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1 Introduction

The Sea-Land biogeochemical linkages (Baltic+ SeaLaBio) project was designed to answer the following research question:

- Can we quantify the carbon flux from land to sea with Sentinel-3 (S3) OLCI and Sentinel-2 (S2) MSI data in the Baltic Sea region? And if not, what are the main obstacles and potential solutions to be addressed in the future?

With this in mind, the overall objective of the project was defined as:

- Develop methods for assessing carbon dynamics and eutrophication in the Baltic Sea through integrated use of **Earth Observation (EO), models, and ground-based data**

This required scientific developments in several topics. The generation of information about carbon dynamics and eutrophication from satellite images in the Baltic Sea required improvements in atmospheric correction and in-water algorithms. Furthermore, the synergistic use of EO and models required modifications in models and generation of new kind of information from EO.

The work package structure and logic of the study is shown in Figure 1 together with the technical deliverables.

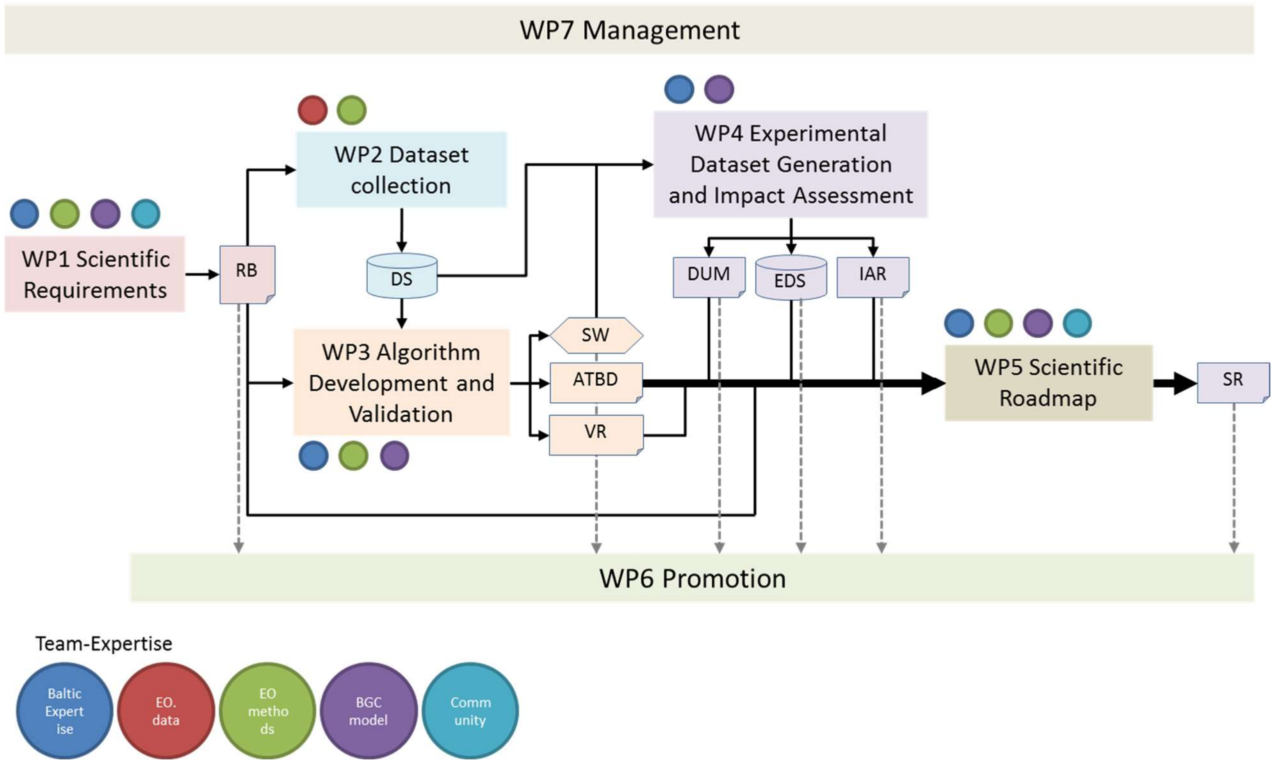

Figure 1. Work logic of the Baltic+ SeaLaBio –project. The deliverables mentioned in the figure are: RB = Requirements Baseline, DS = (Input) Dataset (including Dataset Description), SW = Software, ATBD = Algorithm Theoretical Basis Document, VR = Validation Report, EDS = Experimental Dataset, DUM = Dataset User Manual, IAR = Impact Assessment Report, SR = Scientific Roadmap.

2 Main results

The developments accomplished in the SeaLaBio project have advanced the state-of-the-art in three important fields:

1. **Biogeochemical modelling:** The ERGOM model can now utilize the EO based aCDOM values as input data and, as a result, provide more reliable estimates of light attenuation in water. These improvements enable more realistic simulations of phytoplankton and several other state variables. This is of great importance especially in the norther parts of the Baltic Sea where CDOM has a large effect on light availability for primary production. In addition, the ERGOM model was modified by increasing the spatial resolution from 3 n.m. to 1 n.m. The improved spatial resolution of the ERGOM model is critical especially in scattered coastal areas, also typical for the northern parts of the Baltic Sea.
2. **EO data processing:** A new method for atmospheric correction of satellite images – based on combining the advantages of Polymer & C2RCC – can now provide more reliable water leaving reflectance values. The Neural Network approach can aggregate a large knowledge about natural variability (range, covariance) found in the optical properties of water in the Baltic Sea with a dedicated training for this purpose while POLYMER can account for atmospheric affects due to its polynomial modelling. As a result, the Baltic+ AC can provide smooth maps of reflectance with realistic amplitude over whole scenes. This is a major step towards the formulation of an optimal AC for the Baltic Sea. For in-water inversion a neural network-based method was developed as well. The NN was trained with a reflectance database simulated with Hydrolight defined for the Baltic Sea. Several different architectures were analysed to optimize the model estimation output. However, the NN method was not yet able to reach the estimation accuracy of the empirical band ratio algorithm. In order to assess the performance of the full processing chain (AC & in-water algorithm) a matchup analysis with OLCI data was performed. Various reflectance band ratios were analysed, and the band ratio (665 nm/560 nm) was proven to be the best option. It shows a clear improvement in correlation compared to the C2RCC results. The Baltic+ AC processor has been made available through the GitHub and as a SNAP plug-in.
3. **Use of EO for monitoring carbon fluxes:** Baltic Sea countries should report annual loads of Total Organic Carbon (TOC) and other substances like nutrients and hazardous substances from their rivers to the Pollution Load Compilation (PLC) database maintained by HELCOM. In practice, only Sweden, Finland and Estonia report organic matter loads regularly. Due to climate change, there is a growing interest of TOC load in the PLC project and beyond. SeaLaBio project estimated the TOC loads of the eight largest rivers in the Baltic Sea. This was done by utilizing the EO based aCDOM values derived from areas representing river discharge points and river discharges as input. The PLC only contains data for three of them and in two of the analysed cases a good agreement with EO and in situ-based methods was found. In the third, the likely reason for the underestimate in the EO values is due to the positioning of the extraction area, which may not represent well the water coming from the river.

The experimental dataset generated in the project has been published in the TARKKA (www.syke.fi/tarkka/en) map application of the Finnish Environment Institute, which allows it to be conveniently viewed in map format or as time series. In addition, the dataset is available through machine data interfaces and as files in SYKE's EO Web Accessible Folder (EO-WAF) located at eo.ymparisto.fi/data/water/Baltic_SeaLaBio/.

The project website is available and maintained with result updates at www.syke.fi/projects/BalticSeaLaBio.

The project and its results have been presented at four scientific events and a paper on the results has been submitted to the Geoscientific Model Development Journal.

3 Conclusions and future work

As its final technical deliverable, the project formulated a Scientific Roadmap, which summarizes the results and outlines the next steps of the research required for reaching a better understanding of the carbon dynamics in the Baltic Sea.

The main input for the Roadmap was gathered at two User Consultation meetings held in June and July 2020. Further improvements in all fields presented above are possible and indeed required. Some of the ideas for further development are more technical in nature, such as:

- Refine the current extraction areas for the provision of input data to ERGOM and TOC loading
- Add more input locations to ERGOM
- Recalibration of ERGOM internally dependent processes after introducing CDOM as boundary condition instead of salinity.
- Recalibration of ERGOM dependent processes, e.g. better representation of light climate (CDOM).
- Encourage Baltic states to support EO activities by including relevant in situ measurements in the national monitoring programmes. E.g. there is a lack of data especially about absorption (a400, a440, etc.) and DOC (Dissolved Organic Carbon). Currently, absorption coefficient data is available only along the Finnish coast and the northern coast of Sweden. This limits the geographical scope of the analysis.
- Adaptation of the EO processing methods to MERIS in order to increase the temporal extent of the dataset.

Also, more extensive and dedicated efforts with respect to carbon cycle analysis and understanding are related to:

- Baltic-wide relationships CDOM-TOC, CDOM-DOC, CDOM-POC in river outlets (terrestrial sources)
- EO based datasets for terrestrial loads of TOC, DOC, POC
- Dynamics of terrestrial Organic Carbon in marine environment
- Impact of terrestrial organic carbon on marine carbon cycle by means of models
- Research related to sea-to-atmosphere fluxes (pCO2 estimation)
- New EO sensors suitable for water quality are coming (e.g. CHIME, FLEX) and may create possibilities for continuing the AC development. There was interest for this among the SAG and the team.

In addition, a wider vision for the Baltic Sea called the LEGO (Leveraged use of Earth and Ground Observations) for the Baltic Sea initiative was elaborated. It discusses the need to continue with a more holistic approach for studying, monitoring and managing the Baltic Sea and the need for spatial, temporal and thematic flexibility of information products. The LEGO initiative should bring together experts in monitoring and in situ, EO and modelling, as well as, representatives from e.g. HELCOM working groups and projects, to regularly produce new and revised guidelines to support WFD and MSFD and HELCOM Action Plan revision cycles. In doing so, significant steps to reach the HELCOM vision of “a healthy Baltic Sea environment” can be taken.