Use of Sentinel-3 OLCI images for estimating the trophic status of Tuscany coastal waters

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Abstract. The Trophic Index (TRIX) was developed by Vollenweider, 1998, for the coastal areas of North Adriatic Sea; it combines factors that describe phytoplankton biomass and nutrient availability. It is integrated in the Italian law for coastal marine environment status (D.L. 269/2010), and the environmental attributes used to estimate it are also monitored by the Marine Strategy Directive (2008/56/EC) to characterize the trophic status of coastal waters, with the aim of protect the marine environment achieving and maintaining the Good Environmental Status (GES). TRIX covers a wide range of trophic conditions, from oligotrophy to eutrophy, and has been applied to coastal marine waters in several European seas. One of the key components of this index is chlorophyll a, that is in large part often correlated with the other components. This observation was the basis of TRIX classification using optical data in port waters: first, the relationships between the environmental attributes involved in TRIX computation, particularly Chlorophyll a concentration, and water spectral reflectance were tested using in situ multispectral observations as an alternative method to evaluate the quality and ecological status of some Mediterranean ports (Massi et al., 2019). Then, the same approach was applied to multispectral data acquired by medium-high spatial resolution optical satellite sensors, i.e. the Landsat 8 Operational Land Imager (OLI) and the Sentinel 2 MultiSpectral Instrument (MSI) (Pieri et al., 2021). The results of these works suggested us to test the effectiveness of Ocean and Land Colour Instrument (OLCI) full resolution data for assessing the trophic status of Tuscany coastal waters. As TRIX is computed by in situ data, with all the limits connected, the possibility of obtaining it from satellite data would offer the opportunity of obtaining it at large spatial and time scales.

The dataset included OLCI Full Resolution (300 m) spectral data and in situ TRIX obtained from ISPRA (2008/56/CE Directive implemented by D. Lgs 190/2010, and 2000/60/CE Directive implemented by D. Lgs 152/06 monitoring programmes), selecting the stations at a distance from the coast suitable for remote sensing on the years 2016 – 2017. The first results are promising: the method applied allows a moderately accurate estimation of TRIX all over Tuscany coastal waters, providing an effective means for the operational monitoring of their ecological conditions.

Parole chiave: TRIX, OLCI, Chlorophyll a.

1 Introduction

Trophic state is defined as the total weight of the biomass in a water body at a specific location and time; it is the biological response for nutrient additions to the water bodies (Nauuman,1929). 'Trophic' comes from the Greek word meaning feeding. There are generally three classes distinguished: eutrophic (well-fed) means nutrient rich and is usually associated with high primary productivity; mesotrophic (medium) having intermediate levels of primary productivity; oligotrophic (little-fed), nutrient-poor, and low primary productivity. Anthropogenic activities, such as the application of agricultural fertilisers and manure, the discharge of wastewater and airborne emissions from shipping and combustion processes may lead to nutrient over-enrichment and eutrophication in transitional, coastal and marine waters. In coastal waters in fact one of the main issues is connected to nutrient inputs associated with terrestrial and anthropogenic sources, which can cause ecosystem imbalance such as eutrophication. The latest IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (Bindoff et al., 2019) indicates coastal ecosystems to be under stress not only from ocean warming and sea level rise, but also by non-climatic pressures from human activities on ocean and land. Increased nutrient and organic matter loads in estuaries since the 1970s have exacerbated the effects of warming on bacterial respiration and eutrophication, which in the IPCC scenarios is projected to increase in estuaries due to human activities and intensified precipitation increasing riverine nitrogen loads (Sinha et al., 2017).

The TRophic IndeX (TRIX) developed by Vollenweider (1998) for the coastal area of Emilia-Romagna (northern Adriatic Sea) combines factors that describe phytoplankton biomass and nutrient availability, and it is used by the Italian legislation to characterize the trophic state of coastal waters, via the Legislative decree 152/06 implementing the Water Framework Directive 2000/60/CE. This index was proposed in the framework of the Barcelona Convention, and it is integrated in the Italian law for coastal marine environment status (D.L. 269/2010). The environmental attributes used to estimate it are also monitored by the Marine Strategy Directive 2008/56/EC (MS) (Zampoukas et al., 2012) to characterize the trophic status of coastal waters, with the aim of protect the marine environment achieving and maintaining the Good Environmental Status (GES).

The main environmental conditions, and consequently the TRIX, of marine coastal areas are strongly related to phytoplankton abundance, biomass and dynamics, and can be estimated by the concentration of chlorophyll a, which is a major optically active water constituent. Building on this consideration, Massi et al (2019) have shown that TRIX can be estimated by the processing of multispectral observations collected *in situ*. In a further study Pieri et al (2021) investigated the alternative use of multispectral data acquired by medium-high spatial resolution optical satellite sensors in several Mediterranean port waters. The current study extends the analysis to the use of multi-spectral observations taken by the Sentinel 3 mission through the OLCI sensor, which is particularly suitable for monitoring medium-scale seawater phenomena. In particular, the study explores the possibility of estimating TRIX in the coastal areas of Tuscany (Central Italy) based on satellite reflectance spectra (Rrs) and standard Level 2 Sentinel 3 OLCI Full Resolution data (chlorophyll a concentration, suspended sediment concertation, diffuse attenuation coefficient at 490).

2 Materials and methods

2.1 TRIX

The trophic index TRIX (Vollenweider et al., 1998) is commonly defined by a linear combination of the logarithms of four environmental variables which are directly related to productivity: Chlorophyll a concentration (Chl-a) in mg L^{-1}, Oxygen as absolute percent deviation from saturation (aDO%), total Nitrogen (N) and total Phosphorus (P), in mg L^{-1}. The TRIX index can, therefore, be calculated using the following equation (1):

$$TRIX = (\log 〚Chla * |aDO\%| * N * P) - (-1.5))/1.2〛 \qquad (1)$$

The scale factors 1.5 and 1.2 in equation (1) are based on an extended dataset for evaluating long-term trends and spatial trophic patterns in Italian northern Adriatic (Vollenweider et al., 1998) and Tyrrhenian coastal waters (Giovanardi and Vollenweider, 2004; Penna et al., 2004). TRIX score ranges from 0 to10 covering four trophic states: 0—4 high quality and low trophic status — “High”; 4—5 good quality and moderate trophic status — “Good”; 5—6 moderate quality and high trophic status — “Moderate”, and 6—10 degraded quality and very high trophic status — “Poor”.

2.2 Study area, sampling stations and in situ data

In situ data for TRIX estimation are obtained from ISPRA (MS Directive implemented by D. Lgs 190/2010, and 2000/60/CE Directive implemented by D. Lgs 152/06 monitoring programmes), selecting the stations at a distance from the coast suitable for remote sensing (Fig. 1).

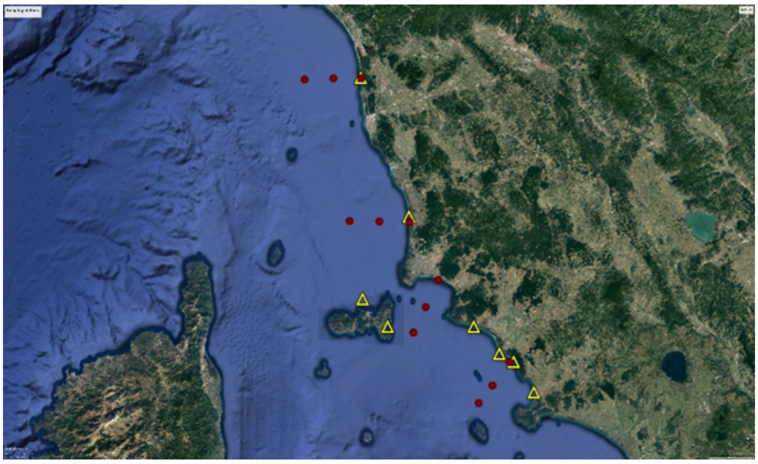

Fig. 1. ISPRA MS (yellow triangles) and Legislative Decree 152/06 (red dots) monitoring stations. Images: Google Earth data SIO, NOAA, US, Navy, NGA, GEBCO, Image © 2021 Terrametrics.

The monitoring network of marine-coastal water bodies, provided for by Legislative Decree 152/2006, is performed in points that are approximately between the distance from the coast of 100 meters and the isobath of 50 meters. The coastal waters of Tuscany have been divided into 14 water bodies, on the basis of morphological, hydrological and bathymetric characteristics. Each of them is classified according to the environmental pressures and the monitoring network has been planned in agreement with the Tuscany Region and currently includes, for each water body, one or more sampling sites, for a total of 19 stations. The monitoring analyses chemical and ecological status: the latter describes the quality of the water based on the status of various biological elements (phytoplankton, macroalgae, Posidonia oceanica, macrozoobenthos), the trophic level of the water (TRIX index) and the presence of non-priority chemical substances in the water (Decreto Legislativo 172/2015).

Among the qualitative descriptors to define the good environmental status (GES) of the waters, Module 1 of MS is dedicated to the monitoring of the chemical-physical parameters of the water column, pelagic habitats and the contaminants present in the water. The areas identified by ISPRA for this monitoring are 4: Fiume Morto, Donoratico, Carbonifera and Collelungo, chosen on the line of some of the stations identified for the implementation of Legislative Decree 152/2006, described above, because they are characterized by different sources, natural or anthropogenic, of pollution: river mouths and / or nutrient inputs, upwelling (presence of upwelling areas of deep waters usually rich in nutrients) or downwelling (areas of accumulation and sinking of high density and low temperature water below lower density and higher temperature waters) and port areas. We selected all the monitoring points, 12, as located at a distance from coast suitable to be covered by the first valid OLCI FR pixel.

In this work 8 monitoring stations belonging to the Legislative decree 152/06 and all the 12 belonging to the MS were identified, as they are located at a distance from coast possibly suitable to be covered by the first valid OLCI FR pixel. We used for all the 20 monitoring stations selected, four environmental attributes to compute TRIX: chlorophyll a (Chl a), mg m^{-3}, oxygen as the absolute percentage deviation from oxygen saturation (DO), %, dissolved inorganic nitrogen (DIN), mg m^{-3}, and total phosphorous (TP) mg m^{-3}, and we computed TRIX. In this study 247 data collected in the years 2016 – 2017 for the 20 monitoring stations selected were available for matchup with satellite data.

2.3 Sentinel 3 OLCI satellite data

Sentinel 3 *a* and *b* is a near-polar orbit satellite constellation: *a* was launched in 2016 and *b* in 2018. Their orbit has a revisit time of 27 days providing global coverage of topography data at mesoscale (inter-track distance at the Equator 104 km using one satellite), with a primary orbit sub-cycle of approximately 4 days.

Sentinel 3 *a* and *b* carry onboard the Ocean and Land Colour Instrument (OLCI), a sensor which collects data in 21 spectral bands with wavelengths ranging from the optical to the near-infrared. Bands vary in width from 400 nm to 1020 nm.

In this work we used the Sentinel 3 OLCI Full Resolution (300 m) products provided by Eumetsat CODA (https://coda.eumetsat.int/) Level 2 NTC full resolution (300 m): Level 2 is obtained by the Baseline AC (BAC) algorithm based on the algorithm developed for MERIS (Antoine and Morel, 1999) and integrating bright pixel correction from OLCI processing chain updated by Moore et. al. (1999, 2017).

All the sensor bands in the visible portion of the spectrum were considered, centred at 400, 412.5, 442.5, 490, 510, 560, 620, 665, 673,75, 681.25, as water surface directional reflectances in the visible range of the spectrum (Rrs). Band ratios of spectral regions that are sensitive to absorption and scattering features (490 and 560 nm) of chlorophyll a are used here as a proxy of chlorophyll a concentration (O'Reilly et al., 2019).The standard OLCI Level 2 products used in this study are: Algal pigment concentration as Chlorophyll a (Chl OC4Me) derived from OC4Me maximum-band-ratio (MBR) semi-analytical algorithm (OLCI Level 2 Algorithm Theoretical Basis Document (a)); Diffuse attenuation coefficient at 490 (KD490) obtained by an artificial neural network as a multiple non-linear regression technique (OLCI Level 2 Algorithm Theoretical Basis Document (b); Total Suspended Matter concentration (TSM) is obtained using the MERIS 1999 Baseline Atmospheric Correction and the OLCI neural net TSM algorithm (Hieronymi et al., 2017 (OLCI Level 2 Algorithm Theoretical Basis Document (b)). An OLCI FR true color map is shown in Figure 2.

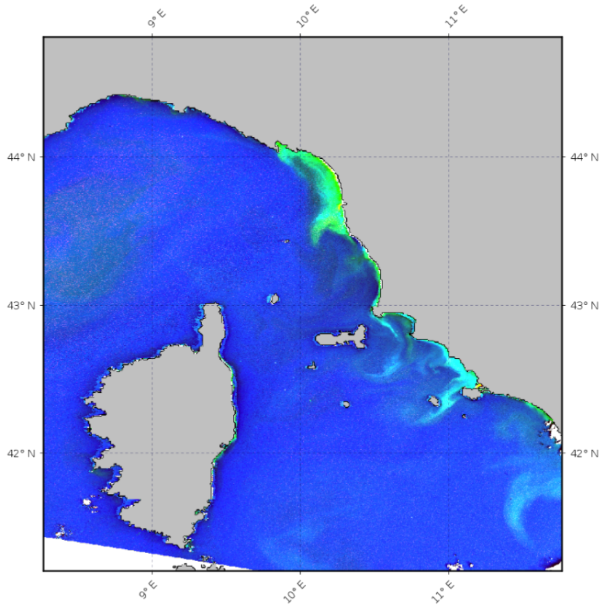

Fig. 2: True color map (bands 17, 6 and 3) on Sentinel 3 OLCI FR (23/06/2016). Image ESA SNAP v8.0 (http://step.esa.int).

2.4 Data analysis

OLCI FR images, showing exact daily matchup with in situ sampling were reprojected (geographic Lat/Lon WGS 84), visualized and analysed using European Space Agency (ESA) Sentinel Application Platform (SNAP) v8.0 and - Sentinel-3 Toolbox (S3TBX) v8.0.6 (http://step.esa.int). First, we selected the ones where cloud and glint flags were absent over the whole study area. Furtherly visual analysis of the images was performed in order to get rid of the ones in which "salt -and – pepper" effect was present.

Pixel extraction was performed via SNAP PixEx operator 1.3 (Copyright (C) 2011 Brockmann Consult GmbH (info@brockmann-consult.de)), on a windows size of 1 X 1 pixels. The level 2 products Rrs, Chl OC4Me, TSM and Kd490 were obtained.

Finally, through the analysis of the spectra related to every single matchup with the samplings we discarded the data showing spectra which had an anomalous shape compared to the ones expected in coastal water.

The investigation then focused on 21 OLCI scenes, from which the values of standard level 2 products were extracted in correspondence with 59 *in situ* TRIX observations. Using this dataset, linear regression analyses were performed between the values of TRIX (dependent variable) and the OLCI products (independent variables).

3 Results

The scatter plot shown in Figure 3 confirms that the *in situ* observations of Chl a and TRIX are highly correlated. This relationship, which is similar to that found in port waters by Massi et al., (2019), is obviously expected, since Chl a is a major component of TRIX.

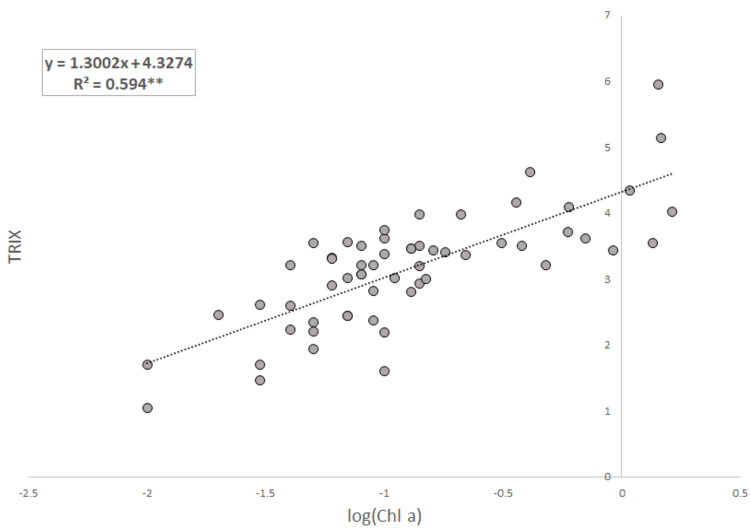

Fig. 3: Scatter plot of in situ Chl a and TRIX (** = highly significant correlation, P<0.01)

The explorative analysis of the correlations between TRIX and some OLCI products gives the results summarized in Table 1. As again expected, TRIX is negatively correlated with the band ratio and positively with all others standard seawater parameters. All correlations are relatively weak but statistically significant.

Table 1. Correlation coefficients found between TRIX and OLCI blue/green band ratio, Chla OC4Me, KD490 and TSM (** = highly significant correlation, P<0.01).

Variables	R
TRIX - Blue/Green	**-0.46****
TRIX – Chl OC4Me	**0.48****
TRIX – Kd490	**0.51****
TRIX – TSM	**0.45****

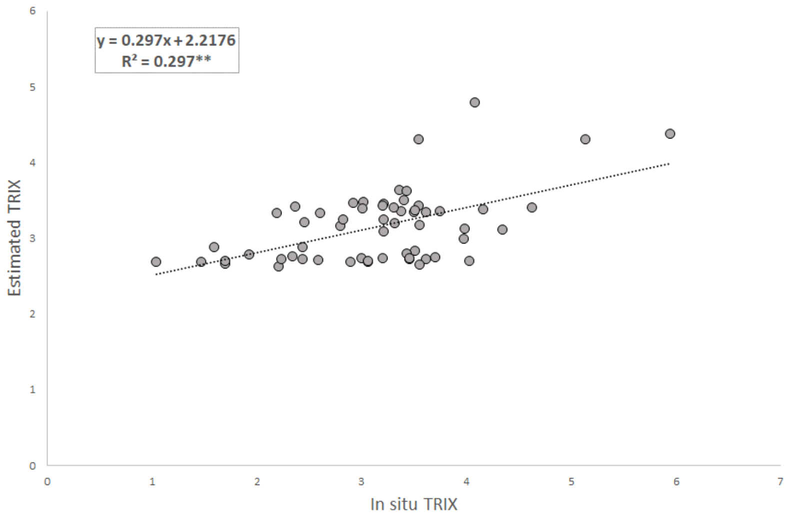

Fig. 4: Scatter plot of in situ and estimated TRIX (** = highly significant correlation, P<0.01)

Based on these results, a tri-variate linear regression model is developed to predict TRIX based on the standard products Chla OC4Me, KD490 and TSM. The scatter plot of TRIX observed *in situ* versus the index estimated through this model is shown in Fig. 4. The estimated values range from about 2 to 5, accounting for about 30% of the observed TRIX variance.

4 Discussion and Conclusions

TRIX is an effective indicator of seawater ecological quality which is widely utilized in Mediterranean coastal areas. The determination of TRIX by seawater sampling and analysis, however, is costly and labor intensive. Recent investigations have shown that the direct and indirect relationships which link TRIX with optically active seawater constituents can provide an alternative monitoring tool based on satellite observations (Massi et al., 2019; Pieri et al., 2021). This possibility is particularly intriguing concerning the images acquired by Sentinel 3 OLCI, which join a good spectral coverage (10 visible bands) to relatively high spatial resolution (300 m) and revisiting frequency (once every 1.9 days with two satellites constellation configuration).

The current paper describes a preliminary analysis of this topic which has been carried out using in situ TRIX observations and standard OLCI products taken in Tuscany during two years. The experimental results substantially confirm the possibility of approximately estimating TRIX via OLCI products, but also highlights some critical issues which should be investigated more exhaustively. In particular, an improvement in TRIX estimation capacity could come from a more thorough exploitation of the spectral information contained in the OLCI imagery. Relying on the findings of the previous investigations, it can be hypothesized that such objective could be fulfilled by a proper utilization of the spectral angle (SA) metric.

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