EUSeaMap

Technical Report No. X

Light data and thresholds

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1 Introduction

Light availability in the water column and at the seabed varies considerably, affecting in particular the depth to which macrophytes (kelp, seaweeds, seagrass, e.g. *Posidonia spp.*) can grow. Light intensity decreases with depth due to the attenuating effects of scattering and absorption in the water column by water molecules, suspended particulate matter, phytoplankton and coloured dissolved organic matter. This attenuation tends to be higher in coastal waters, due to suspended and dissolved matter being washed down rivers, higher phytoplankton concentrations and suspension of sediment caused by wave action in shallow waters.

Light attenuation is the variable used to define the infralittoral zone, where irradiance from the sun is still sufficient to allow significant photosynthetic activity of vegetation such as kelp and seagrass. It can also be used to define the upper circalittoral zone where the light reaching the bottom is estimated to range between 1% - 0.01% of the surface light thereby allowing the photosynthesis of sciaphilic algae such as the Fucales (deep water *Cystoseira* and *Sargassum* spp.), Laminariales, Desmarestiales and Sporochnales as well as red algal (Rhodophycean) species. In the Mediterranean some characteristic communities such as coralligenous assemblages consisting of more or less massive bioconstructions formed by coralline algae, as well as Rhodolith (Maerl beds) thrive in this zone.

In the Baltic polyhaline and fully marine zones, the lower threshold of the infralittoral was mapped using the threshold developed for the North and Celtic Seas, i.e. corresponding to the depth limit of kelp (*Saccharina latissima*, *Laminaria digitata* and *L. hyperborea*). Further North the oligohaline and mesohaline zones lack kelp communities, which are used to define the lower threshold of the infralittoral in the Atlantic EUNIS. Instead, the threshold was defined by the deepest occurrence of algal-dominated biotopes.

2 Data layer preparation

2.1 Computing light in the water column

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In the project two methods of accessing light levels in the water column were used. Ocean colour satellite imagery is quite effective to provide large extent maps of light attenuation at high spatial and temporal resolution. Several models are commonly used to derive Kd_{PAR} (down-welling photosynthetically available radiation) maps from satellite imagery. For EUSeaMap, an improved Kd_{PAR} layer has been estimated from radiance measured by MERIS (Saulquin *et al.,* in prep.), the Medium Resolution Imaging Spectrometer Instrument aboard the European Envisat satellite.

Depth zones can be determined by intersecting the depth data layer with these light attenuation values and using a pre-defined threshold. The fraction of surface light which reaches a given depth is computed using the formula:

$$Fr = e^{-h/D_m} \qquad (1)$$

Where h is the depth and $D_m = Kd_{PAR}^{-1}$ is sometimes referred to as mean penetration depth.

High resolution MERIS imagery (HR with 250 m pixel size) was processed from 2003 to 2008 for the area shown in figure XXXX (limited by 13W, 18E, 36N, 60N. These 250m products are particularly relevant for the steeper shores found in the Mediterranean as well as for complex rocky shores like those found in some Atlantic shores. Within the work for EUSeaMap, the algorithm to predict Kd_{PAR} from the MERIS satellite data has been improved for coastal waters by statistical analysis against *in situ* data collected across the regions as described below on the various basins.

Figure 1: Overview Zeu (photic depth) as computed from MERIS imagery.

2.1.1 Kinetic energy model for waves – North and Celtic Seas

2.2 Validating light thresholds

In order to check the validity of the 1% and 0.01% light thresholds retrieved from satellite imagery, comparisons were carried out with ground-truth data for each basin. In the Atlantic, acoustic measurements of kelp forests from 2006 and 2007 surveys in Brittany at a number of sites were plotted against the photic zone as derived from the KPAR. In the Mediterranean since *in situ* light values were not available, a more comprehensive validation was achieved (see Appendix XXXX). The modelled 1% light layer was tested against the known distribution of *Posidonia oceanica* meadows with a good health status and whose lower limit is known to be limited by decreasing light. The approach was carried out on 40 selected meadows sites in Spain, France and Italy by identifying the largest homogenous polygons and ensuring that fragmented areas were excluded in the process. The bathymetry used to intersect with the KdPAR file to yield the photic zone was from the best available DTMs (resolution of approximately 100m). The lowest percentage of light value from the 250m MERIS data was selected in each of the 40 polygons and the statistics were computed. In view of the log-normal distribution the median value of 0.82 % was therefore considered a valid threshold value for the hard limit of the infralittoral / circalittoral boundary and the lower quartile (0.34%) and upper quartile (1.6%) were considered as fuzzy values to be used in the creation of a confidence map for this limit.

The lower limit of the upper Circalittoral zone, reported to occur at 0.01% residual light, is defined by the limit of the deepest extension of sciaphilic algal. However, the distribution of these algae is not only poorly known and mapped but also limited in spatial extension and is far too fine scale with respect to the broad scale 250 pixel resolution of the model. The assessment was therefore not possible for lack of knowledge of these communities and the 0.01% value was taken for granted. In an attempt to express its uncertainty and give proper warning to users, it was decided to derive fuzzy limits of 0.005% and 0015%] for this boundary.

In the Baltic Sea the above method was used for the polyhaline and fully marine parts of the Baltic Sea area (Kattegat and Skagerrak) and the 1% threshold was confirmed by checking against 198 diving transects.

In the oligo- and mesohaline parts of the Baltic Sea proper (inside Öresund and the Danish Belts), the ratio between Secchi depth and depth was instead used to map the thresholds. The maximum depth/Secchi depth ratio recorded (1,2 and 1.8 for respectively oligo- and mesohaline areas) was used as the lower limit of the fuzzy threshold. The 75 percentile (2 and 3.2 for respectively oligo- and mesohaline areas) was used as the upper limit of the fuzzy threshold for the transect data. The percentile levels were chosen as the expected fraction of the data that is likely to show the deepest occurrence of macroalgae and the resulting threshold values were examined and judged to give a reasonable result.

2.3 Rationale

Light availability in the water column and at the seabed varies considerably, affecting in particular the depth to which macrophytes (kelp, seaweeds, seagrass, e.g. *Posidonia spp.*) can grow. Light intensity decreases with depth due to the attenuating effects of scattering and absorption (by water molecules, suspended particulate matter, phytoplankton and coloured dissolved organic matter) in the water column (turbidity). This attenuation tends to be higher in coastal waters, due to suspended and dissolved matter being washed down rivers, higher phytoplankton concentrations and suspension of sediment caused by wave action in shallow waters.

Light attenuation is the variable used to define the infralittoral zone, where irradiance from the sun is still sufficient to allow significant photosynthetic activity. On Atlantic coasts the decrease in light levels with depth is typically reflected in four zones (Hiscock 1996):

- Infralittoral - dense kelp (Laminaria)
- Upper circalittoral - sparse seaweeds and sciaphilic algae
- Lower circalittoral - encrusting algae only

In the Mediterranean, the differences in light levels reaching the bottom delimit four basic zones:

- Infralittoral - seagrass and photophilic[13] algae
- Upper circalittoral - sciaphilic[14] brown and red algal species
- Lower circalittoral - survival of sparse sciaphilic algae originating from the upper circalittoral
- Abyssal - no light and no plant life

Biological zoning in the Mediterranean is affected by variables which are different from, but in some cases overlapping, those in the North and Celtic seas. In the Mediterranean, the infralittoral zone starts at low tide level and extends down to the deepest limit of *Posidonia oceanica* growth. The lower limit of the infralittoral is therefore defined as the area up to which the light intensity is such that seagrasses (i.e. *Posidonia oceanica*) and photophilic algae can survive. This threshold value is estimated to be equivalent to 1% of the light irradiance reaching the bottom of the seafloor.

The circalittoral zone starts from the lower limit of the infralittoral and extends to the maximum depth where multicellular photosynthetic forms can exist. The assemblages found in this zone are therefore characterised by the predominant presence of sciaphilic algal communities. The circalittoral can also be divided into upper circalittoral and lower circalittoral zones on the basis of the amount of light reaching the seabed. In the upper circalittoral, the light reaching the bottom is estimated to range between 1% - 0.01% of the surface light thereby allowing the photosynthesis of multicellular algae. The light reaching the bottom in the upper circalittoral is sufficient to allow the photosynthesis of different brown algae communities such as the Fucales (deep water *Cystoseira* and *Sargassum* spp.), Laminariales, Desmarestiales and Sporochnales as well as red algal (Rhodophycean) species. Characteristic communities present in this zone are the coralligenous assemblages consisting of more or less massive bioconstructions formed by coralline algae, as well as Rhodolith (Maerl beds) consisting of loose lying, living or dead, coralline red algae, usually aggregated into masses on shell gravel mixed with coarse sand. On the contrary, the lower circalittoral is characterised by having less than 0.01% of the surface light reaching the seabed and multicellular algae are therefore generally not present in great quantities, as light becomes an increasingly limiting factor.

Computing light levels in the water column

There are two ways of accessing light levels in the water column. The first is by using the very simple "Secchi disk" method which is still the standard method used in oceanography cruises. While somewhat over-simplistic, this method enables comparisons between basins and also makes it possible to benefit from historic data sets. In the Baltic Sea where high concentrations of detritic matter in the ocean are a drawback to using satellite imagery, it can be a valuable alternative, as explained in the section on the Baltic below.

The second method uses satellite observations of the diffuse attenuation coefficient of the down-welling spectral irradiance at wavelength 490 nm (Kd_{490}) or the diffuse attenuation coefficient for the down-welling photosynthetically available radiation (Kd_{PAR}), which is an effective method to provide large extent maps of light attenuation at high spatial and temporal resolution. Several models are commonly used to derive the Kd_{490} and Kd_{PAR} maps from ocean colour satellite sensors, such as the Medium Resolution Imaging Spectrometer Instrument (MERIS) aboard the European Envisat satellite, the Sea-viewing Wide Field-of-view Sensor (SeaWiFS), and the Moderate Resolution Imaging Spectroradiometer (MODIS). Most of these existing models have been calibrated on open ocean waters and provide good results in these areas, but tend to underestimate the attenuation of light in turbid coastal waters.

The infralittoral zone can be determined by intersecting the depth data layer with these light attenuation values and using a pre-defined threshold. The 1% threshold is still the subject of discussion in the scientific community and it is within the remit of this project to attempt to validate it with suitable ground-truth data for both the Atlantic and the Mediterranean. This fraction () of surface light which reaches a given depth is computed using the formula:

$$Fr = e^{-h/D_m} \qquad (1)$$

Where h is the depth and $D_m = Kd_{PAR}^{-1}$ is sometimes referred to as mean penetration depth.

For EUSeaMap, an improved Kd_{PAR} layer has been estimated from radiance measured by the MERIS sensor (Saulquin *et al.,* in prep.).

Figure 1: Overview of the MERIS swath zone.

Two types of products were processed. Level 2 Reduced Resolution (RR at 1 km) products were first processed from 2003 to 2008, including all four basins (limited by 13W, 18E, 36N, 60N). In the second phase, the same area was subsequently processed using high resolution Meris images for the same period (HR at 250 m), which made it possible to be fully in line with the resolution specifications of the project. Unfortunately, the latter products were not available for this study and will be delivered in October 2010 for use in a later update. These 250m products are particularly relevant for the steeper shores found in the Mediterranean as well as for complex rocky shores like those found in Brittany. These light layers represent a further significant improvement beyond the resolution of the data. Within the work for EUSeaMap, the algorithm to predict Kd_{PAR} from the MERIS satellite data has been improved for coastal waters by statistical analysis against *in situ* data collected across the regions as described below on the various basins.

Computing the photic zone boundary is simply a matter of intersecting the 1% light layer with the depth layer. If the actual depth at any location is shallower or deeper than the photic depth, the pixel is respectively flagged as infralittoral or upper circalittoral. It should be emphasised here that the quality of the bathymetry has a strong bearing on the quality of this result. This should be borne in mind in the comparison with ground truth data.

2.4 Light thresholds in the North and Celtic Seas

In order to check the validity of the 1% light threshold as retrieved from satellite imagery, a comparison was carried out with ground-truth data. In the Atlantic, acoustic measurements of kelp forests from 2006 and 2007 surveys in Brittany at a number of sites (Abers, Héaux de Bréhat, Triagoz, Méloine, Molène and Ile de Groix, see Méléder *et al*. 2010) were plotted against the photic zone as derived from the 1km resolution K_{PAR} (Figure 1).

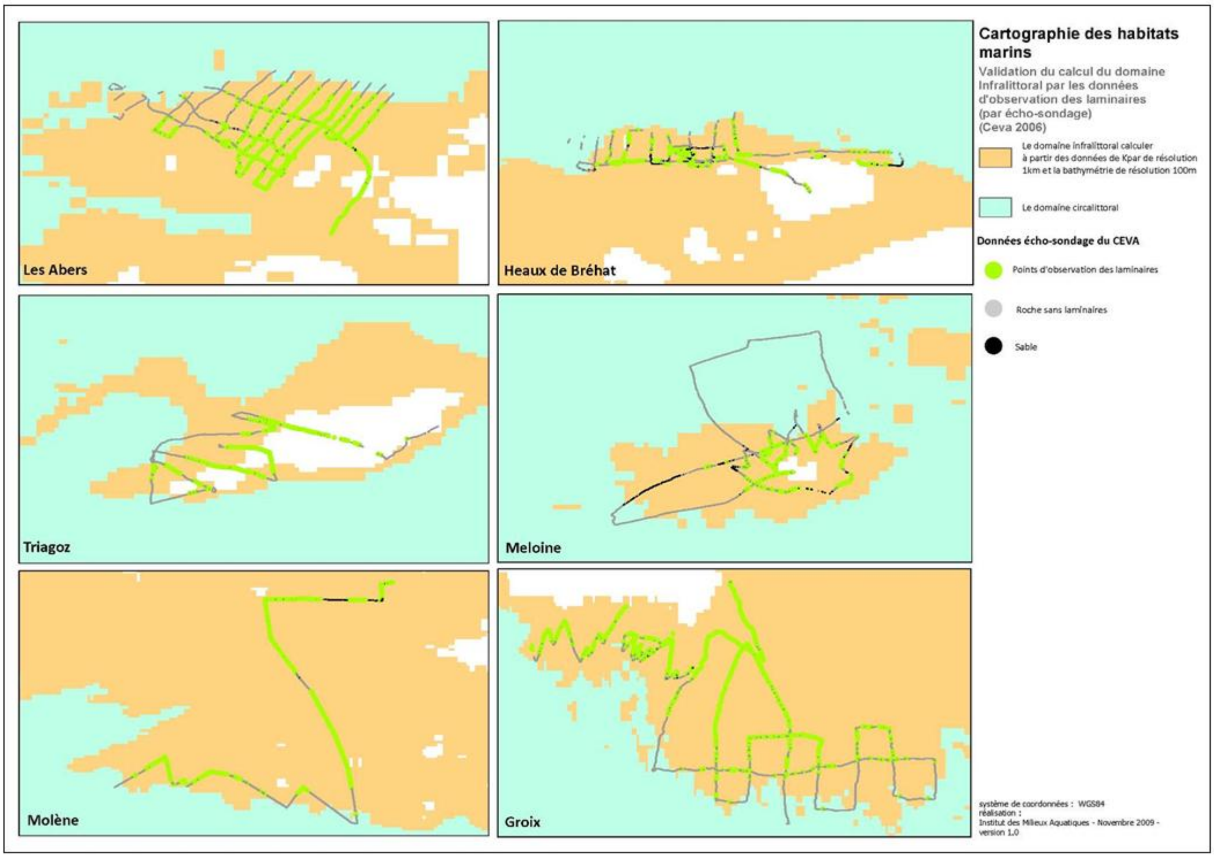


Figure 1 Echo-integration of single beam sounder data showing the presence of kelp forest (green dots, as opposed to bare rock shown as grey dots) overlaid on infralittoral zone (orange) from 1 km resolution Meris imager.

What can be seen from these maps is that kelp are very seldom present in the aphotic zone (in blue) and also that in quite a number of cases, kelp presence actually stops when the transects cross the photic zone boundary. However, limited value should be given to such comparisons, because the retrieval of the photic zone is based on best depth available data. In this case in Brittany, the depth file is a 100 m resolution DTM (Digital terrain model) derived from SHOM soundings. For an initial assessment of the quality of the comparison, the interpolation error map delivered with the DTM should be consulted to check whether the depth value at each location is reliable. Following that step, the 1% light value was propagated throughout the whole Atlantic area of the project to delineate the photic (or infralittoral) zone.

Some research questions still remain with regard to the use of such imagery. So far, mean annual values over a multiple year period have been used. It would be interesting to look at monthly or seasonal values as well. Discussions in meetings revolved around the seasonality for threshold testing, e.g. March – end of June to cover the recruitment and growth period, but there are many conflicting opinions in the literature. For example, the winter period might be important with respect to the length of time needed for species to store light energy, or perhaps it is best to examine a ratio of the summer to winter means. Differences between regions for species (*Posidonia*, *Fucus* and *Laminaria*) must also be considered. It was also suggested that means corrected for seasonal variability be sought.

2.5 Light thresholds in the Mediterranean

2.5.1 Definition and validation of the infralittoral / circalittoral boundary

The passage from the infralittoral to the circalittoral zone is marked by the degree of light reaching the sea bottom, whereby past a certain threshold of light photosynthesis of seagrasses and photophilic algae cannot occur. According to bibliographical data, it is hypothesised that this limit is set at 1% of surface light reaching the sea bottom. However, since the hypothesised values may not necessarily coincide with those generated by the modelled light layer, it is important that the modelled light layer be validated. Since *in situ* light values were not available for the Mediterranean, the modelled 1% light layer (Buia et al., 2003) was tested against the known distribution of *Posidonia oceanica* meadows with a good health status and whose lower limit is known to be limited by decreasing light rather than to other anthropogenic causes (i.e. anchoring, pollution, water quality alteration or trawling).

Statistical analysis of the light values of the evaluated meadows was subsequently used to further define the final threshold value to be used in the model, as well as the values to be used as fuzzy values of this limit. The approach was carried out on selected meadows in Spain, France and Italy using the average daily light data obtained from MERIS images on a 1 km resolution averaged over the period 2003-2008. The bathymetry used to intersect with the Kd_{PAR} file to yield the photic zone was from the best available DTMs in Italy and France (resolution of approximately 100m).

Two approaches were used to test the estimated 1% light value and define the value for the hard limit to be used in the definition of the infralittoral / circalittoral boundary which are described below.

2.5.2 Choice of good condition Posidonia meadows

In France, the meadows known to have the best conservation status based on scientific bibliography and expert knowledge, along with meadows located in noteworthy marine protected areas, were considered. Polygons were chosen within these meadows where the lower limit of the meadow was known to be in good health and where it is expected that its extension is limited only by decreasing light levels. Four sites were chosen on the French mainland located from Hyeres eastward and five sites were chosen around Corsica. The location names in which the polygons fall are given in Table 1.

In Italy, *Posidonia oceanica* meadows which were the object of validation procedures in Italy belong to three categories: a) meadows for which ISPRA-owned specific cartographic and bathymetric information on the good conservation status of the meadow lower limit (Elba island) exists, b) meadows hypothesised as having good conservation status on the basis of information derived from the Posidonia national monitoring scheme carried out since 2003 by the Italian Ministry of the Environment (*Programma di monitoraggio Legge 979*). In this case, the meadows considered in the validation process were chosen if the lower limit was identified as being progressive (which implies that the meadow lower limit distribution is influenced only by decreasing light levels). Meadows with other types of lower limit (sharp, erosive, progressive) were considered for the validation process only if they had a conservation index (% live Posidonia: dead matte; from Moreno et al., 2001) range of 1.0-0.9, and their conservation status (defined on the basis of leaf density with respect to depth, from Buia et al., 2003) was classified as being excellent or in normal equilibrium, and c) an additional set of polygons identified in the Ligurian coastal area by selecting the meadows with the most intact lower limit on the basis of best expert judgement.

The Posidonia meadow polygons related to point b) above were selected by identifying the largest homogenous appearing polygon within which each station/point data was located and ensuring that fragmented sparse peripheral areas were excluded in the process. The names of the locations proximate to which each of the polygons holding Posidonia meadows is listed below and amounts to 20 locations (Table 2).

In Spain, the_Posidonia meadows used in the validation process were those which were known to have good conservation status in terms of their lower limit and not exposed to the effects of fish trawling and anchoring, based on expert opinion. Only those meadows which had recently been mapped and which had high resolution cartographies were considered. A further refinement of the Spanish dataset was carried out in order to eliminate some polygons in which the bathymetric values were not coherent with the presence of Posidonia meadows. This process was performed manually by checking each polygon with the final bathymetric layer and/or (where available) with high resolution isobaths (i.e. Balearic Islands). The names of the 11 locations near which each of the polygons holds Posidonia meadows is listed in Table 1.

2.5.3 Light fraction estimated from pixels on lower limit of Posidonia meadows

This first approach looked at the light fraction value of all pixels intercepting the lower limit of 29 Posidonia meadows located in France and Italy and considered to have good conservation status. The lower limit was selected manually as being the boundary “furthest offshore”. This approach was tested mainly on the argumentation that it should provide a more robust statistical evaluation since it would entail evaluating a higher number of data records for all available Posidonia meadows. It only concerned selected French and Italian meadows.

Table 1 Posidonia sites selected for validation in the three Mediterranean countries.

Meadow location	Area
Port-Cros	SE France
Cannes	SE France
Iles de Lérins	SE France
Porquerolles	SE France
Southern Bastia	Corsica
Alèria	Corsica
Archipelago of Lavezzi	Corsica
Scandola	Corsica
Calvi	Corsica

Meadow location	Region
Bega de Mar	Alicante
Cap de La Nao	Alicante
Santa Pola	Alicante
El Oasis	Alicante
West Parc National Calbarque	Murcia
East Parc National Calbarque	Murcia
Calabardina	Murcia
Ibiza	Balearic Is.
Maiorca	Balearic Is.
Menorca	Balearic Is.
South Alicante	Alicante

Meadow location	Region
Punta Licosa	Campania
Camerota	Campania
Torre Paola	Lazio
S. Lorenzo	Liguria
Porto Maurizio	Liguria
S. Stefano Sud	Liguria
Capo Berta	Liguria
Capo Cervo	Liguria
Ospedaletti - Capo Nero	Liguria
P.ta S.Martino-Capo Verde	Liguria
Alghero	Sardinia
Arbatax	Sardinia
S. Antioco	Sardinia
Olbia	Sardinia
Asinara	Sardinia
Capo Carbonara	Sardinia
Maraone - AMP Isole Egadi	Sicily
Antignano	Tuscany
Foce Tirso	Tuscany
Carbonifera	Tuscany

The distribution of the obtained values and the statistical parameters of the resulting light dataset are indicated in table 2 and figure 3. These values (mean of 2.17% and median of 1.52%) are generally higher than what would be expected from bibliographic references. A closer look at a specific site in Port-Cros (Figure 4) shows the difficulty of choosing the lower boundary, due to the very high variability of light values (up to 8%) and associated depth (from 24 to 46 m), which shows either that many points are not on the lower boundary or that there are other factors besides light limiting the deeper extension of the plants (sediment type, human pressure, cartographic error, etc.). Based on the above-mentioned argumentation, it was decided that this validation approach would not be considered for the purpose of defining the infralittoral zone limit.

Table 2 Statistics of the observed light values associated with the French and Italian Posidonia meadow lower limits

	Valid N	Mean	Geometric	Median	Minimum	Maximum	Percentile	Percentile	Std.Dev.
Fr_Light	979.00	2.17	1.64	1.52	0.20	9.86	0.69	4.80	1.82

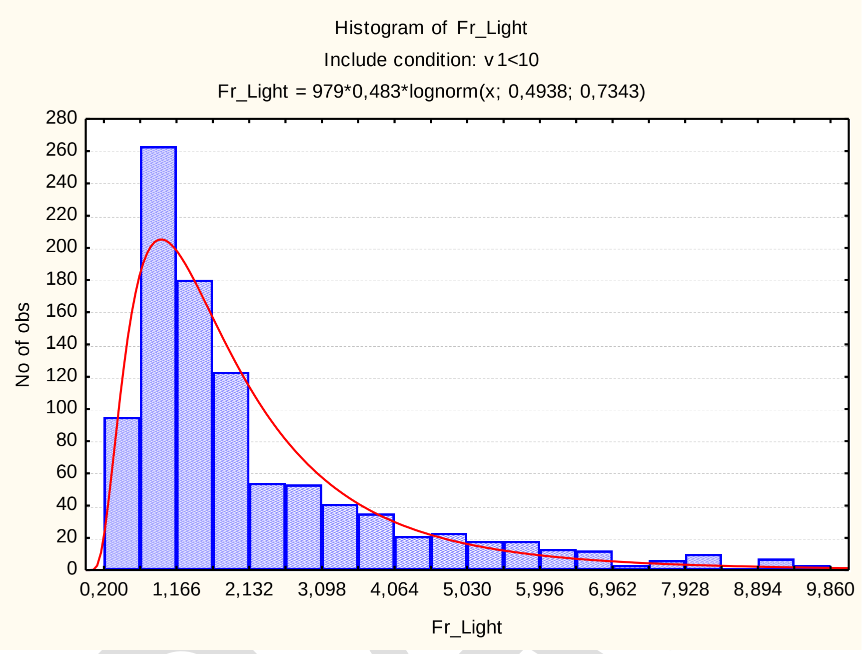


Figure 2 Histogram of the observed light values associated with the French and Italian Posidonia meadow lower limits

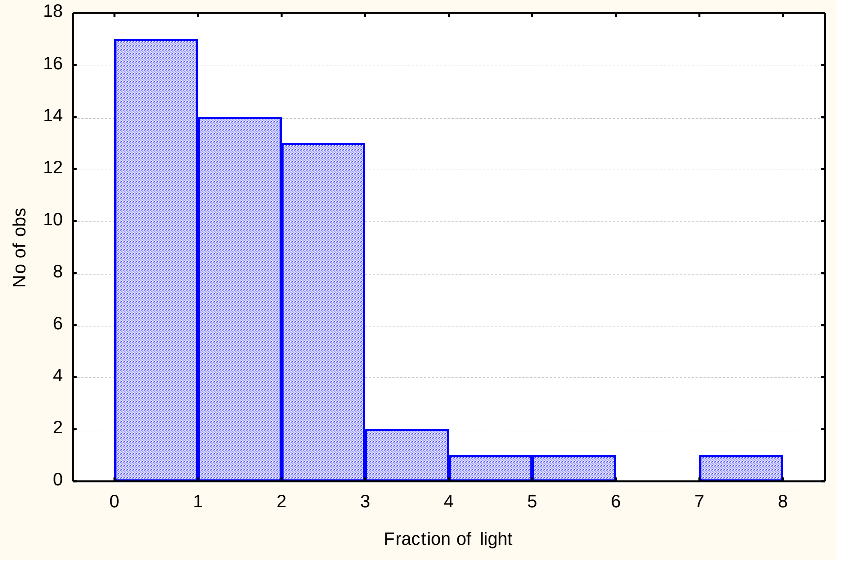


Figure 3 Histogram of light fraction values observed for the Port Cros Posidonia meadow lower limit.

2.5.4 Minimum light values observed in Posidonia meadows

The second approach consisted in selecting the lowest pixel value in each of the 40 Posidonia meadows located in Italian, French and Spanish waters and considered as having good conservation status. The statistics of this data set are listed below (see table 3 and figure 5). Both the mean and median values observed on the overall lie very close to the expected hypothesised minimum value of light (1%) that is expected to allow the photosynthesis of Posidonia. In view of the log-normal distribution the median value of 0.82 % was therefore considered a valid threshold value for the hard limit of the infralittoral/circalittoral boundary and the lower quartile (0.34%) and upper quartile (1.6%) were instead considered as valid fuzzy values to be used in the creation of a confidence map for this limit. Refer to the fuzziness section to visualise the resulting buffer.

Table 3 Statistics of the minimum light values observed in Italian, French and Spanish Posidonia meadow polygons.

Descriptive Statistics (Statistica_luce_final.sta) Include condition: v24 > 20 Exclude condition: v18 < 40 or v24 = 41 or v24 = 46 or v24 = 48

	Valid N	**Mean**	**MG**	**Median**	**Min**	**Max**	**LQ**	**UQ**	**Pct10**	**Pct90**	**Std.Dev.**
Min_%	40	1.136	0.751	0.821	0.165	3.623	0.340	1.609	0.188	2.535	0.997

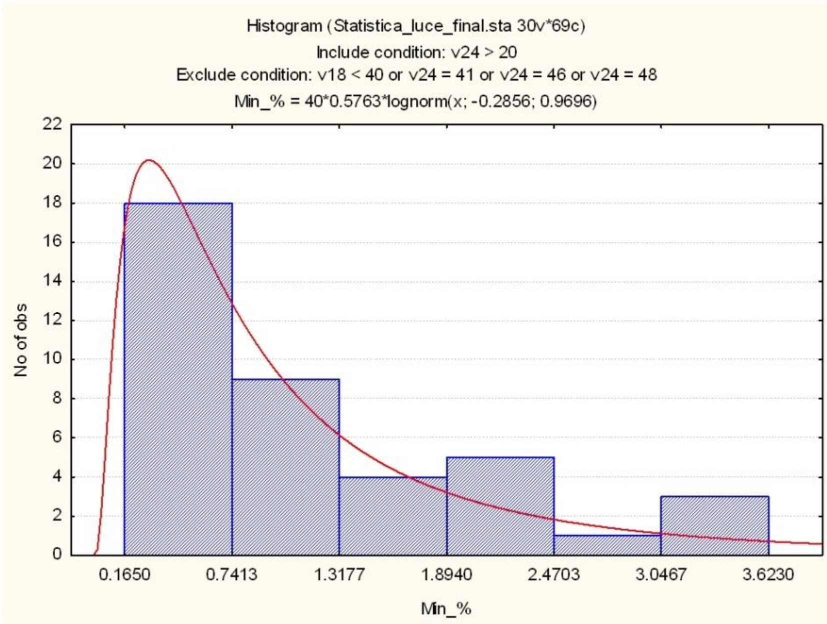


Figure 4 Histogram of the observed minimum light values associated with 40 Italian, French and Spanish Posidonia meadow polygons.

The quality of the fit between the photic zone and Posidonia meadow extension is shown in Figure 5. This fit was actually computed with the 1% value (prior to adopting 0.82%), however the difference is negligible. It should be noted that the quality of the underlying bathymetry is crucial in this validation. However good our field data may be, if the Zeu computation is jeopardised by approximate bathymetry, then the validation process is meaningless. In the Lavezzi Islands area, the DTM comes from unbiased soundings and the error of the kriged DTM remains within the 1-5m range.

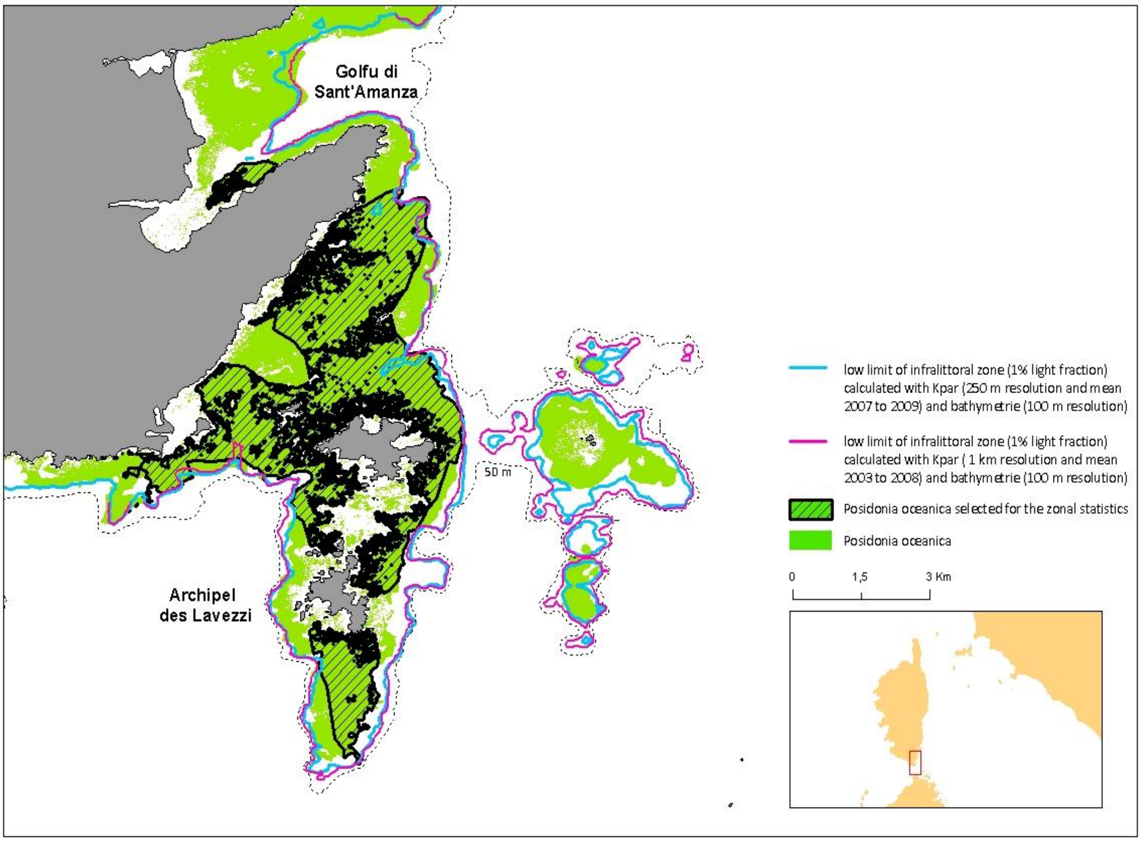


Figure 5 Visual comparison between satellite-derived photic depth Z_{eu} computed from 1km and 250 m MERIS imagery respectively in red and blue, and lower limit of Posidonia beds in Corsica (Lavezzi Archipelago).

2.5.5 Definition and validation of the upper / lower circalittoral boundary

The lower limit of the upper Circalittoral zone is defined by the limit of the deepest extension of sciaphilic algae photosynthesis (brown algae *Cystoseira*, *Sargassum*, *Laminaria)*. According to bibliographic literature, this is defined as 0.01% surface light reaching the sea bottom. However, the distribution of these sciaphilic algae is not only poorly known and mapped but also limited in spatial extension and is far too fine scale with respect to the broad scale 250 pixel resolution of the model. A validation of the modelled 0.01% light layer with respect to these assemblages is therefore not possible, since our previous experience with the validation of 1% light-Posidonia indicated that fine scale point data are not useful for validation of interpolated variable values reported on large size pixels such as those used in the present project. The conclusion is that the 0.01% light layer cannot be validated using the very same assemblages that are presumed from literature to be indicative of the change in this variable threshold.

In an attempt to express the uncertainty of the latter limit and give proper warning to users, it was decided to derive fuzzy limits for this boundary. As fuzzy limits could not be based on statistical quartiles data as was the case for the photic zone, the project opted for a range using the same proportion of the central value [0.005 to 0015%]. Refer to the fuzziness section to visualise the resulting buffer.

2.6 Light thresholds in the Baltic Sea

2.6.1 Computing Baltic light levels

Due to high amounts of coloured dissolved organic matter, frequent cloud cover and a lack of optical field data for sea-truthing, remote sensing of the optical properties of Baltic waters at a regional scale is difficult (Kratzer *et al*. 2003). An alternative approach, which was successfully applied earlier (Al-Hamdani & Reker 2007, HELCOM 2009), is using Secchi depth data. The method described in Al-Hamdani and Reker (2007) was refined, and additional data were incorporated, to produce a euphotic zone depth raster for the Baltic Sea.

Secchi depth data were obtained via the International Council for the Exploration of the Sea (ICES): Aarup's collection (Aarup 2002) covering 1902 to 1998 and additional data covering 1999 to 2008. Also the Finnish Environment Institute (SYKE) provided further data points for the years 2000 to 2008. For the interpolation of the light layer, only data from 1980 or later and covering months from which a reliable estimate of the growing season (March to October) mean could be derived were used. In total, the interpolation was based on data for 5738 locations.

At many of these locations, Secchi depths had been measured repeatedly, and monthly means were calculated. The main growing season from March to October was covered with at least one measurement per month at 277 locations. For these, "growing season means" were calculated, which were strongly correlated to the monthly means from April to October. Thus, a linear regression function was determined for each of these months (R_2 ranging from 0.77 to 0.86; Figure 7). For the locations where data were not available for the whole March to October period, but at least for one of the months between April and October, the growing season mean was estimated based on the month with the best-fitting regression line.

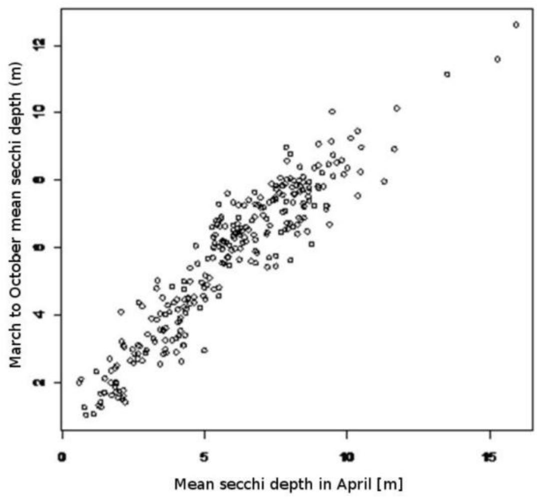


Figure 6 Scatter plot of April mean secchi depths vs. growing season (March to October) mean secchi depths, n=277.

However, this approach neglects inter-annual variability, and the density of data points was spatially very variable. To avoid pseudo-patchiness, the study area was subdivided into squares with a side length of 10km. For each square, the growing season means of all data points within were averaged and assigned to the points' mean centre. A secchi depth raster with a spatial resolution of 200m was then interpolated from the mean centres based on local trend surfaces. Cross-validation showed a mean error caused by the interpolation of below 1m and without a clear spatial pattern. Finally, a low pass filter was applied.

To derive euphotic zone depths from secchi depths, conversion factors ranging from 1.7 to 3.5 have been suggested in literature (Al-Hamdani and Reker, 2007, and references therein; Holmes 1970). For the Skagerrak and Kattegat, the secchi depths were compared to euphotic zone depths derived from Aqua-MODIS satellite imagery at 1km resolution. A factor of three gave the best fit. This is backed up by Holmes (1970). Figure 8 shows the final euphotic zone depth raster.

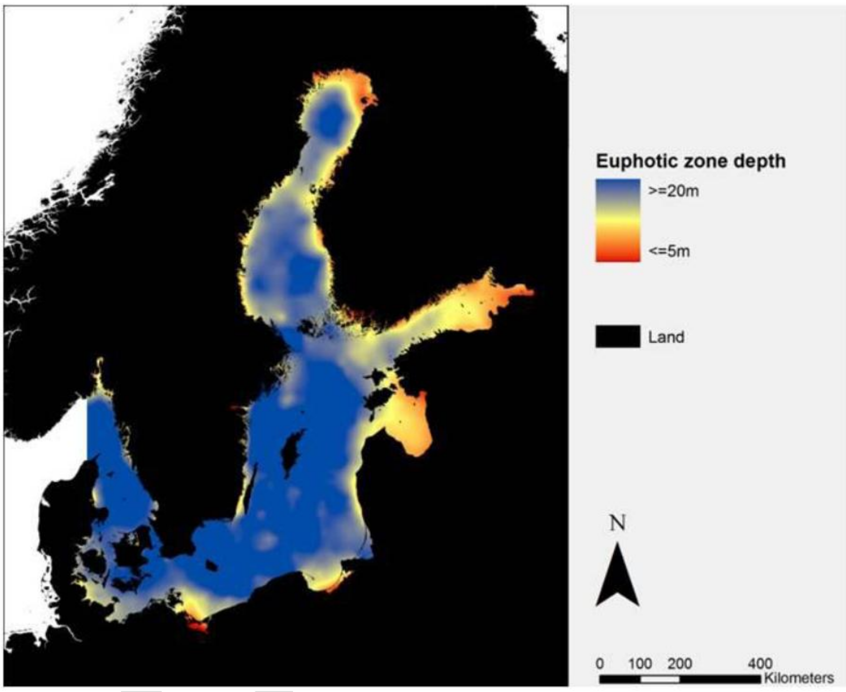


Figure 7 Euphotic zone depths for the Baltic Sea derived from secchi data.

The analyses of thresholds for light were done separately for (1) oligohaline, (2) mesohaline and (3) polyhaline and fully marine zones, since the biological communities used to define the thresholds differ greatly between the salinity zones. In the oligo- and mesohaline parts of the Baltic Sea proper (inside Öresund and the Danish Belts), the ratio between Secchi depth and depth was instead used to map the thresholds. In the polyhaline and fully marine parts of the Baltic Sea area (Kattegat and Skagerrak), the Kd_{PAR} layer produced from MERIS data was used to map the thresholds between infralittoral and circalittoral and between upper and lower circalittoral.

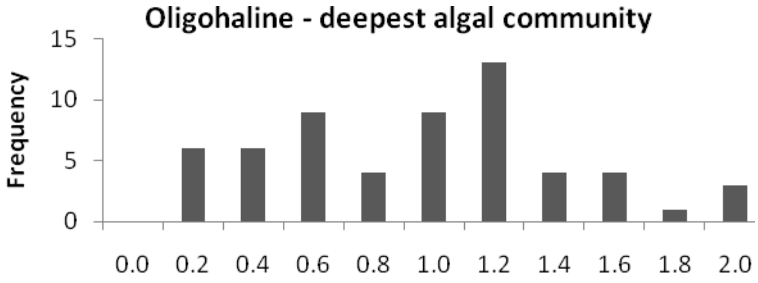
2.6.2 Oligohaline and mesohaline zones

The oligohaline and mesohaline zones lack kelp communities, which are used to define the lower threshold of the infralittoral in the Atlantic EUNIS. Instead, the threshold was defined by the deepest occurrence of algal-dominated biotopes.

The field data set used to set the threshold values came from a total of 902 diving transects from the Swedish and Finnish coasts, 70 from the oligo- and 832 from the mesohaline salinity zones. The data was compiled from a number of different studies, using a standard method for monitoring of phytobenthic communities in the Baltic Sea (Kautsky 1992; HELCOM 1999). In short, diving transects were placed perpendicular to the shoreline, from the shore to the deepest occurrence of macroalgae or plants and the substratum type and surface cover of all algae, plants and sessile animals were noted within depth sections in a 6-10 m wide corridor along the transect line. The transect method is designed to monitor depth distribution of organisms and the data were therefore expected to be well suited to defining the light-related thresholds.

For threshold analyses, each transect section from the diving transects was classified into preliminary EUNIS classes using the BalMar tool (reference) and the deepest finding of biotopes dominated by macroalgae was recorded for each transect and used in the analyses. The depth/Secchi depth ratio for the deepest recording was calculated as the ratio between the depth recorded during the inventory and the Secchi depth taken from the interpolated data layer (data ref code?).

The results from the analyses are shown in Figure 8 and Table 4. The analyses identified a large variation in the largest depth/Secchi depth ratio. Part of this variation is likely to come from the fact that the depth distribution of algae at a certain site can be set by substrate limitation instead of light limitation. This is likely the case for a large part of the recordings of depth limit at a depth/Secchi depth ratio much below 2. However, part of the variation is likely due to errors in the Secchi depth layer.



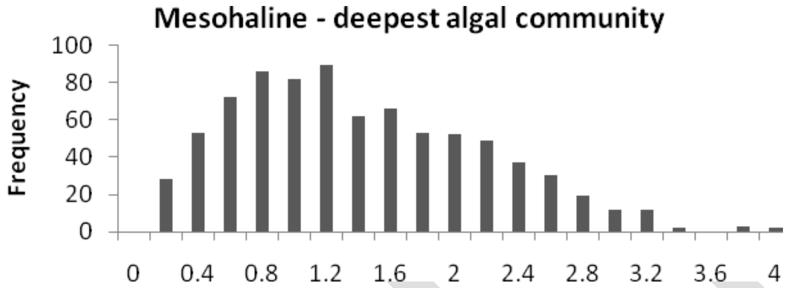


Figure 8 Histograms of depth distribution of the deepest location found of algae-dominated communities in transects.

Table 4 The thresholds defined for the oligo- and mesohaline salinity zones. The values are depth/Secchi depth ratio.

	Fuzzy threshold	Definition	Statistica	Value (D/SD)
Oligohaline				
Infralittoral/circalittoral	upper	Depth of algal domination	75 percentile	1.2
Infralittoral/circalittoral	lower	Depth of algal domination	max	2.0
Mesohaline				
Infralittoral/circalittoral	upper	Depth of algal domination	75 percentile	1.8
Infralittoral/circalittoral	lower	Depth of algal domination	max	3.2

The maximum depth/Secchi depth ratio recorded was used as the lower limit of the fuzzy threshold, after removing one or a few extreme outliers apparently resulting from errors in the Secchi depth layer. The 75 percentile was used as the upper limit of the fuzzy threshold for the transect data. The percentile levels were chosen as the expected fraction of the data that is likely to show the deepest occurrence of macroalgae and the resulting threshold values were examined and judged to give a reasonable result.

The wide fuzzy threshold results in a large uncertainty around the light thresholds derived from the Secchi depth layer. It was also clear from the analyses that the defined thresholds tend to overestimate the depth distribution in some regions while underestimating it in other regions. For instance, the depth of the infralittoral is underestimated in offshore areas of the Baltic Proper, in some parts of the Eastern Baltic Proper and some coastal areas in the Bothnian Bay. This means that the mapping of the biological zones in the Baltic Sea could be greatly improved by a better light layer for the Baltic Sea, for instance produced from MERIS data.

2.6.3 Polyhaline and fully marine zones

In the polyhaline and fully marine zones, the lower threshold of the infralittoral was mapped using the threshold developed for the North and Celtic Seas. The relevance of this threshold in the Kattegat and Skagerrak was tested using the depth limit of kelp (*Saccharina latissima*, *Laminaria digitata* and *L. hyperborea*) in 198 diving transects collected with the method described above and in most transects the maximum depth. Only three of the transects (<2%) had presence of kelp below 1% light from the Kd_{PAR} layer, indicating that this threshold is relevant in the polyhaline and euhaline salinity zone as well in the Kattegat and Skagerrak..

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