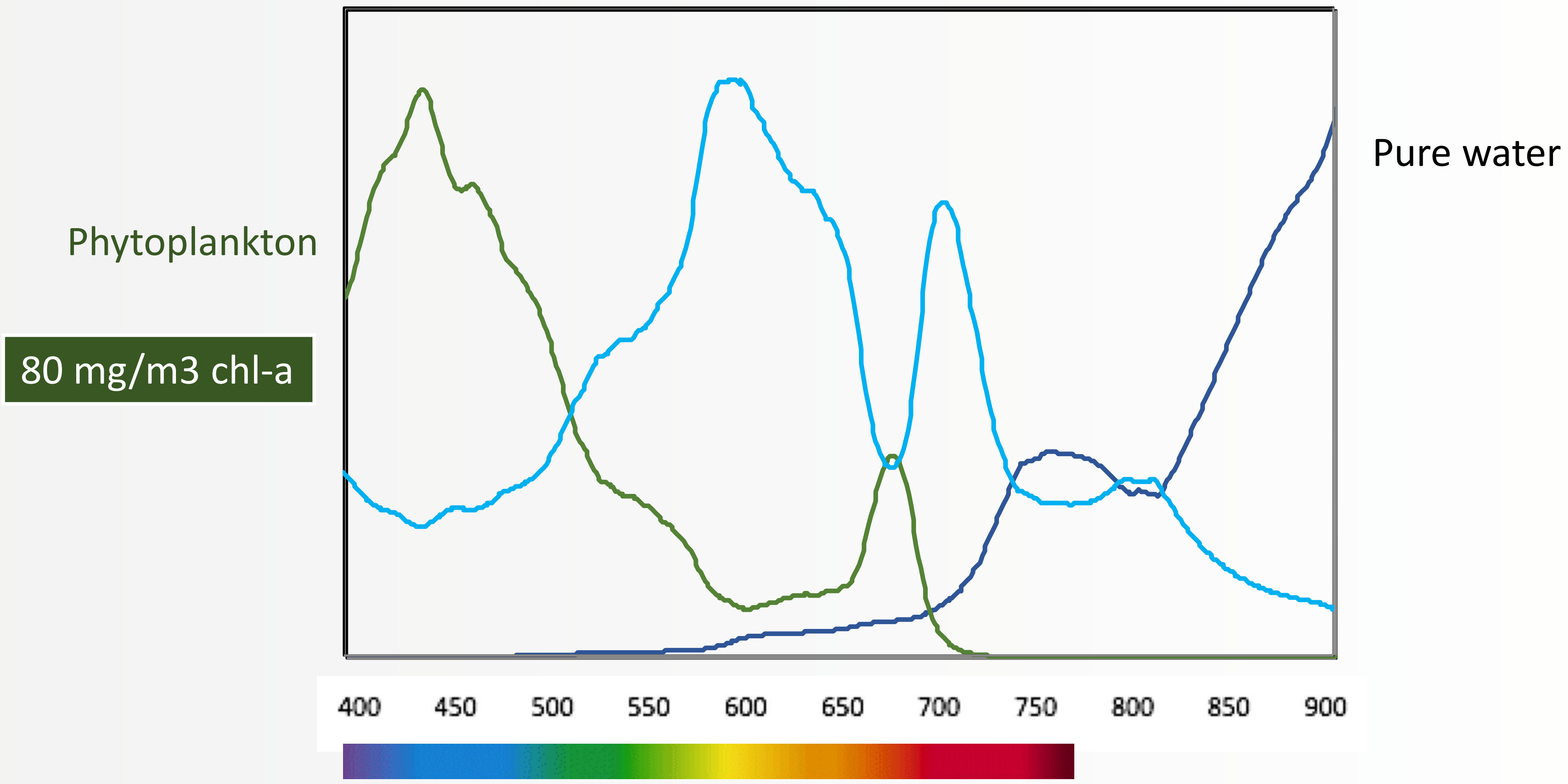
Water reflectance



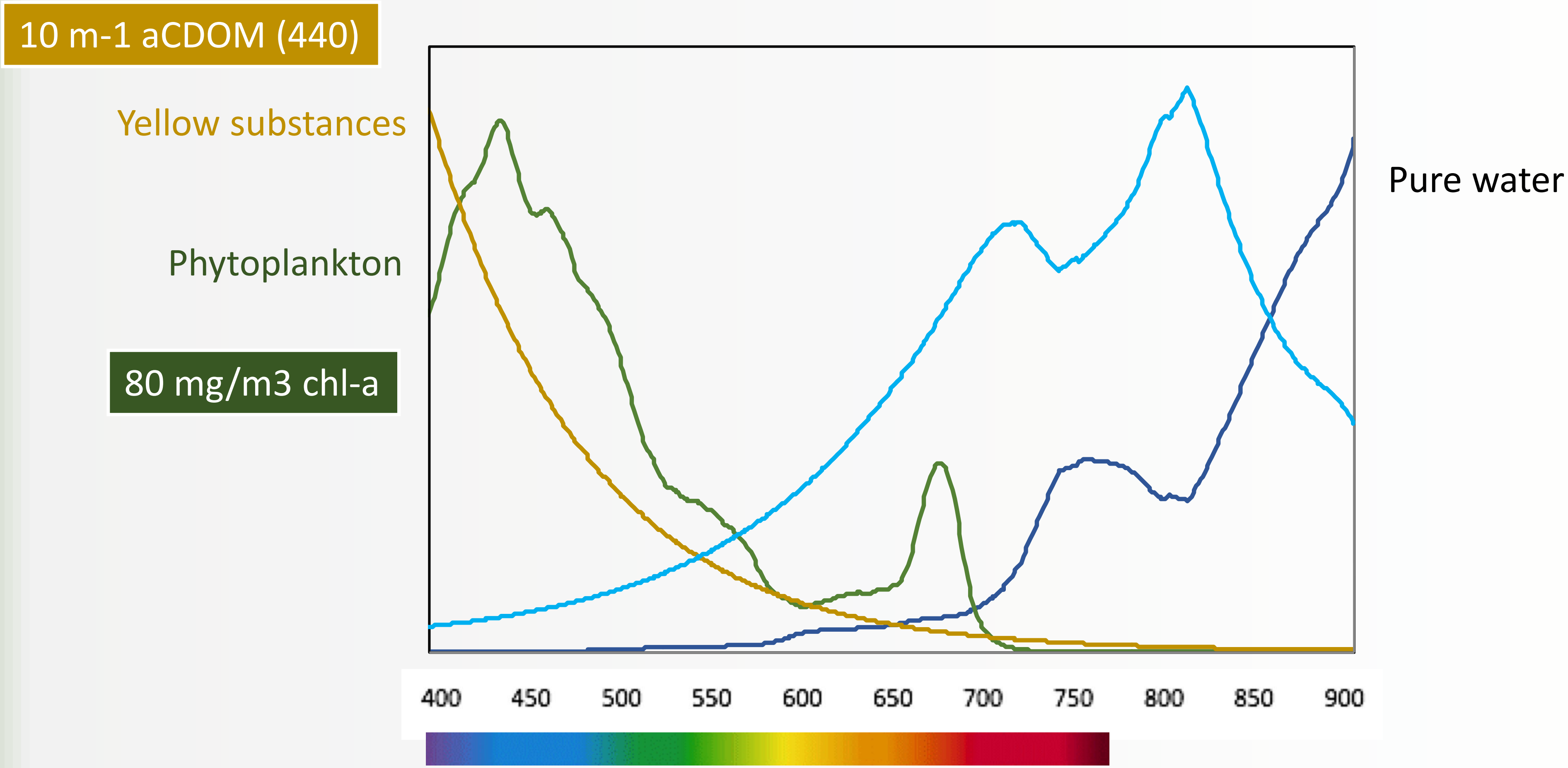
Water reflectance



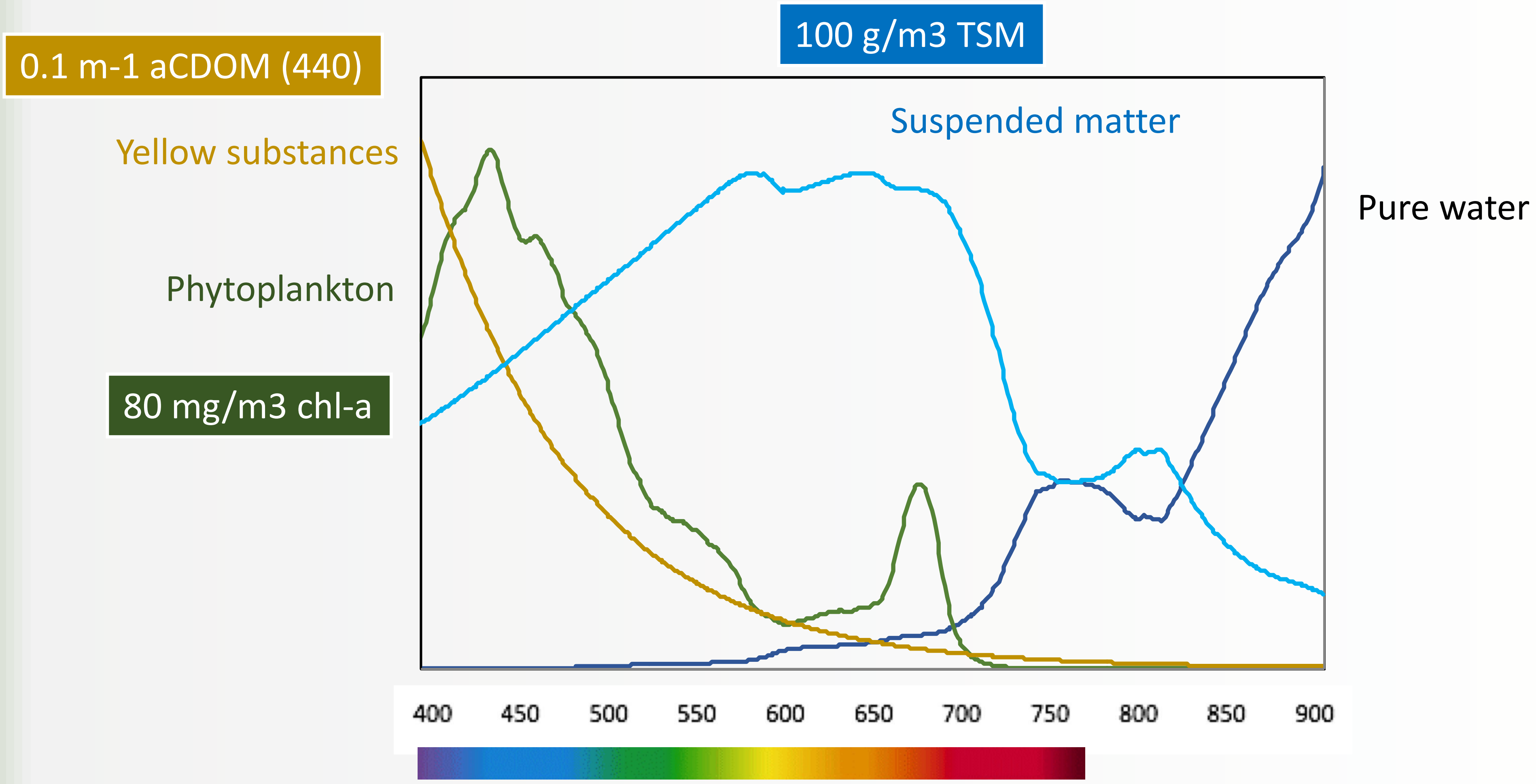
Water reflectance



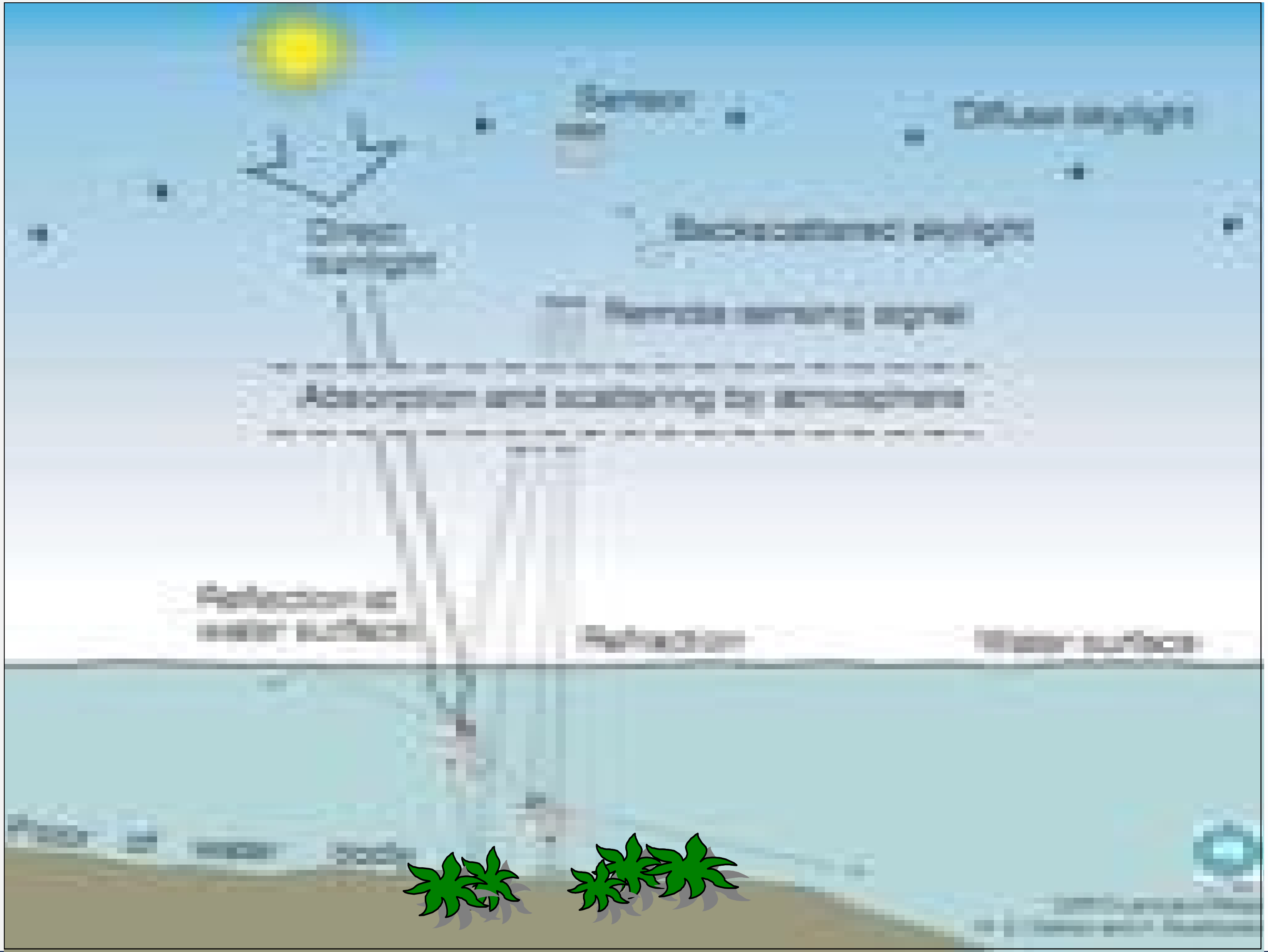
Water reflectance



Water reflectance



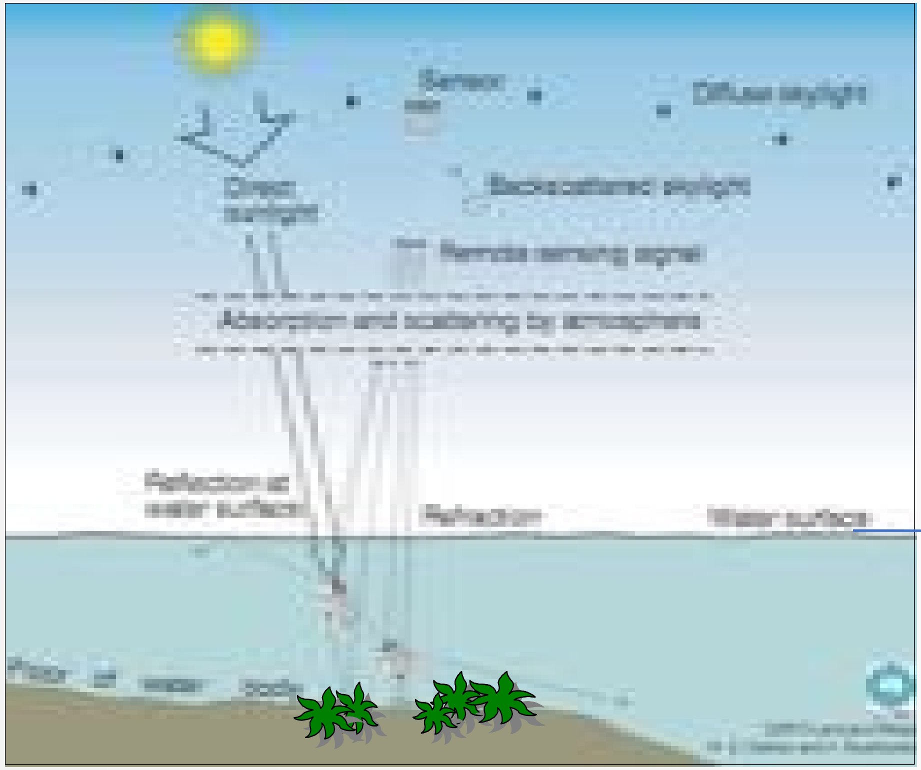
Radiative transfer

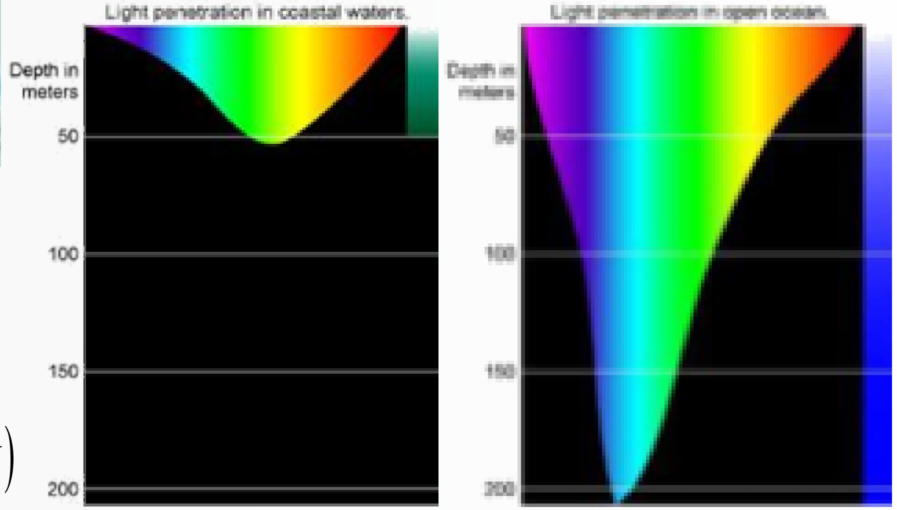


Radiative transfer

Radiative transfer in the atmosphere

$$\rho_{w}(\lambda) = \frac{\pi\left[L_t(\lambda) - L_{a\uparrow}(\lambda)\right]}{T_{v\uparrow}(\lambda)\left[E_0(\lambda)\cos\theta_s\, T_{s\downarrow}(\lambda) + E_{d\downarrow}(\lambda)\right]}$$





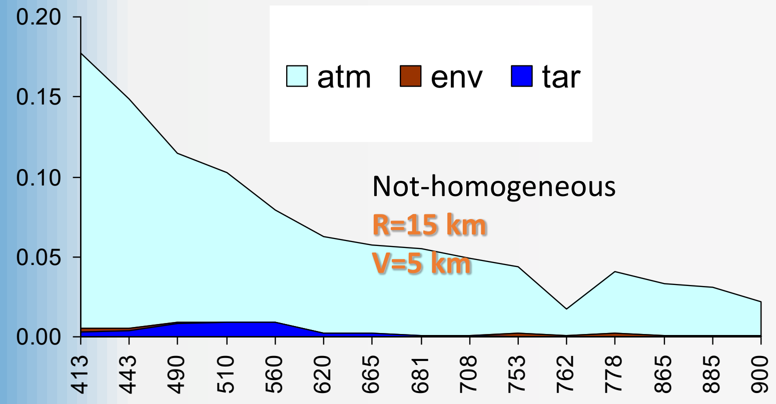
Radiative transfer in the water column

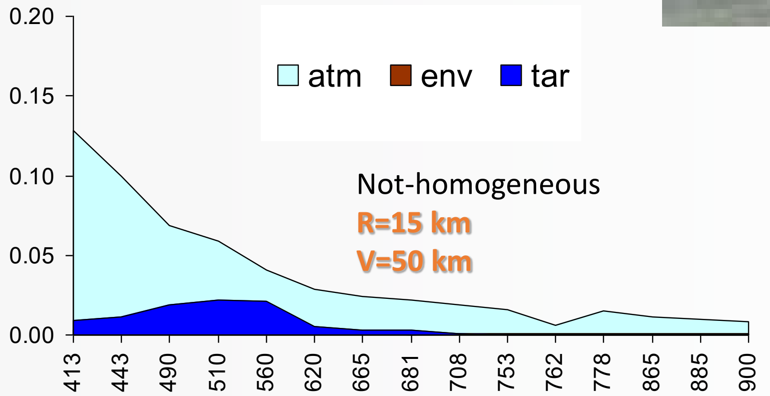
$$r_{rs}(\lambda)_{modelled} = f\left(C_{CHL}, C_{CDOM}, C_{TR}, X_{PHY}, X_{TR}, q_{ij}, A_i, A_j, H, S_C, S_{TR}, a^*_{TR}(\lambda_{TR}), Y\right)$$

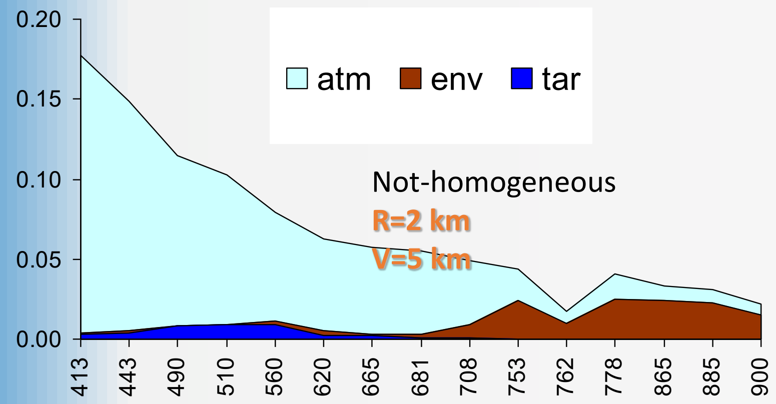
Radiative transfer

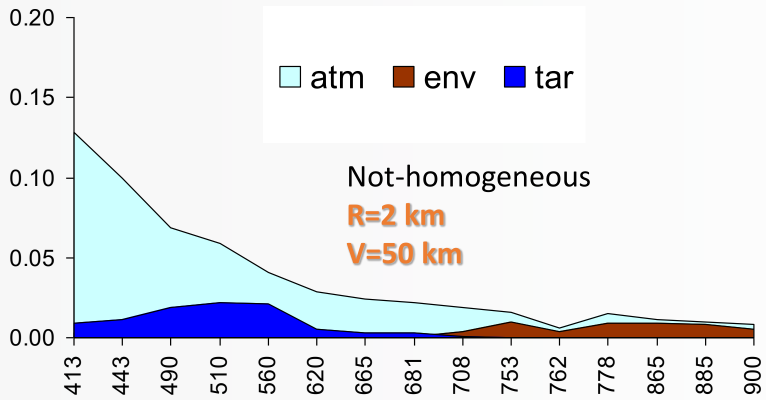
$$\rho^*(\theta_s,\theta_v,\phi_s-\phi_v)=\rho_a(\theta_s,\theta_v,\phi_s-\phi_v)+\frac{T(\theta_s)}{1-\rho_e S}\left(\rho_c(M)e^{-\tau/\mu_v}+\rho_e(M)t_d(\theta_v)\right)$$

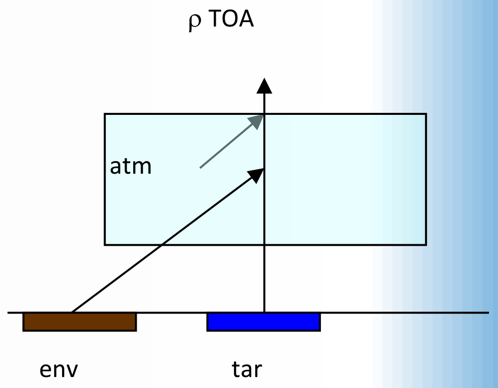
Contribution from the **target**, the **atmosphere** and the **environment** to the TOA reflectance signal











6SV algorithm

RT and image processing

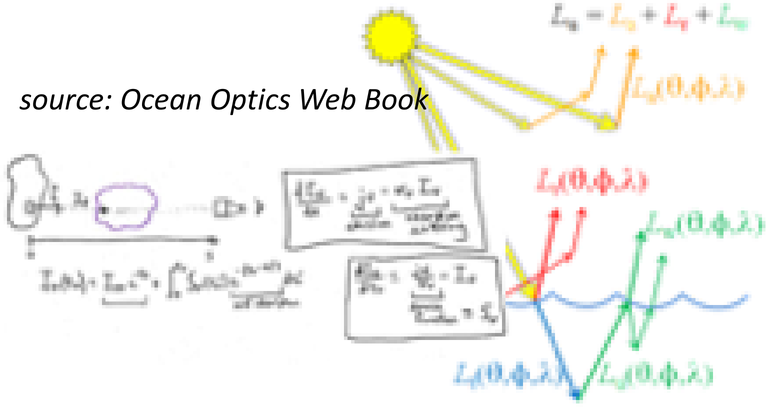
Digital Numbers → Radiometric calibration → TOA Radiance → Atmospheric correction → Remote Sensing Reflectance (Rrs) → Bio-optical models → WQPs (chl-a) maps

6Sv - POLYMER

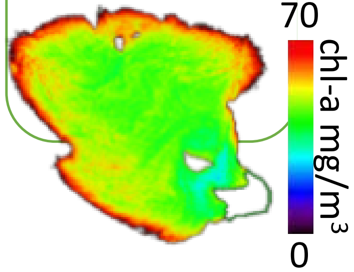
BOMBER

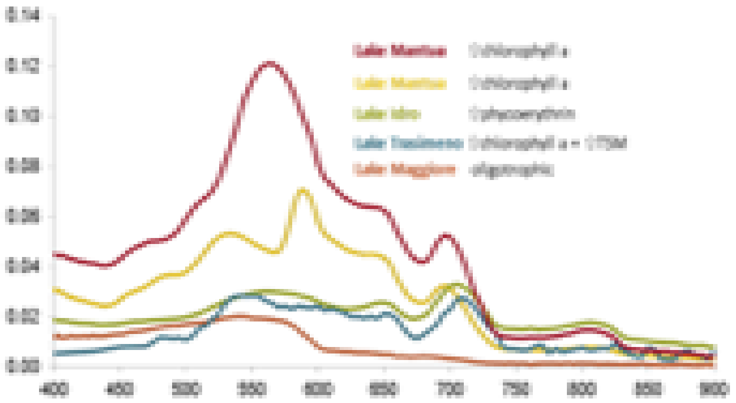
Neural Networks (Atm. Corr. + WQPs models)

C2R – C2RCC



source: Ocean Optics Web Book

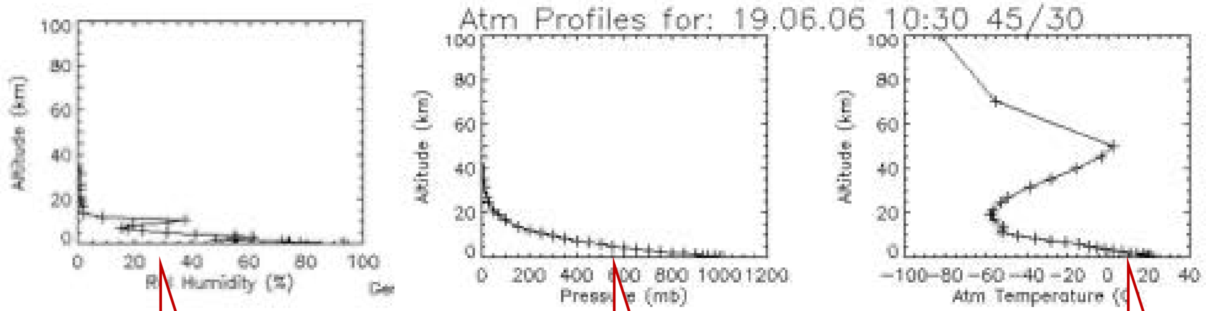




$$R(0-) = R(0-)^{dp}\left(1 - A_0 e^{\left(-\left(\frac{1}{\cos(\vartheta_w)} + \sqrt{D_0^C\left(1+D_1^C u\right)}\right)\kappa H\right)}\right) + A_1 \rho e^{\left(-\left(\frac{1}{\cos(\vartheta_w)} + \sqrt{D_0^B\left(1+D_1^B u\right)}\right)\kappa H\right)}$$

RT and image processing

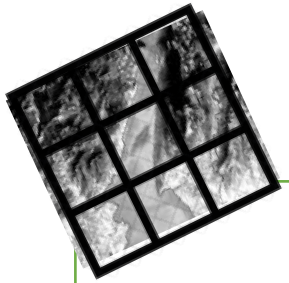
source: https://atmcorr.gsfc.nasa.gov/ (Barsi et al.. 2003; 2005)



t = 0.65
Lu = 2.88
Ld = 4.46

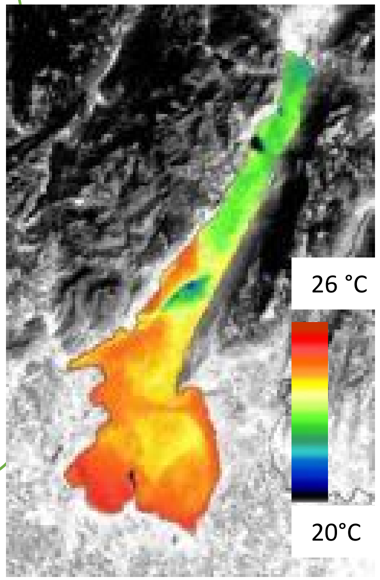
$$L_{\text{sen}} = \tau[\varepsilon L_\lambda(T_{\text{RTE}}) + (1-\varepsilon)L_d] + L_u$$

$$T_{\text{RTE}} = \frac{K_2}{\ln\left[\frac{K_1}{L_\lambda(T_{\text{RTE}})} + 1\right]}$$



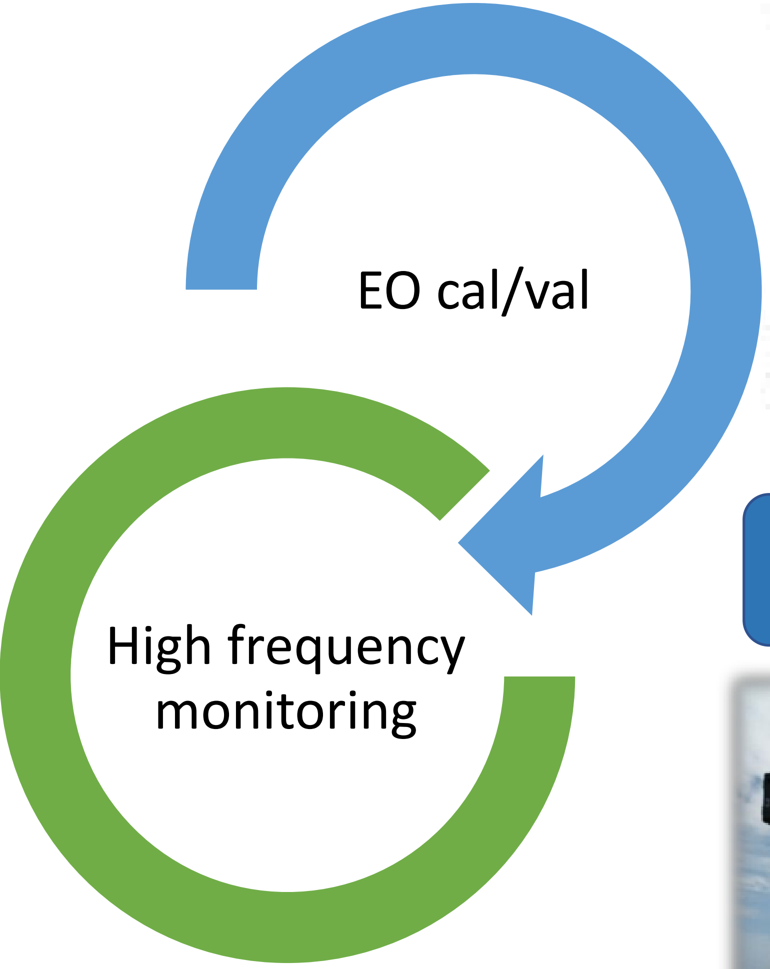
Digital Numbers → Radiometric calibration → TOA Radiance → Atmospheric correction → BOA Radiance → Planck law → Thermal proprieties (e.g LSWT)

RT modelling based on Barsi



Fieldworks and data

Fieldworks and data



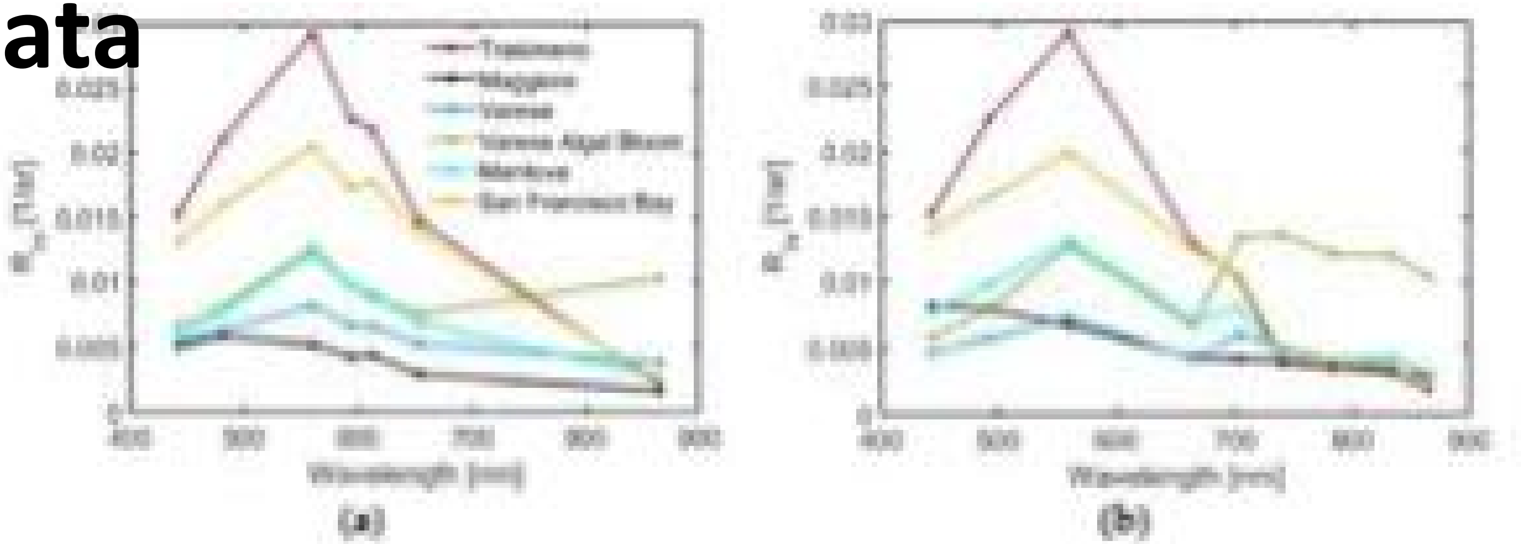


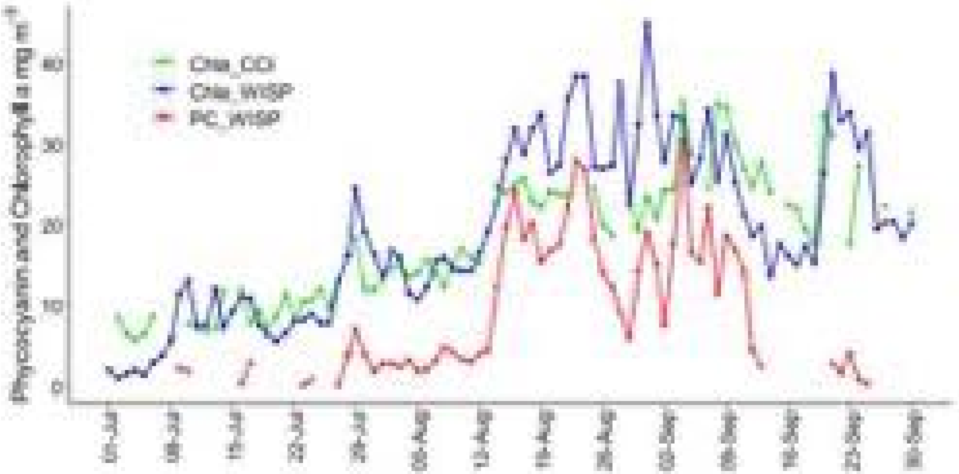
Figure 7. Remote sensing reflectance (R_{rs}) spectra derived from DSF atmospheric correction over different case studies using (a) Landsat-9 and (b) Sentinel-2 imagery.

Niroumand-Jadidi et al., 2021

WISP-Station

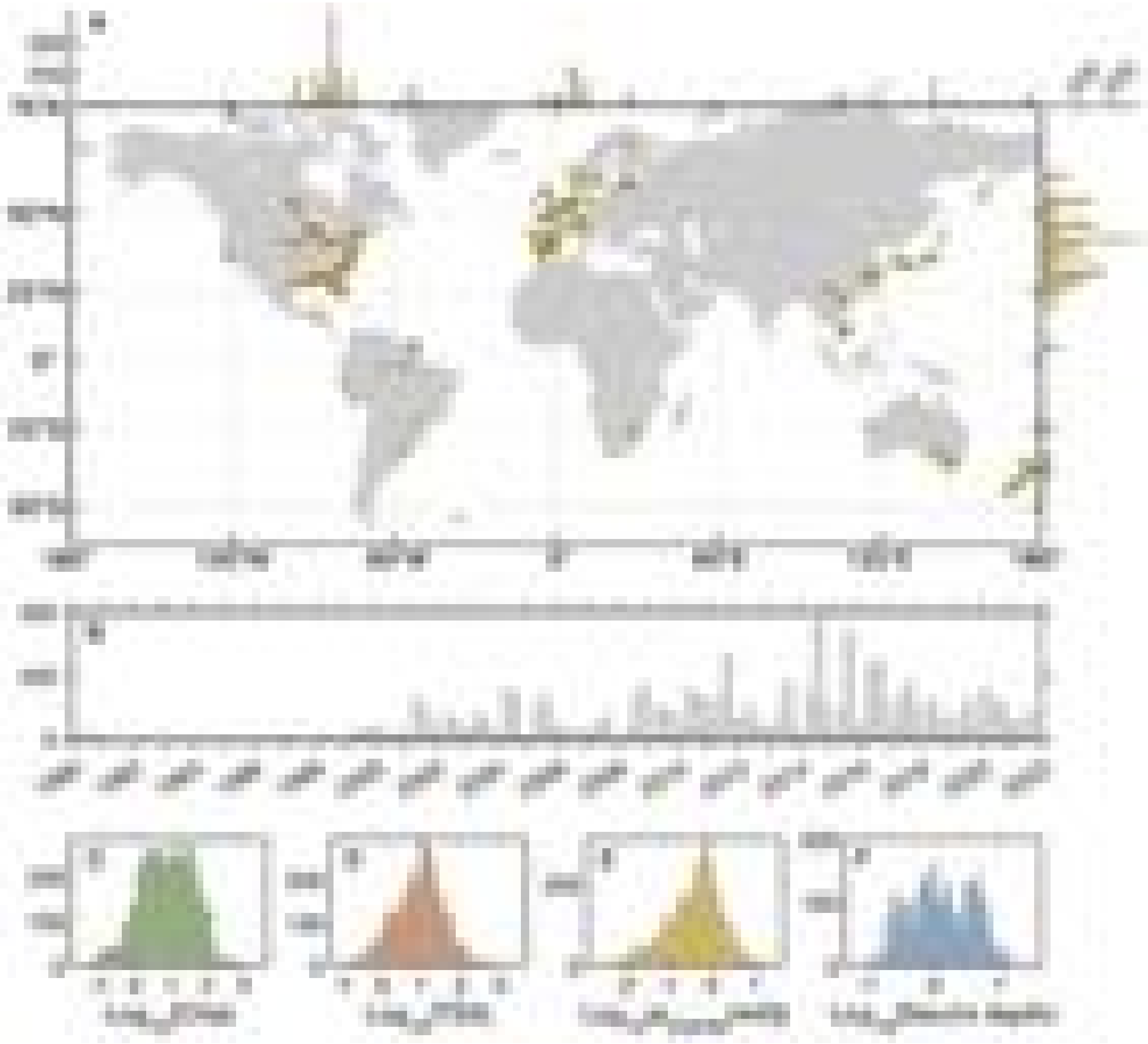
HYPERNETS - HYPSTAR®

Floating RoX



Free et al., 2019

Fieldworks and data



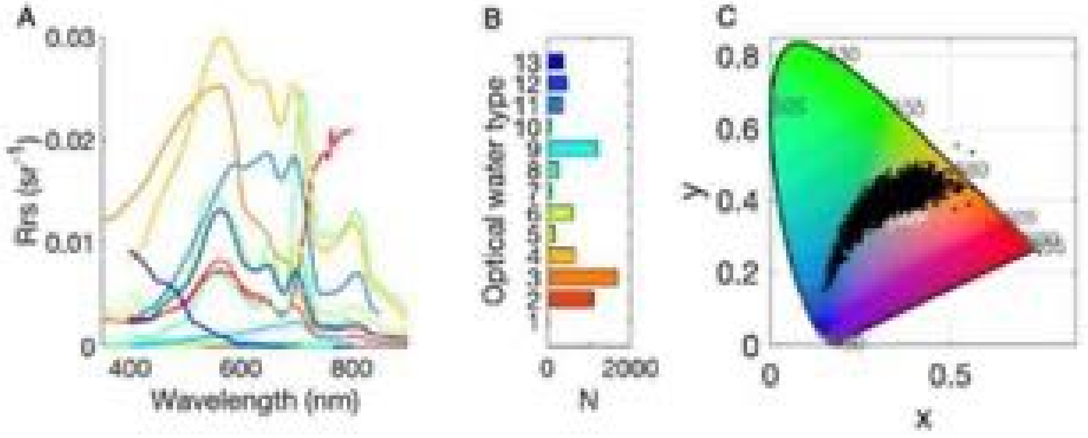
scientific **data**

OPEN

DATA DESCRIPTOR

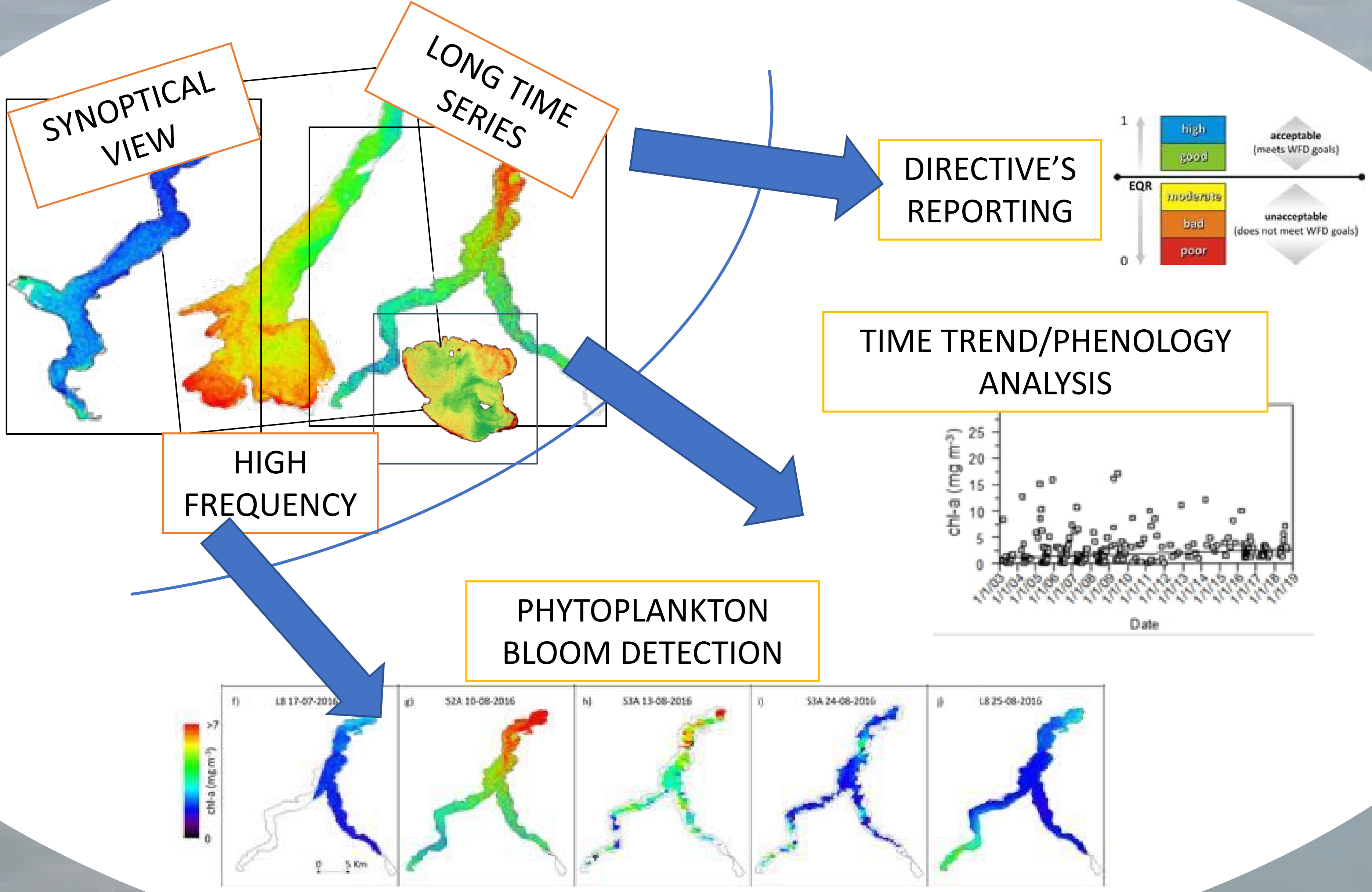
GLORIA - A globally representative hyperspectral *in situ* dataset for optical sensing of water quality

Moritz K. Lehmann et al.



Techniques – FIELD WORKS

From satellite data to information



Key operational MS sensors

Envisat MERIS

21 spectral bands

→ To distinguish the variety of water components (e.g PFT)

300 m resolution

→ To map mesoscale patterns

1-2 days revisit

→ To capture highly dynamic processing (HABs, Upwelling, oil-spill

sentinel-3

USGS LANDSAT

13 spectral bands

→ To distinguish the variety of colors of substrates

10 m resolution

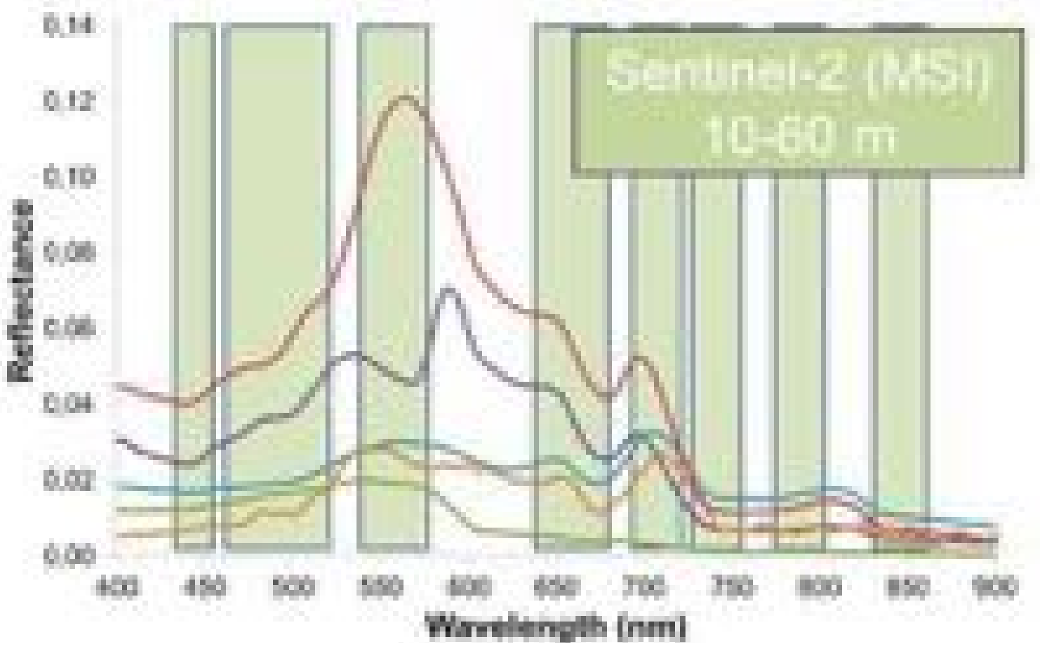
→ To map the patchy distribution of benthic environments

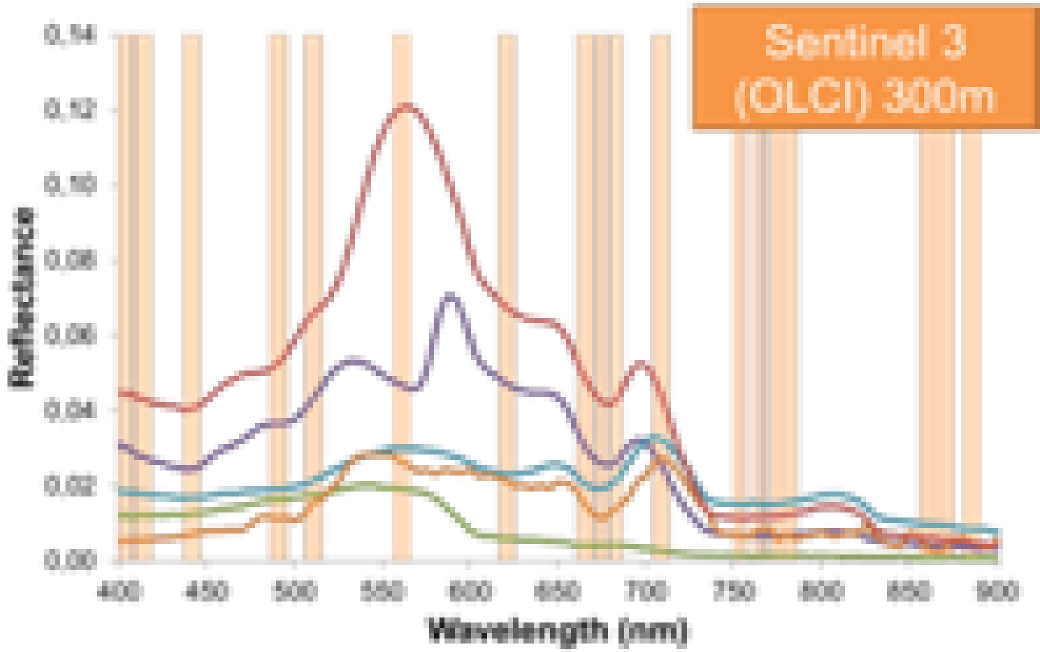
5 days revisit

→ To capture processes such as macrophyte phenology, shifts to other communities, lost of colonised substrates

sentinel-2

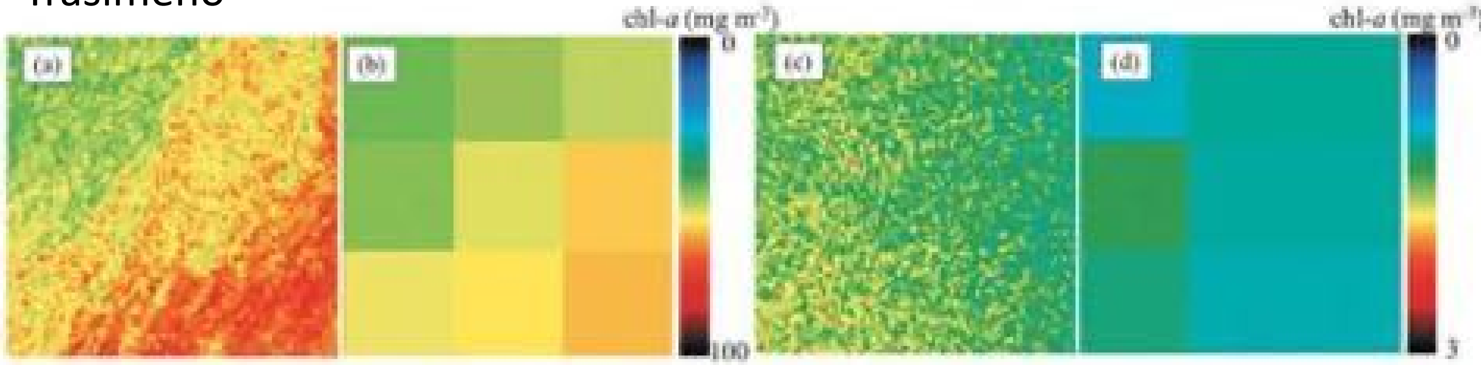
Italian lakes from MSI and OLCI



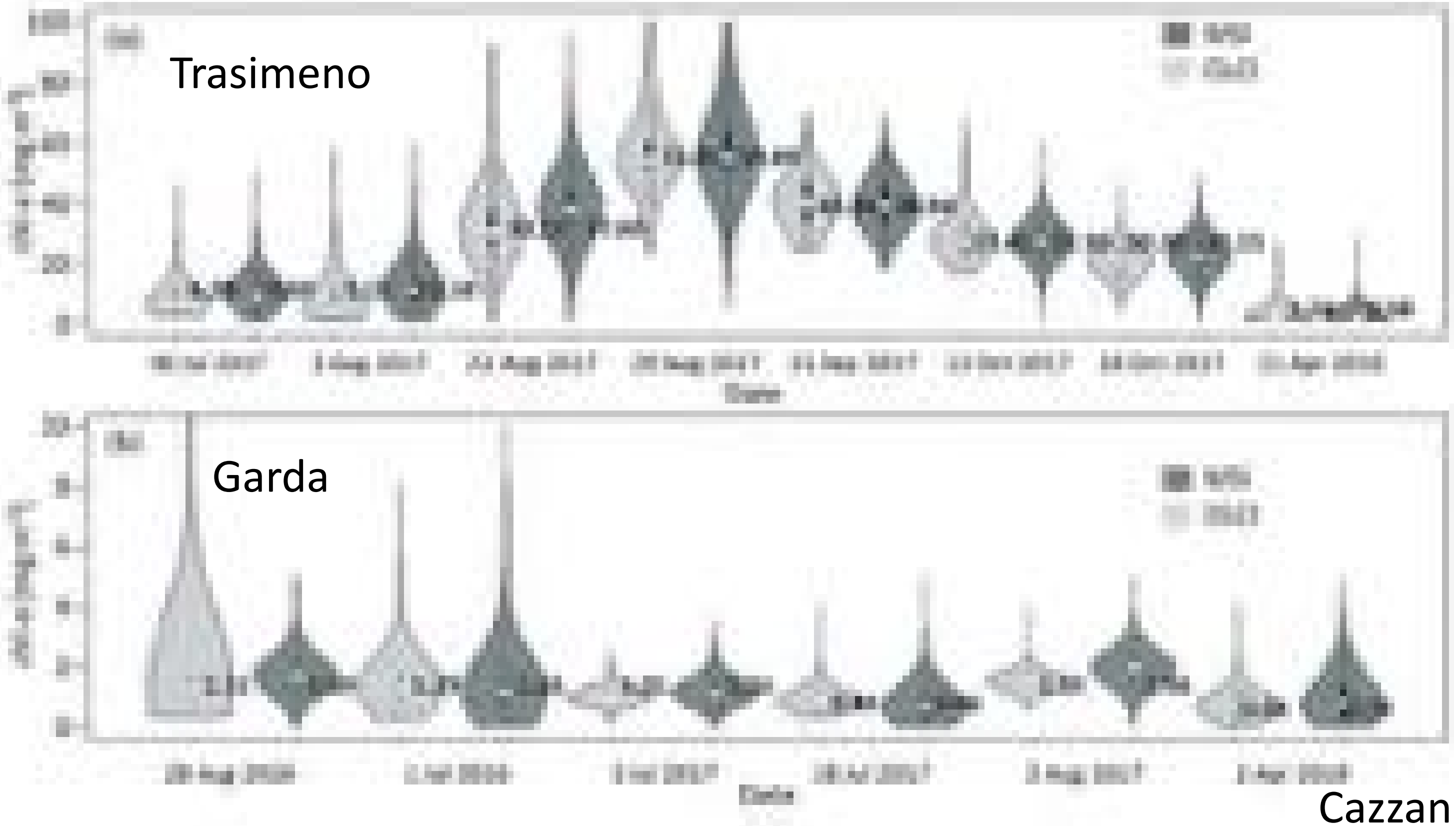


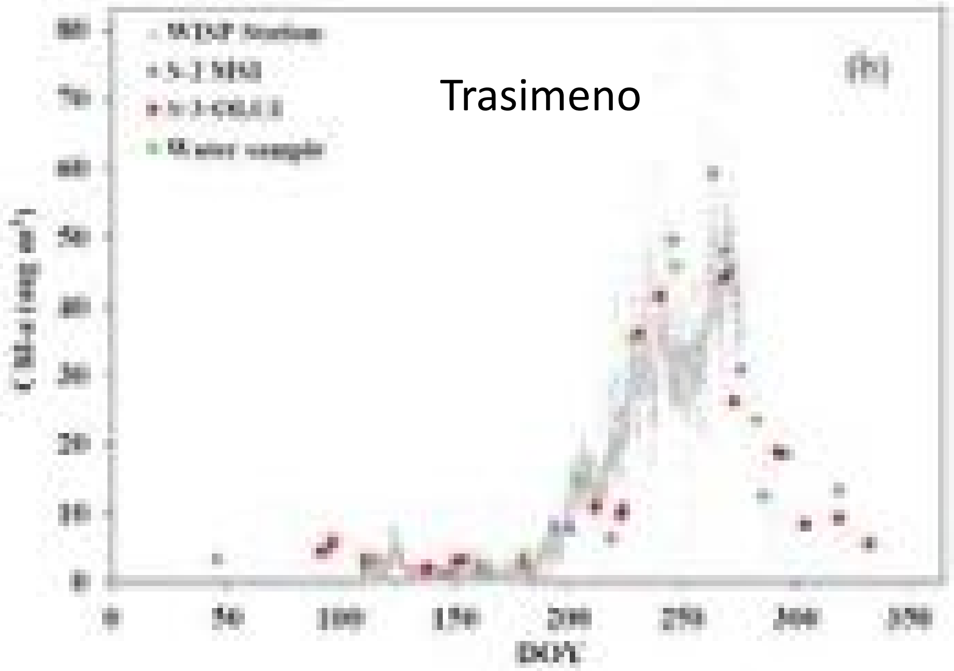
Comparison of S2-MSI and S3-OLCI (e.g. Chl-a)

Trasimeno   Garda



Consistent retrievals of water quality parameters (e.g. Chl-a) in various aquatic ecosystems with broad ranges of trophic status from S2-MSI and S3-OLCI





Cazzaniga et al., 2019

Bresciani et al., 2020

WFD reporting

The EU Water Framework Directive - integrated river basin management for Europe

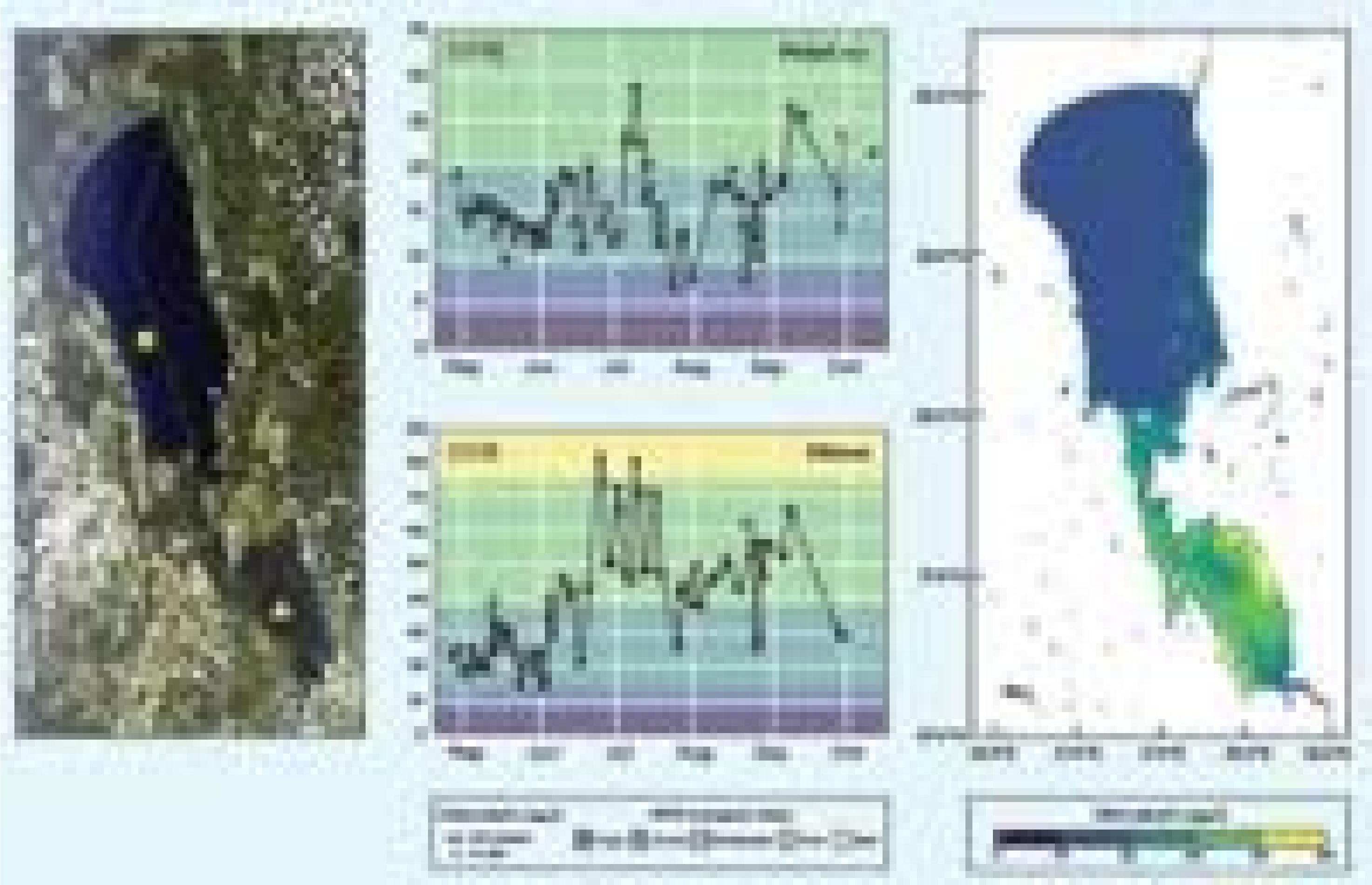
The white paper looks at current satellite-based opportunities through a WFD lens

Papathanasopoulou et al., 2019

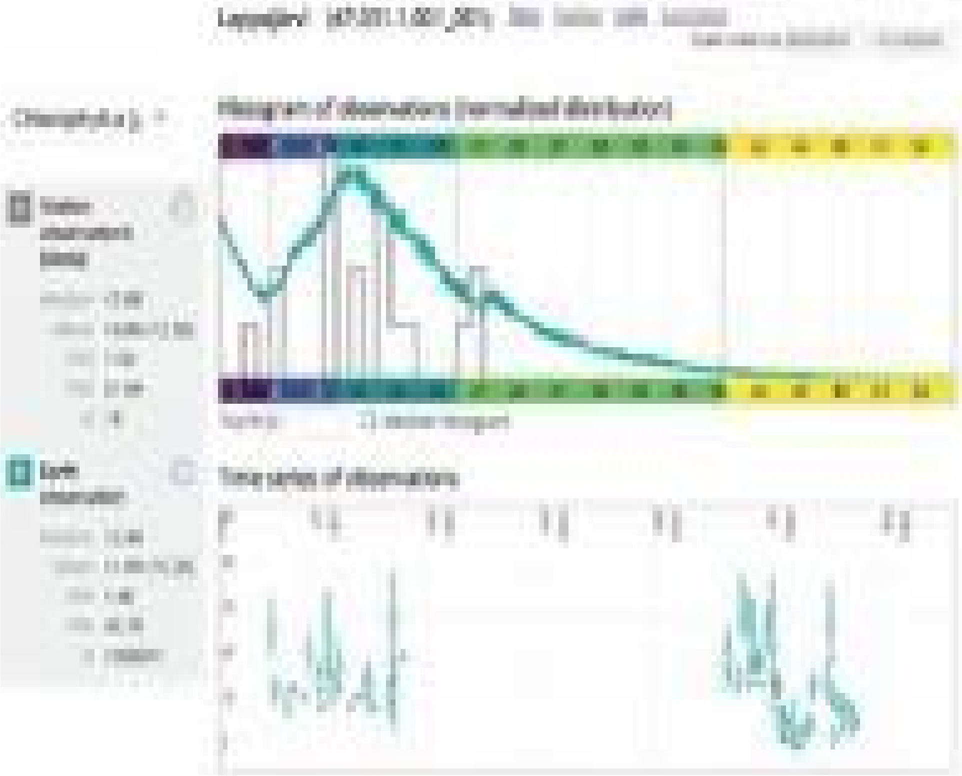
WFD reporting for EU member states

Estonia

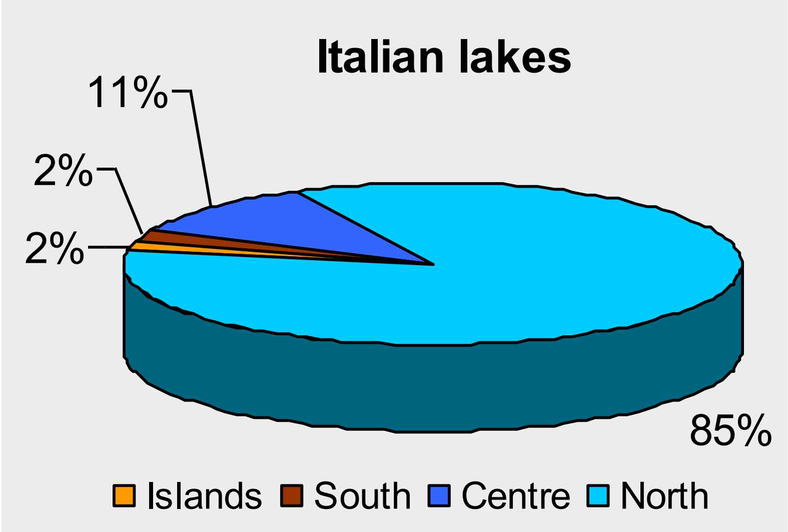
Papathanasopoulou et al., 2019



Finland



WFD reporting in Italy



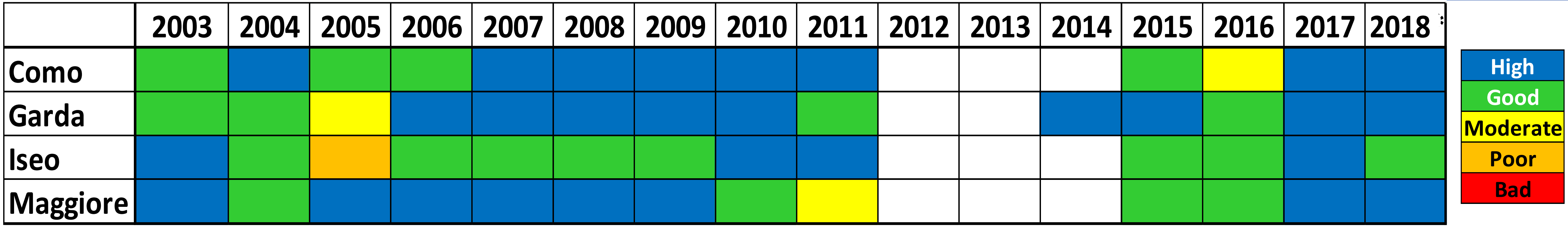
457 Italian lakes have to be monitored for the WFD

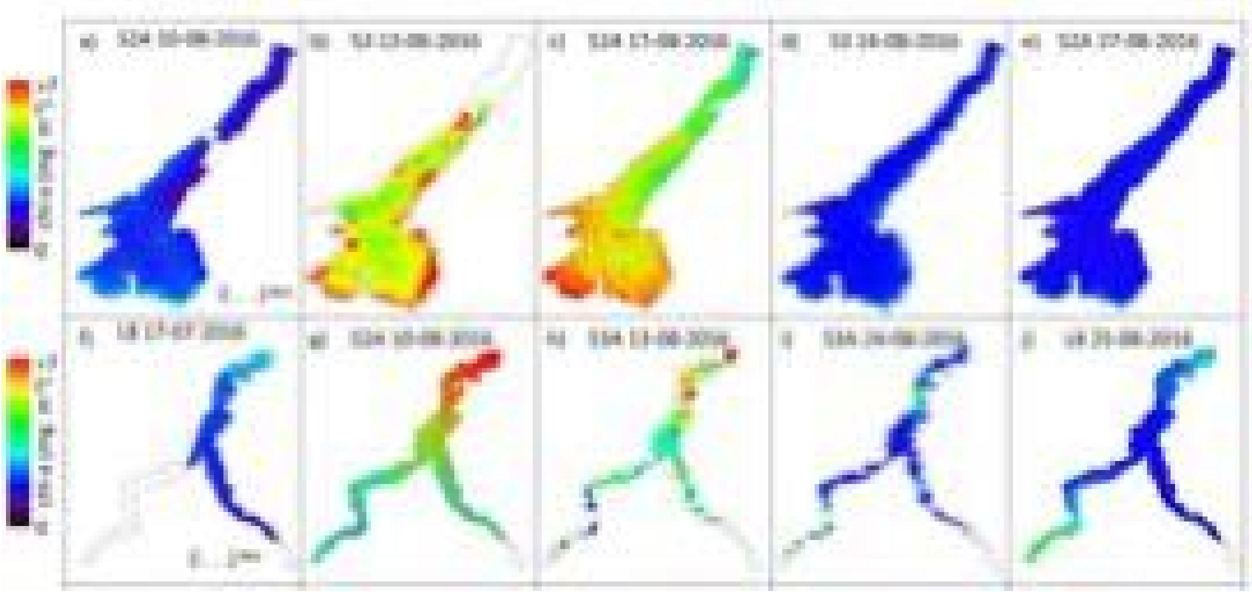
Optical satellite observation can be considered in seven biological and physico-chemical elements (deep and shallow water).

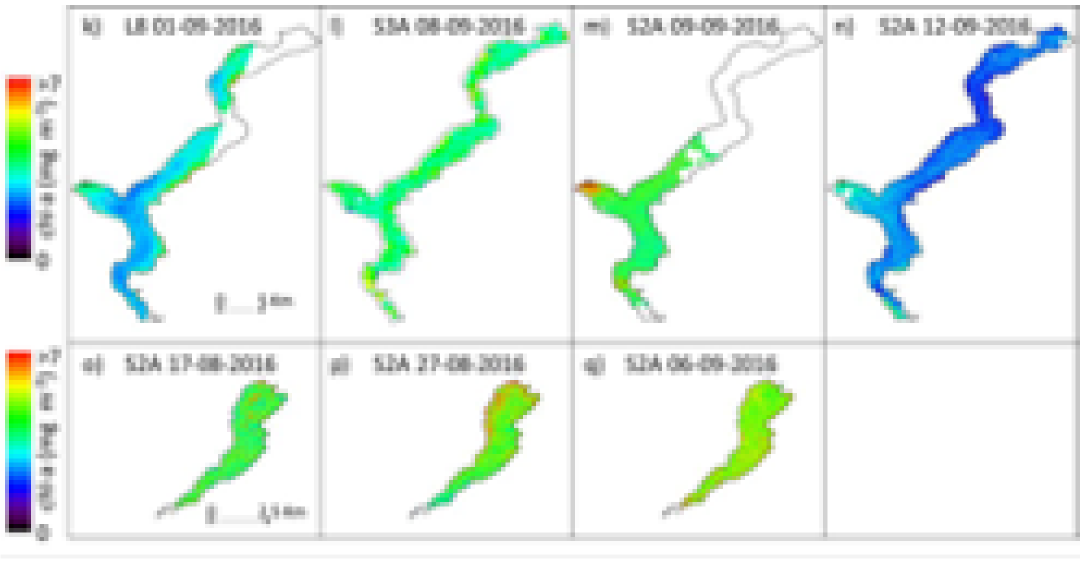
Major improvements possible for ***frequency of blooms*** because this requires high spatio-temporal coverage.

Supporting WFD – clear lakes

Chl-a concentrations time series obtained from different satellites from 2003 in different years of the subalpine lakes studied. The classes water quality as defined in the WFD (Wolfram et al., 2009)

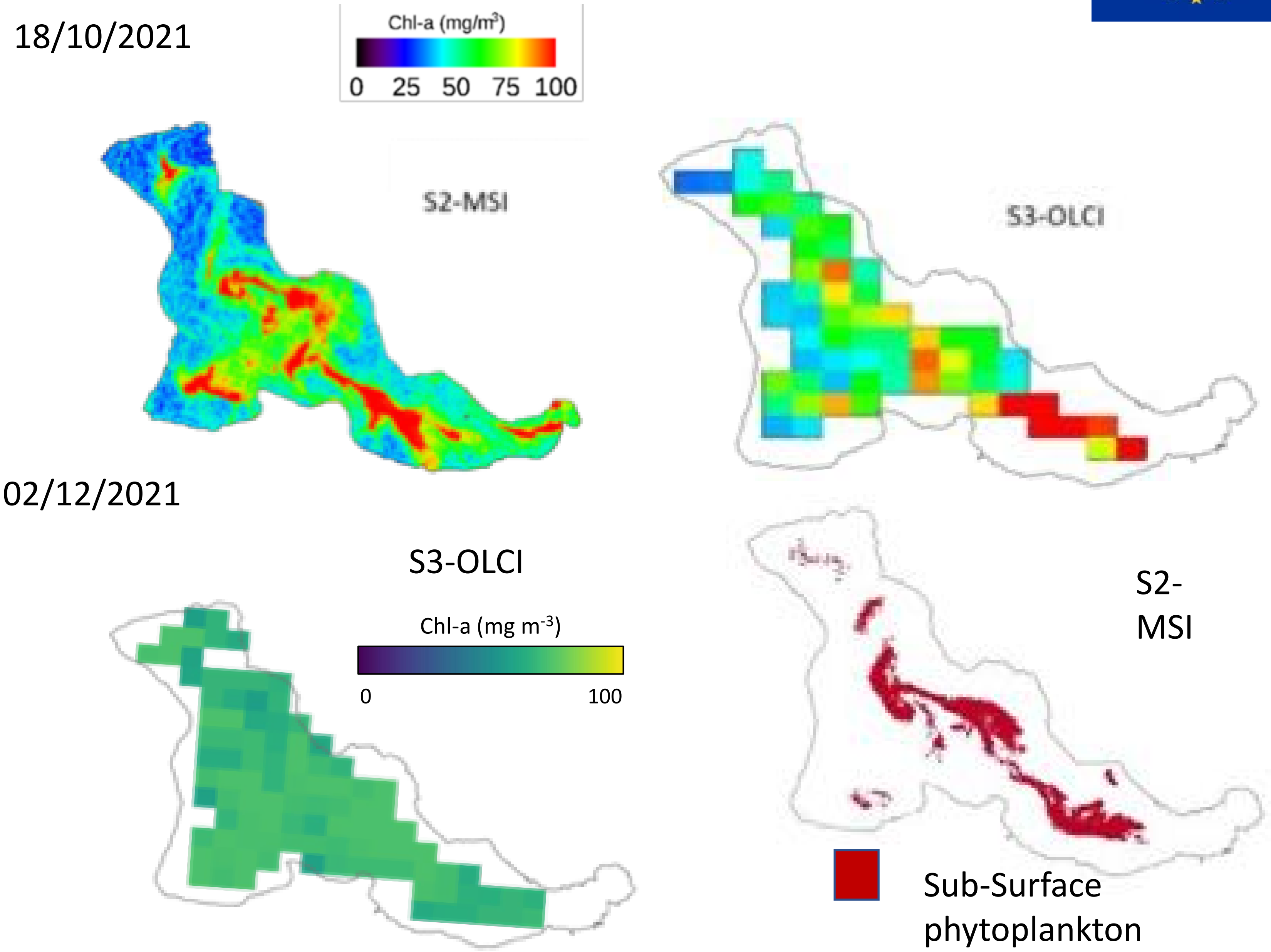


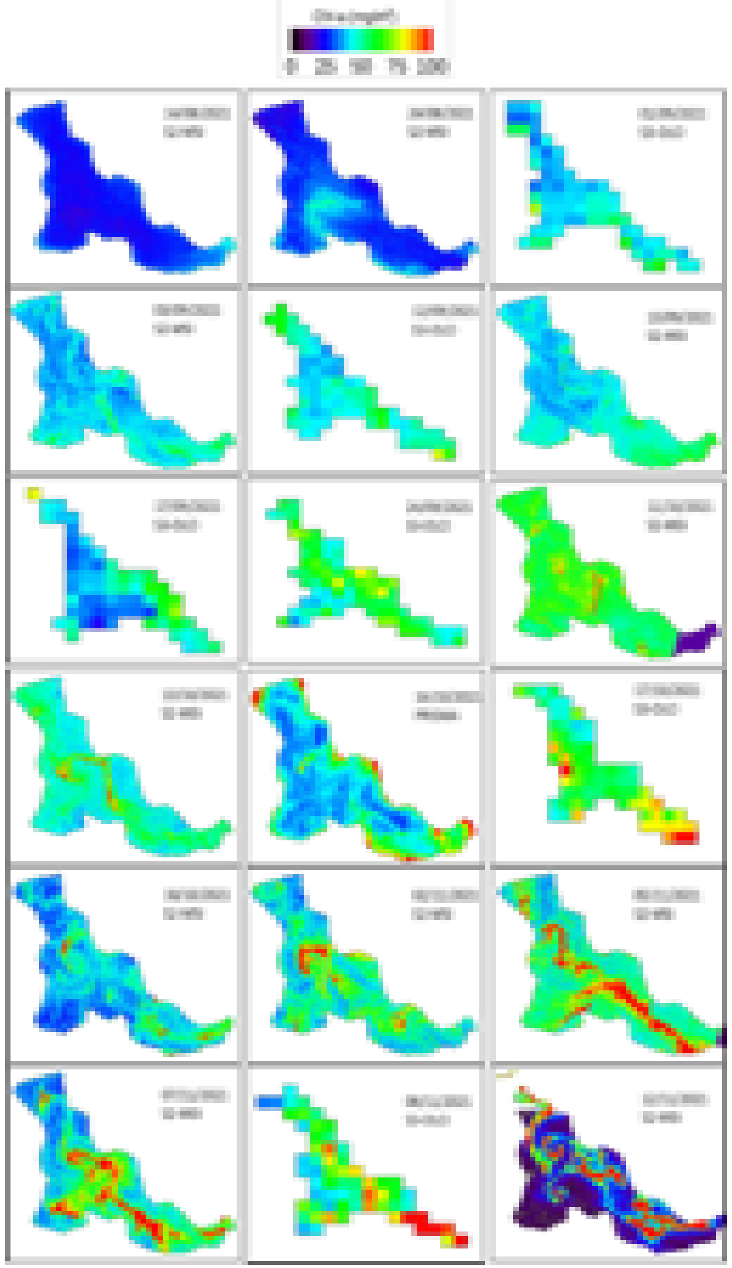




Bresciani et al., 2018

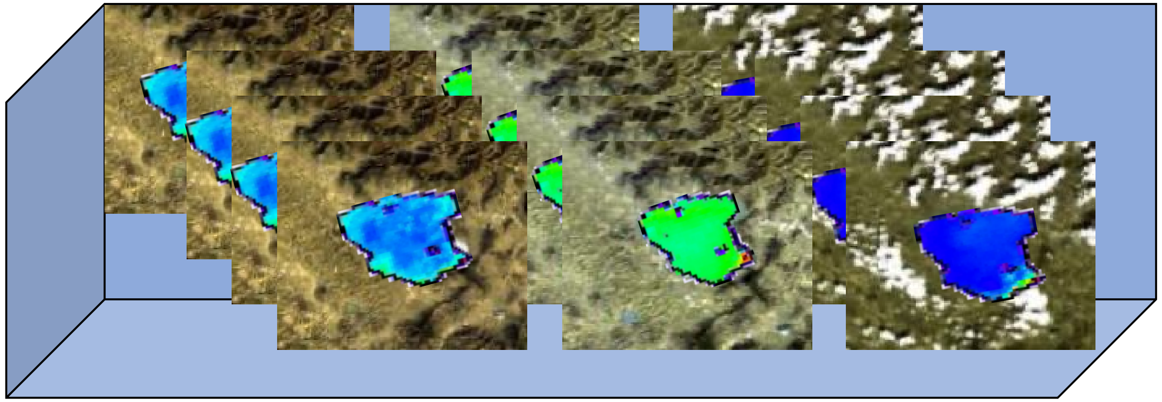
Supporting WFD – eutrophic lakes

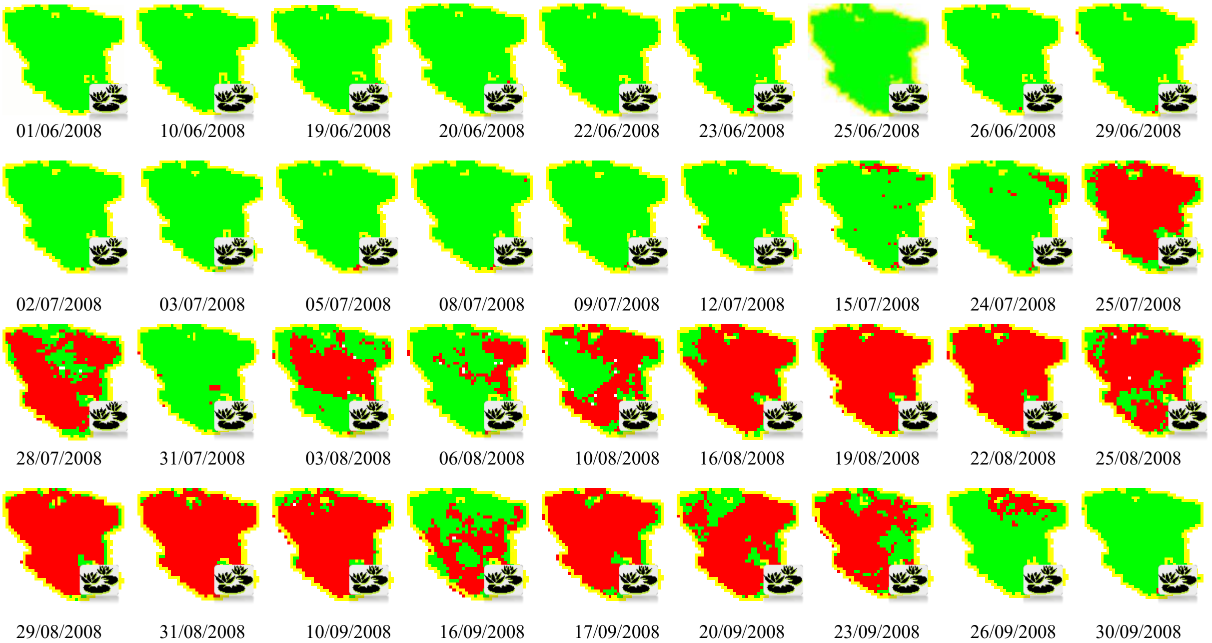




Supporting WFD – turbid waters

Providing of useful and easily readable information about the status of a lake





Chl-a < μ+σ (13 mg/m^3)

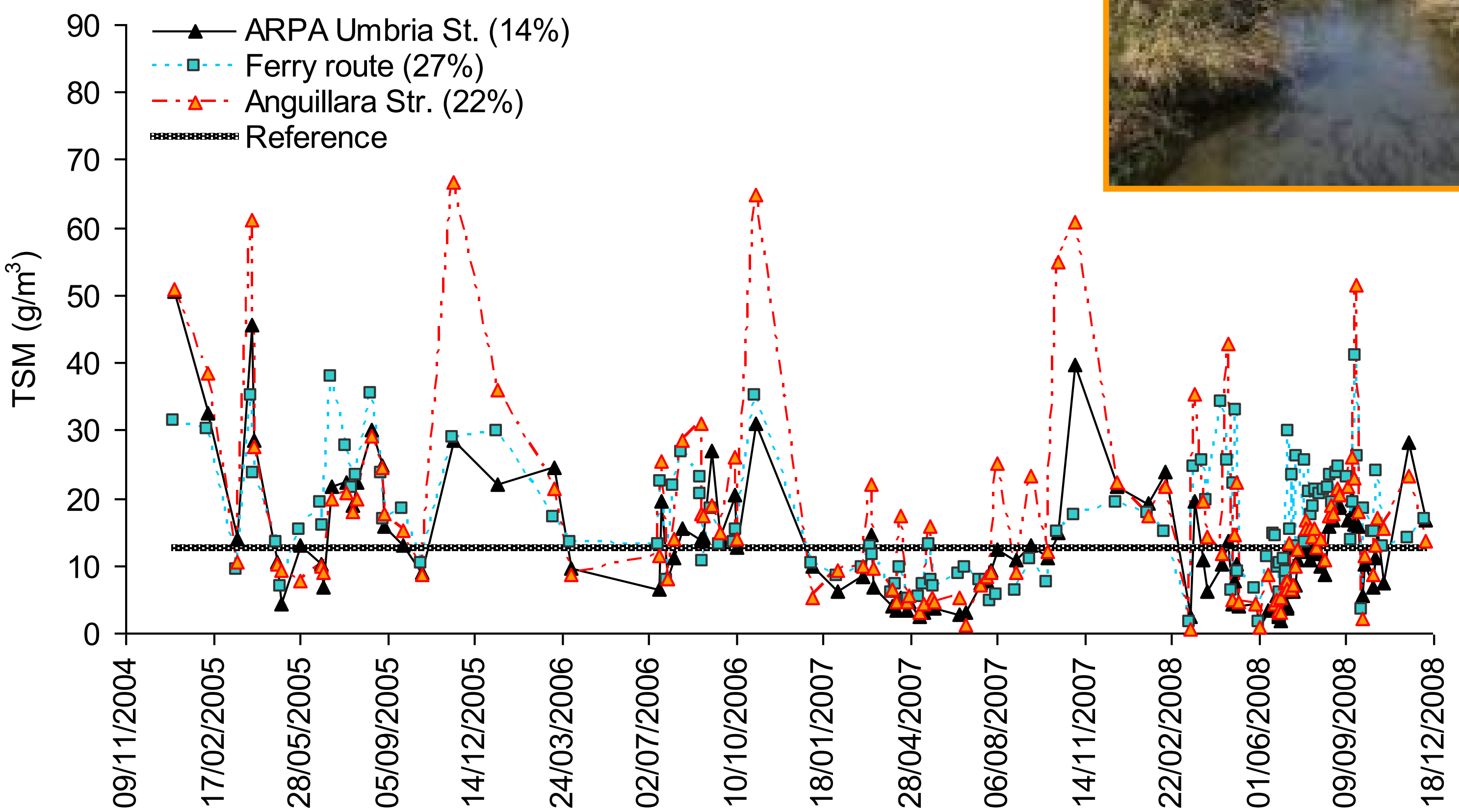
Chl-a > μ+σ (13 mg/m^3)

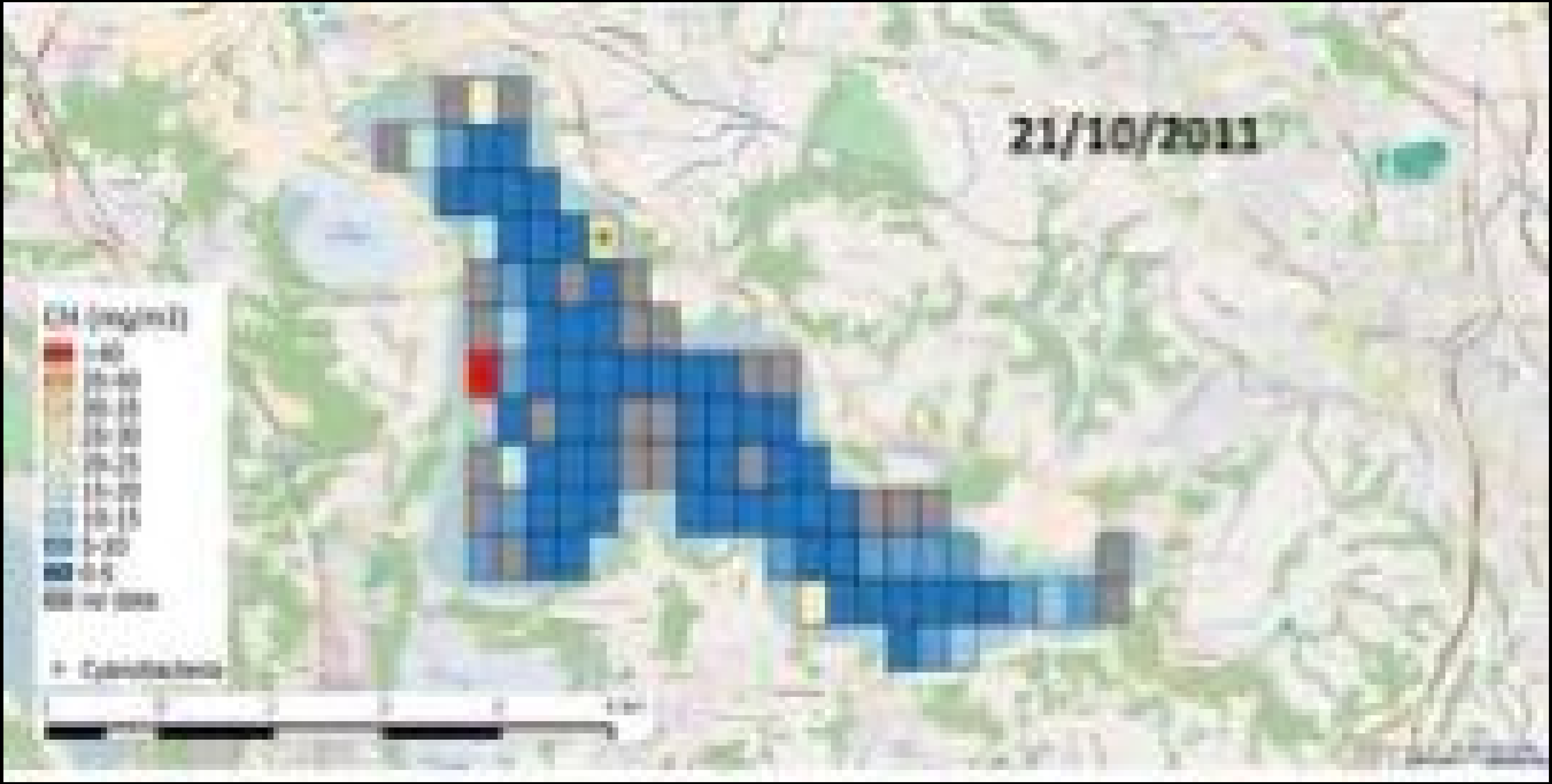
TSM < μ+σ (20 g/m^3)

TSM > μ+σ (20 g/m^3)

Supporting WFD field sampling

Sustaining the identification of most appropriate in-situ measuring points

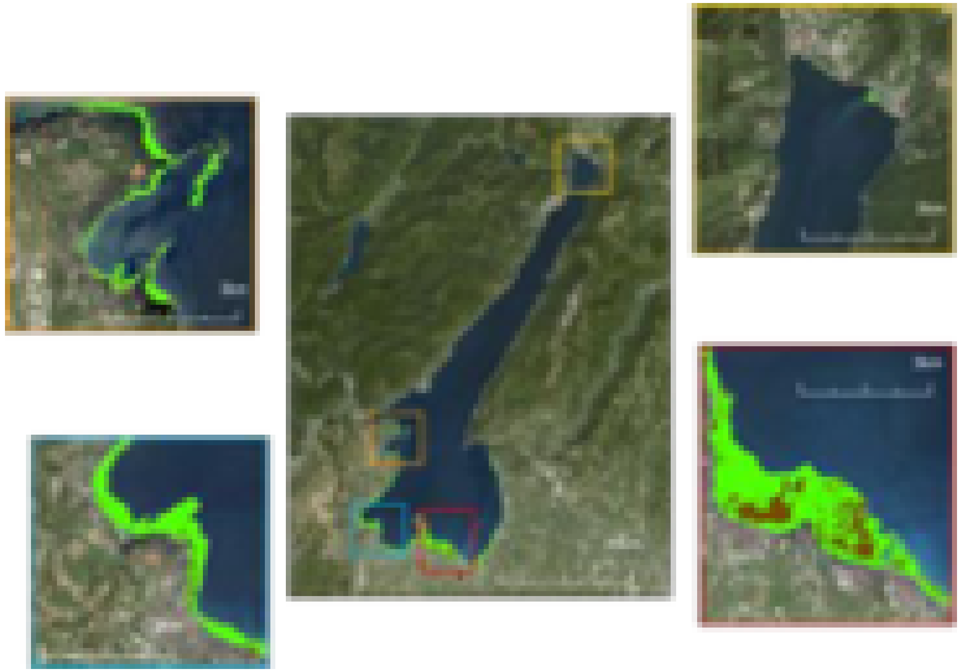


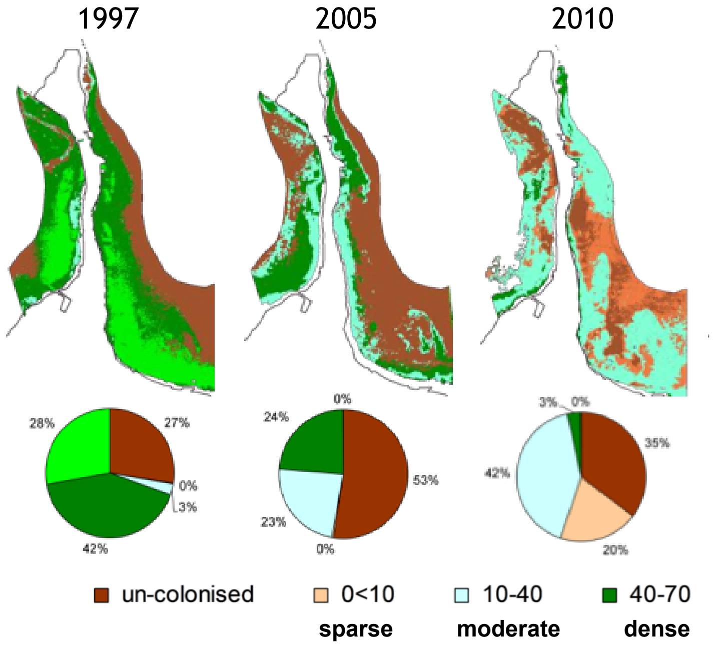

21/10/2011

WFD reporting in shallow waters

Macrophytes are extremely valuable components of the aquatic ecosystem as they have well recognised ecological functions

Approximately **17 km²**, of the coastal zone including in the first 7 meters bathymetric range, have the presence of macrophytes

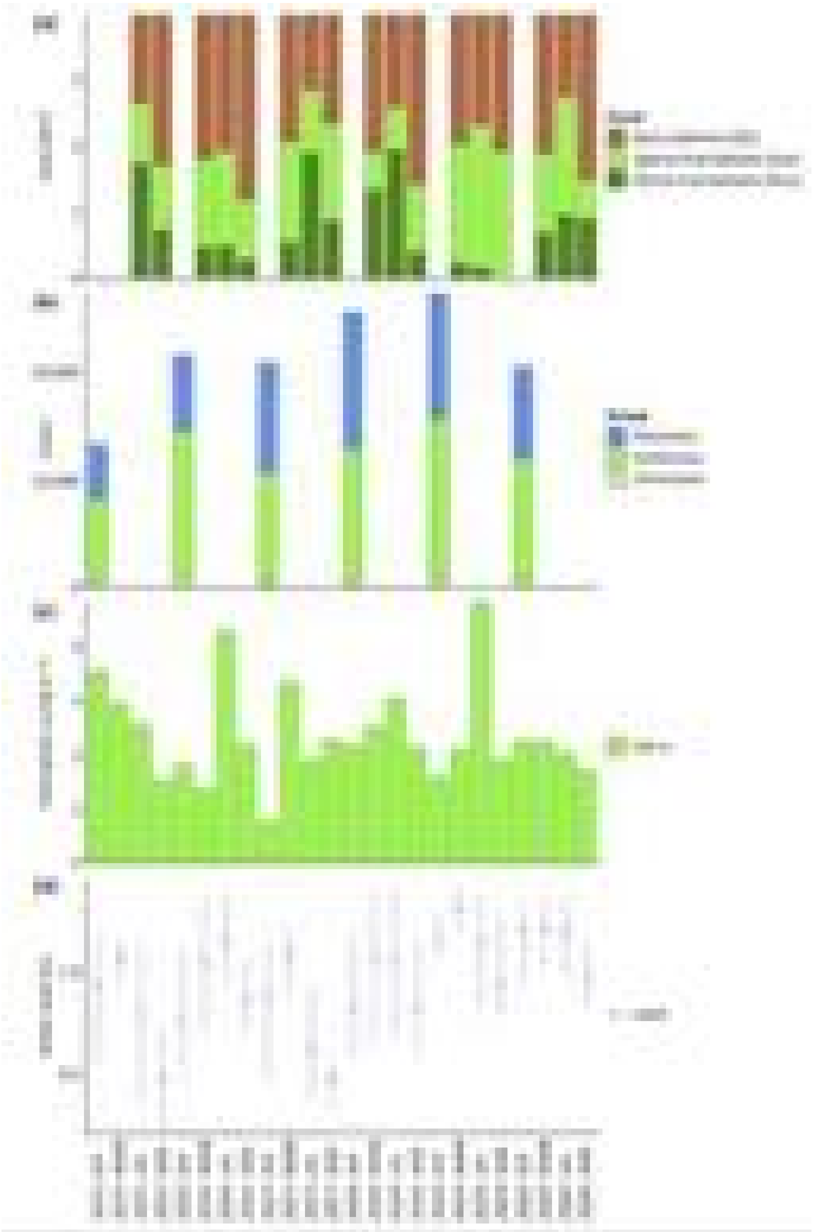




MIVIS images collected over a period of **14 years** (1997-2011) were used to assess changes in submerged macrophytes colonization patterns in southern Lake Garda. The results show a considerable modification (**reduction**) in terms of macrophyte structural complexity and colonized areas.

Giardino et al., 2010

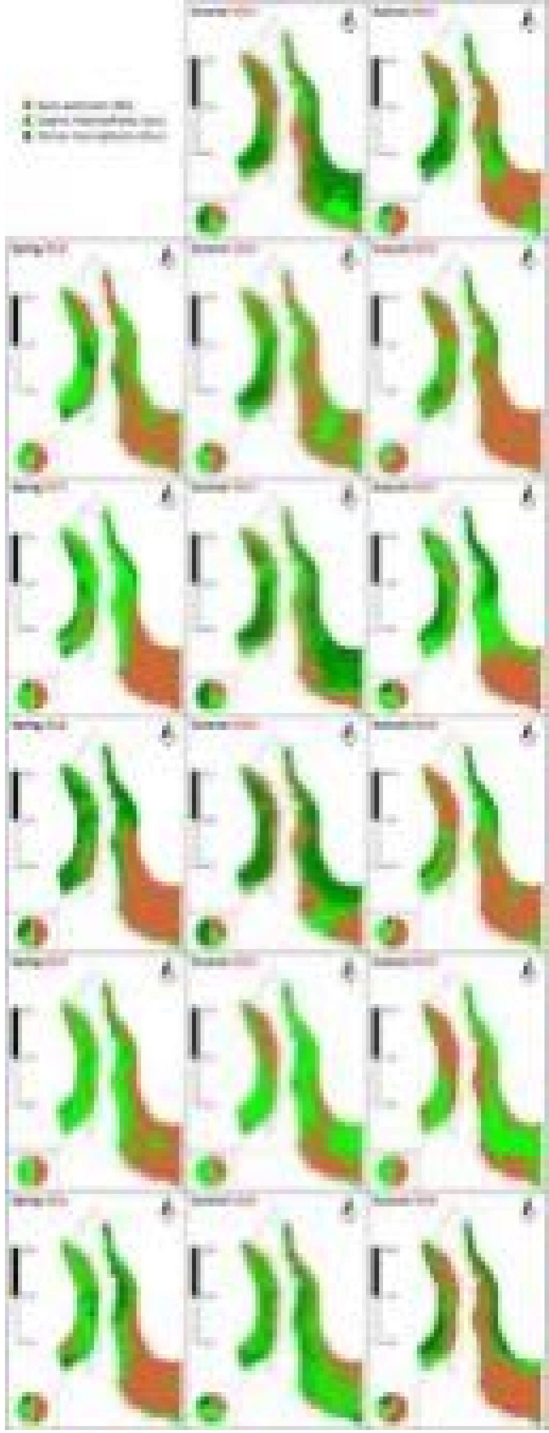
WFD reporting in shallow waters



Evaluation of Macrophyte Community Dynamics in Lake Garda

Factors influencing macrophyte community:

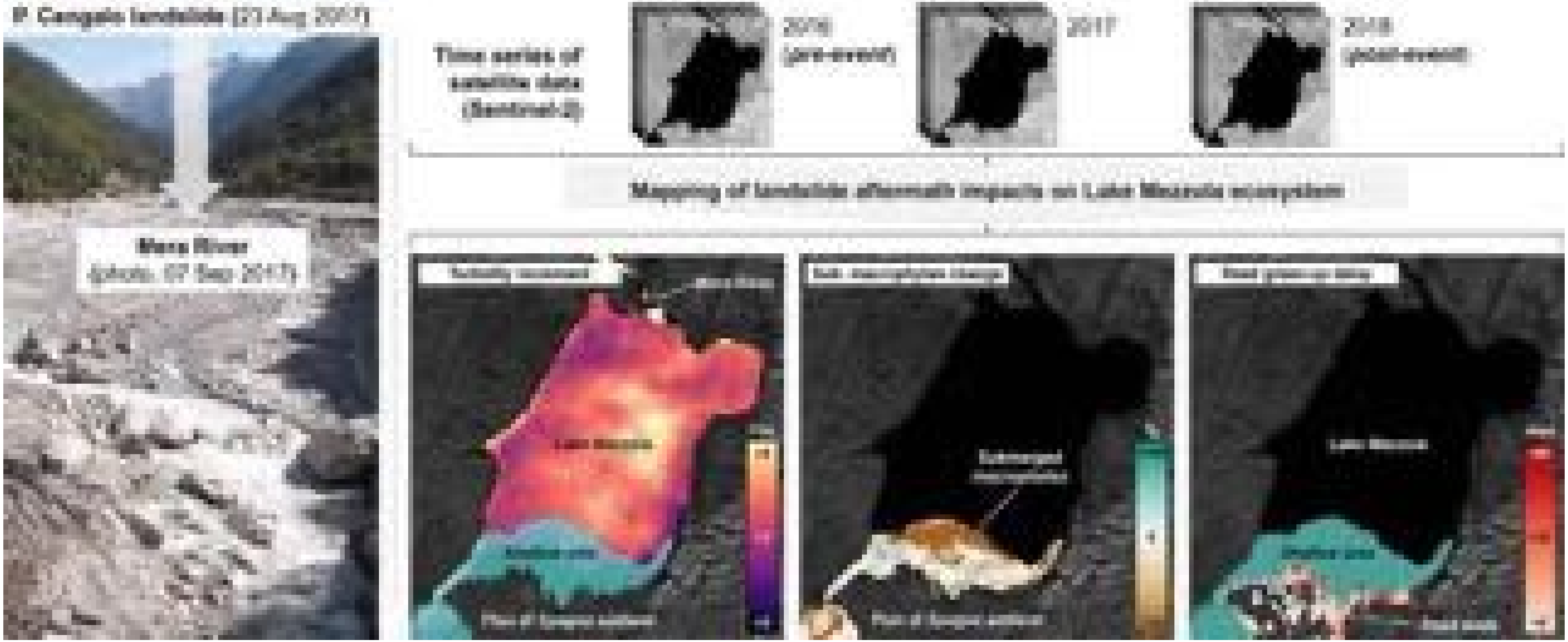
- Herbivores
- Transparency and Chl-a
- Water Level
- Winter wave height
- Tourism – boat traffic (revealed following COVID-19 regrowth)



Ghirardi et et al., 2022

Natural hazards

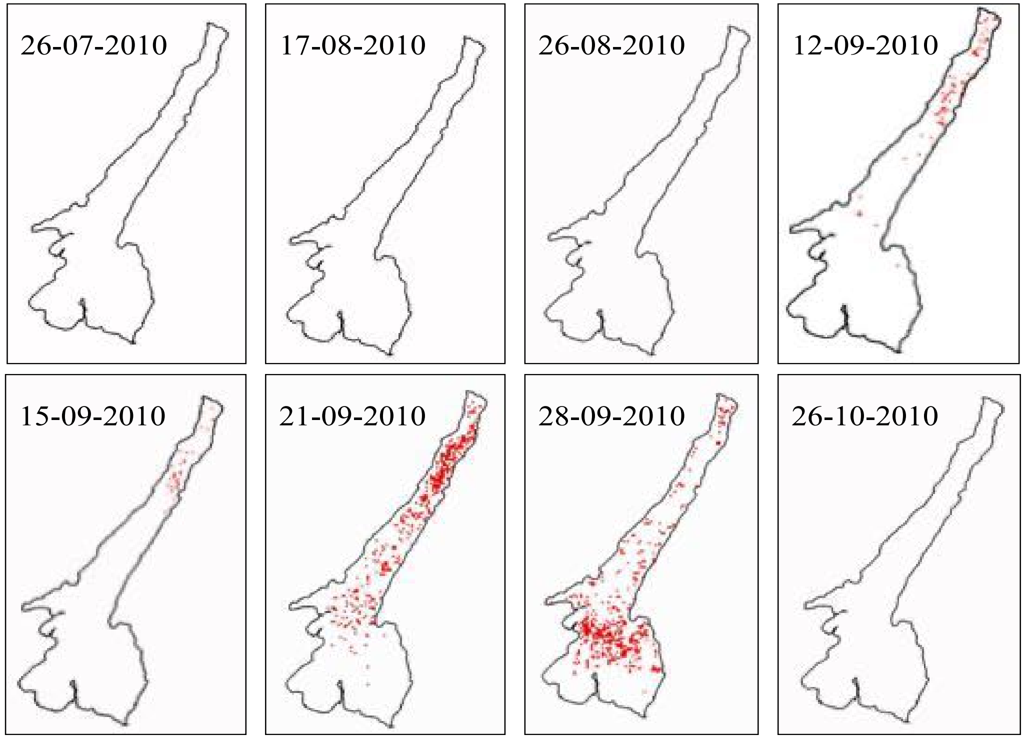
Assessing temporal evolution of key ecosystem variables after an upstream landslide in perialpine Lake Mezzola (northern Italy)

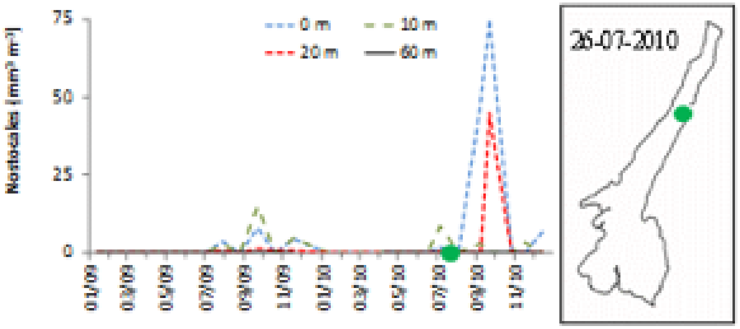


Villa et al. (2020).

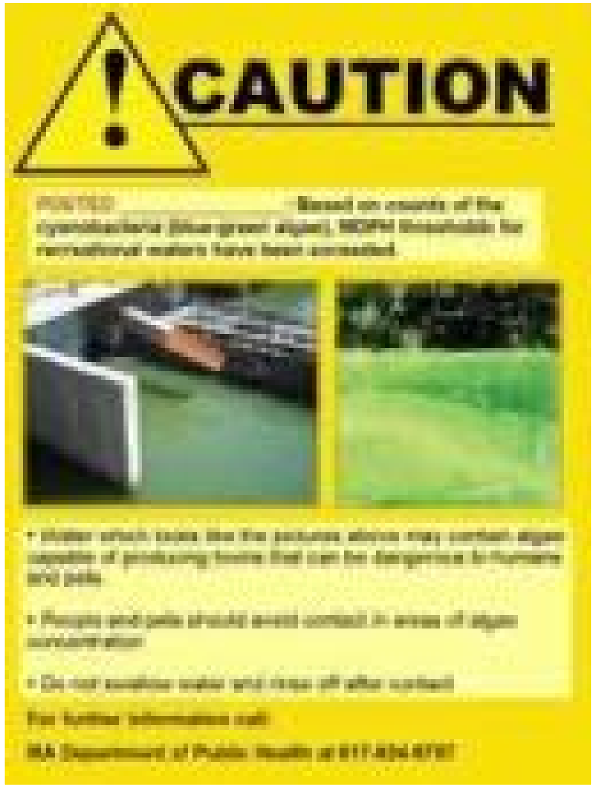
Natural hazards

Algal blooms strongly condition water quality. In some cases some algal groups (cyanobacteria) can produce toxic substances, which are dangerous for the aquatic fauna and human health and hence hinder the uses of water.



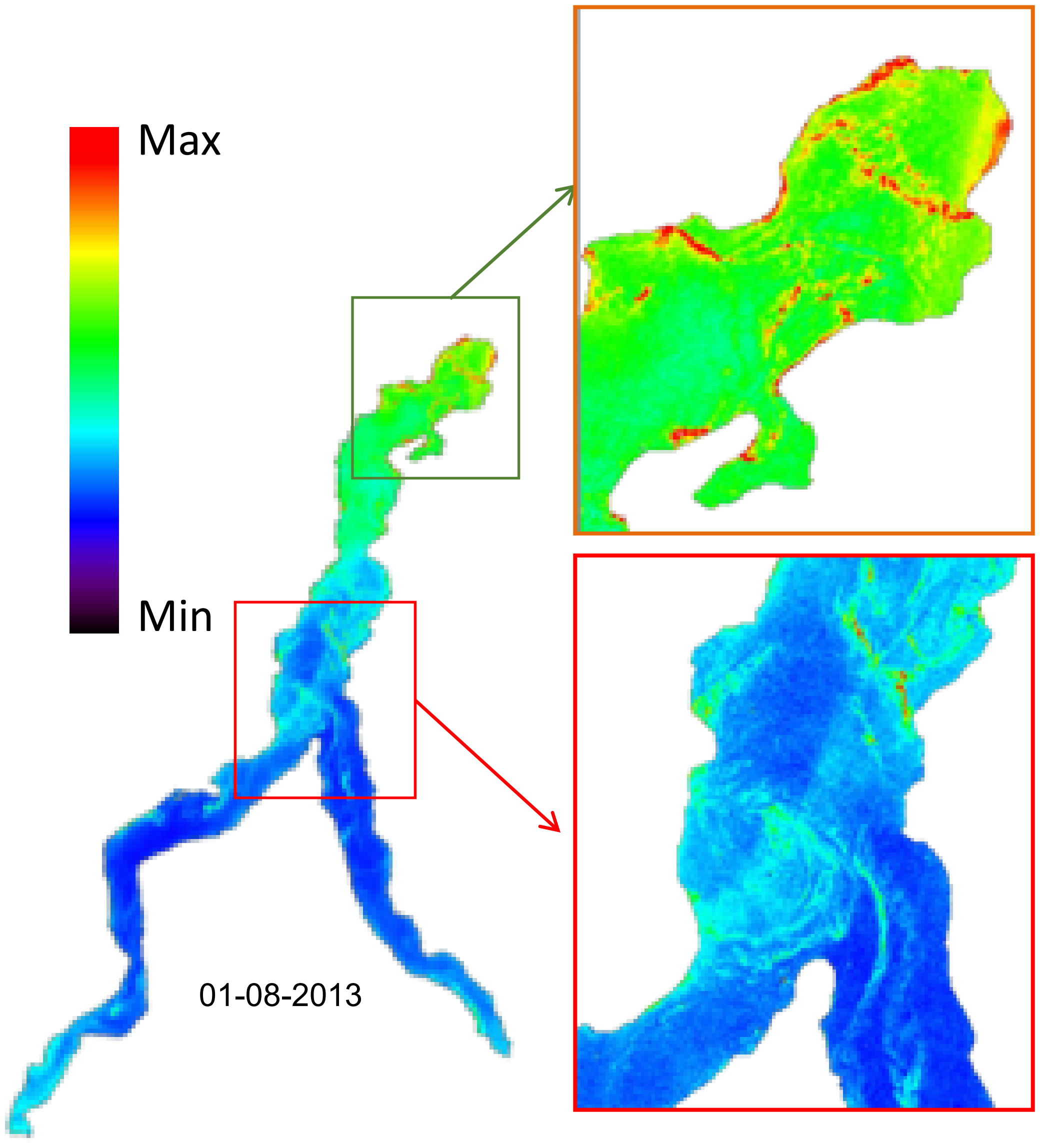


Pixel MERIS with surface cyanobacteria.



Detection of cyanobacterial blooms from MERIS

Natural hazards

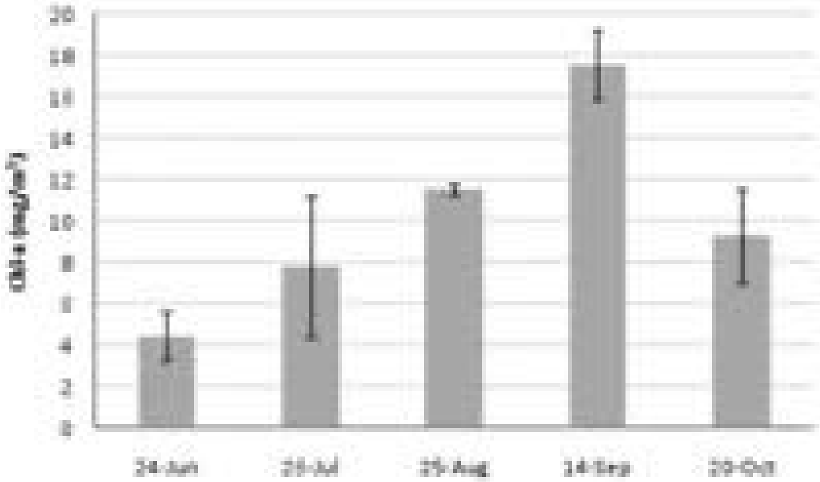


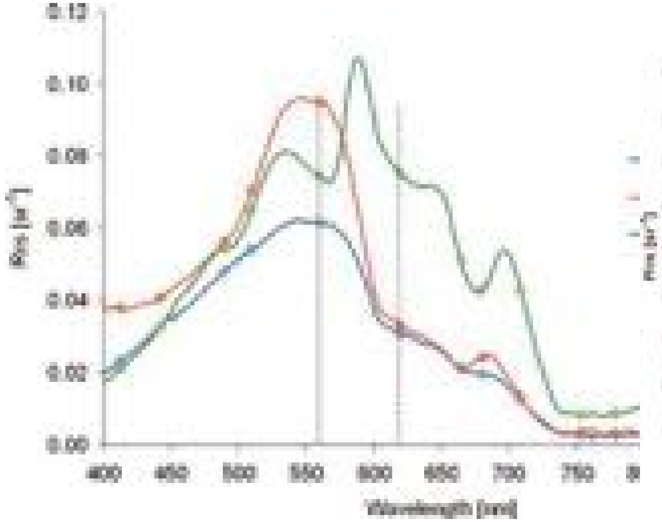
Dolichospermum lemmermannii

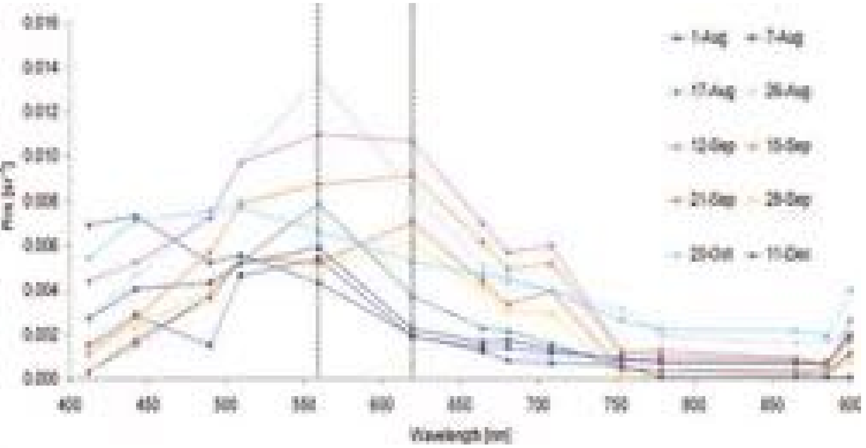
Phytoplankton phenology

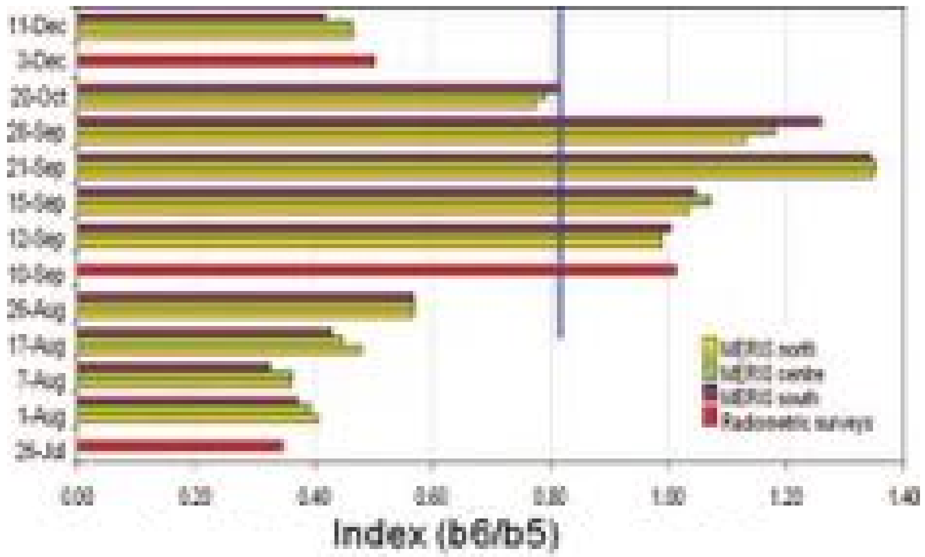
Detection of starting/ending phase of algal bloom

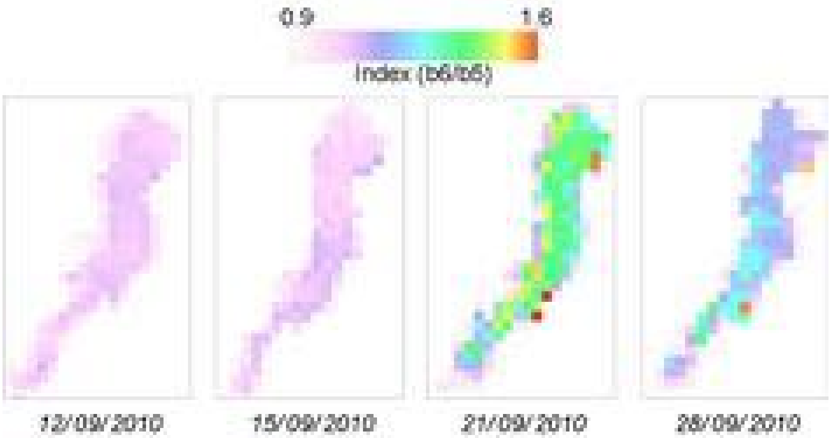
Planktothrix spp.
Aphanocapsa sp.
2010







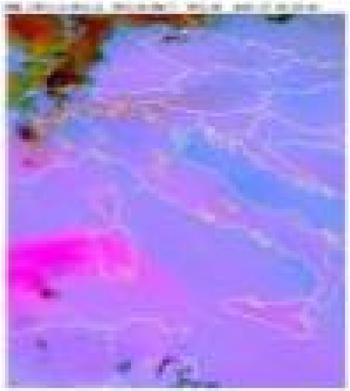


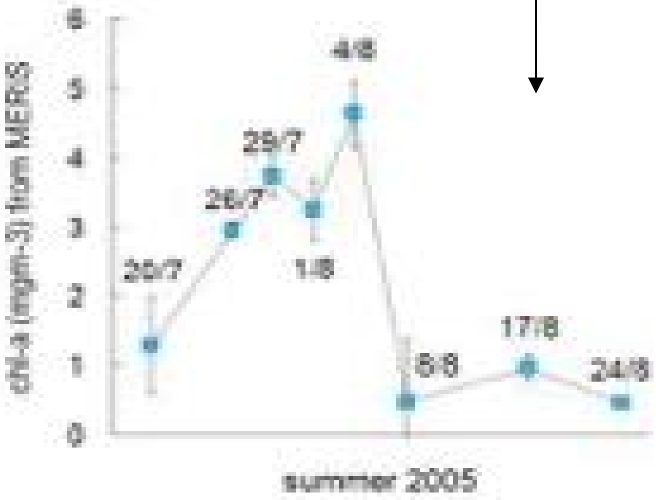


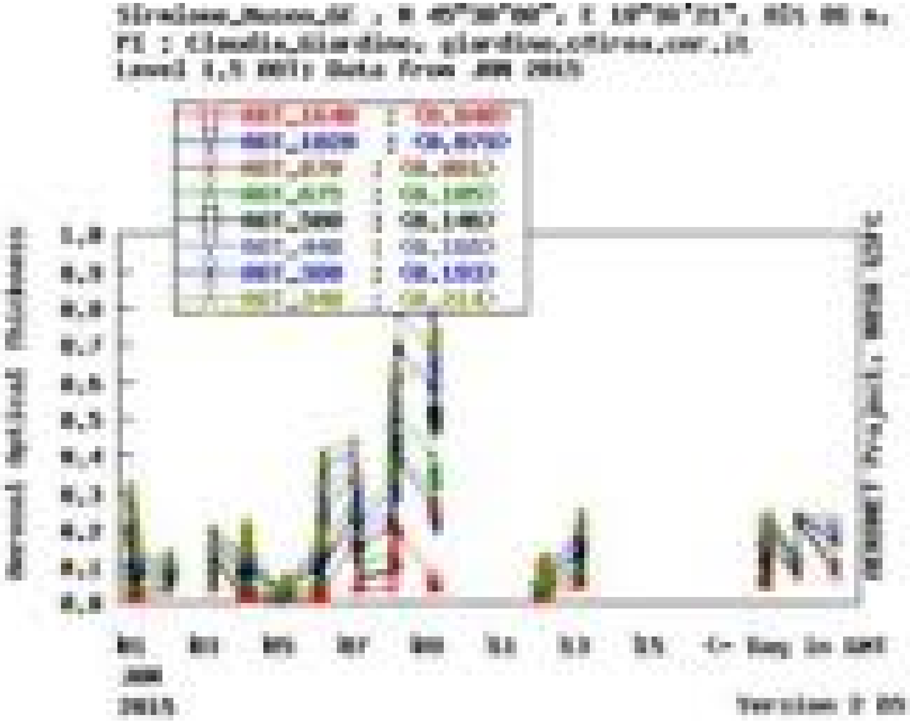
Bresciani et al., 2011

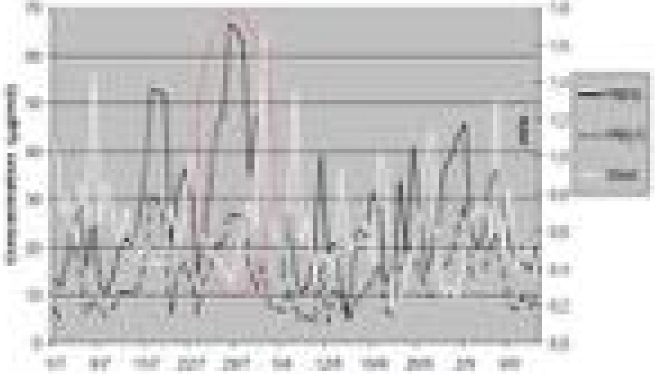
Natural hazards

The effect of Saharan dust deposition in water quality









PM data measured in Bosco Fontana. The dust event is detected when PM10 is sensible higher than PM2.5 (red the circle)

Water temperature and P data analysis revealed the chl-a increase was not due to those two factors

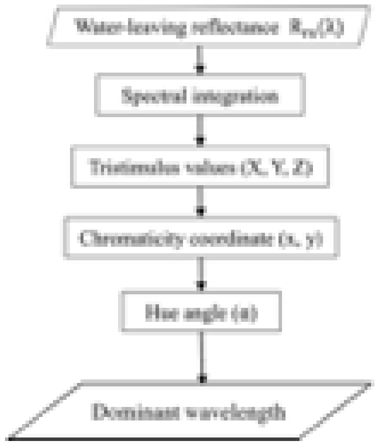
Dinicolantonio et al., 2011

Mountainous lakes

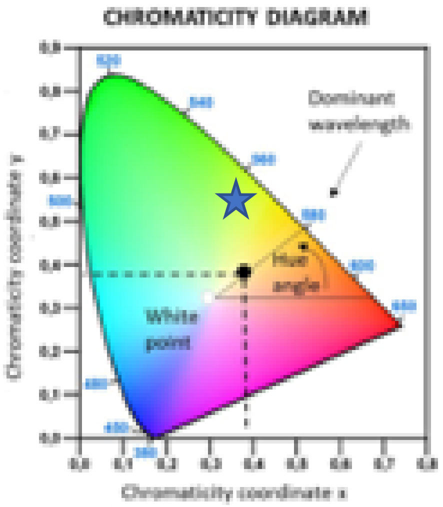
Picture by Giudo Nigrelli, 03/10/2018

Mountainous lakes

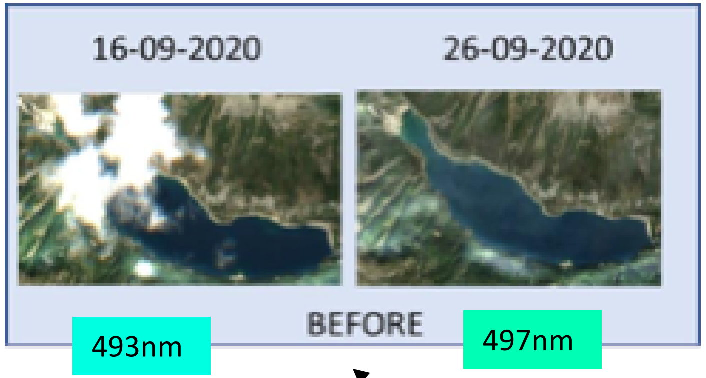
Matta et al., 2024

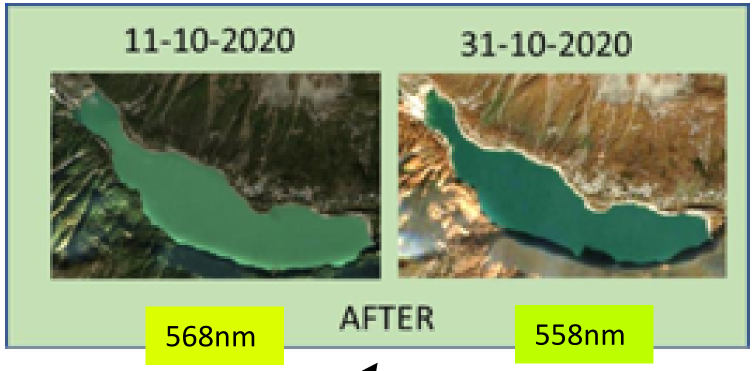


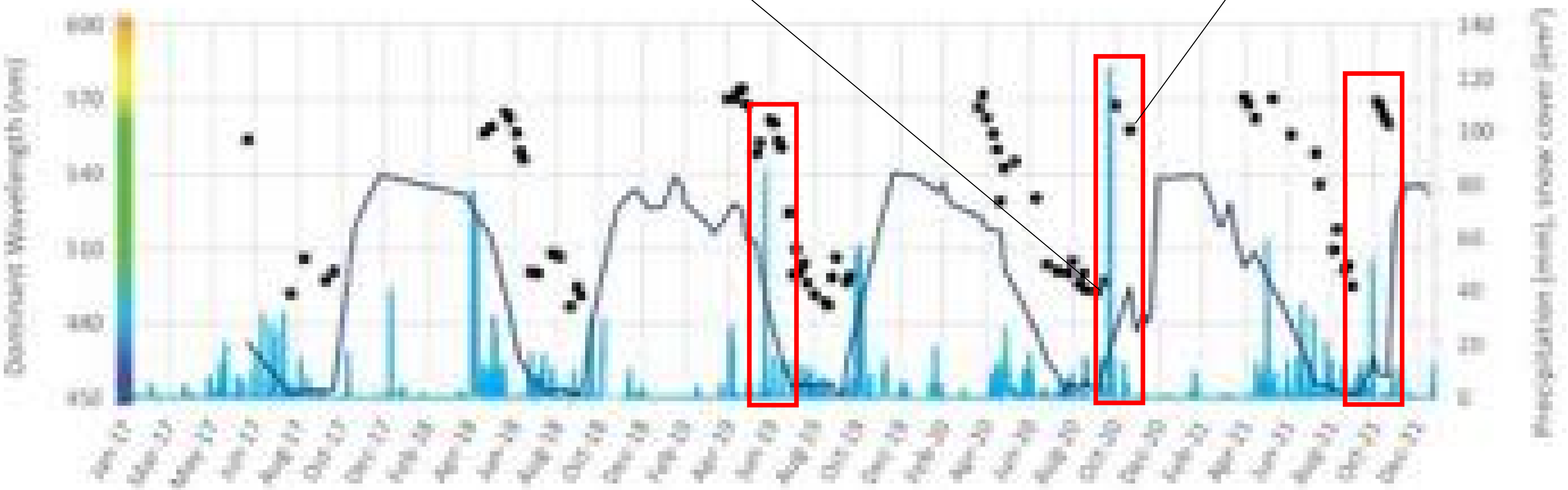
Scheme for the retrieval of water color data (modified from Ye and Sun 2022)



Increasing of dominant wavelengths values after rainy events







- Snow cover
- Precipitations measured at Cresole Villa meteo station
- Median dominant wavelength for Lake Ceresole

Pit lakes

PIT LAKES	DOTS	1580
Active	●	338
Ceased	●	1188
Doubtful	●	54

$$DL = \frac{L}{2\sqrt{\pi A}}$$

Region	Area (km^2)
Piemonte	25,387
Valle d'Aosta	3448
Lombardia	23,663
Trentino Alto-Adige	1746
Veneto	948
Liguria	1789
Emilia-Romagna	13,998
Toscana	21

Step 1: identification of all water bodies in the Po river basin using regional databases and S2 imagery

Step 2: identification of all pit lakes in the Po river basin

$$\boldsymbol{WAVI} = (1+L)\frac{B8 - B2}{B8 + B2 + L}$$

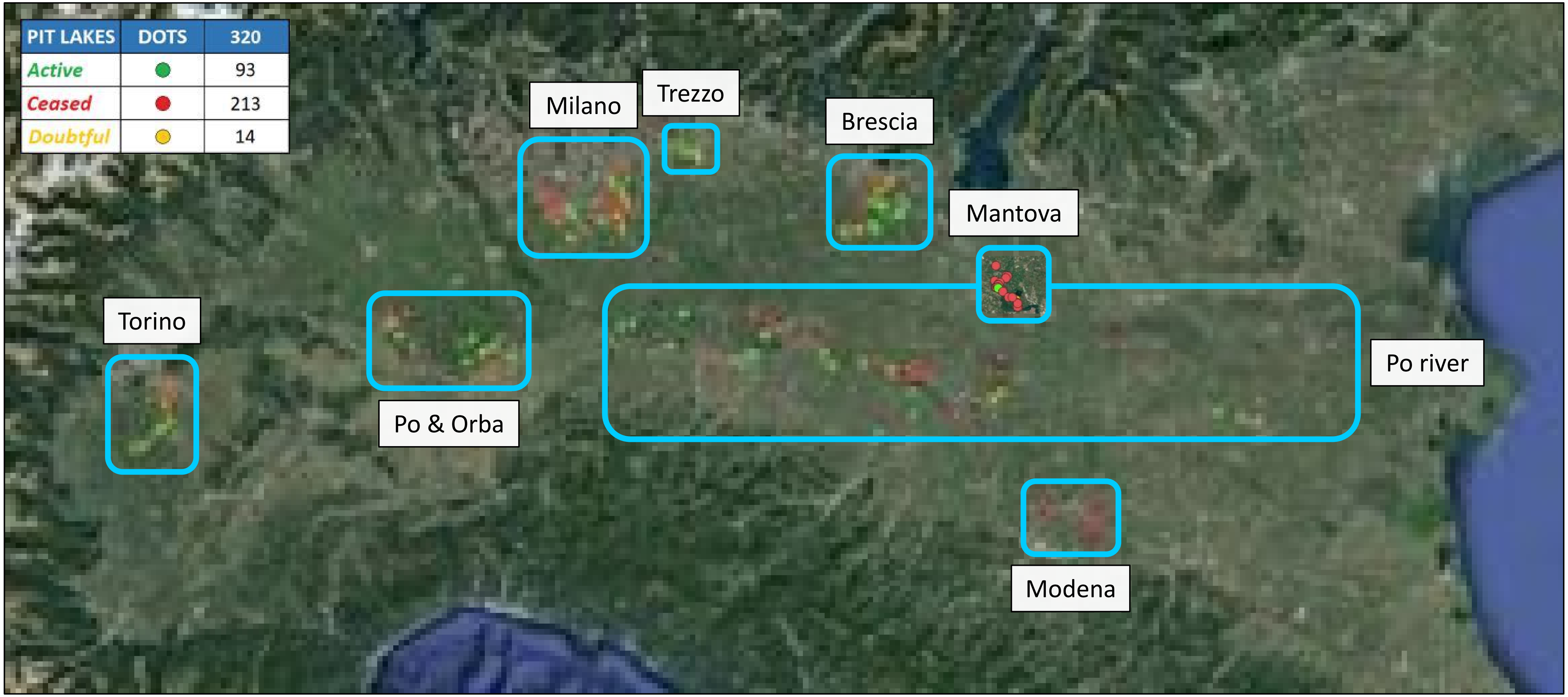
Step 3: morphological and morphometric analysis

$$\boldsymbol{RWI} = \frac{(B3 + B5) - (B8 + B8A) + B12}{B3 + B5 + B8 + B8A + B12}$$

Water bodies identification

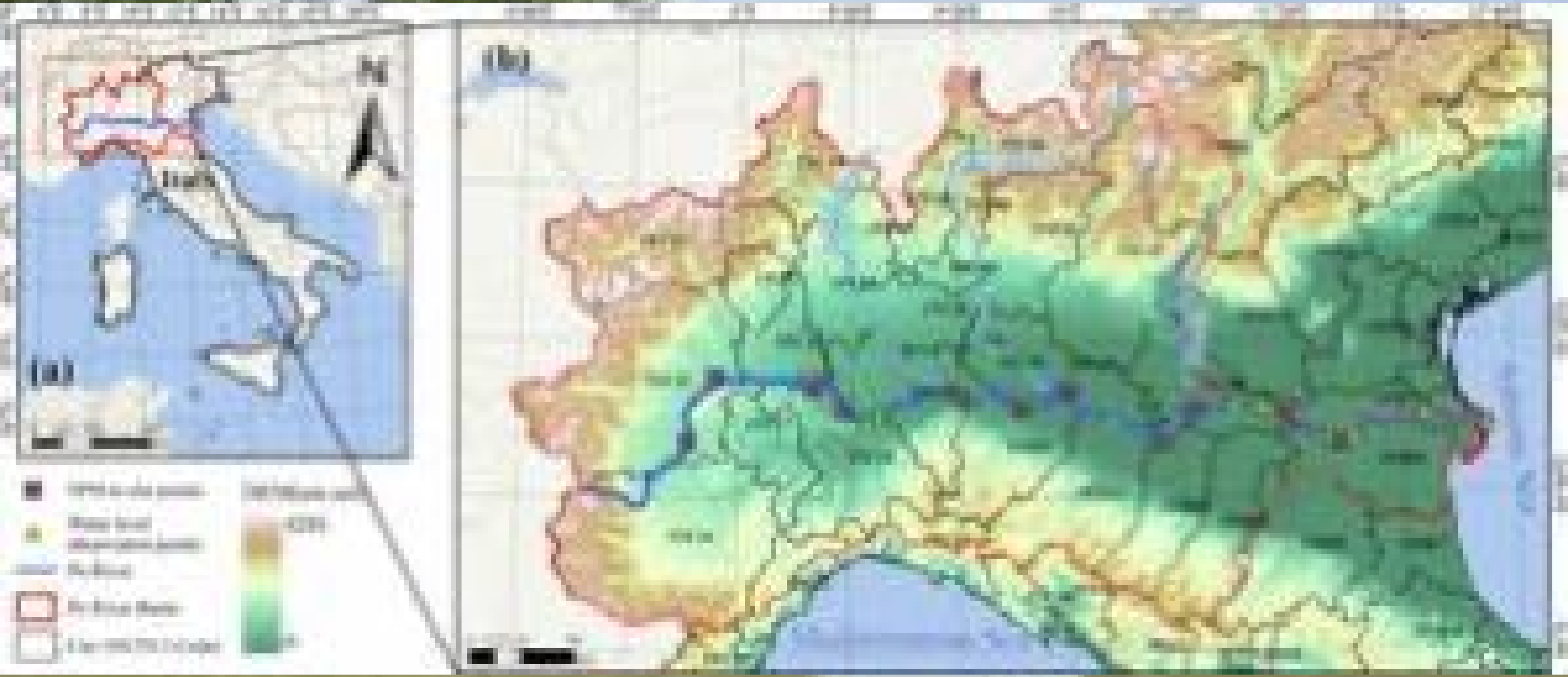
Pit lakes

Creation of a heterogeneous dataset based a **subsample of lakes** differentiated by several factors: ***optical properties***, ***location*** (isolated or connected to the river), ***morphology*** and ***age*** (based on cessation of mining activity).

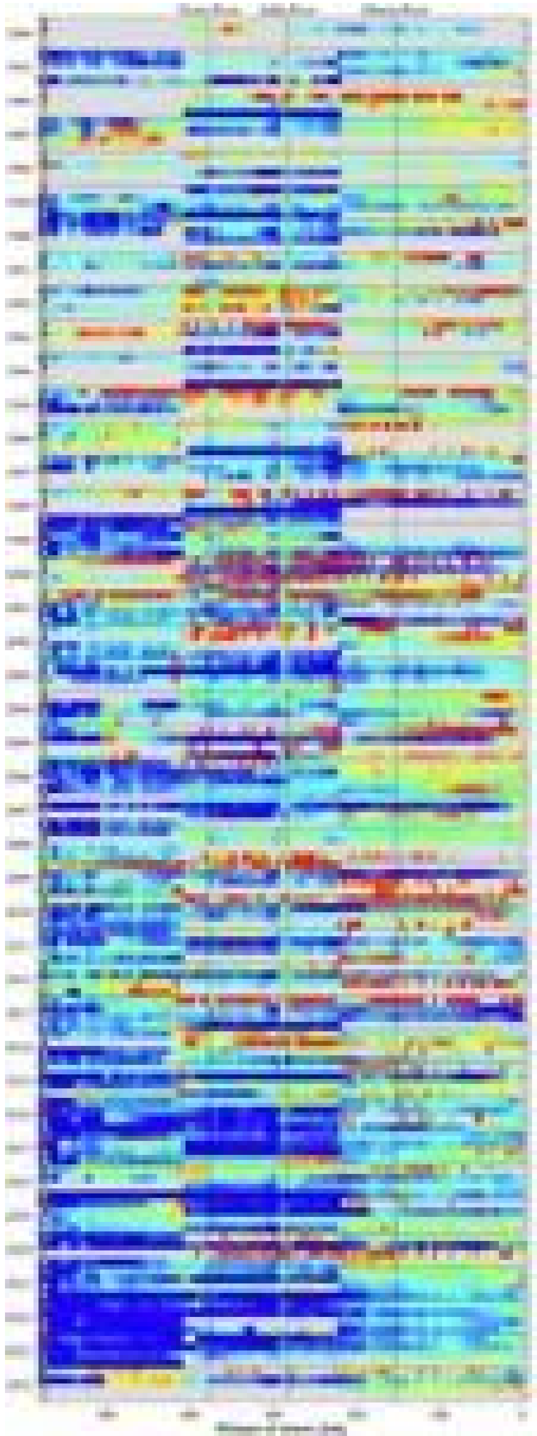


Rivers

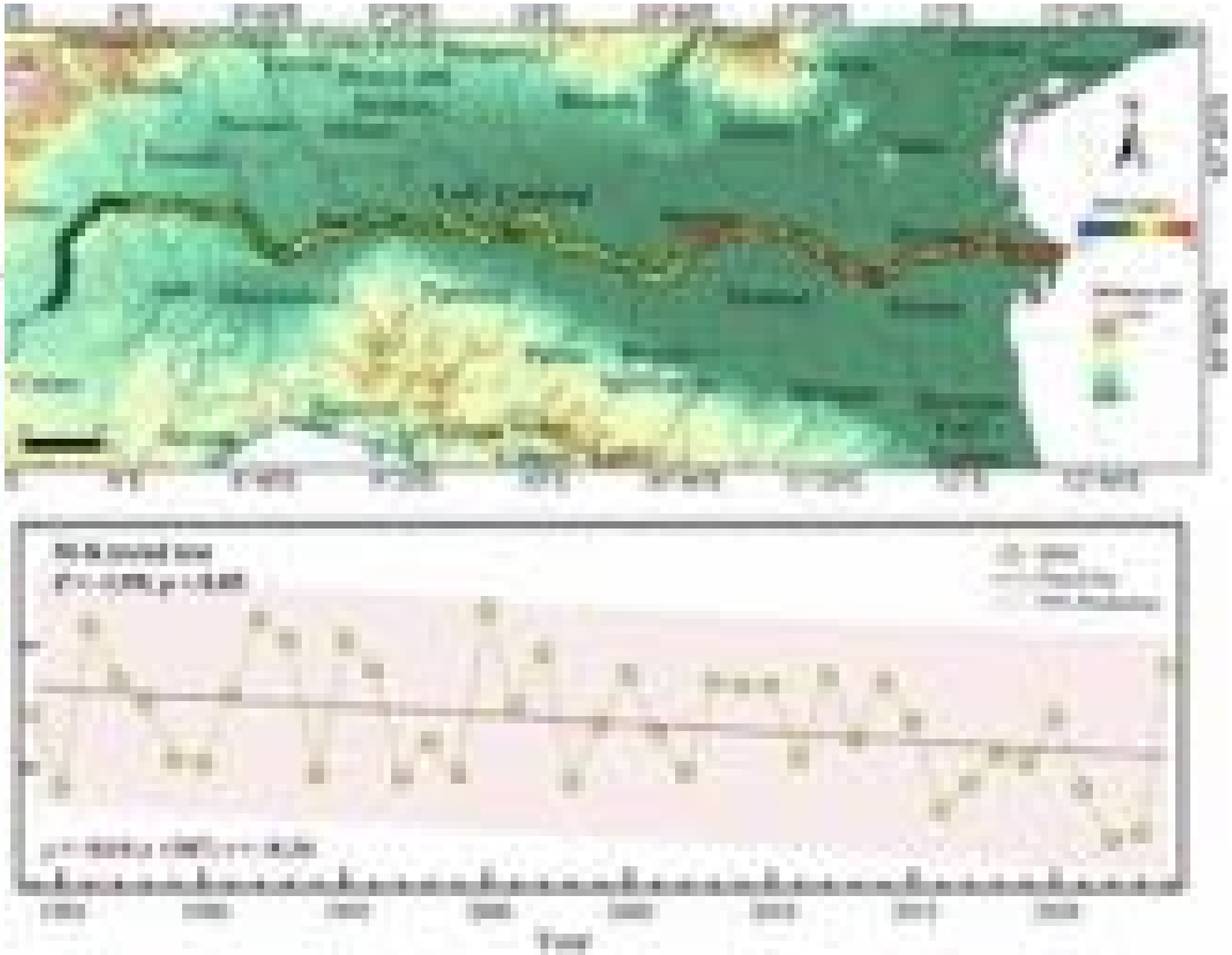
Rivers



Rivers



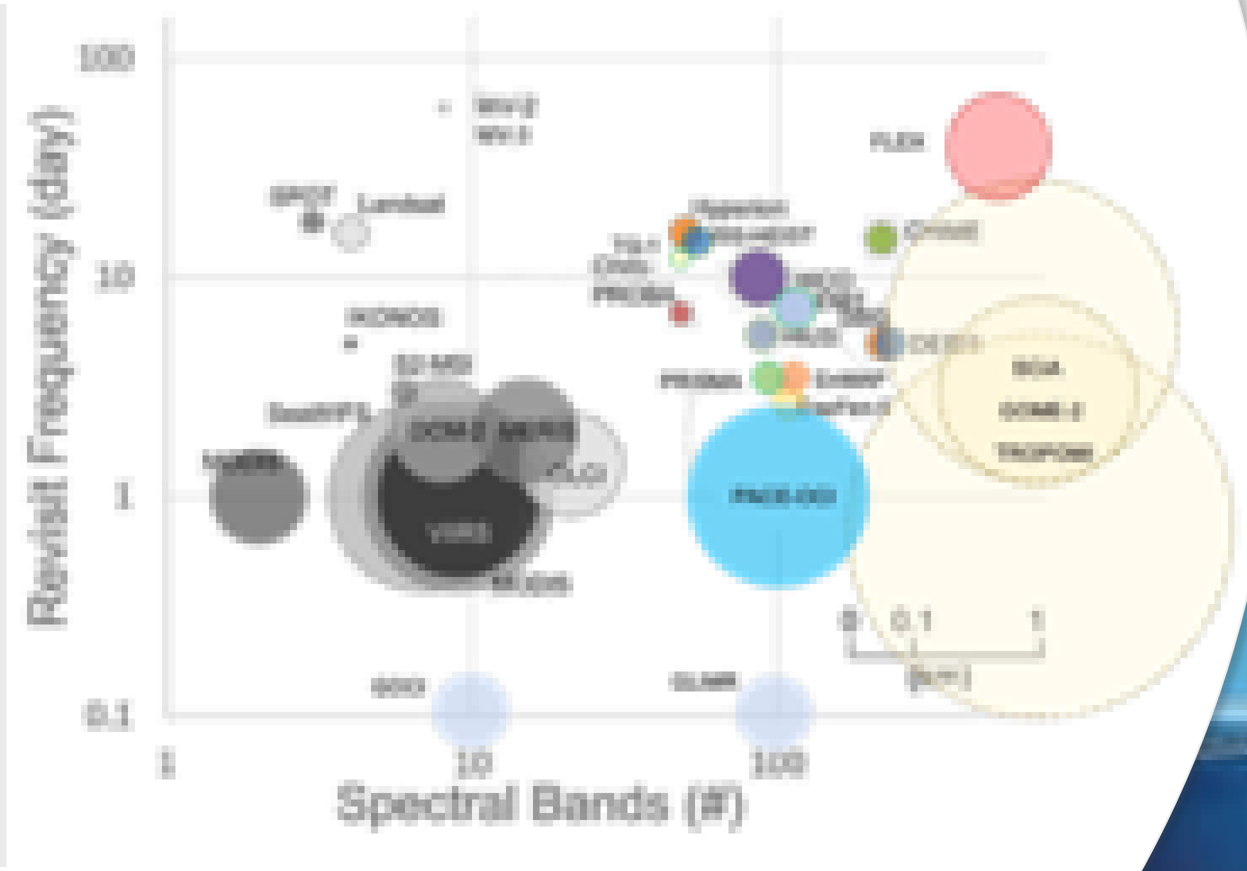
Distribution of SPM concentrations in the Po River, 1984–2024, each raster is 5 km.

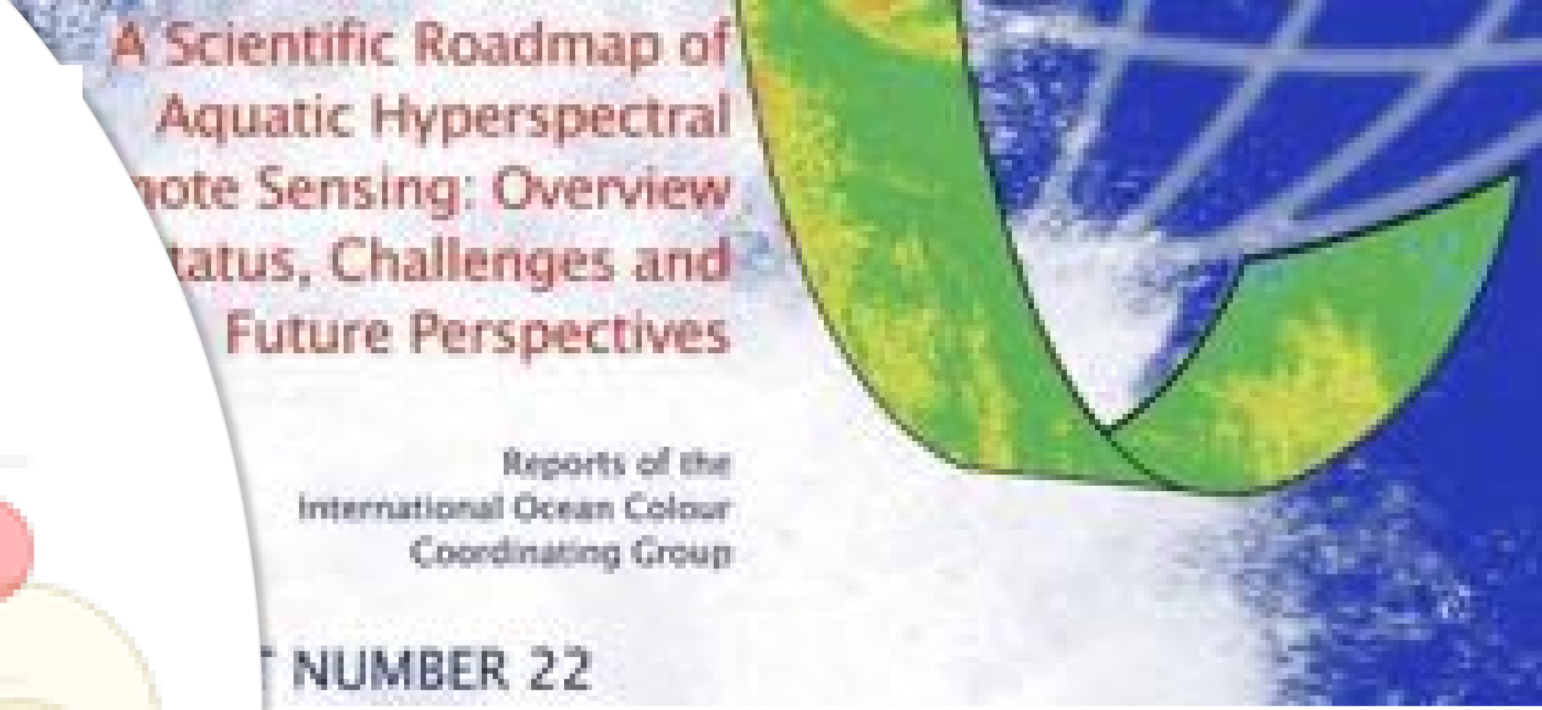


Top: Multi-year average SPM from 1984 to 2024 (each point represents 5 km);; Bottom: inter-annual variability

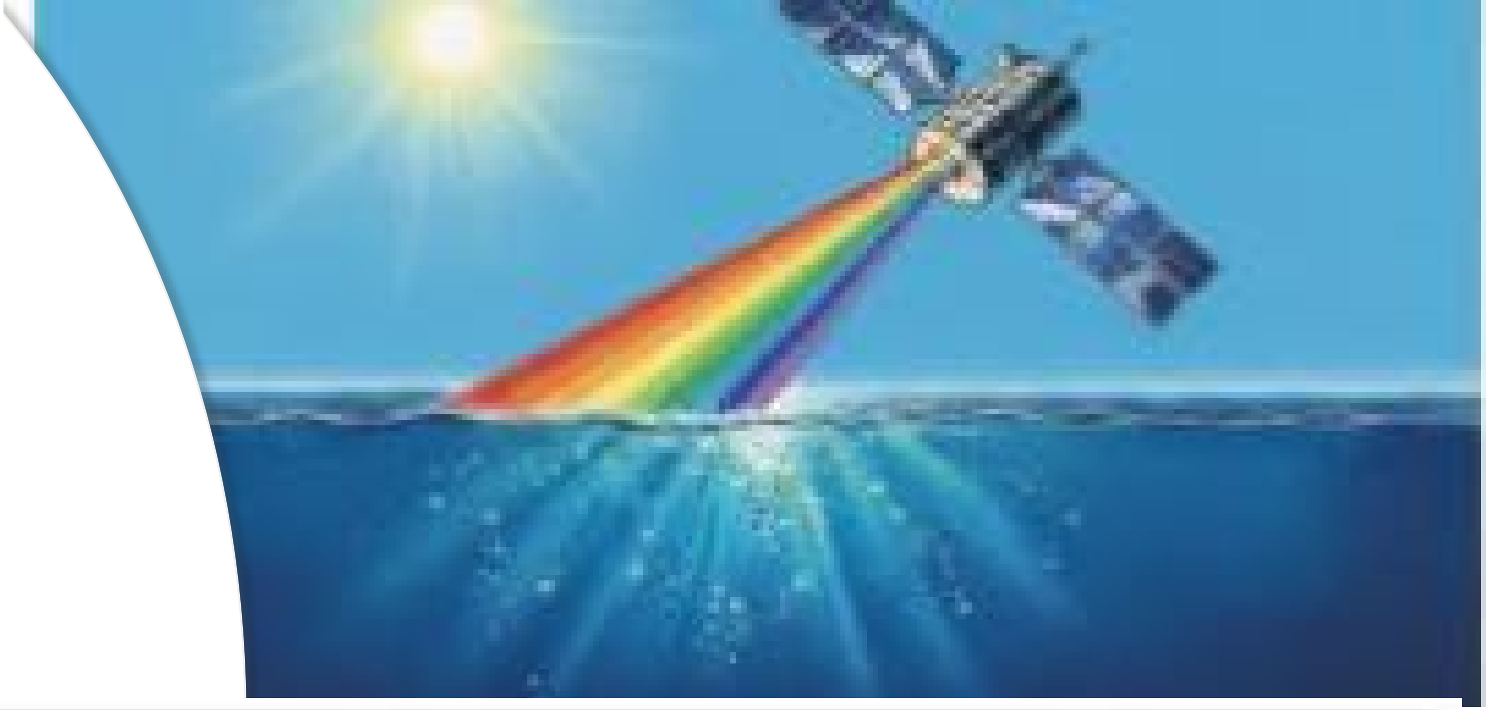
Yang, et al., 2026

HYPERSPECTRAL Satellite Sensors





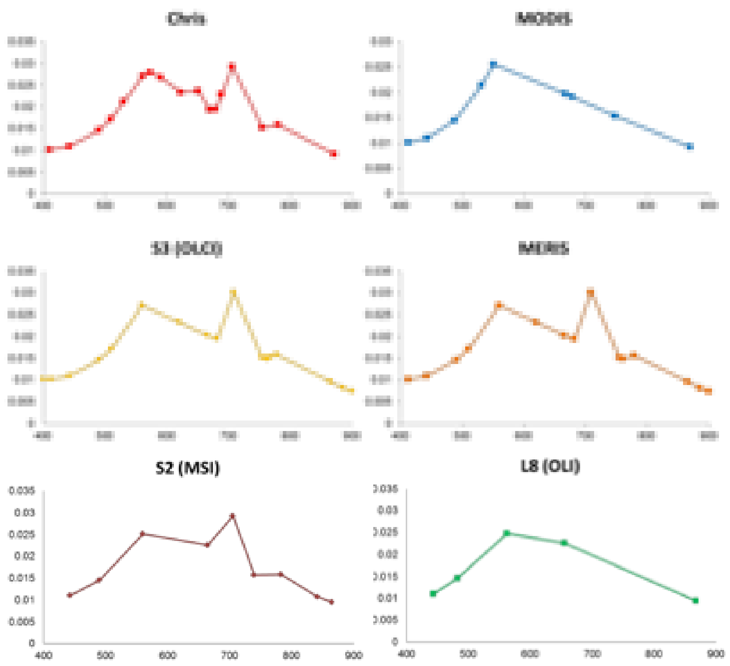
Key precursor HYPERSPECTRAL sensors for inland waters

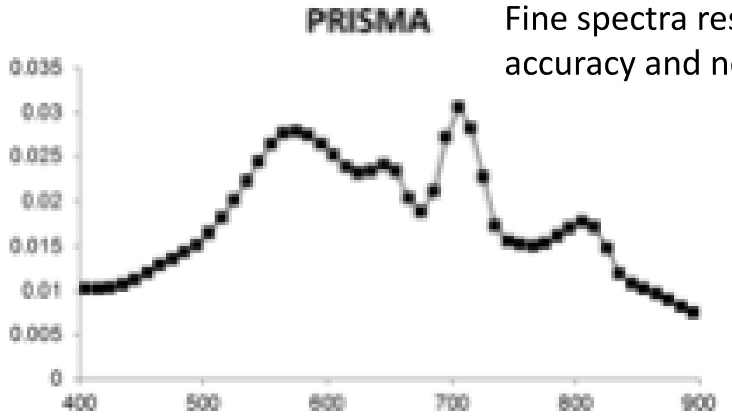


	PRISMA (ASI)	DESIS (DLR)	EnMAP (DLR)
Launch	March 2019	June 2018	April 2022
Spatial Resolution	30 m	30 m	30 m
Spectral Range/Width	63 bands in VNIR (≈10 nm)	60 bands in VNIR (≈10 nm)	65 bands in VNIR (≈6.5 nm)
Orbit	Sun-synchronous	ISS	Sun-synchronous
Standard Atmospheric Correction	MODTRAN (land based)	PACO (land based)	PACO (land based) MIP (water based)

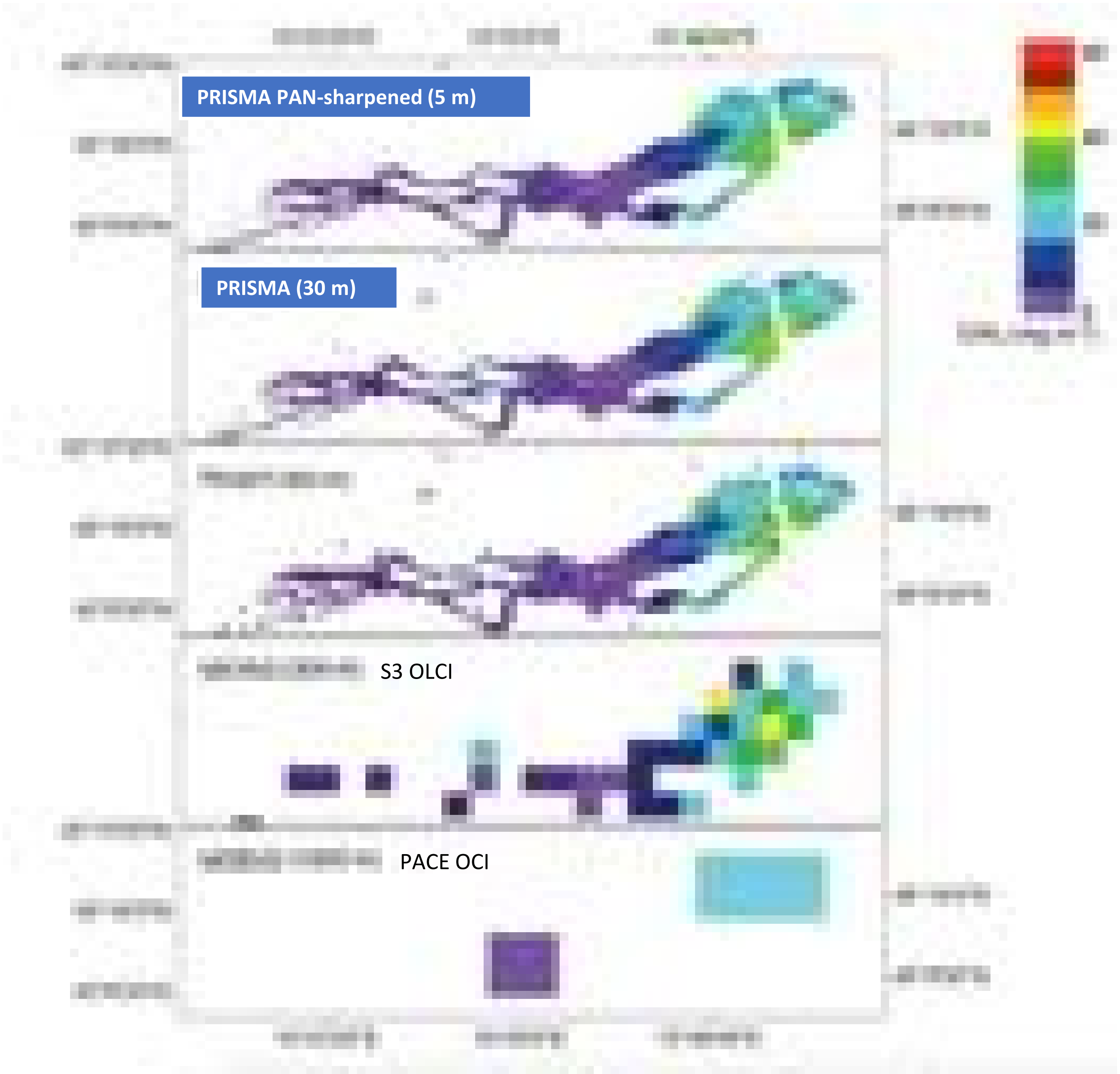
PRISMA

Agenzia Spaziale Italiana

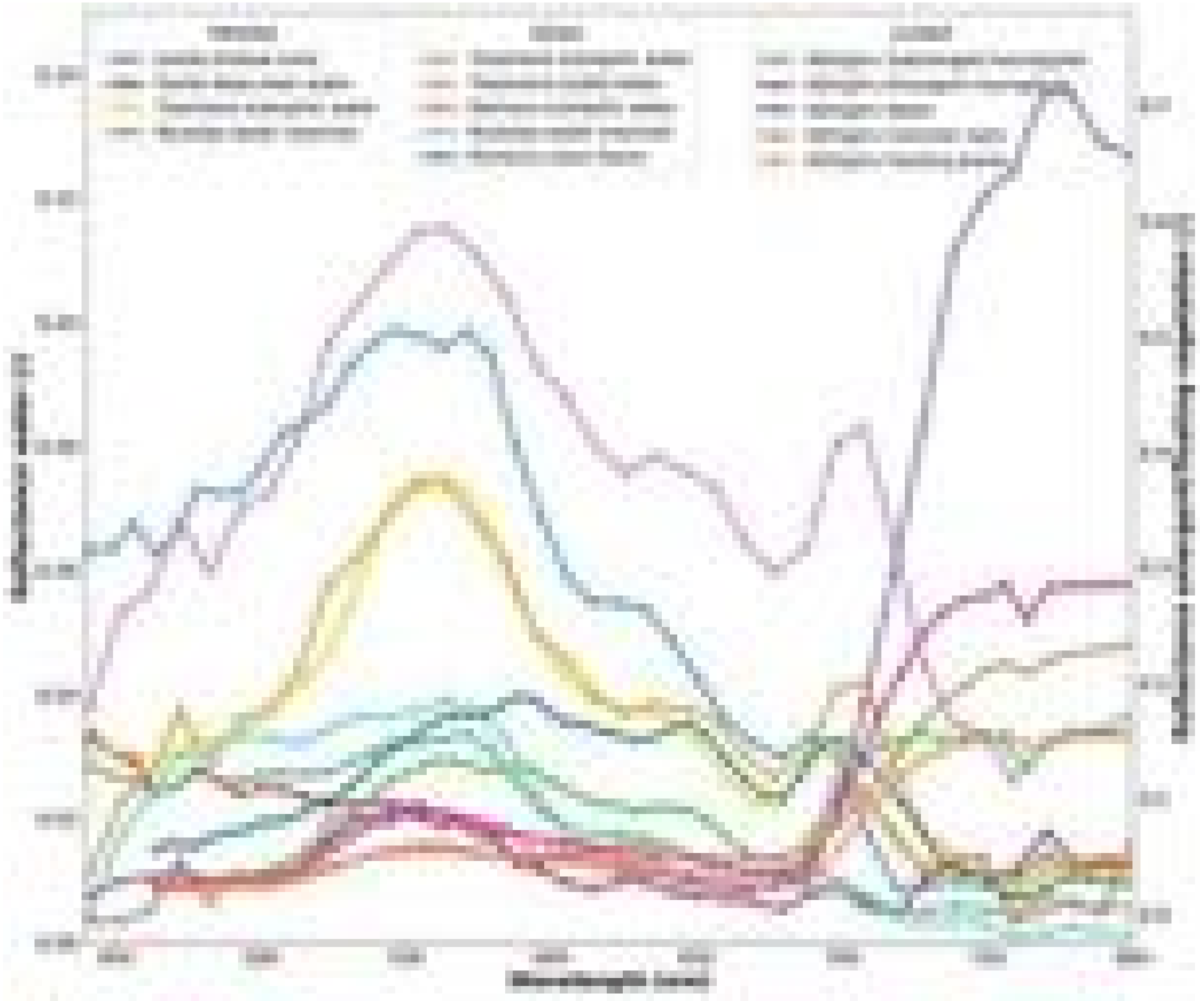




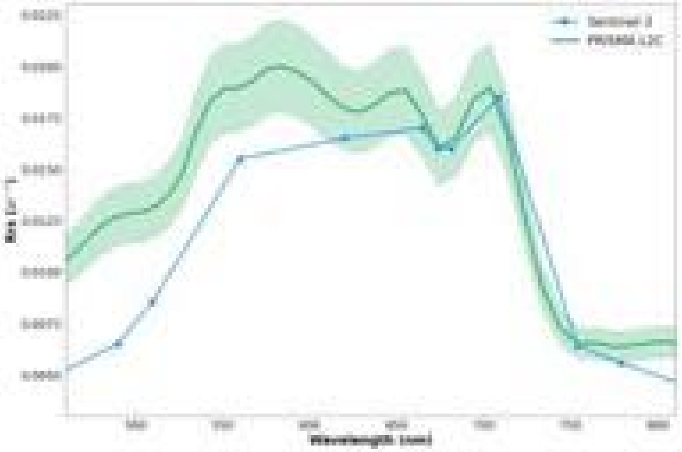
Fine spectra resolution for improved accuracy and new applications



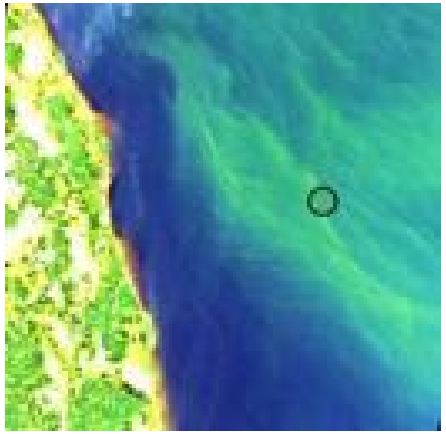
Hyperspectral satellite data

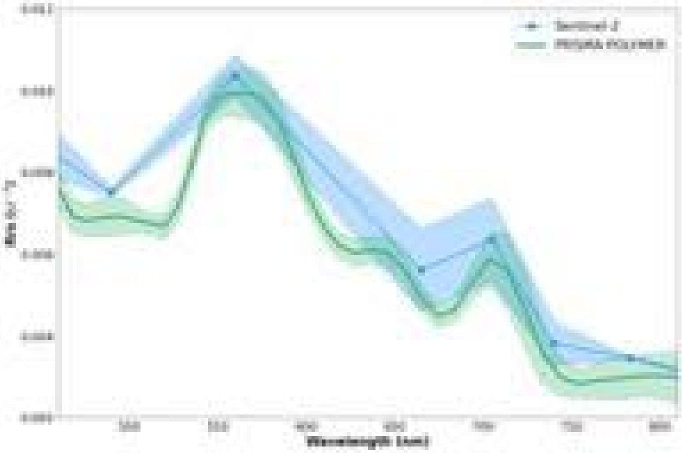


Lake Võrtsjärv



Lake Peipsi





Data and techniques

Line Height

Band ratio

Convolution to filter responses of eye

Dominant wavelengths

Classifiction (land cover -> water cover)

Machine learning for phycocyanine and plant treats

Bio-optical modelling for deep and shallow waters

Dierssen et al., 2021

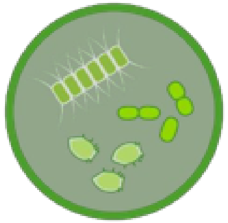
Phytoplankton pigments (chl-a, chl-b, phycocyanin, algal scum)

Total suspended matter (organic/inorganic)

Dominant wavelengths

Aquatic plants mapping and treats

Phytoplankton: chlorophyll-a



- The most prolific primary producers occurring in the oceans and freshwaters
- In inland waters, the need for monitoring is mostly on management (chl-a as a proxy of phyto biomass; EU WFD)

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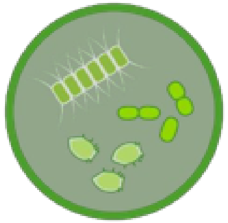

BOMBER *(Bio-Optical Model Based tool for Estimating water quality and bottom properties from Remote sensing images) (Giardino et al., 2012)*

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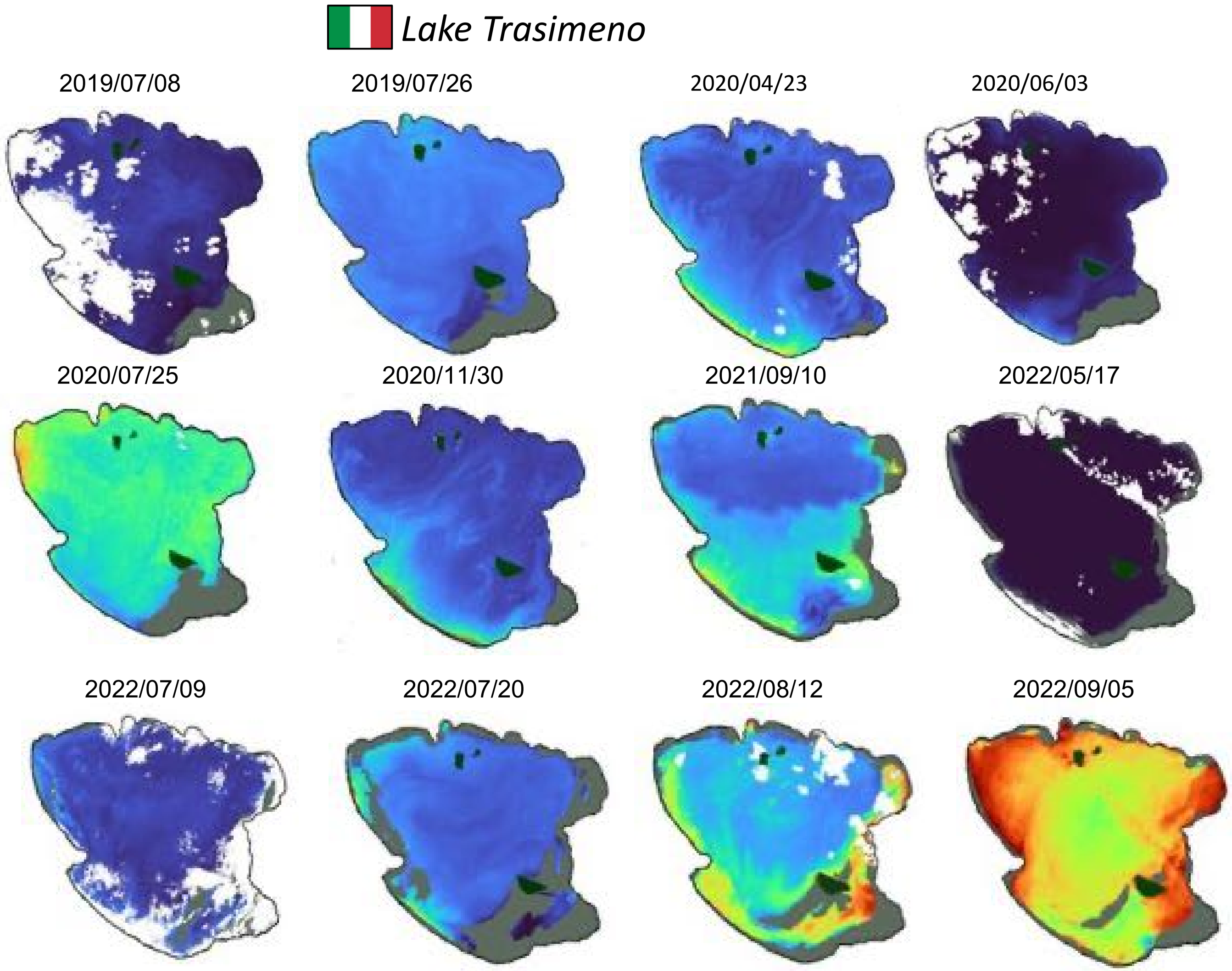

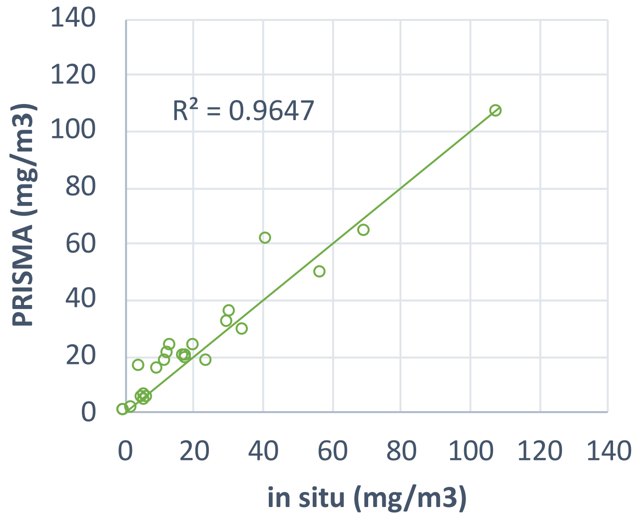

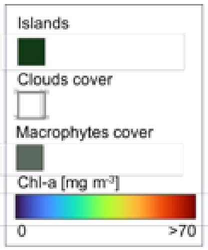

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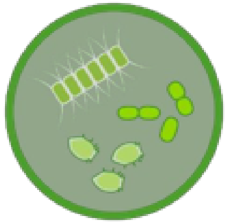

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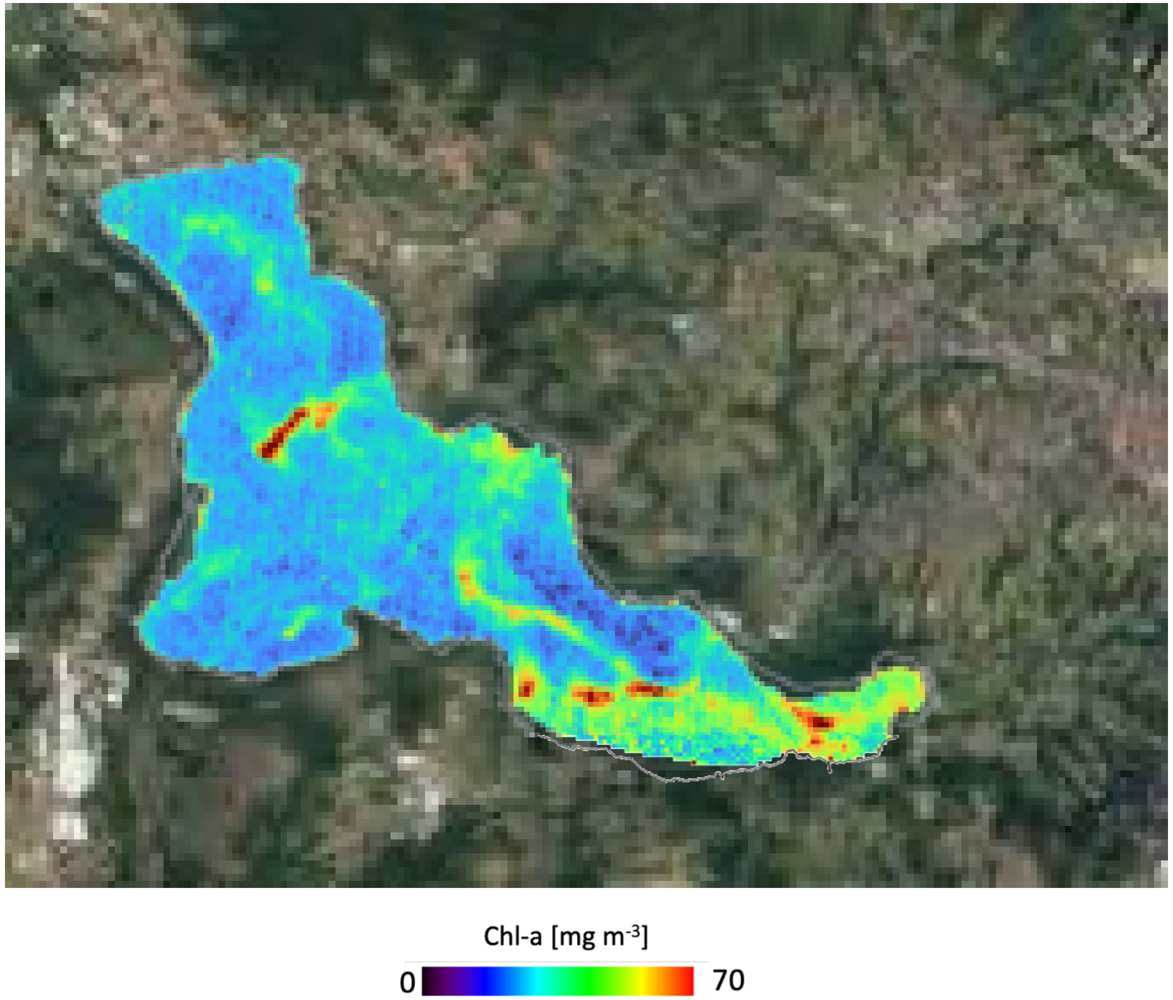
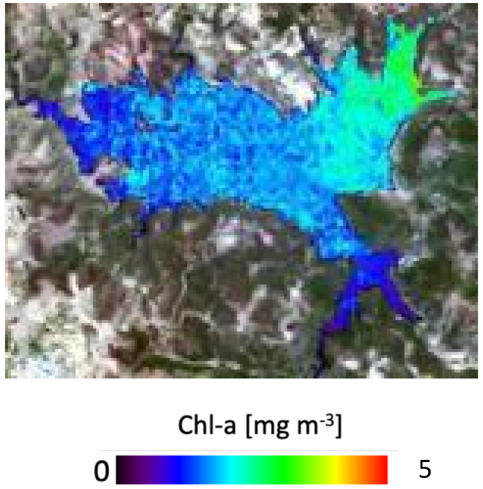
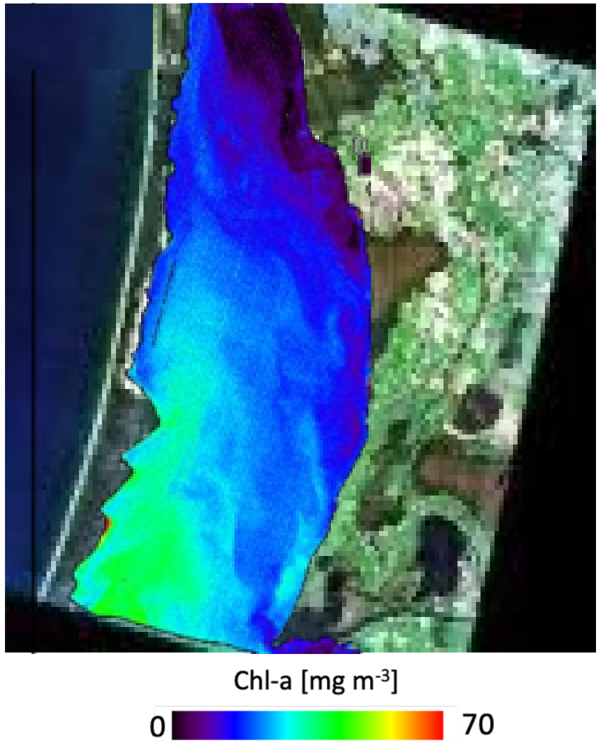
Lake Varese 2021/10/16



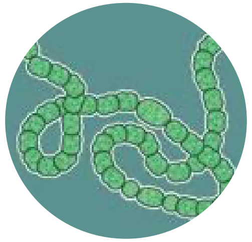
Lake Mulargia 2020/07/08



Curonian Lagoon 2020/09/20



Phytoplankton: cyanobacteria (PC)



Eutrophication is leading to a significant increase in phytoplankton biomass and the frequency of algal blooms, including potentially harmful cyanobacterial algae

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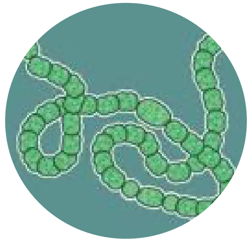

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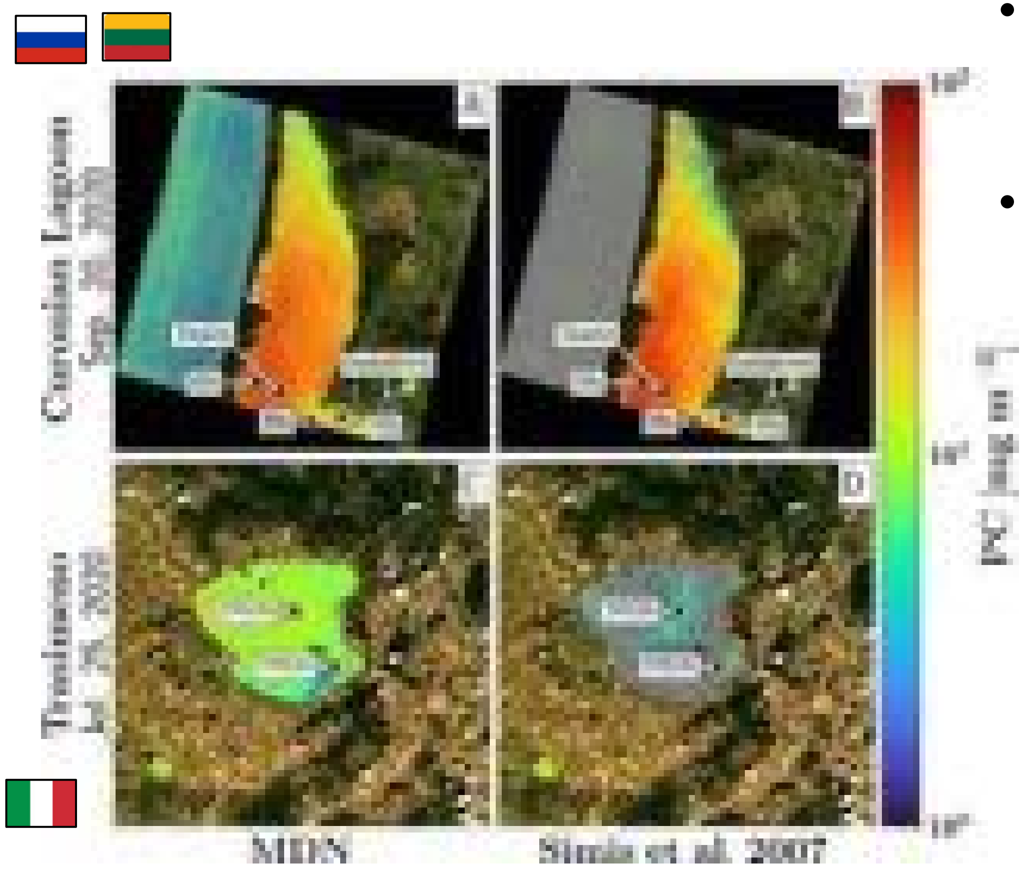

O’Shea et al., 2022

- *Mixture Density Networks (MDN) for retrieving PC from HICO or PRISMA data (O’Shea et al., 2022)*
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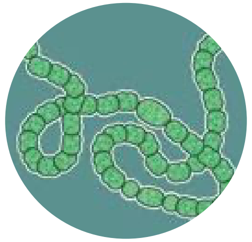

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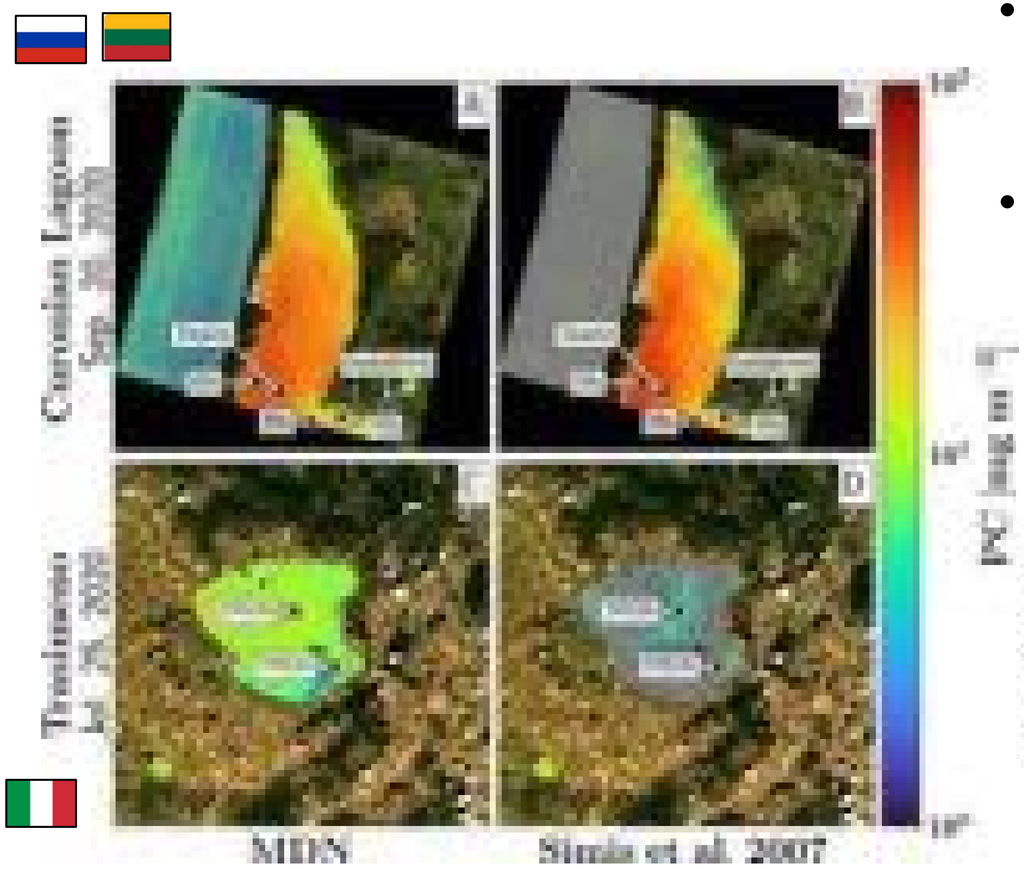

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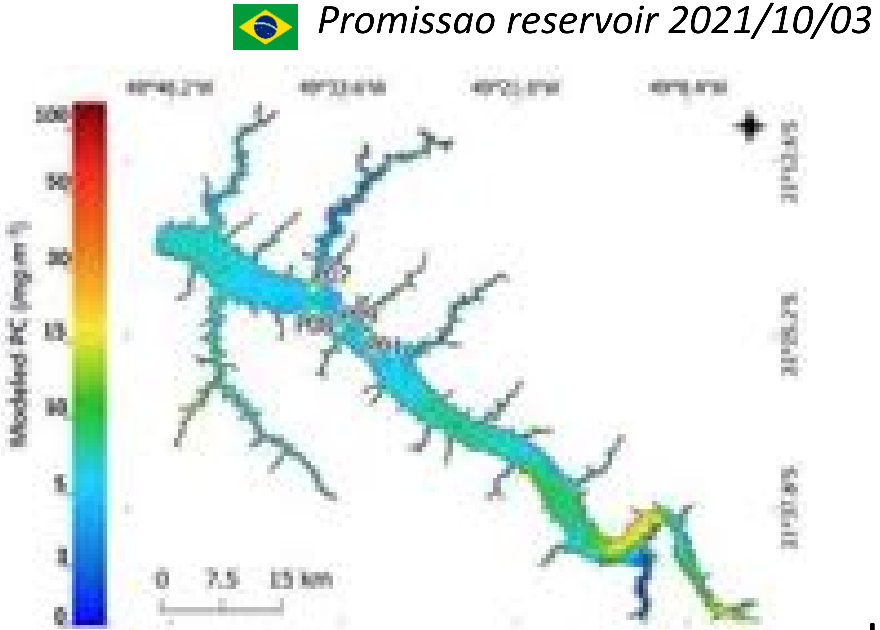
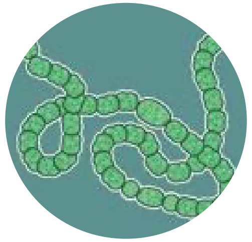
Promissao reservoir 2021/10/03

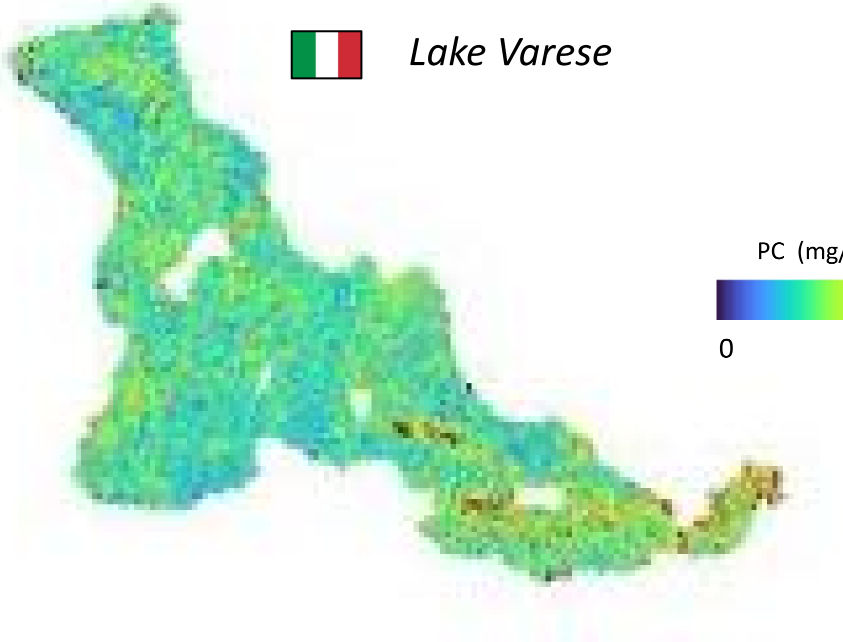


Lima et al., 2023

Phytoplankton pigments (PCs)

Lake Hume 2022/09/03



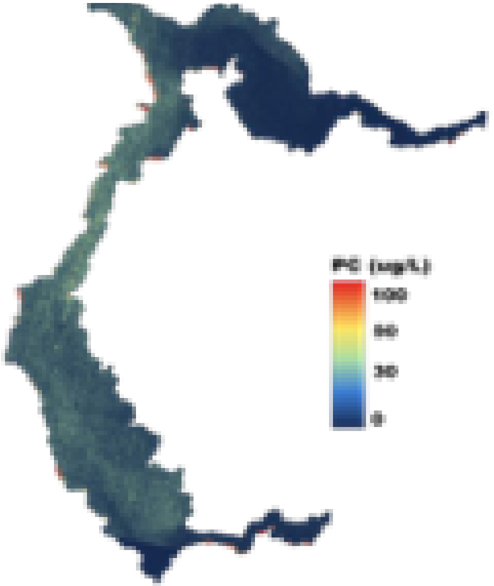


Lake Varese

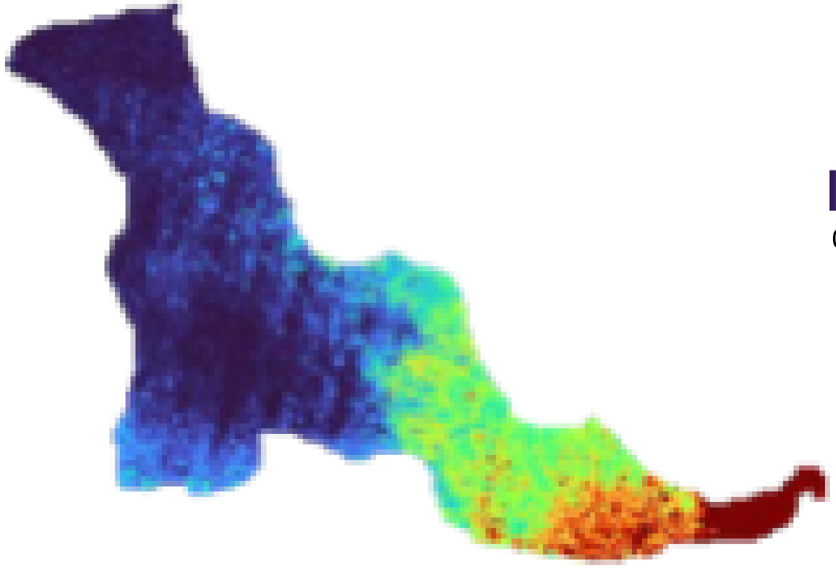
PC (mg/m³)

0 80

CHIME-like (from PRISMA)
16/10/2021



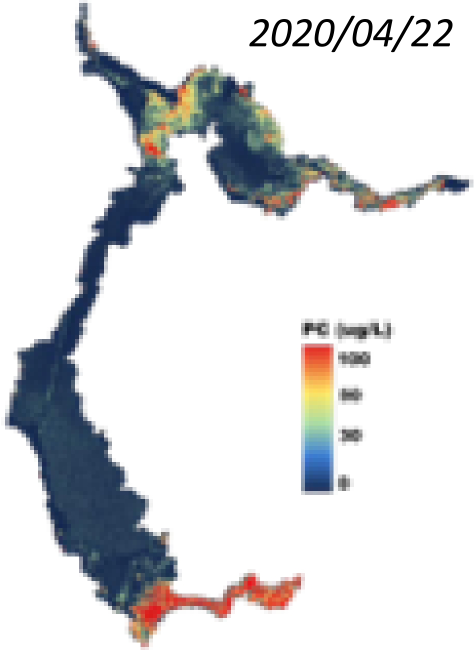
2020/04/22



PC (mg/m³)

0 20

CHIME-like (from EnMAP)
01/08/2022



Phytoplankton pigments (HABs)

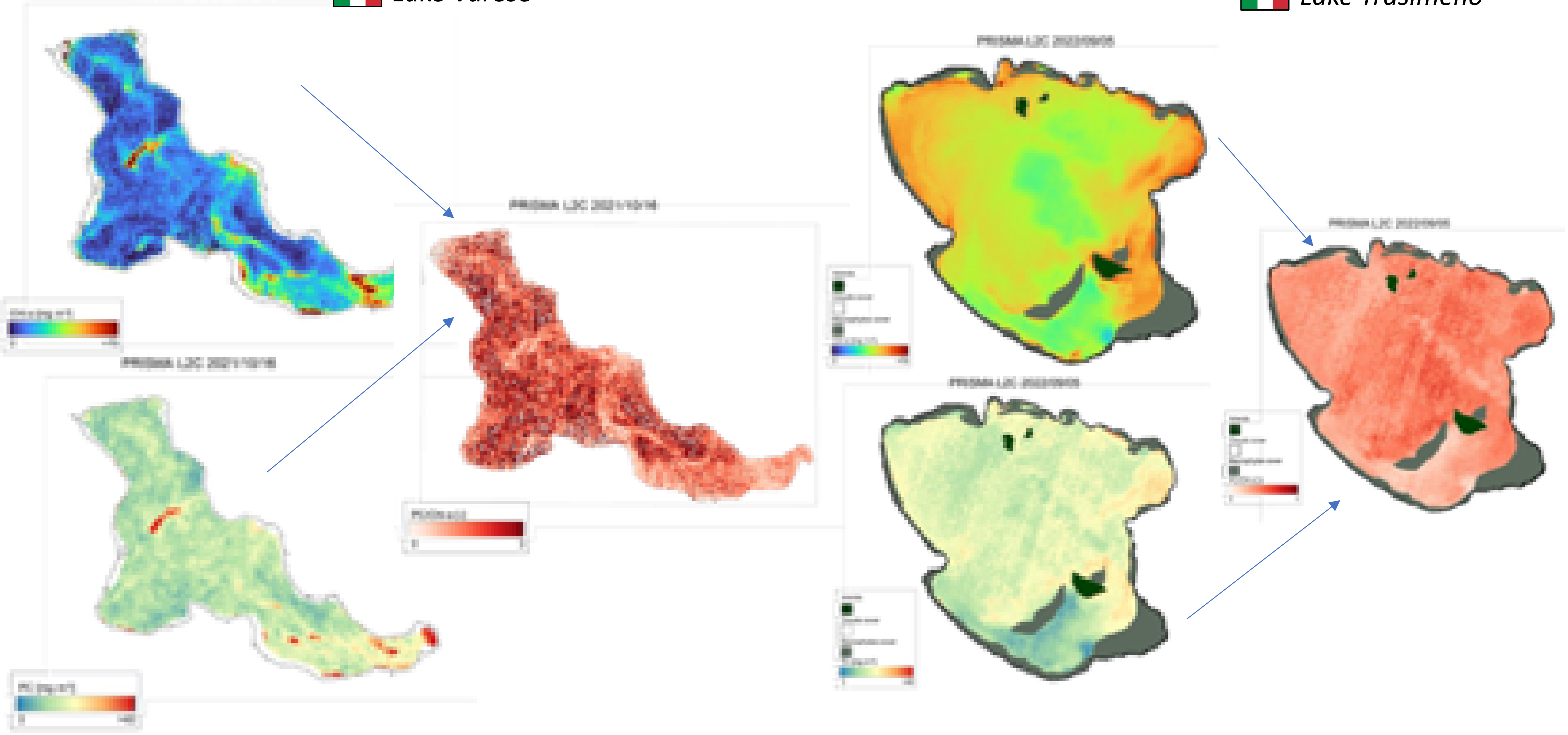
Chl-a and phycocyanin as assertive indicators for the presence of potentially harmful cyanobacterial algae from EO

Lake Varese

Lake Trasimeno

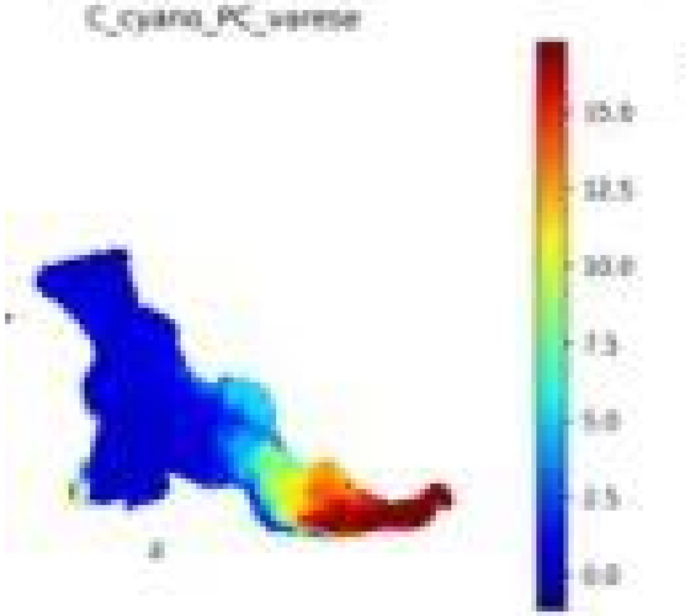
BOMBER (deep water)

MDN for PC

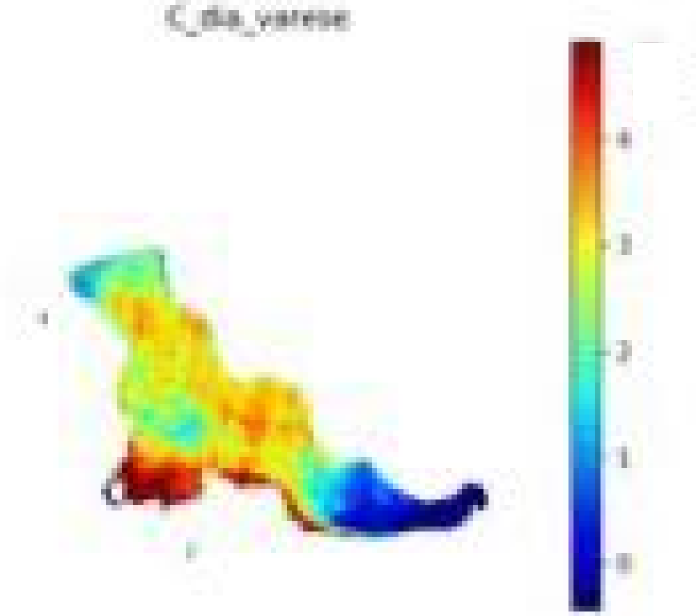


Phytoplankton pigments (PFT)

Lake Varese 2025/08/01



Chl-a (mg/m^3)



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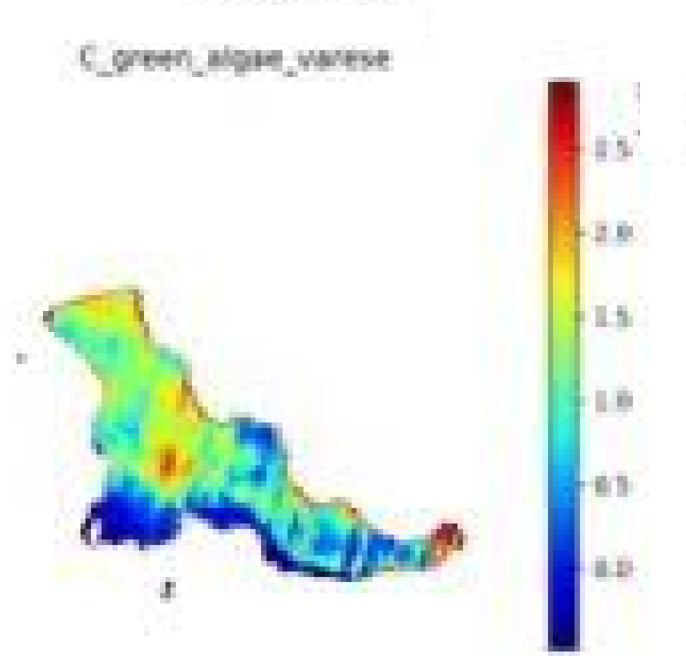
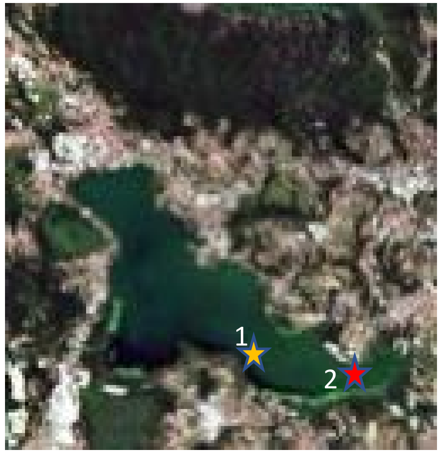
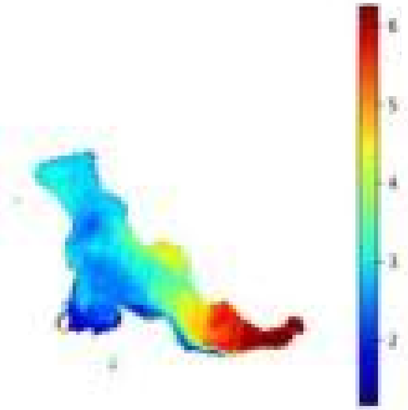


Chl-a (mg/m^3)



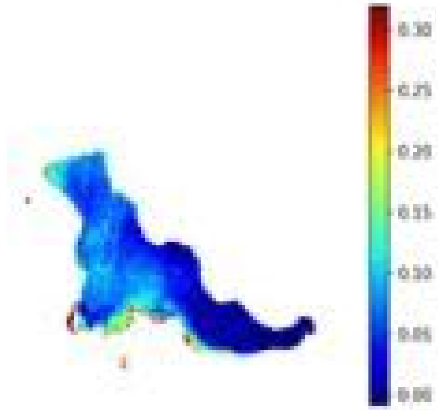
From EnMAP 01/08/2022 to CHIME-like

TSM



TSM (g/m^3)

CDOM

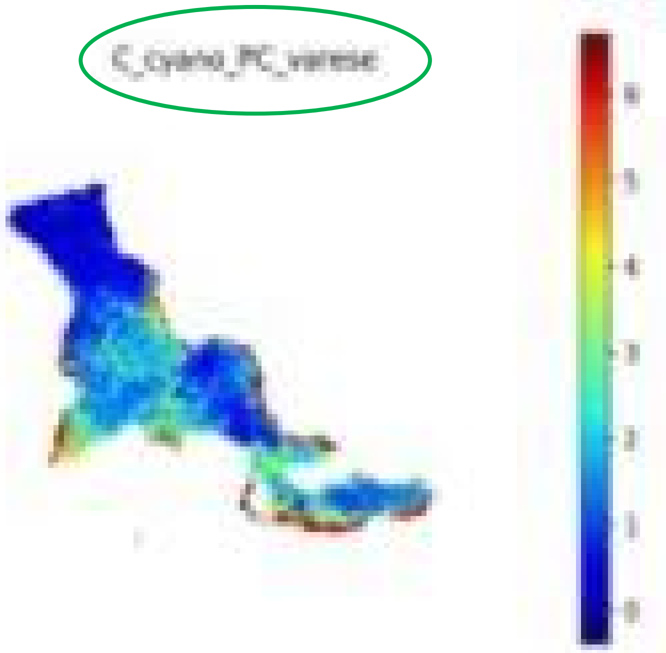


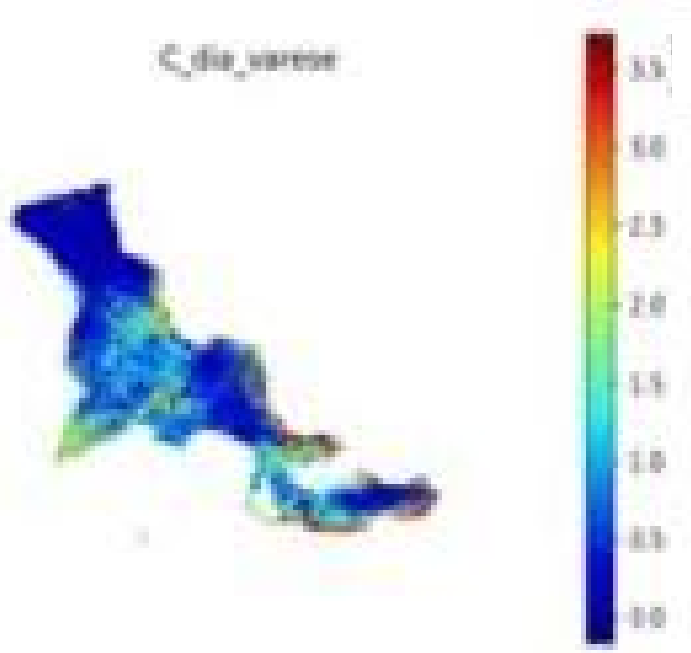
CDOM (m^{-1})

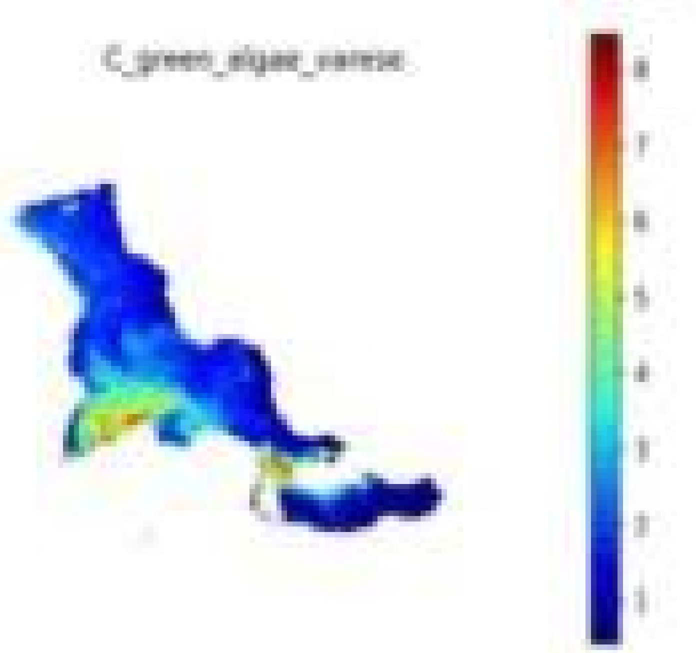
In situ	Chl-a (ug/L)
V_Bodio (1)	4.39
V_Schiranna (2)	22.27

Phytoplankton pigments (PFT)

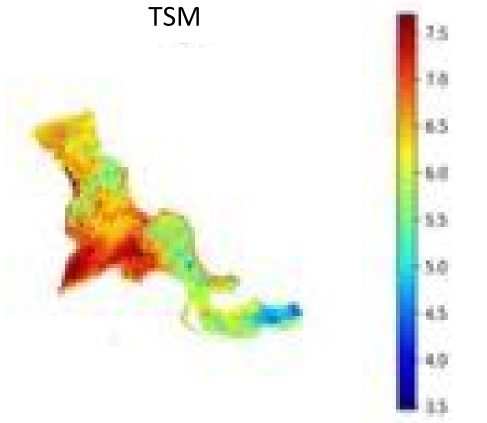
Lake Varese 2024/06/28

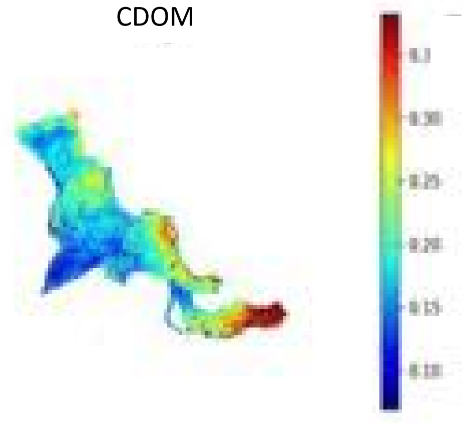






From PRISMA 28/06/2024 to CHIME-like



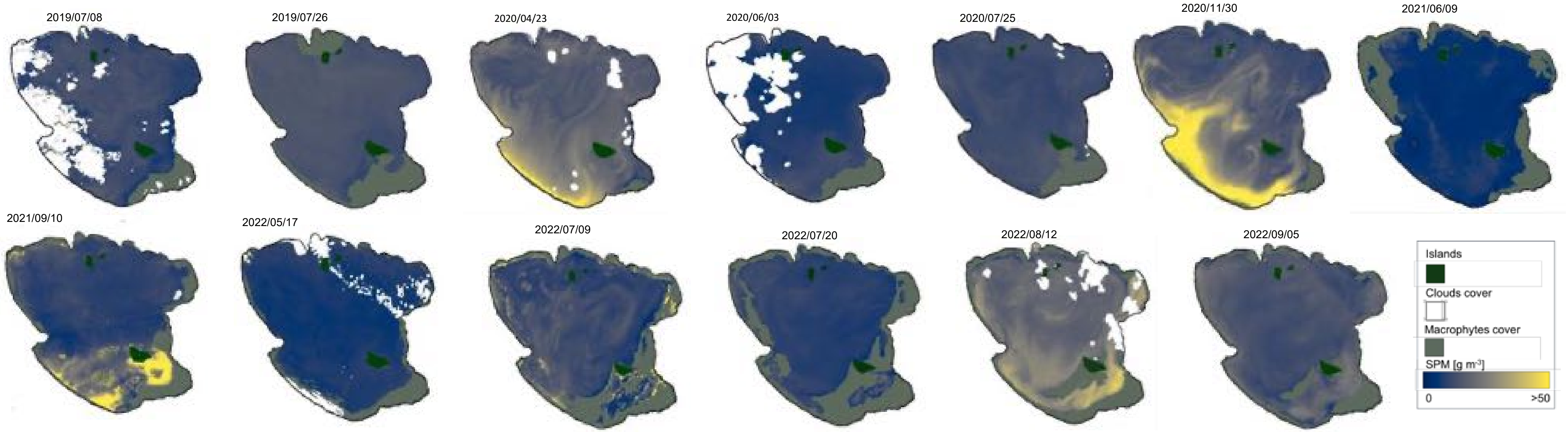


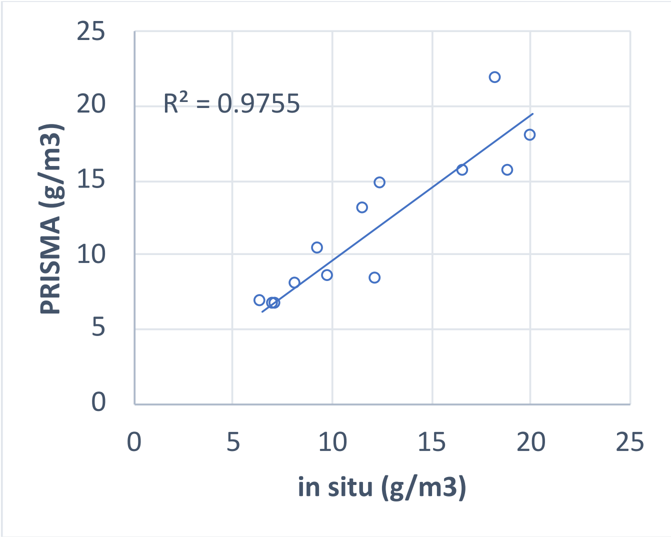
In situ	Chl-a (ug/L)
V_Bodio (1)	14.85
V_Schiranna (2)	8.68
V_Gavirate (3)	13.70

Total suspended matter

Play a fundamental role in the aquatic ecosystem as they regulate two major transport routes of materials and contaminants

Lake Trasimeno





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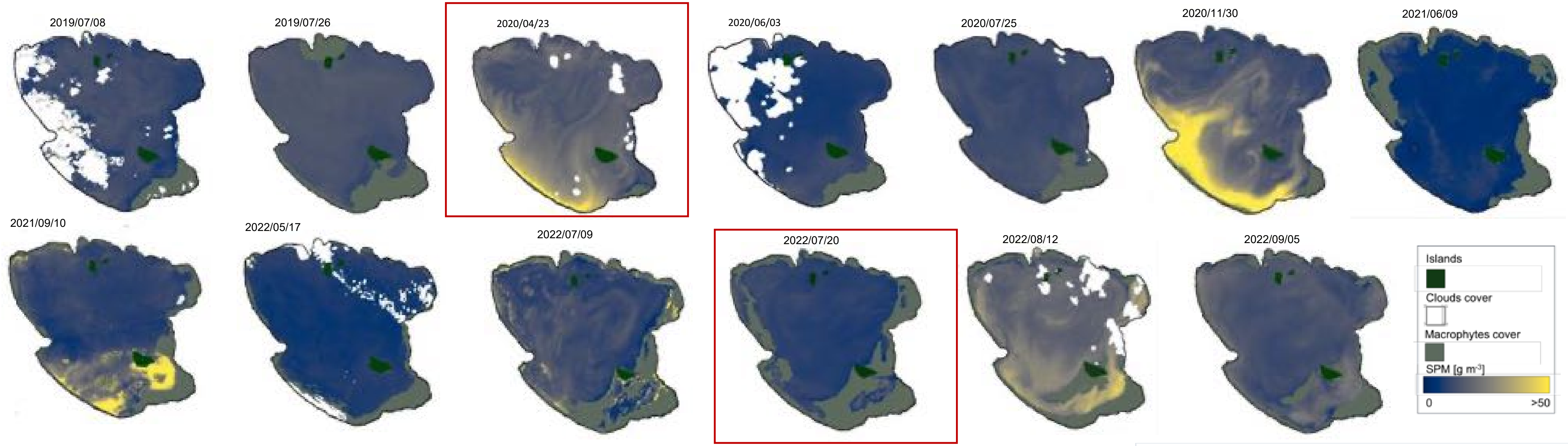
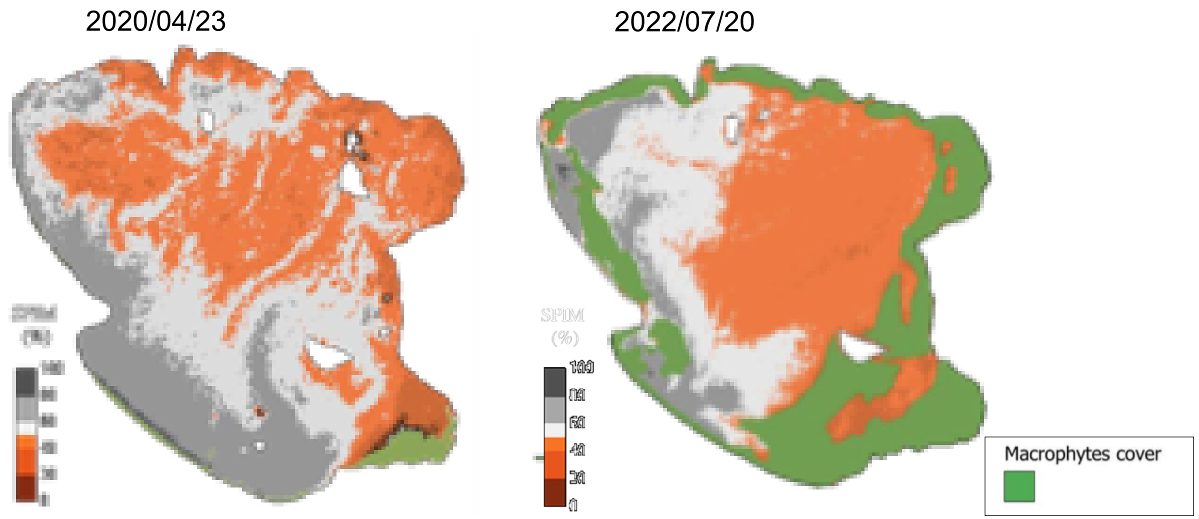
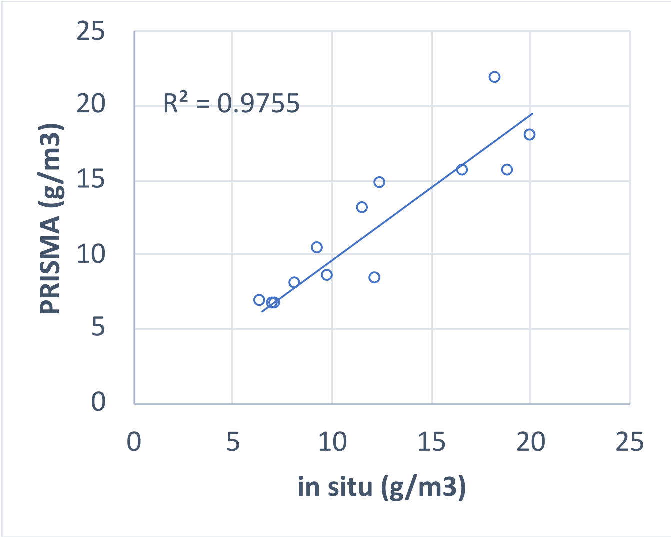


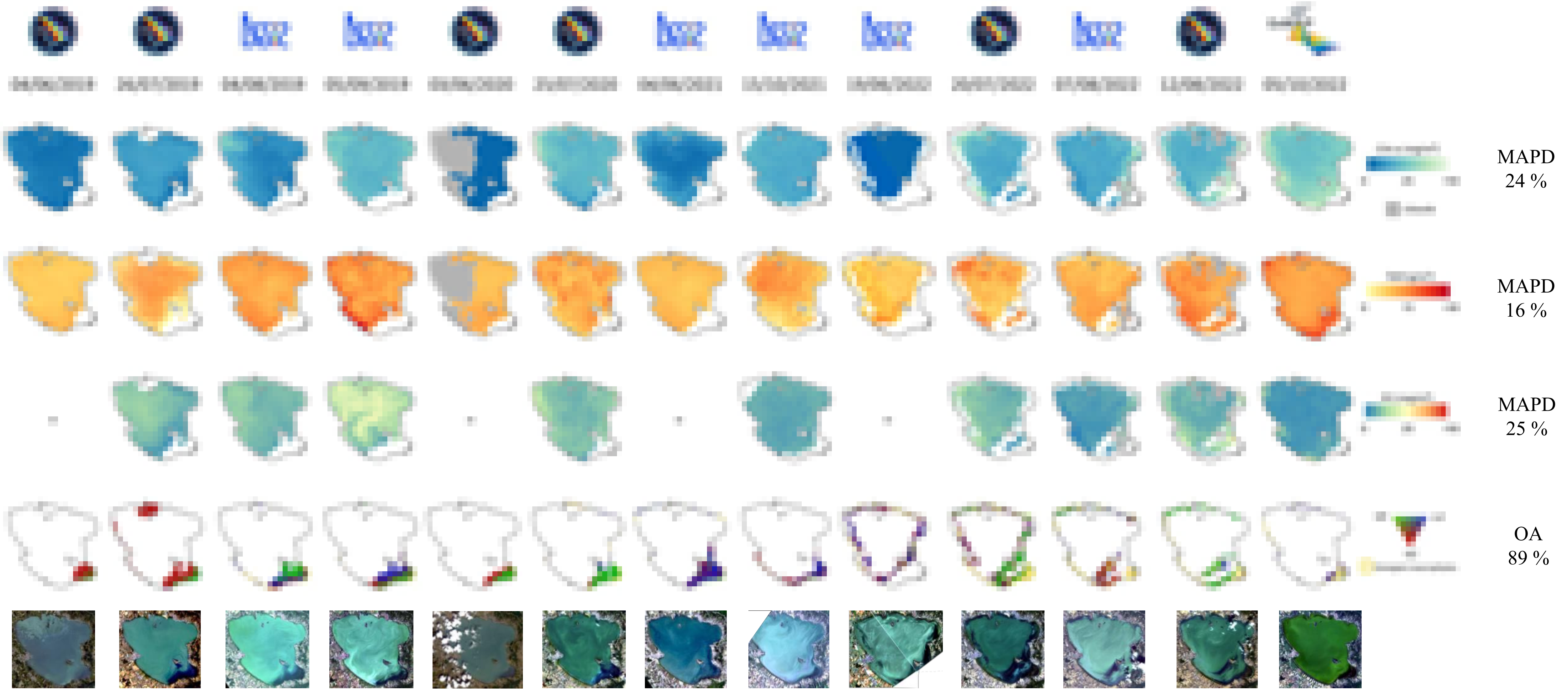
BOMBER (organic and inorganic b_bp parametrisation)





A full picture over time

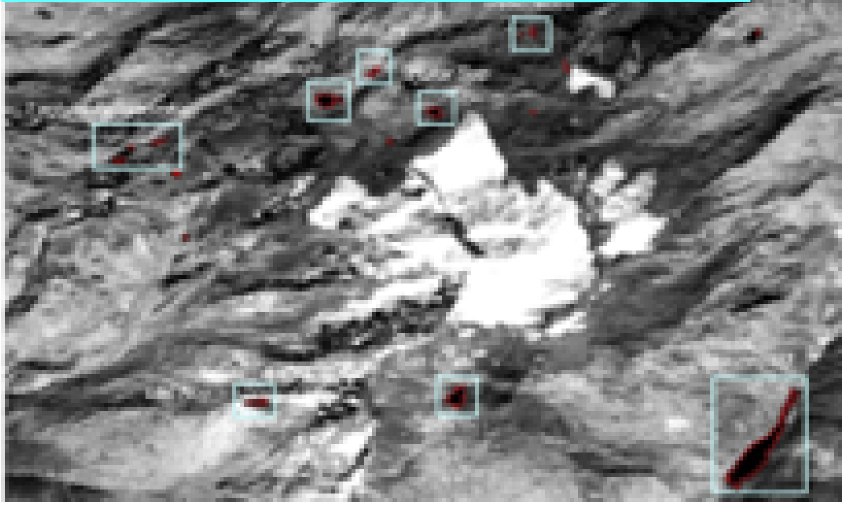
Fabbretto et al., 2024

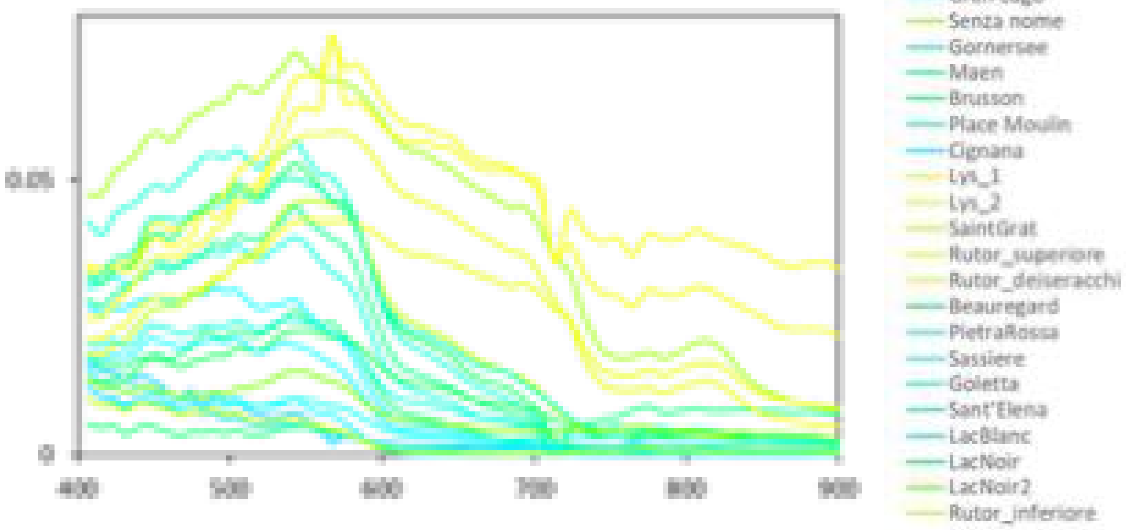


Chromaticity for alpine lakes

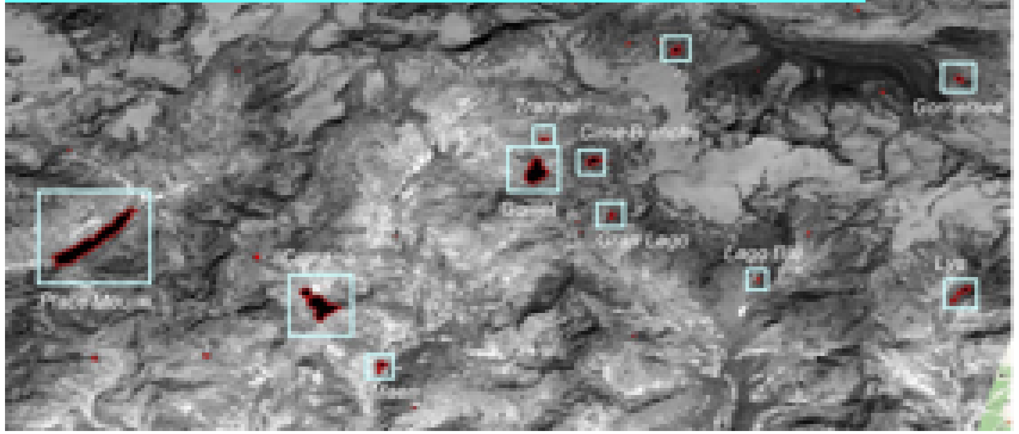
Aosta Valley 2023/09/24

Rutor 2023 -> 62% of lakes > 0,01 Km²





Plateau Rosa 2020 -> 34% of lakes > 0,01 Km²



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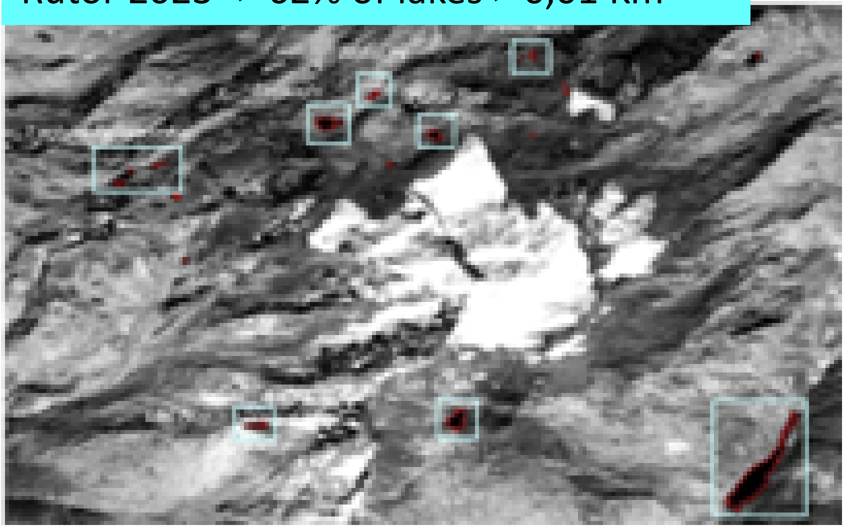

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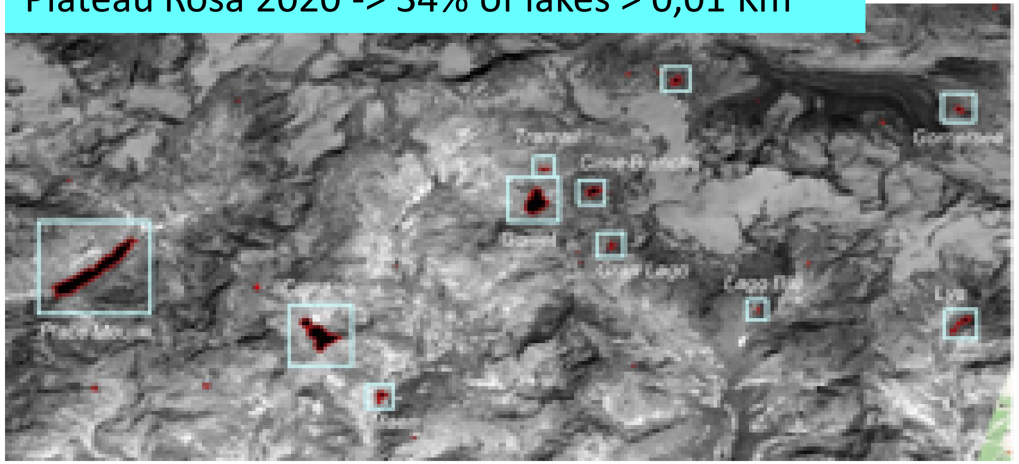
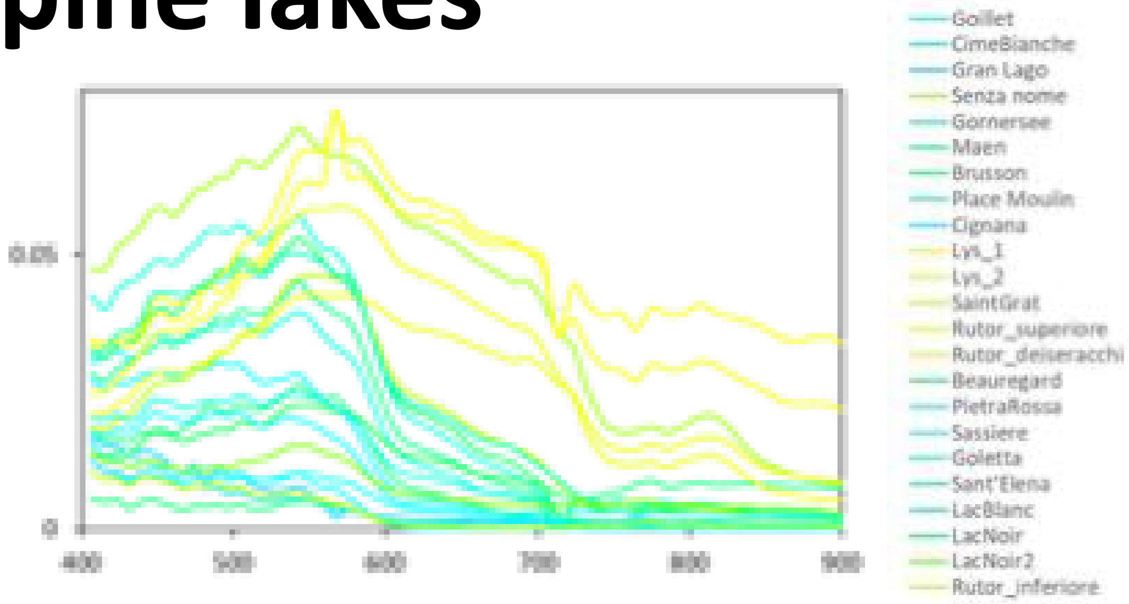
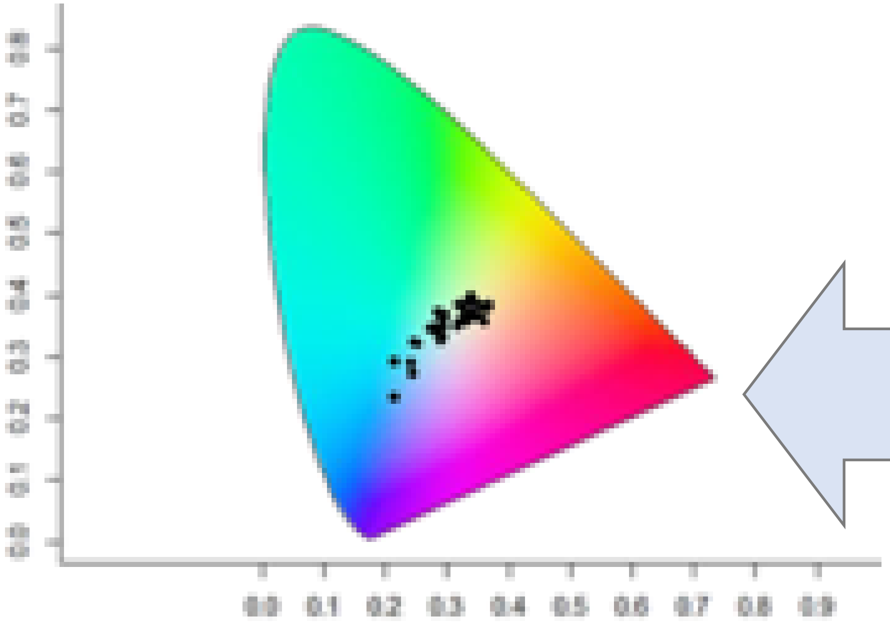
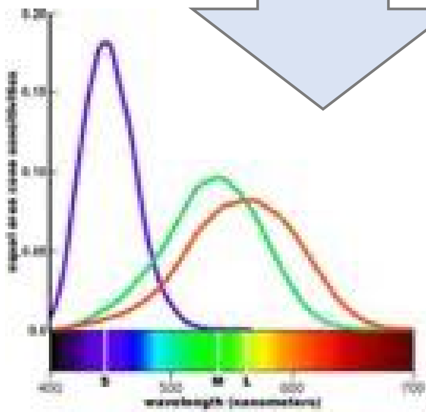


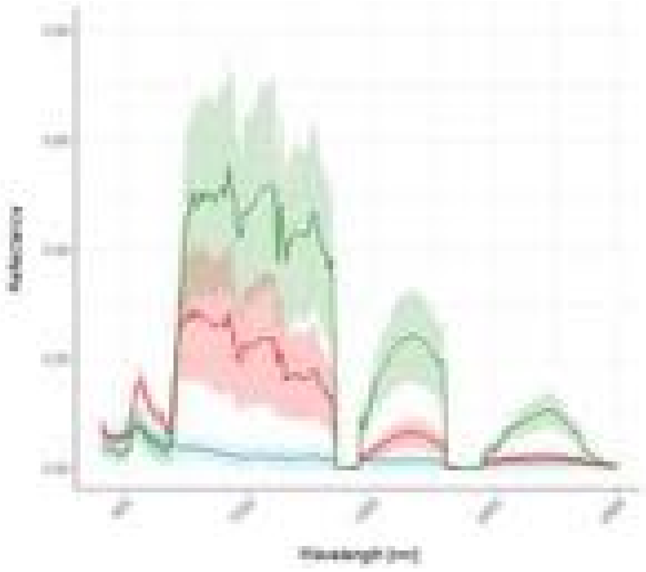


Convolution with eye response filters (no coefficients for multispectral band setting needed), kindly checked by Hans van der Woerd

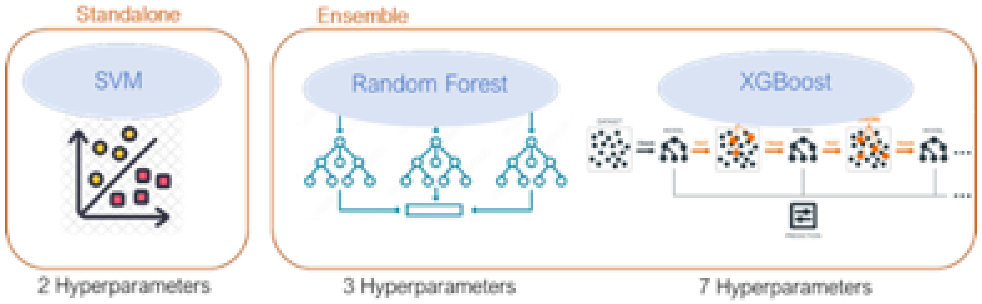




Floating matters

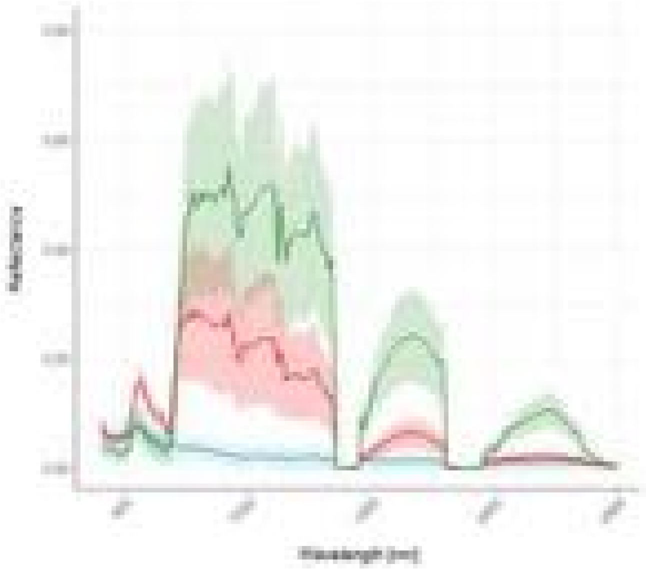


Classification techniques



Floating matters

	Reference		
Prediction	AS	AV	OW
AS	8%	0%	0%
AV	0%	25%	0%
OW	0%	0%	68%



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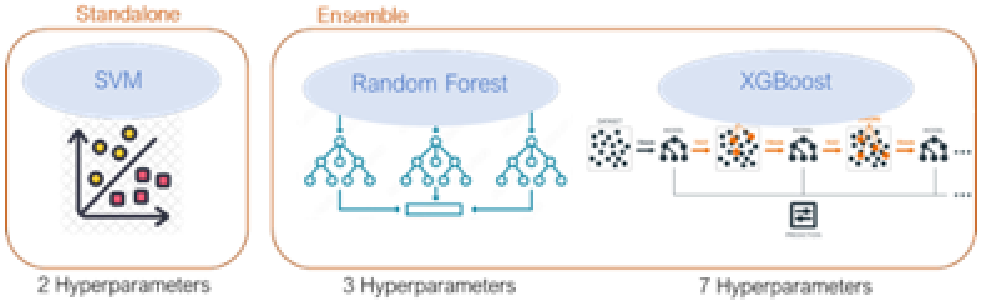
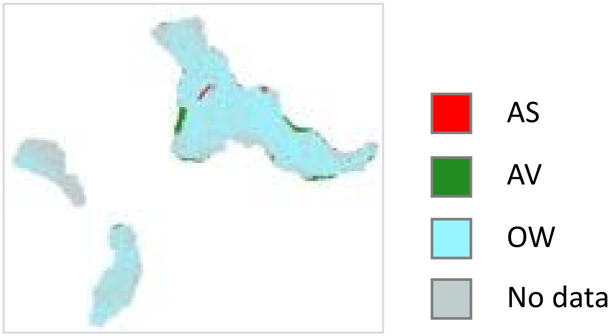


Lake Varese 2021/10/16



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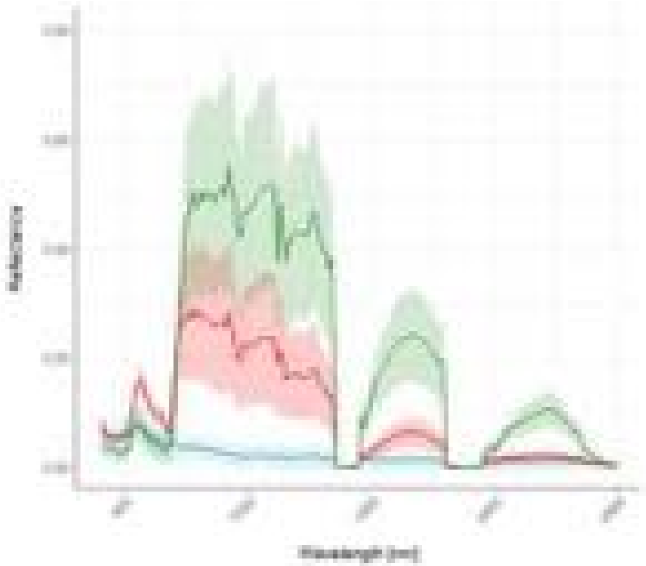

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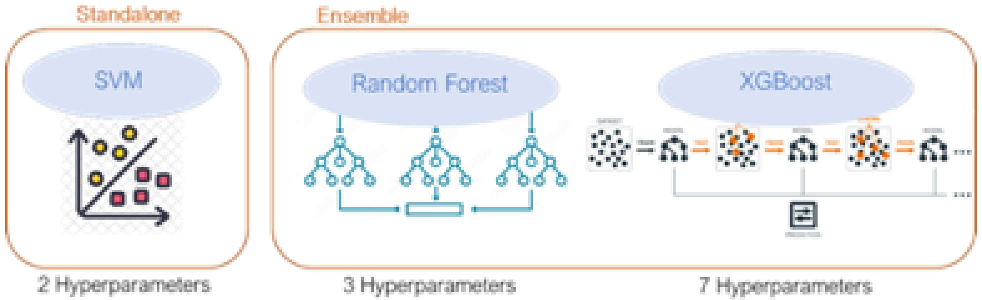
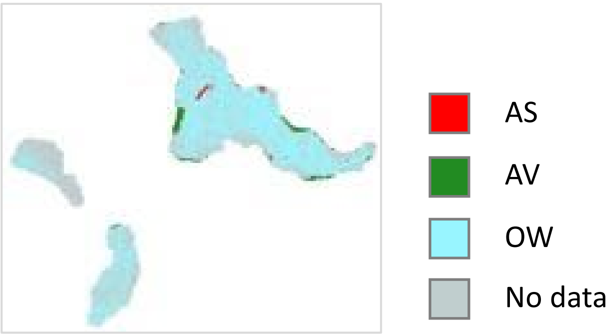
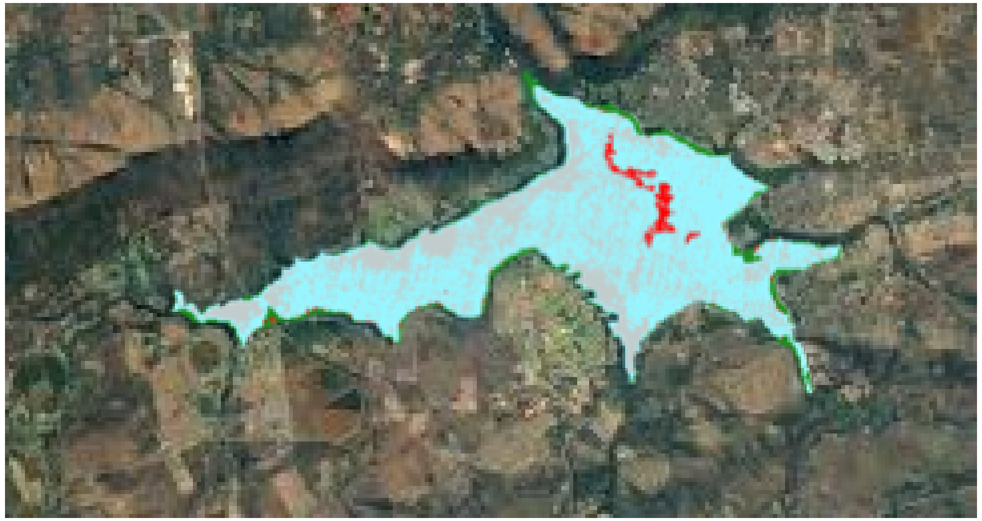


Lake Varese 2021/10/16



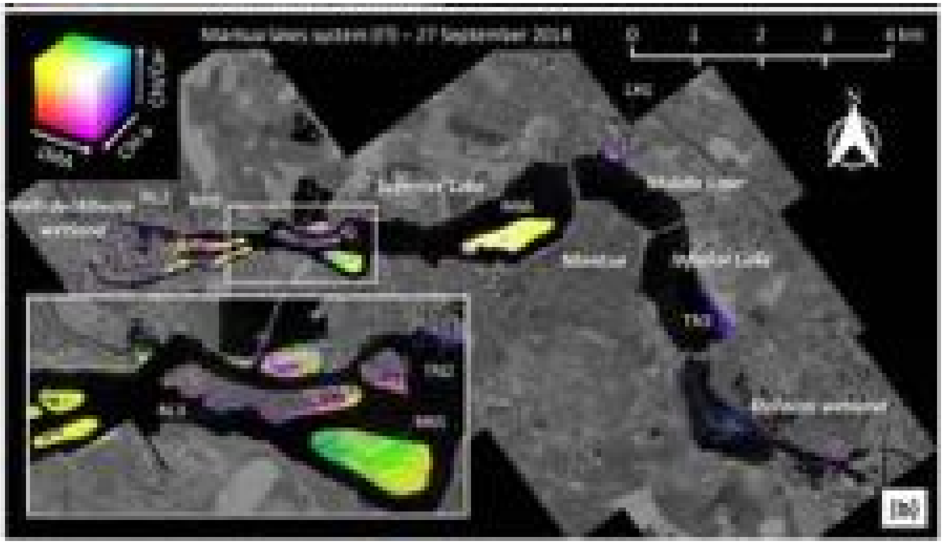
Hartbeespoort reservoir 2020/05/15



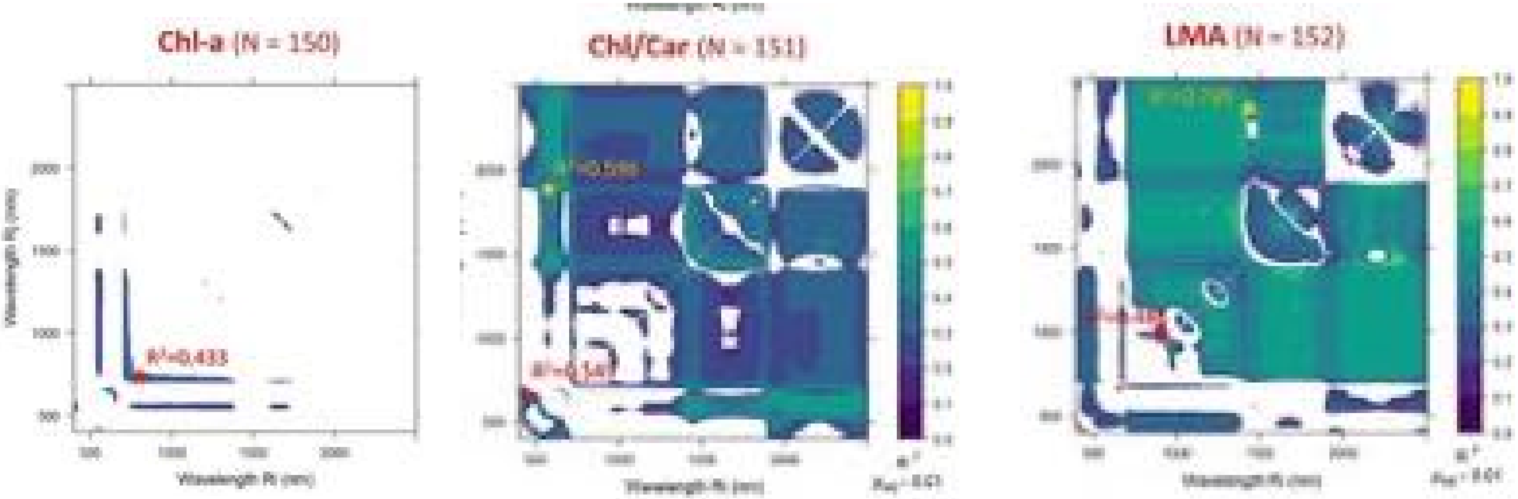
Lake Taihu 2023/10/18

Lake Taihu 2021/06/06

Macrophyte spectro-functional traits

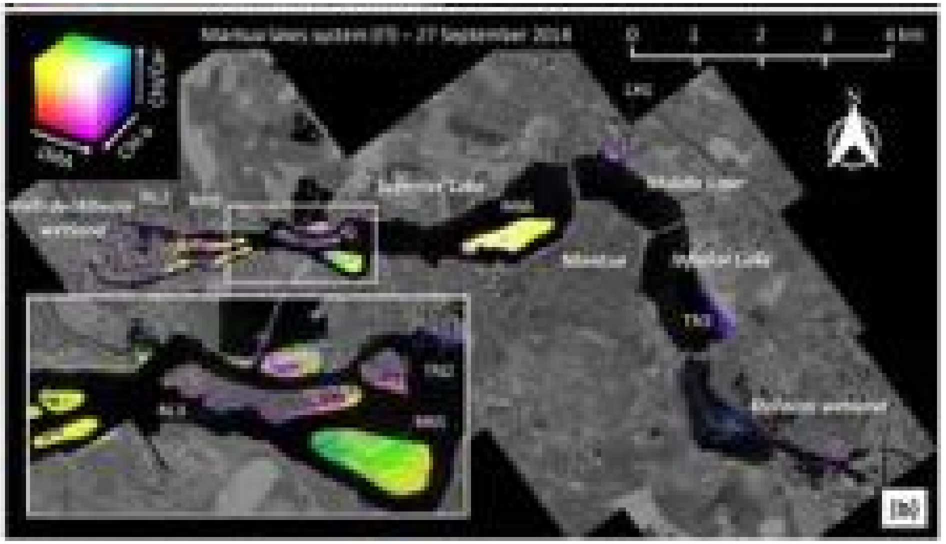


VNIR APEX



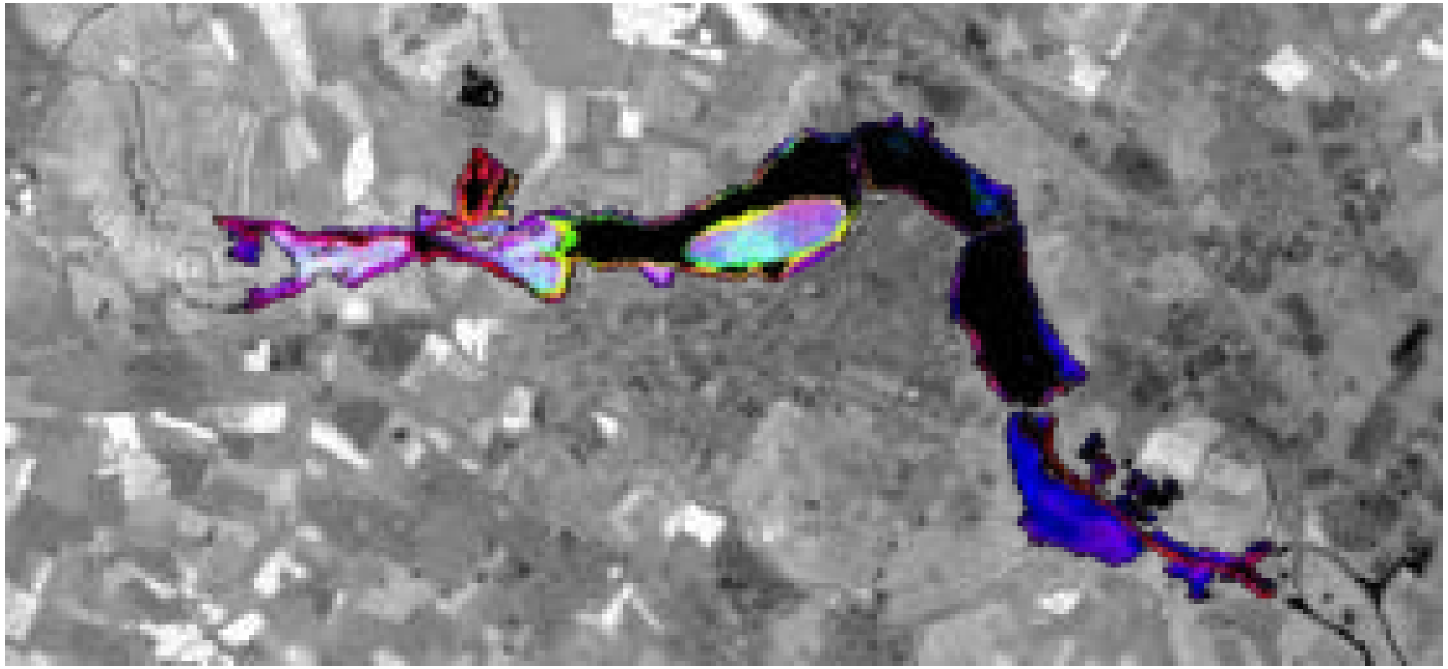
Villa et al., 2021

Macrophyte spectro-functional traits

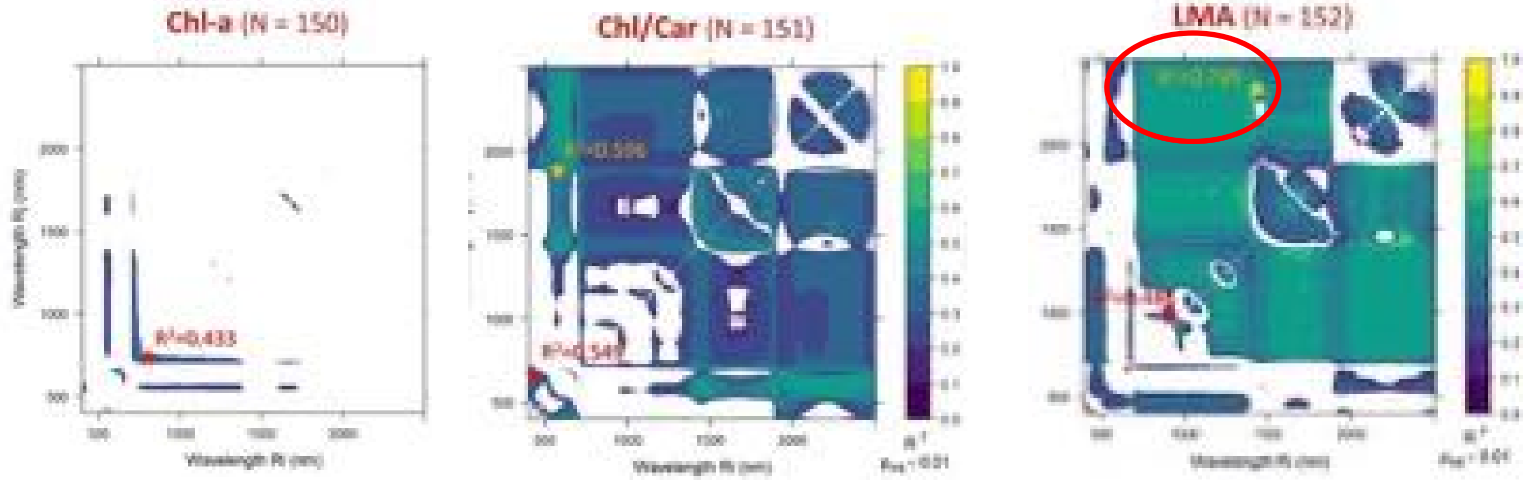


VNIR APEX

Lake Mantua 2023/08/25



VNIR-SWIR PRISMA

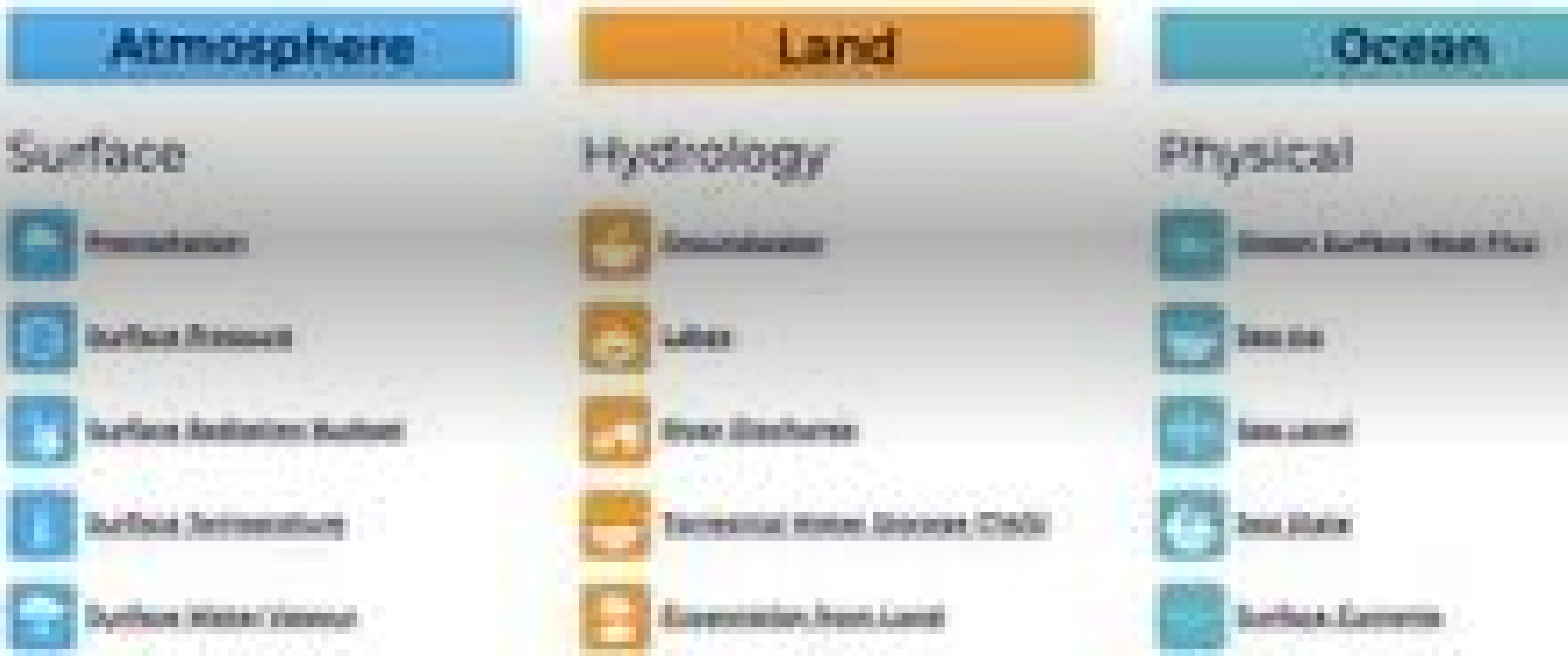


Villa et al., 2021

EO to support global studies: ECV & EBV

ECV are identified based on the following criteria:

- **Relevance:** The variable is critical for characterizing the climate system and its changes.
- **Feasibility:** Observing or deriving the variable on a global scale is technically feasible using proven, scier understood methods.
- **Cost effectiveness:** Generating and archiving data on the variable is affordable, mainly relying on coordinated observing systems using proven technology, taking advantage where possible of historical datasets.



The influence of climate change is already clearly evident in many of Earth's lakes

nature communications

Article | Published: 31 August 2020

Rapid worldwide growth of glacial lakes since 1990

Dan H. Shugar, Aaron Burr, Umesh K. Haritashya, Jeffrey S. Kargel, C. Scott Watson, Maureen C. Kennedy, Alexandre R. Bevington, Richard A. Betts, Stephan Harrison & Katherine Strattman

Nature Climate Change 10, 939–945(2020) | Cite this article

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Article | Open Access | Published: 06 March 2020

Global lake thermal regions shift under climate change

Stephen C. Maberly, Ruth A. O'Donnell, R. Iestyn Woolway, Mark E. J. Cutler, Mengyi Gong, Ian D. Jones, Christopher J. Merchant, Claire A. Miller, Eirini Politi, E. Marian Scott, Stephen J. Thackeray & Andrew N. Tyler

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Article

Lake heatwaves under climate change

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Lakes & Reservoirs

Science, Policy and Management for Sustainable Use

REVIEW ARTICLE

Impacts of water level changes in the fauna, flora and physical properties over the Balkhash Lake watershed

Kuanysh B. Isbekov, Vyacheslav N. Tsoy, Jean-Francois Crétaux, Nikolai V. Aladin, Igor S. Plotnikov, Guillaume Clos, Muriel Berge-Nguyen, Saule Zh. Assylbekova

First published: 16 May 2019 | https://doi.org/10.1111/lre.12263 | Citations: 1

Hydrological Processes

Research Article

Recent trends in Canadian lake ice cover

Claude R. Duguay, Terry D. Prowse, Barrie R. Bonsal, Ross D. Brown, Martin P. Lacroix, Patrick Ménard

First published: 27 February 2006 | https://doi.org/10.1002/hyp.6131 | Citations: 144

Science of the Total Environment

Effects of climate change and episodic heat events on cyanobacteria in a eutrophic polymictic lake

Maciej Bartosiewicz, Anna Przytulska, Bethany N. Deshpande, Dermot Antoniades, Alicia Cortes, Sally MacIntyre, Moritz F. Lehmann, Isabelle Laurion

Remote Sensing of Environment

Changes of water clarity in large lakes and reservoirs across China observed from long-term MODIS

Shenglei Wang, Junsheng Li, Bing Zhang, Zhongping Lee, Evangelos Spyrakos, Lian Feng, Chong Liu, Hongli Zhao, Yanhong Wu, Liping Zhu, Liming Jia, Wei Wan, Fangfang Zhang, Qian Shen, Andrew N. Tyler, Xianfeng Zhang

Increasing body of evidence on regional to global climate change in lakes from remote observations

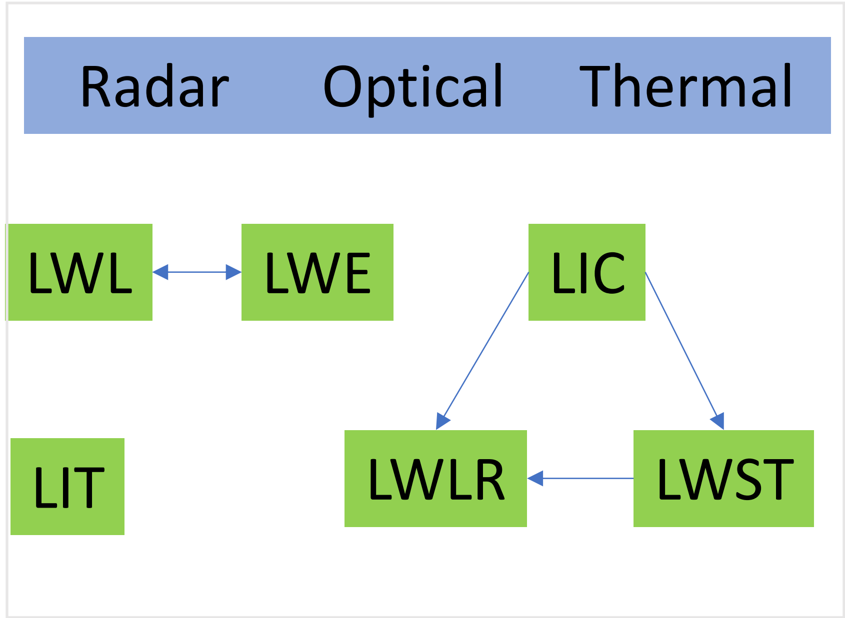
Lakes Climate Change Initiative (cci) dataset

Essential Climate Variables (ECVS) products:

- Lake Water Extent (LWE) & Level (LWL)
- Lake Ice Cover (LIC) & Ice Thickness (LIT)
- Lake Surface Water Temperature (LSWT)
- Lake Water-Leaving Reflectance (LWLR)

All with uncertainties

The Lakes_cci data set



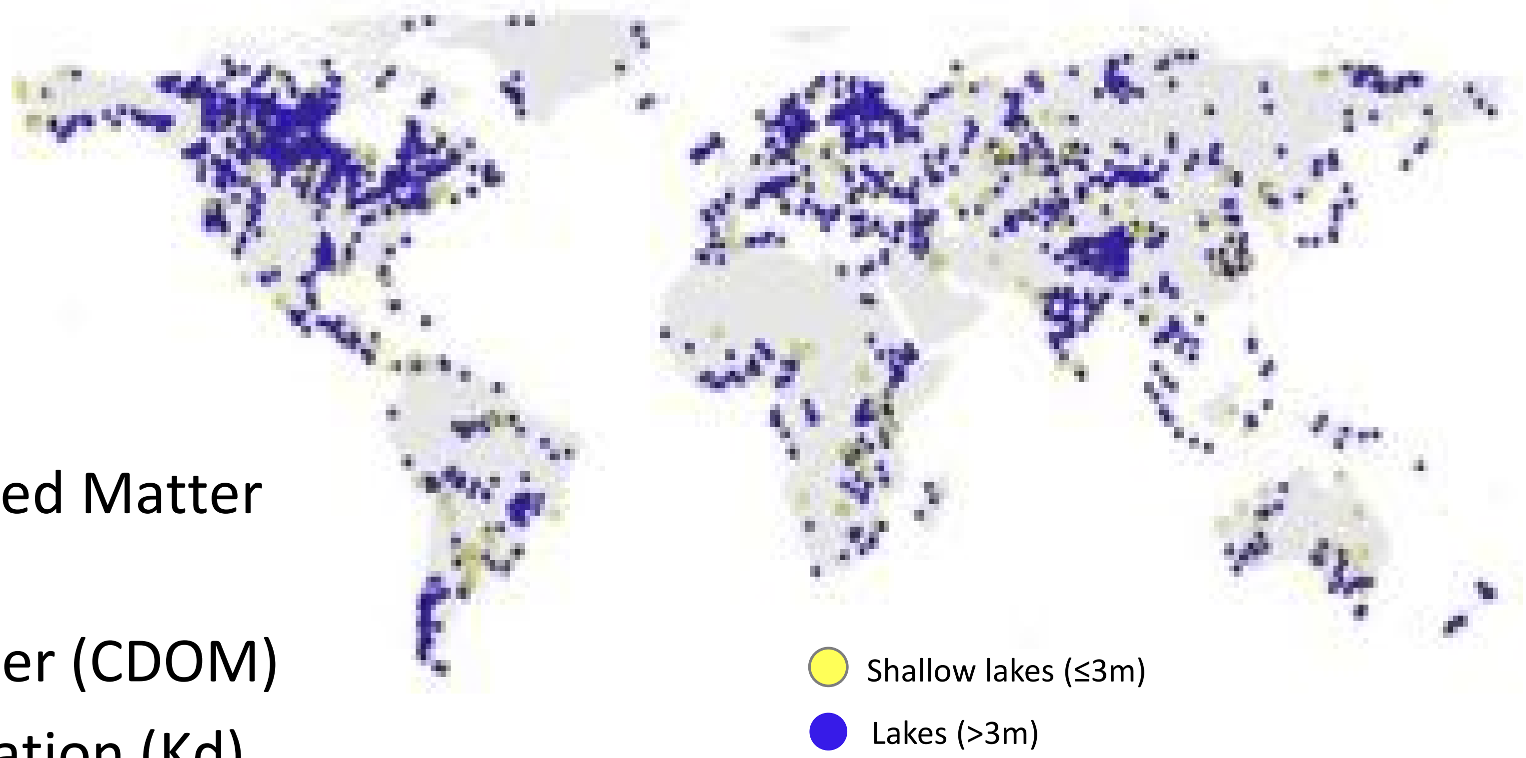
Carrea L., Cretaux J-F., Liu X., et al., Satellite-derived multivariate world-wide lake physical variable timeseries for climate studies, Nature Sci Data 10, 30 (2023).

Lakes_cci dataset

Global, stable, consistent, long-term satellite-based products of the Essential Climate Variable 'Lakes'

- **Lake Water-Leaving Reflectance (LWLR)**

- Chlorophyll a (Chla)
- Turbidity (v2.1) → Total Suspended Matter (TSM)
- Coloured Dissolved Organic Matter (CDOM)
- Diffuse downwelling light attenuation (Kd)
- Phycocyanin (PC)



A total of 2024 lakes, at spatial resolution of 1/120 deg grid, on daily basis data spanning 1992-2023 (V.3)

Global trends in shallow lakes

Shallow lakes and wetlands form a major component of inland waters and provide many ecological services, particularly important for carbon storage and biodiversity.

Main aims:

i) To assess medium- to long-term trends (2003–2020) in Chl-a and turbidity using Theil–Sen trend analysis

ii) To investigate potential drivers of Chl-a through Structural Equation Modeling (SEM)

Datasets

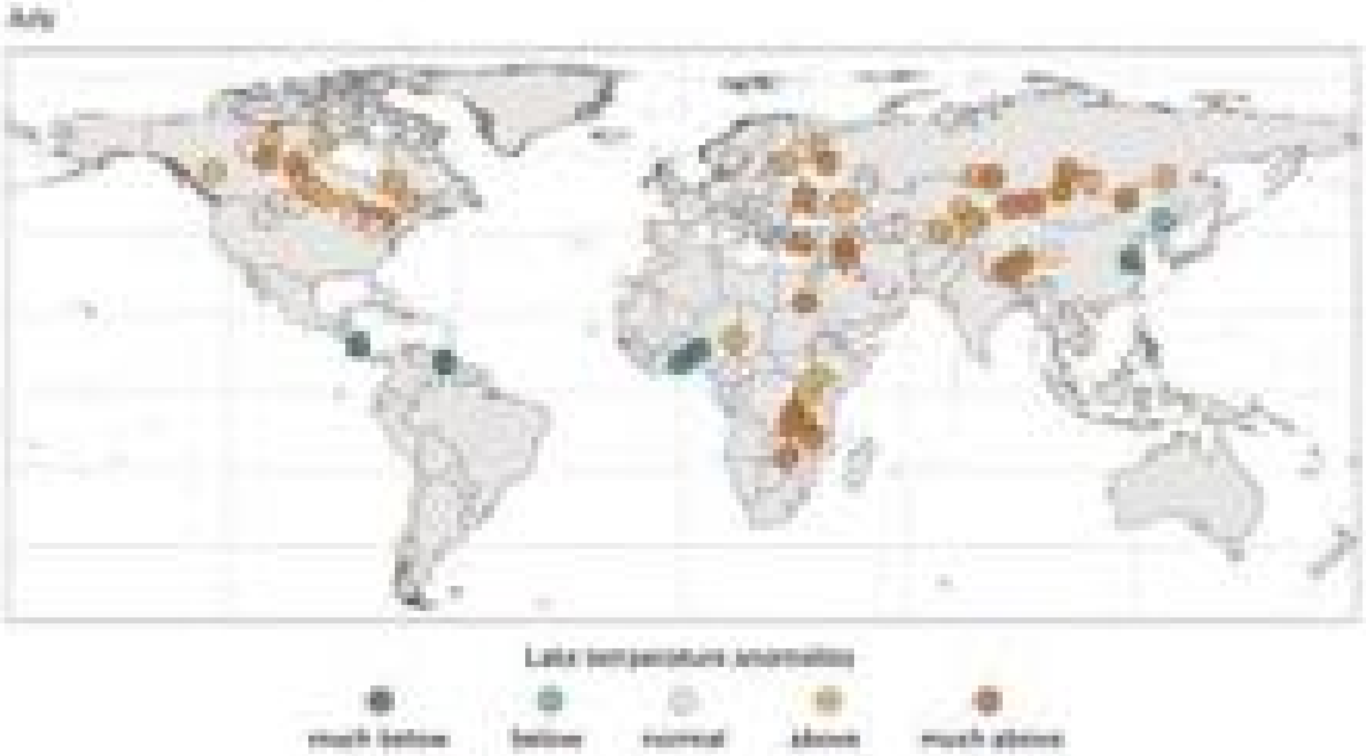
Variable	Data Source
Chl-a	Lakes_cci
Turbidity	Lakes_cci
LSWT	Lakes_cci
Mean annual Air Temperature (T_a)	DOSE v2 (Database Of Sub-national Economic Output)
Mean annual Precipitation (P_a)	DOSE v2
Population (Pop)	DOSE v2
Gross regional product (GRP)	DOSE v2
Hydromorphological data and lake catchment	HydroLAKES and HydroBASIN

Caroni et al., 2025

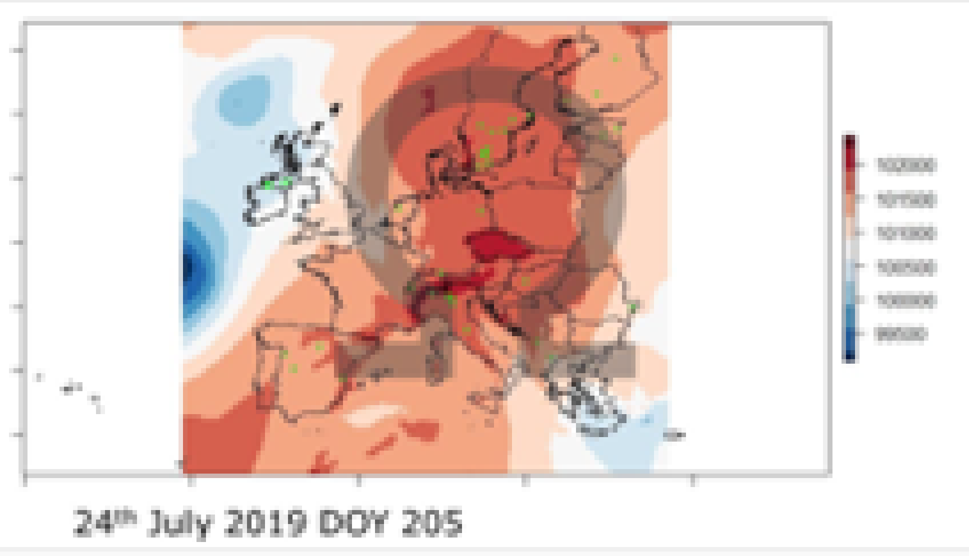
Trend analysis

- ✓ The majority of shallow lakes in our dataset have experienced increases in turbidity and in Chl-a concentration in the last two decades
- ✓ In most lakes turbidity (50%) and Chl-a (48%) increased with LSWT, suggesting an impact of climate warming on lake water quality

Lakes Climate Change Initiative (cci) dataset



European lakes responses to heatwaves in 2019



Chl-a data (Lakes CCI dataset) were examined for any potential responses during the **2019 double heatwave** period for 36 European lakes, evaluating how the response varies depending on latitude, total concentration of phosphorus and the average depth of the lake.

- The results show that the timing and magnitude of the **response to the heatwave** events depends on lake depth and nutrients.
- **Deeper lakes** respond **sooner** probably because of higher temperatures leading to stronger stratification thereby improving the light climate but with the response strength dependent on nutrient status.
- In contrast, **shallower lakes** and lakes at lower latitudes showed more **asynchrony** with a greater response after the heatwave event probably as a result of internal and external loading.

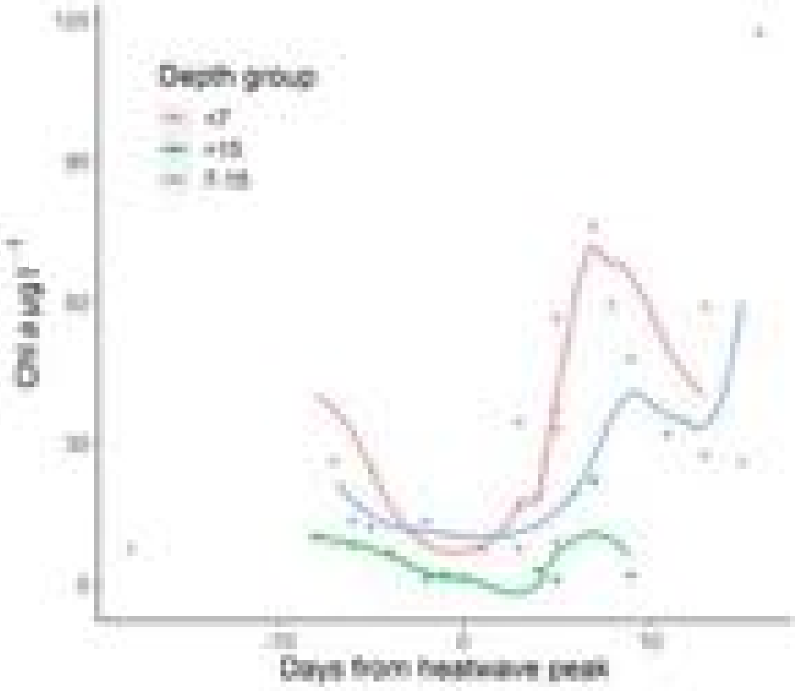


Figure. Timing and concentration of peak chlorophyll-a with respect to the second 2019 heatwave.
Source: Free et al. 2022, Ecol Indicators.

Free et al., 2021

Exploring the satellite-derived lakes variables

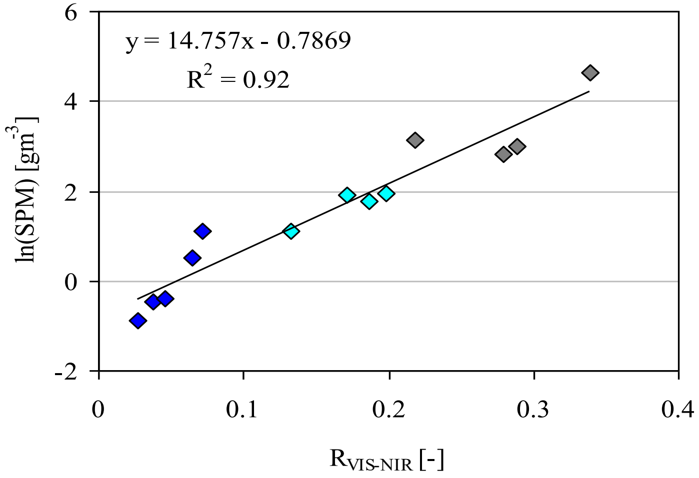
https://lakescci.climate-indicators.brockmann-consult.de/

Understanding the glacier-lake interaction

- Detection of mountain lakes, whose morphological variations are indicators of deglaciation processes
- Monitoring the moraine-dammed lakes as they may be unstable and potentially susceptible to sudden discharge of large volumes of water and debris

ALOS-AVNIR2

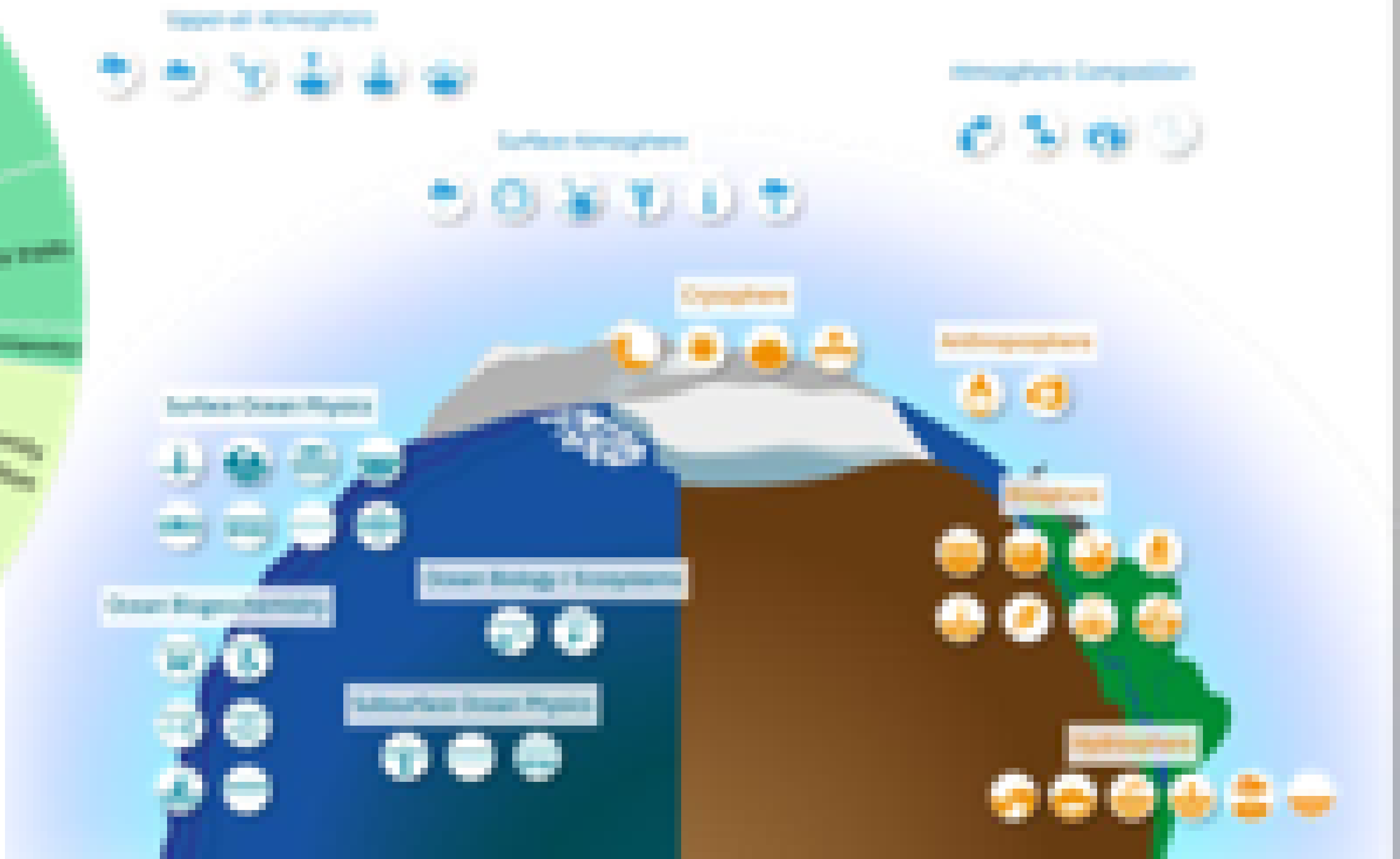
In situ



European Commission

https://global-surface-water.appspot.com/

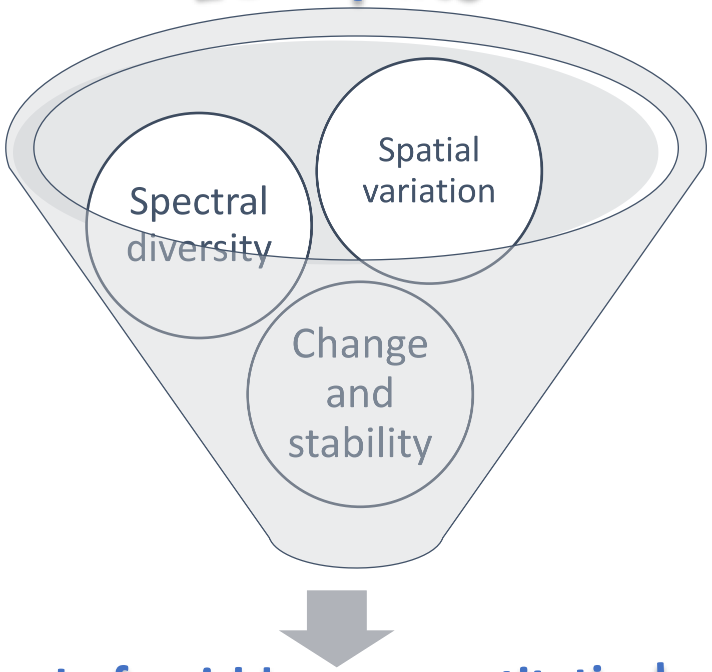
EO to support global studies: ECV & EBV



Freshwater EBV

NATIONAL BIODIVERSITY FUTURE CENTER

EO inputs



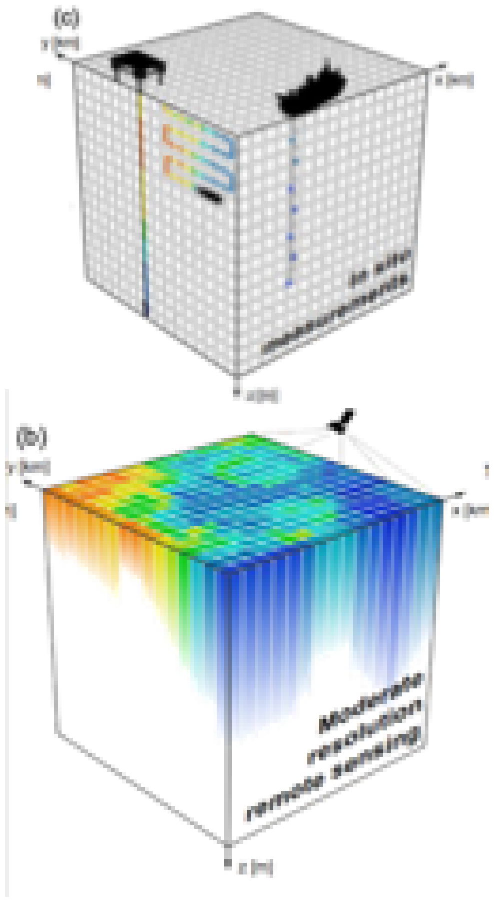
A set of variables to quantitatively measure changes in biodiversity

EO helps to **track change in global biodiversity** over a range of scales in a consistent, unbounded and repeatable manner; EO is a key element to assess the **Essential Biodiversity Variables (EBV)** (Turak et al. 2017)

Muller-Karger et al (2018) Satellite sensor requirements for monitoring esseessential biodiversity variables of coastal ecosystems. Ecol Appl. https

Freshwater EBV

NATIONAL BIODIVERSITY FUTURE CENTER



In situ data, ground infrastrctures

Sentinel 2, Landsat, Sentinle-3, PRISMA, EnMap, airborne data, drones

Adaptive band-ratio (a-BR) based on spectral features (Heggerud et al., 2023)

Chromaticity (Van der Woerd et al., 2019)

Bio-optical model inversion (Giardino et al., 2012, Gege at l. 2014)

MDN Machine Learning (O'Shea et al., 2012)

Multidimensional spectral features (Villa et al. 2015)

Community composition of phytoplankton

Community composition and species traits of macrophytes

Ecosystem functions (Harmful and non-harmful blooms)

EBVs

EO to support SDG


EDITORIAL article

Front. Remote Sens., 19 August 2025

Sec. Multi- and Hyper-Spectral Imaging

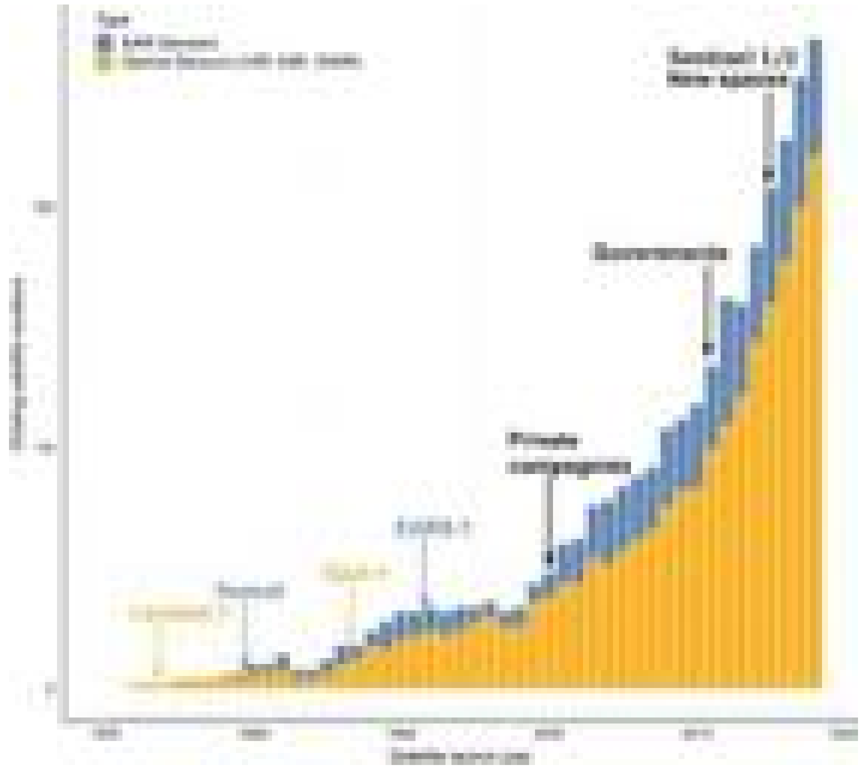
Volume 6 - 2025

Editorial: Achieving SDG 6: Remote Sensin

Applications in Sustainable Water Manager

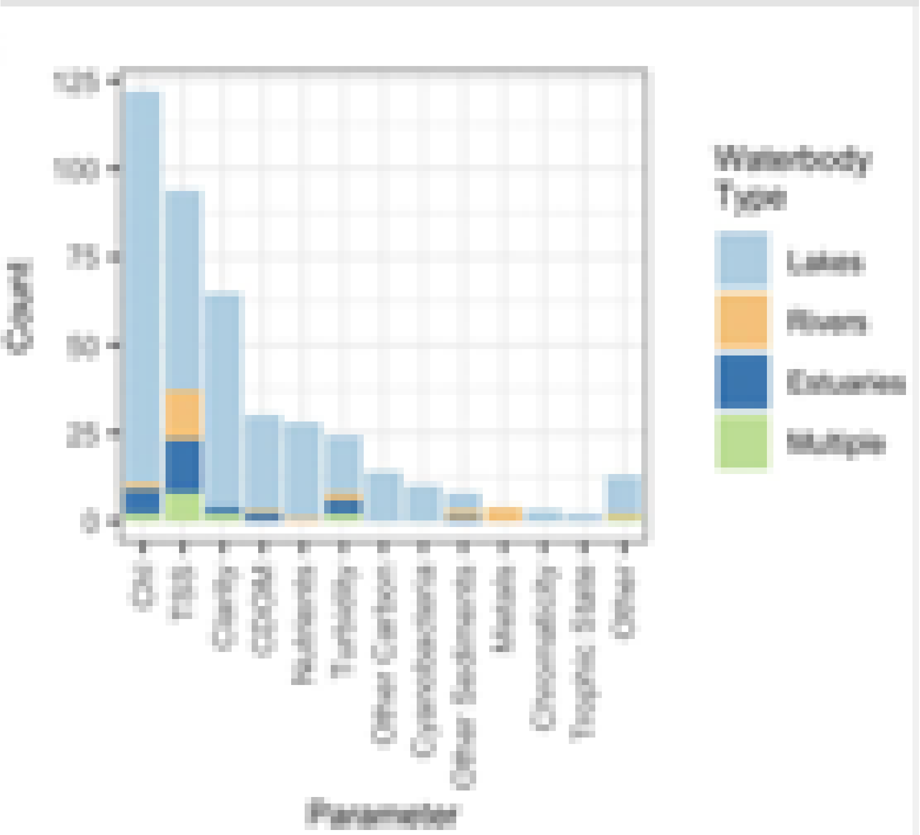
Mhd. Suhyb Salama *

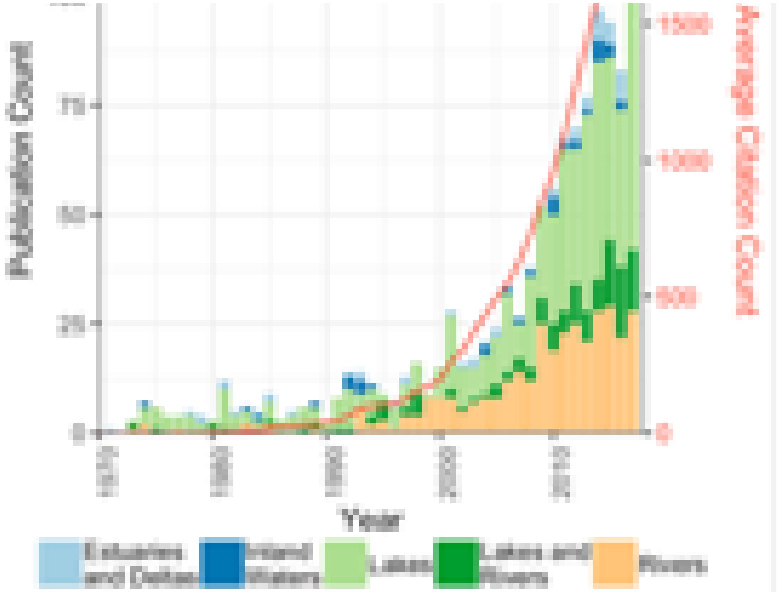
Conclusions



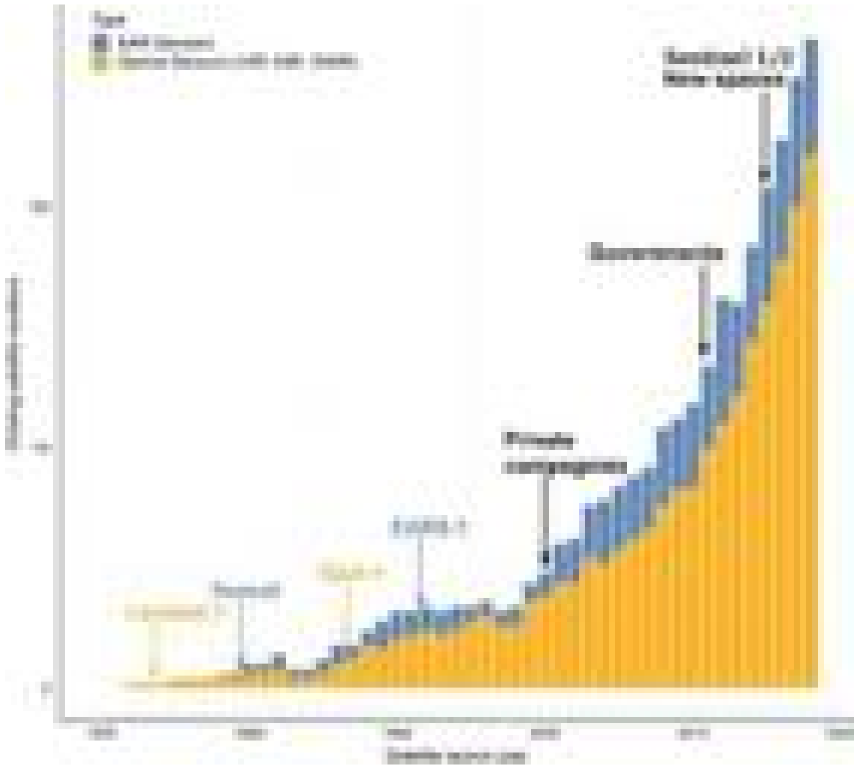
Cumulative number of near-polar orbiting, high resolution satellites in the optical and microwave domains (Tonneau et al., 2020)

Trends for "inland Water Remote Sensing" (Topp et al., 2020)

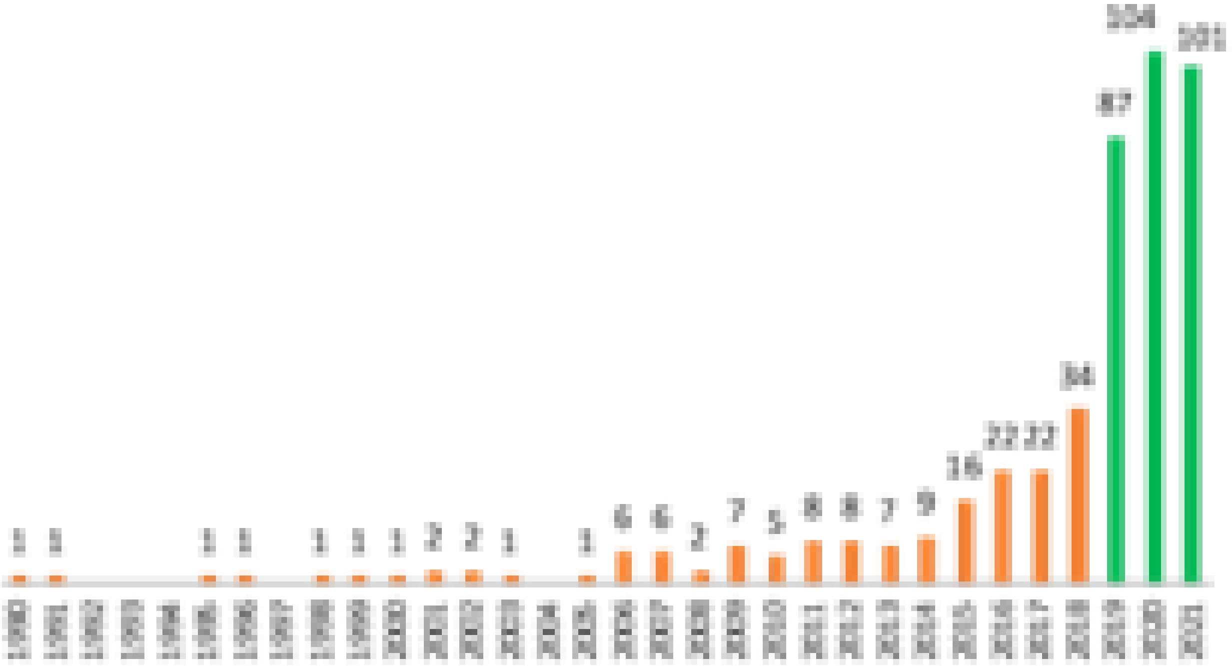




Conclusions



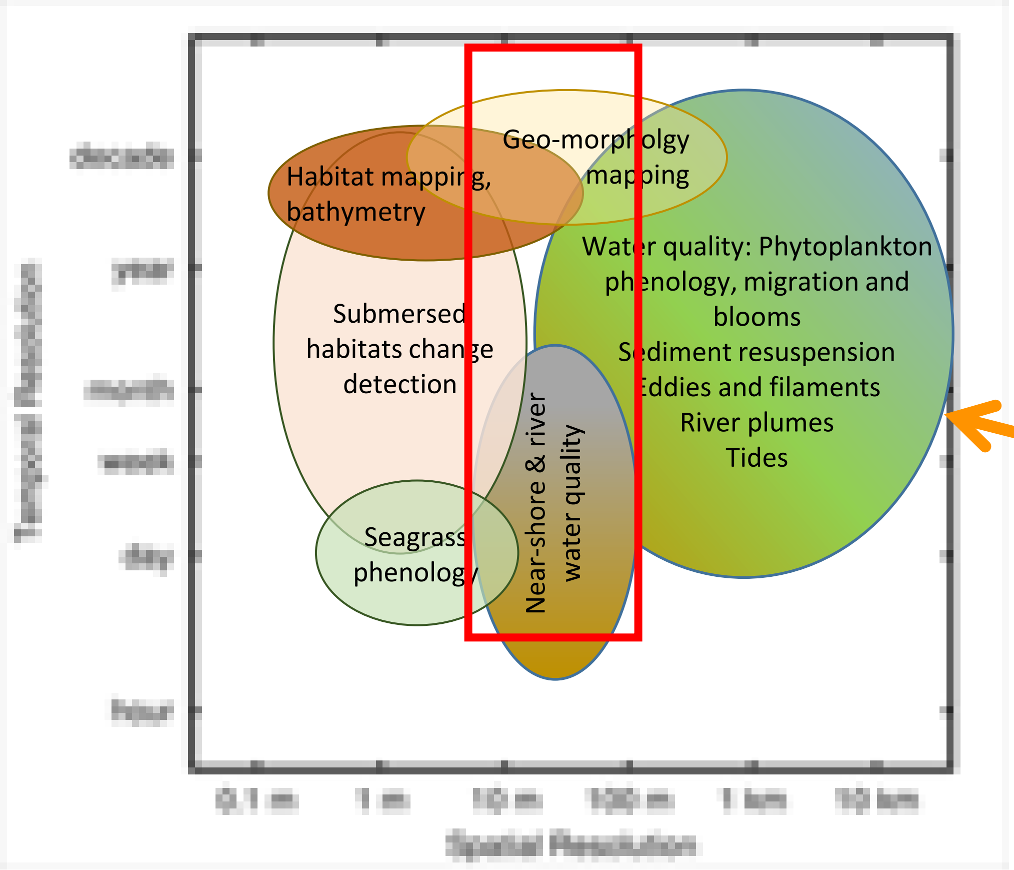
Trends for "inland Water Remote Sensing" (Topp et al., 2020)



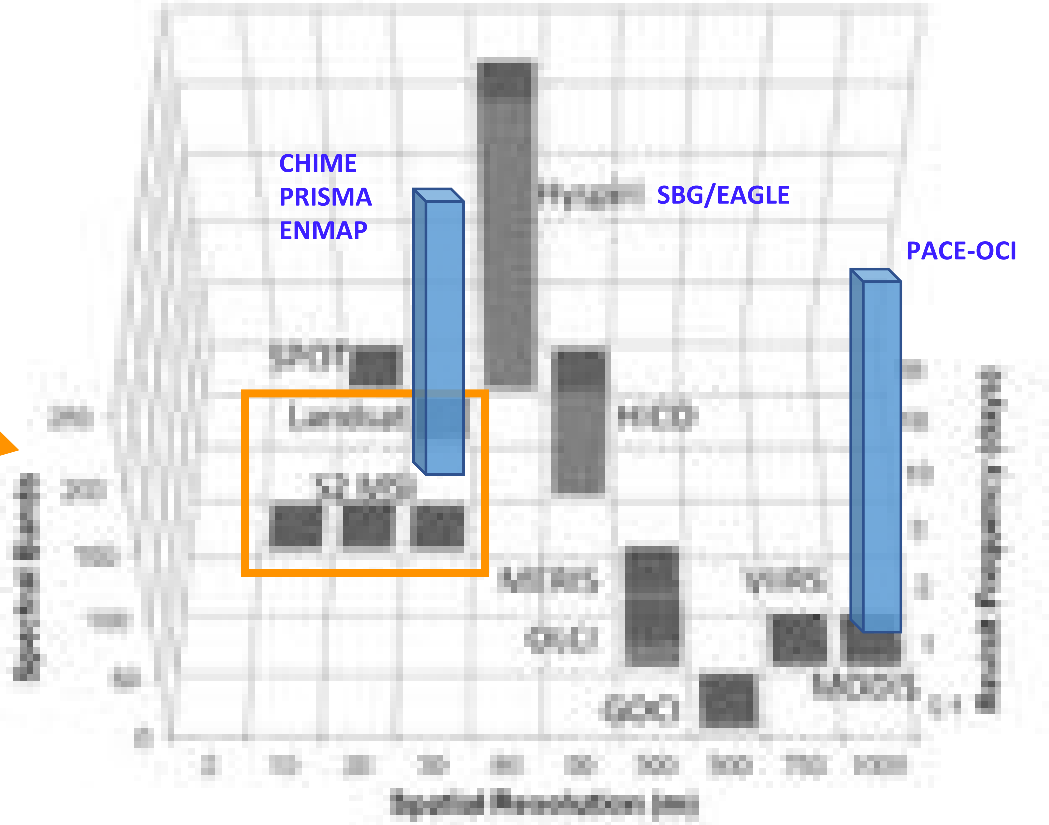
Trends for "satellite"+ "global lakes" + "climate change"

A matter of resolutions

(Vittorio' slides too)



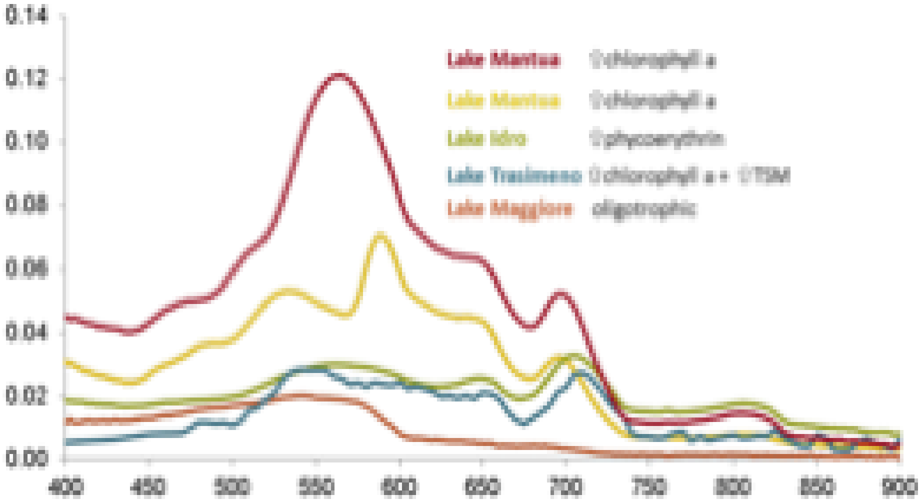
Hedley et al. 2018 - *Modified*



Hestir et al., 2015

A matter of resolutions

Spectral: optically shallow, and optically deep waters (gradients of clear, turbid and productive waters & varying bottom visibility)

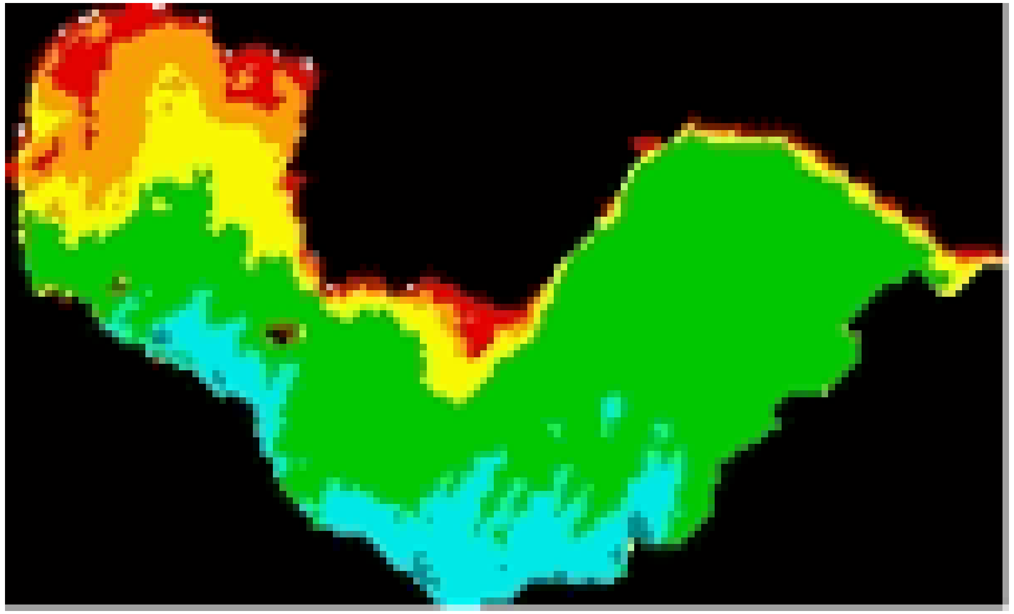


Spatial: patchy distribution of water and bottom properties

Hestir et al., 2015

A matter of resolutions

Temporal: extremely high dynamic systems



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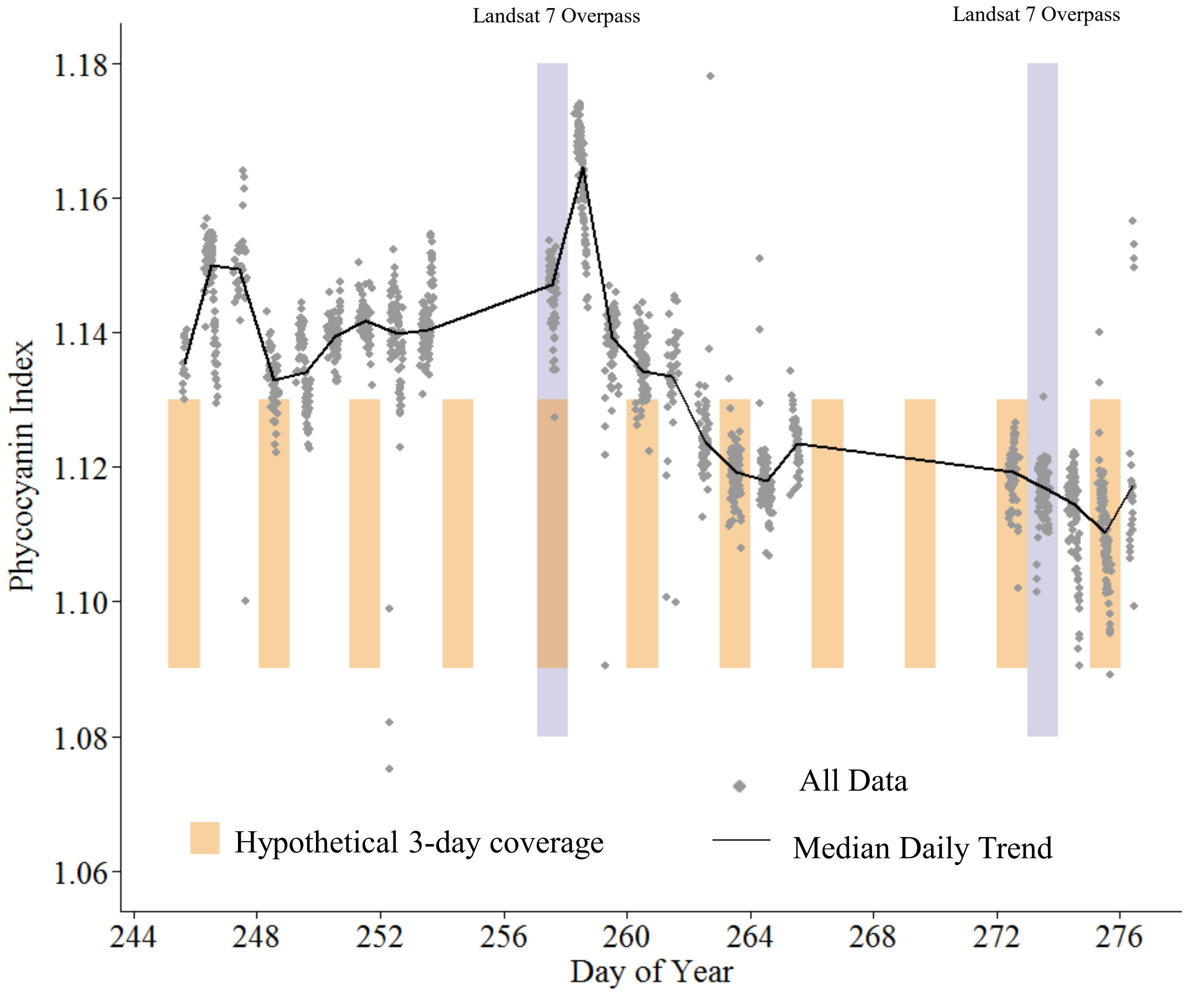
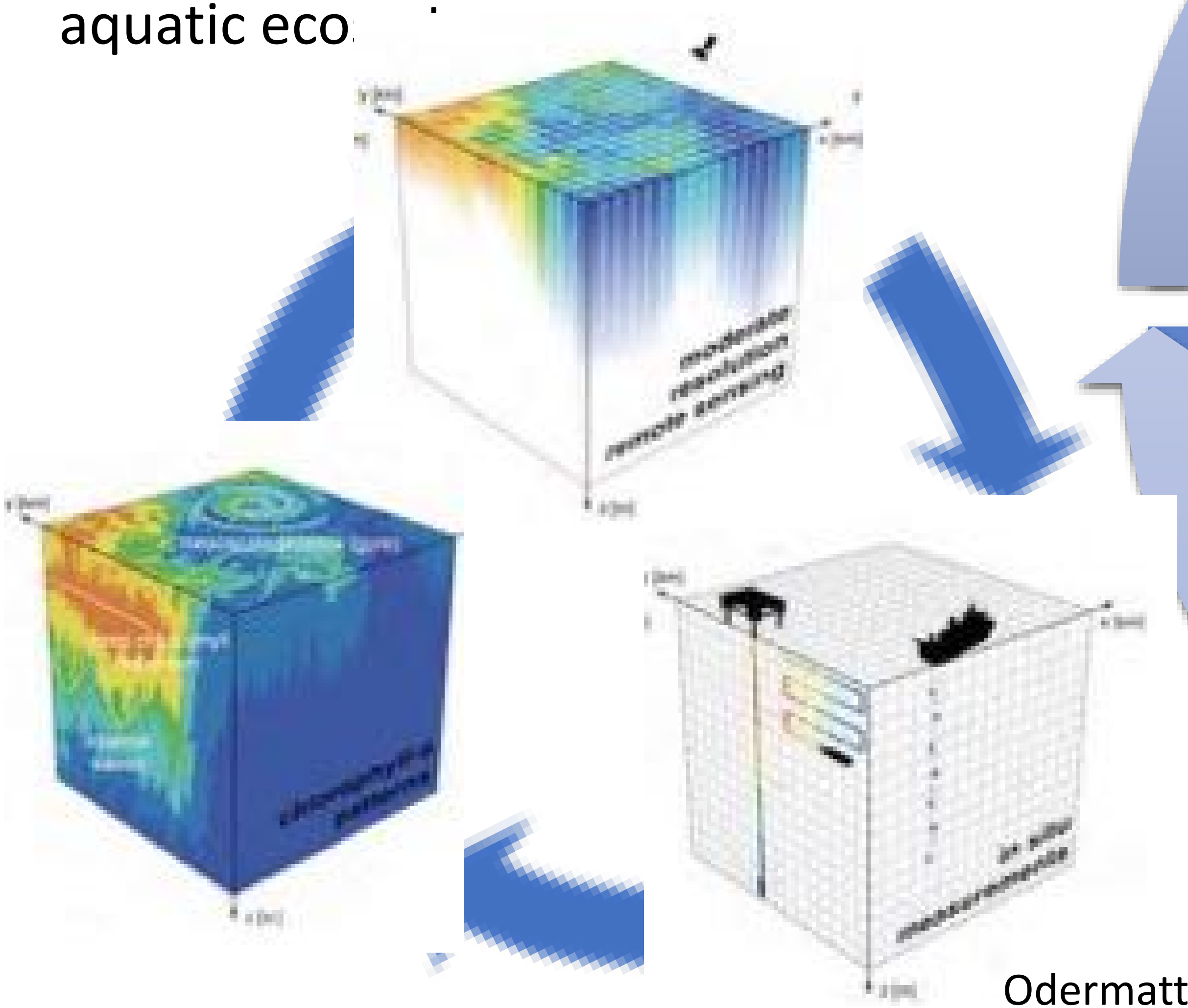


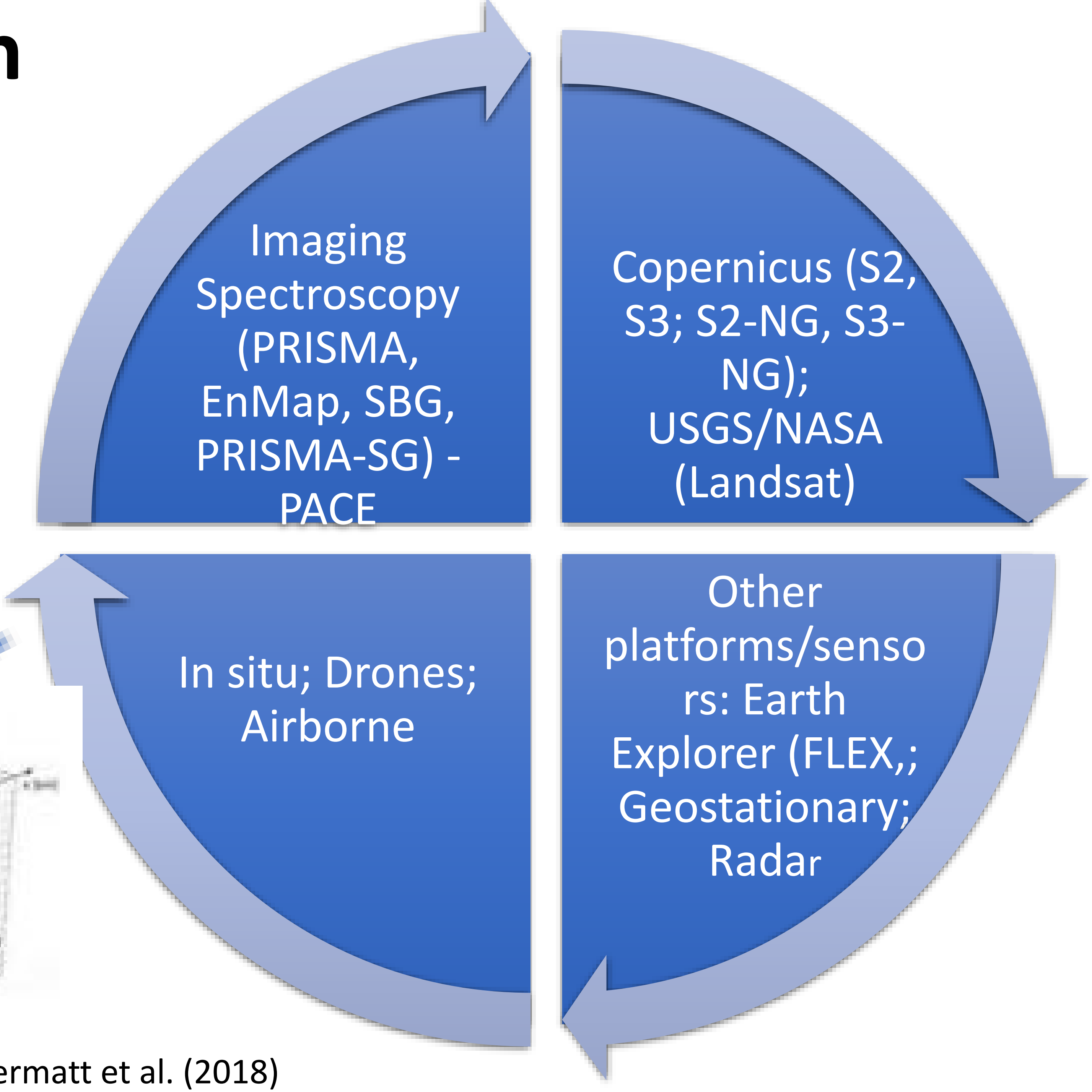
Radiometry: atmosphere, adjacent lands, sun/sky glints, etc. strongly impacts on the water signal (more than 80% of signal is due to atmosphere)

A matter of integration

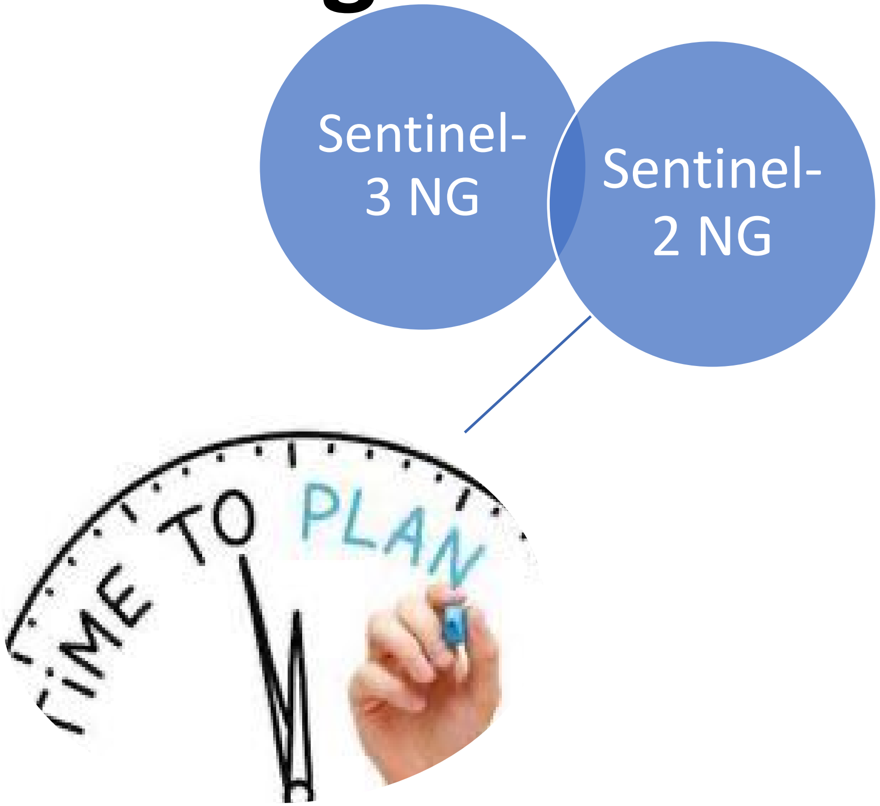
Multi-sensor approach help to cover the wide variety of resolutions needed to observe aquatic eco



Odermatt et al. (2018)



Looking ahead



- Additional bands
  - ‘**Carotenoid**’ band at 470 or 473 nm (proposed for terrestrial plant)
  - ‘**Phycocyanin**’ band 620 nm (+ one at 650 nm for algorithm (note: S2 has band 4 at 665 nm)
  - ‘**Particulate material**’ band at 810 nm band
  - ‘**Macroplastic** ’ band at 1070 nm

- Improved spatial resolutions

Looking ahead

Sentinel-3 NG

Sentinel-2 NG

PRISMA-SG

PRISMA Second Generation

- **STRIPMAP image**: VNIR/SWIR GSD ≤ 30 m and PAN GSD ≤5 m, swath ≥30 km; Imaging Capacity > 2.000.000 km^2
- **SPOTLIGHT image** (on-demand): VNIR/SWIR GSD ≤10 m and PAN GSD ≤5 m, swath ≥30 km; Imaging Capacity > 200.000 km^2
- On demand techniques of SWATH enlargement and **SNR enhancement** on a single pass using the platform agility

Looking ahead

Sentinel-3 NG

Sentinel-2 NG

PRISMA-SG

Earth Explorer

Galene

Understanding coastal and inland ecosystem properties and processes

Payload	350 - 450 kg / Power: 300 W
Hyperspectral Instrument (HSI)	120 bands [0.38 - 1.7 µm] – adjustable spectral resolution (3 nm VIS, 10 nm IR, 20 nm SWIR), SNR ~800, GSD: 30 m
Panchromatic camera (PAN)	[0.38 – 0.9 µm], Minimum radiance: 10^{-5} W m^{-2} sr^{-1} / GSD: 5 m
Multi-Angular Polarimeter (MAP)	12 viewing angles, +/- 60° nadir, 6 polarized bands (5 VIS + 1 NIR), GSD: 100 m, Noise-equivalent polarized reflectance: 10^{-4}
Swath / Revisit / Tilt	250 km / 10 days / Tilt ~45° across-track
Lifetime	5 years
Payload	350 - 450 kg / Power: 300 W

GEO AQUA WATCH

IOCCG
International
Ocean Colour
Coordinating Group

Thanks!

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