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GEOGRAPHICAL STUDIES OF UNDERWATER LIGHT DYNAMICS IN THE COASTAL ARCHIPELAGO OF SW FINLAND, BALTIC SEA

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ABSTRACT

The underwater light field is an important environmental variable as it, among other things, enables aquatic primary production. Although the portion of solar radiation that is referred to as visible light penetrates water, it is restricted to a limited surface water layer because of efficient absorption and scattering processes. Based on the varying content of optical constituents in the water, the efficiency of light attenuation changes in many dimensions and over various spatial and temporal scales. This thesis discusses the underwater light dynamics of a transitional coastal archipelago in south-western Finland, in the Baltic Sea. While the area has long been known to have a highly variable underwater light field, quantified knowledge on the phenomenon has been scarce, patchy, or non-existent.

This thesis focuses on the variability in the underwater light field through euphotic depths (1% irradiance remaining), which were derived from *in situ* measurements of vertical profiles of photosynthetically active radiation (PAR). Spot samples were conducted in the archipelago of south-western Finland, mainly during the ice-free growing seasons of 2010 and 2011. In addition to quantifying both the seasonal and geographical patterns of euphotic depth development, the need and usability of underwater light information are also discussed. Light availability was found to fluctuate in multiple dimensions and scales. The euphotic depth was shown to have combined spatio-temporal dynamics rather than separate changes in spatial and temporal dimensions. Such complexity in the underwater light field creates challenges in data collection, as well as in its utilisation. Although local information is needed, in highly variable conditions spot sampled information may only poorly represent its surroundings. Moreover, either temporally or spatially limited sampling may cause biases in understanding underwater light dynamics. Consequently, the application of light availability data, for example in ecological modelling, should be made with great caution.

Keywords: Underwater light, euphotic depth, Secchi depth, spatio-temporal variability, *in situ* sampling, coastal archipelago, Baltic Sea

TIIVISTELMÄ

Vesien kirkkaus tai vaihtoehtoisesti sameus vaikuttaa vedenalaisluonnon toimintaan monin tavoin. Valaistusolosuhteiden merkitys ympäristömuuttujana korostuu erityisesti elämää ylläpitävän perustuotannon kautta, sillä näkyväksi valoksi kutsumamme auringonsäteilyn osuus mahdollistaa yhteyttämisen niin vedessä kuin kuivalla maallakin. Vedessä valo ei kuitenkaan tunkeudu pintakerrosta syvemmälle, sillä erilaiset absorptio- ja sirontaprosessit vaimentavat sen etenemistä tehokkaasti. Valosäteilyn vaimenemistehokkuus taas vaihtelee moniulotteisesti vedessä olevien vaimentavien ainesten pitoisuuksien mukaisesti. Tässä väitöskirjassa käsitellään vedenalaisen valon vaihteludynamiikkaa Itämeren rannikolla. Tutkimus keskittyy Lounais-Suomen saaristoon, joka laajana saaristovaihettumavyöhykkeenä tarjoaa monipuolisen ja vaihtelevan tutkimusalueen. Tämän saaristoalueen on jo pitkään tiedetty olevan valaistusolosuhteiltaan hyvin vaihteleva, mutta tarkkaa tutkimustietoa näistä vaihteluista oli saatavilla hyvin vähän, jos lainkaan.

Väitöskirja perehtyy vedenalaisten valaistusolosuhteiden vaihteluun käsittelemällä erityisesti veden valaistun pintakerroksen, eli eufoottisen kerroksen, paksuutta ja sen muutoksia. Eufoottiset syvyydet, joissa 1 % pintakerroksen läpäisevästä auringonsäteilystä on jäljellä, määriteltiin jäättömänä aikana kasvukausina 2010 ja 2011 mitatuista valomäärän syvyysprofiileista. Sen lisäksi, että tutkimuksessa tuotettiin mitattua tietoa valaistun kerroksen alueellisista vaihettumista ja kasvukauden aikaisista muutoksista, työssä pohditaan myös valomäärätiedon tarvetta ja sen soveltamiseen liittyviä haasteita. Koska valon saatavuuden muutokset ovat alueellis-ajallisesti moniulotteisia ja -tasoisia, ei edustavan aineiston kerääminen ja edes kattavan tiedon tehokas hyödyntäminen ole yksiselitteistä tai ongelmatonta. Alueella, jossa olosuhteiden vaihtelut ovat suuria, paikallisen tason tiedonkeruun merkitys korostuu, mutta samalla yksittäisten mittauspisteiden edustavuus voi olla hyvinkin heikkoa. Joko alueellisesti tai ajallisesti rajalliset kenttämittaukset taas saattavat aiheuttaa vääristyneen yleiskuvan veden valaistusolosuhteista. Näin ollen valoaineistojen soveltaminen, esimerkiksi ekologiseen mallinnukseen, on syytä tehdä harkiten ja huolella.

Avainsanat: Vedenalainen valo, eufoottinen syvyys, näkösyvyys, alueellis-ajallinen vaihtelu, *in situ* -näytteenotto, saaristorannikko, Itämeri

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CONTENTS

LIST OF ORIGINAL PUBLICATIONS

This thesis consists of a summary and the following four papers. The papers are referred to in the text by their Roman numerals:

I Luhtala H., Tolvanen H. and Kalliola R. 2013. Annual spatio-temporal variation of the euphotic depth in the SW-Finnish archipelago, Baltic Sea. Oceanologia 55, 359–373.

II Luhtala H. and Tolvanen H. 2016. Spatio-temporal representativeness of euphotic depth *in situ* sampling in transitional coastal waters. Journal of Sea Research 112, 32–40.

III Luhtala H. and Tolvanen H. 2013. Optimizing the use of Secchi depth as a proxy for euphotic depth in coastal waters: an empirical study from the Baltic Sea. ISPRS International Journal of Geo-Information 2, 1153–1168.

IV Luhtala H., Kulha N., Tolvanen H. and Kalliola R. 2016. The effect of underwater light availability dynamics on benthic macrophyte communities in a Baltic Sea archipelago coast. Hydrobiologia. Advance online publication, doi: 10.1007/s10750-016-2759-x.

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1 INTRODUCTION

The relevance of solar radiation for aquatic environments is manifold (Fig. 1). For example, aquatic primary production is controlled by the availability of underwater light, which refers to the visible part of the solar radiation spectrum that penetrates into water and illuminates aquatic environments. While primary production relies on phytoplankton in pelagic waters, in shallow coastal areas, benthic communities also contribute to photosynthetic activity. However, the ecological importance of light penetration is not restricted to primary production. The light availability has a great influence on predator–prey relationships that rely on vision and hiding. Changes in water clarity can therefore lead to, for example, changes in the competitive efficiency between tactile and visual predators (Sørnes and Aksnes 2004; Haraldsson et al. 2012). Moreover, the abiotic environment is also affected as the absorption of solar radiation releases energy, which contributes to ocean circulation, water mixing, and stratification by heating water masses (Woods et al. 1984; Dera and Woźniak 2010). Finally, the importance of water clarity in regards to recreational and aesthetic values should not be underestimated.

However, the illuminated water column is restricted to the very surface layer of seas and oceans because the radiation is efficiently attenuated in water as a function of distance (e.g. Woźniak and Dera 2007; Arst 2010). The intensity of the two attenuation mechanisms, i.e. absorption and scattering, depends on the optical properties of the water column. Natural waters include varying amounts of dissolved and suspended materials and each component attenuates radiation in its specific band of wavelengths. Since the concentrations of these substances vary in time and space, the quantity and quality of underwater radiation also varies (Kirk 2011).

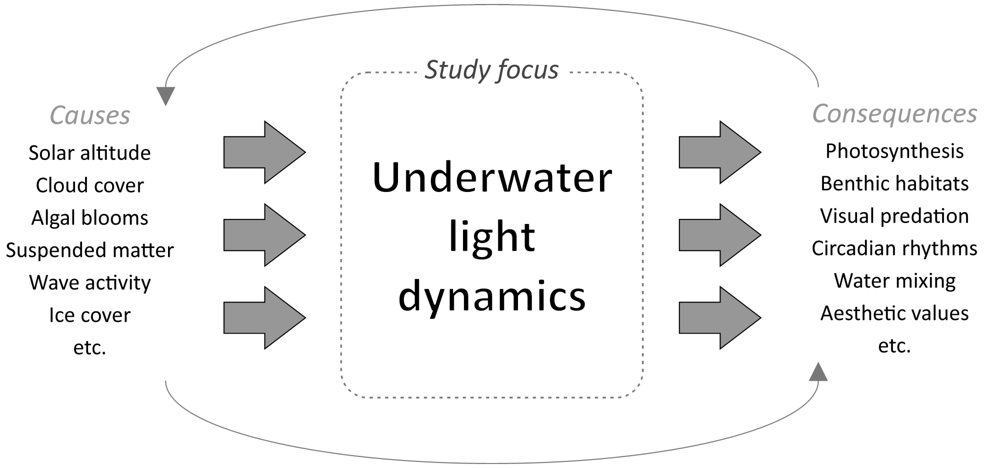

Figure 1. Illustration on the causes and consequences that influence underwater light availability. Interactions also occur directly between the causes and consequences. The focus of this research is, for the most part, on the underwater light dynamics, i.e. on the spatial and temporal variations in the light availability in water.

The underwater light field can be quantified using several techniques. A common method to illustrate the depth of light penetration is to define the illuminated surface water layer called the euphotic zone. According to widespread practice, the lower limit of the zone, i.e. the euphotic depth, has been identified as the depth at which 1% of visible light entering the water remains (e.g. Reinart et al. 2001; Kirk 2011). At its simplest measure, a visual estimate of water transparency can be obtained by Secchi disc measurements (e.g. Tyler 1968; Preisendorfer 1986). While measurements of water properties have traditionally been conducted by *in situ* spot sampling, nowadays modern methods, such as remote sensing and unmanned operational systems are gaining increasing attention.

This thesis deals with underwater light dynamics in the Baltic Sea and the coastal archipelago in south-western Finland. While the uniqueness of the area makes it an interesting study location, it also sets some challenges. The Baltic Sea is regarded as a particularly sensitive and vulnerable ecosystem where the level of environmental loading and human pressures are relatively high (Dybern and Fonselius 1981). Consequently, numerous agreements – global, regional, and national – have been implemented to protect the area and to regulate activities there. The Baltic Marine Environment Protection Commission (Helsinki Commission, HELCOM) is a major regional actor in reaching the common goal of a healthier Baltic Sea, while the legislation of the European Union (EU) sets its own binding guidelines and obligations for Baltic Sea research and other operations. Among the most relevant directives for the Baltic Sea environment are the Marine Strategy Framework Directive (2008/56/EC), the Water Framework Directive (2000/60/EC), and a recent directive on Maritime Spatial Planning (2014/89/EU).

To fulfil international guidelines, binding legislation, and voluntary agreements, research is needed to provide both data and information, as well as new knowledge and understanding on the processes and interactions affecting the environment. Nevertheless, despite its high importance for aquatic life, the availability of underwater light has been poorly recognised in Finnish coastal waters. Many other aspects of marine environments, both biological and physical, have either been studied much more extensively or have been monitored already for decades, while the underwater light data are still rather scarce and patchy, even at the Baltic Sea scale. Although the long history of Secchi depth measurements, common knowledge of algal life cycles, as well as the visibly oscillating influences of riverine discharges underpin the concept that the underwater light field must undergo changes during the growing season, actual measurements of solar radiation in water have been rare. Previous studies of the optical properties of water have been mostly executed in other parts of the Baltic Sea with only a limited spatio-temporal resolution. The specific focus of those research activities have typically been on remote sensing techniques and applications (e.g. Kratzer et al. 2003; Zhang et al. 2003; Darecki et al. 2005; Stock 2015; Attila et al. 2013) and/or on the characteristics of optically active substances (e.g. Ficek et al. 2004; Kowalczuk et al. 2005; Siegel et al. 2005; Asmala et al. 2012; Harvey et al. 2015a).

The aim of this thesis is to quantify the changes in the underwater light field and to reflect the need and usability of such data. The focus is on spot sampling and *in situ* data collection, as the work relies on vertical light profiles, which have been surveyed in the transitional waters of the south-western Finnish archipelago, mainly during 2010 and 2011. The novelty of the work lies in the employment of a geographical study approach, as well as in the utilisation of a less frequently applied main variable, i.e. euphotic depth, in a poorly investigated and complex study location.

The specific objectives of this thesis are:

1) To quantify changes in the underwater light availability in the waters of the south-western Finnish archipelago.

2) To evaluate the applicability of underwater light measurements in coastal waters through assessing the representativeness of *in situ* sampling.

3) To assess how well the traditional Secchi depth measurements represent underwater light availability in a transitional coastal archipelago.

4) To identify the demand for underwater light information in ecological modelling in a coastal environment.

The associated four original, scientific papers are summarised below (see also Fig. 2):

Paper I presents the general patterns of underwater light dynamics in the south-western Finnish archipelago. A method to define the depth of 1% surface radiation is introduced and applied to a broad, multidimensional field survey in the archipelago waters in 2010. The data quantify the spatial and temporal variability in euphotic depth dynamics in a complex archipelago environment and also discusses the vertical heterogeneity in light attenuation efficiency. The light availability is further mirrored to changes in optically derived proxies of turbidity and chlorophyll fluorescence.

Paper II continues to quantify changes in underwater light availability by introducing sampling networks of denser spatial resolution. The ability of *in situ* spot samples to represent their immediate surroundings was assessed through the statistical analysis of comparative data within three networks. The spatio-temporal changes in euphotic depth dynamics was further considered by introducing an anomaly detection procedure that was adjusted to the spot sampling data. The effect of randomness upon spot sample representativeness was also discussed.

Paper III focuses on the numerical relationship between Secchi- and euphotic depths (1% depth). The conversion coefficient that links these two optical parameters varies according to the optical properties of water and therefore, a local calibration of coefficients is needed. The study evaluates the conversion procedure and assesses the suitability of different conversion criteria.

Paper IV discusses the link between the underwater light availability and the distribution of submerged vegetation. The impact of illumination dynamics on macrophyte community structure and species composition is studied in the natural environment at the macrophyte community level with inventory data collected during 2010. The intra-seasonal variability in underwater light availability is included in the statistical analyses to evaluate the role of changing illumination conditions on the formation of macrophyte communities.

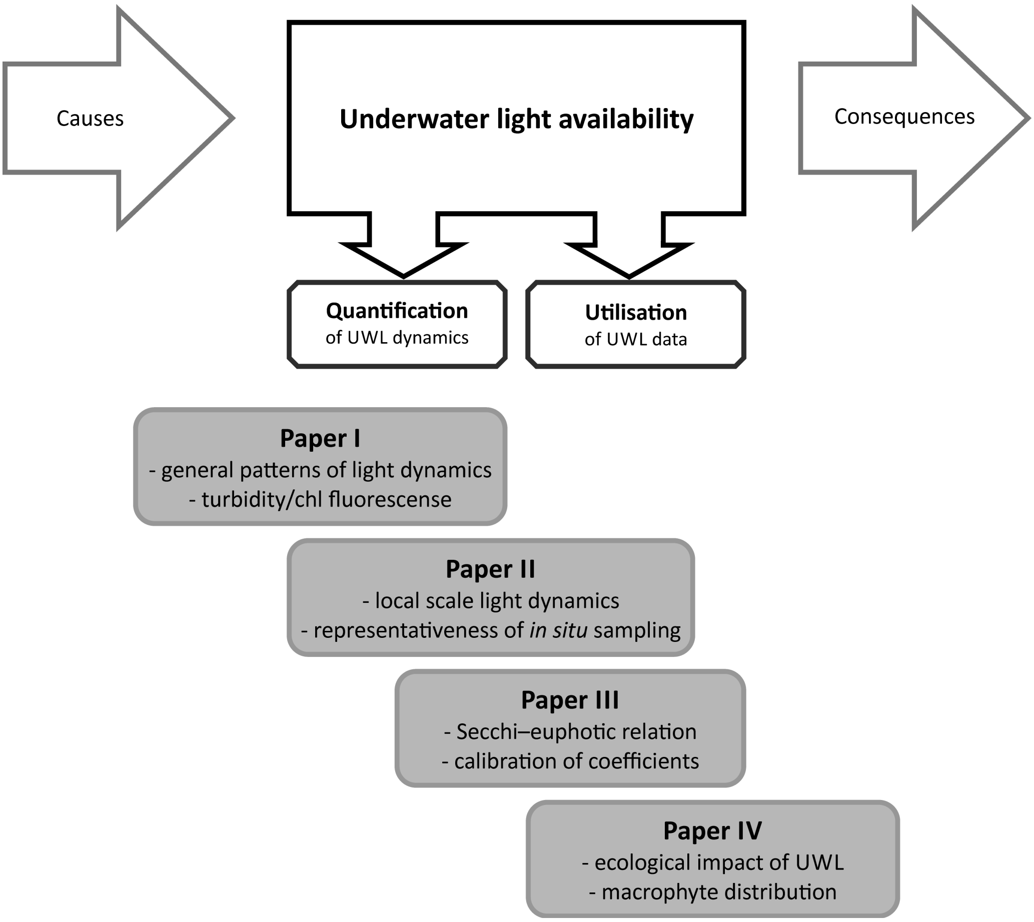

Figure 2. Simplified illustration of the topics discussed in papers I–IV.

2 BACKGROUND

2.1 Theoretical background of underwater light dynamics

2.1.1 The origins of underwater light

Life on Earth is sustained by the Sun. The electromagnetic spectrum of solar radiation is often described and classified according to its wavelengths (λ), measured in metres (m). Although the entire spectrum includes a selection of radiation types, such as gamma rays, X-rays, microwaves, and radio waves, the human eye is sensitive to only a small proportion of this spectrum (Liou 2002). This proportion, which consists of wavelengths of approximately 400–700 nm, is referred to as visible light or simply as light, which in turn, can be divided into a spectrum of colours. The continuum of colours starts from blue light with shorter wavelengths, through green and yellow towards the longest wavelengths seen as red light. This same spectrum of ~400–700 nm is also commonly used to define the waveband of Photosynthetically Active Radiation (PAR). In this thesis, the terms ‘light’ and ‘PAR’ are henceforth used interchangeably when referring to this respective waveband.

Before solar radiation reaches the water surface, it must first penetrate the atmosphere. Not only does the amount of incoming radiation fluctuate in regular diurnal and annual cycles but also randomly over various time scales (see Fig. 3). In general, the regular patterns are guided by the rotational movements of Earth. Seasonality in light availability varies with latitude, being most pronounced at the poles but also very notable still at the high latitudes of the Baltic Sea. More local fluctuations are caused by atmospheric conditions, such as cloud cover and concentrations of other attenuating particles, both natural and anthropogenic, in the air. Cloud cover influences both the quantity and the directional quality of the incoming radiation. Therefore, the light that meets the sea surface can be either direct sunlight or diffuse sky light with a more complex angular distribution (Liou 2002).

When the light photons finally reach the sea surface, while most of the radiation penetrates through the air–water interface into the water and from the subsurface layer further into the depths, part of the radiation is reflected upwards, i.e. back to the atmosphere. In theory, if radiation was unidirectional and the sea surface completely flat, the proportion of reflected light would vary according to Fresnel’s Law, such that the reflected proportion would remain very low at high solar elevation angles but would increase steadily when the angle between the horizon and the Sun decreases (Sathyendranath and Platt 1990; Kirk 2011). However, in natural environments, sky light is often diffused and the sea surface has some roughness due to wave activity, which tend to decrease the amount of reflected radiation (e.g. Payne 1972; Nakajima and Tanaka 1983; Schubert et al. 2001).

At the air–water interface, the unreflected part of solar radiation is refracted according to Snell’s Law, in which the angular distribution of light changes more towards the vertical direction in the water column (Sathyendranath and Platt 1990; Kirk 2011). At a wind-disturbed wavy sea surface, refraction causes short-term irradiance fluctuations, i.e. high-frequency light flashes induced by the so-called ‘focusing effect’ (e.g. Schenck 1957; Stramski and Dera 1988; Schubert et al. 2001). During winter, in turn, the light penetration is affected by ice and snow cover. The attenuation efficiency of ice varies according to its properties, pure ice being more transparent than ice layers including inhomogeneities (e.g. Grenfell and Maykut 1977; Light et al. 1998). As pure ice exists rarely in natural waters, light is usually efficiently attenuated in sea ice. Complete darkness in water can be achieved if the ice cover is further overlaid by snow (Schubert et al. 2001; Woźniak and Dera 2007).

2.1.2 Optically active substances in water

Although solar irradiance attenuates rather similarly in air and water, it does so more efficiently in the latter. Consequently, light does not penetrate very deeply into the water column. Irradiance is absorbed and scattered by optically active substances, each of which focus on certain spectral compositions of wavelengths (e.g. Jonasz and Fournier 2007; Woźniak and Dera 2007; Arst 2010). Both absolute and relative concentrations of these components vary in space and time, resulting in variations in the quantity and quality of the underwater light field. In absorption, electromagnetic radiation is transformed into other forms of energy (Woźniak and Dera 2007), which in practice means that PAR is removed from the water column. Scattering, on the other hand, does not remove PAR but instead causes divergences from its original path. It increases the total path-length of light photons travelling through the water, which in turn, increase the probability of absorption (Kirk 2011).

While attenuation is more efficient in natural waters than in pure water, it also occurs in the latter as the water molecules themselves absorb light (Woźniak and Dera 2007). Absorption is stronger in longer wavelengths and very inefficient at the blue end of the spectrum, which is why clear waters in larger quantities seem blue to the human eye (Kirk 2011). In natural waters, optically active substances alter the wavelengths of maximum light penetration, which changes the colour of the water masses. The three main groups of components that attenuate solar radiation in water are presented below.

The first group consist of photosynthetically active pigments, which absorb solar radiation and utilise its energy in primary production. Each group of pigments, such as

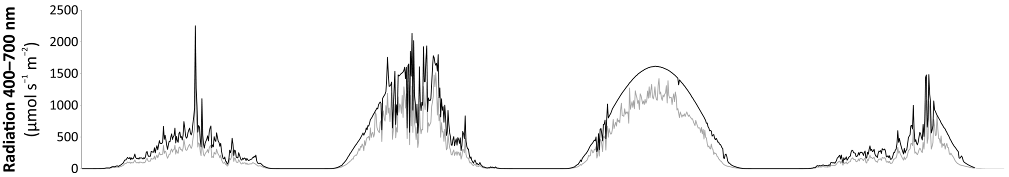

Figure 3. An example time series of PAR measurements taken in the middle archipelago (Seili) during four days in May 2011. The time series presents diurnal/nocturnal variability and also some irregular fluctuations during the day time due to variability in cloud cover. The black line represents incoming radiation measured above the sea surface and the grey line shows underwater irradiance values measured approximately at a depth of one metre.

chlorophylls, carotenoids, and biliproteins, absorb different wavelengths of PAR (Kirk 2011). Chlorophyll *a* is the most common and most important pigment as it is present in almost all photosynthetically active organisms (Wetzel 2001). It has two absorption maxima: one at the blue spectrum and one at the red (Ficek et al. 2004). Consequently, the absorption efficiency is lower in the green part of the spectrum and waters with high primary production rates thus appear green.

Coloured dissolved organic material (CDOM) refers to a group of humic substances originating from the decomposition of organic material (Kirk 2011). This group includes a complex mixture of compounds that are derived from various sources, either leaching from land or produced in water (Chen et al. 2004; Kowalczuk et al. 2005; Jonasz and Fournier 2007). These compounds are sometimes referred to as yellow substances as they strongly absorb shorter wavelengths of visible light and shift the PAR penetration maximum towards yellow wavelengths. In general, CDOM concentration is inversely correlated with the salinity of water, and thus, less saline coastal waters often have higher CDOM concentrations than open waters (Vodacek et al. 1997; Bowers et al. 2000; Boss et al. 2001).

The third main component of optically active substances in natural waters is the group known as suspended particulate matter (SPM). SPM includes material of both organic and inorganic origin, such as detritus and mineral particles (Woźniak and Dera 2007). Inorganic material usually dominates in coastal waters, whereas open seas include more substances of organic origin (Kratzer et al. 2003; Astoreca et al. 2012). Typically, while suspended particles scatter light efficiently, the quantity and quality of attenuation varies according to both the chemical and physical properties of the particles (Woźniak and Dera 2007).

2.1.3 Optical parameters describing underwater light properties

Since the optical properties of water masses are of interest to several research fields, there are also several methods and definitions to describe underwater light availability. As usual, the research goal in question determines the quality and quantity of the information needed. Euphotic depth is one of the most commonly discussed parameters describing underwater light availability. It refers to the illuminated surface water layer where there is enough PAR available for photosynthetic activity. The thickness of the euphotic zone can be assessed through different foundations according to the research interest.

One biological viewpoint could be to define a (light) compensation depth, in which the zero net primary production occurs as community gains and losses balance each other (Sverdrup 1953). The water layer above this depth is the zone where photoautotrophic production exceeds heterotrophic consumption within a given time scale (Tett 1990). At the species level, compensation depths vary as some producers can sustain photosynthetic activity in deeper and consequently less illuminated waters than other species (Lüning 1981; Dennison 1987; Morrissey and Sumich 2012). It should be noted that water masses in the upper layer of the water column are always under circulation. Owing to water mixing, phytoplankton moves through variable light conditions and is not exposed to constant light for a very long time (Schubert and Forster 1997; Reinart et al. 2000). Whenever the depth of a mixed layer increases, the total rate of photosynthesis decreases because the average amount of accessible PAR decreases (e.g. Reinart et al. 2000; Kirk 2011). Eventually, below the so-called critical depth, light intensity becomes too low to sustain net photosynthesis and phytoplankton biomass will decrease (Kirk 2011).

Another way to evaluate the thickness of the photosynthetically active layer is to focus on the availability of underwater light. A common delimitation for the euphotic zone has been the depth at which PAR penetration decreases to 1% of the surface value (Fig. 4) (e.g. Reinart et al. 2001; Lee et al. 2007; Arst 2010; Kirk 2011). Consequently, the euphotic depth could be estimated by measuring the quantity of PAR at different depths in the water column and by then computing the depth at which the relative amount of PAR has attenuated to 1%. Assessing underwater irradiance is simpler than measuring rates of photosynthesis and respiration, which is presumably why defining euphotic depths by the 1% rule has become very popular in the aquatic sciences. It is stated to provide convenience and standardisation for estimating the thickness of photosynthetic layer (Zhang et al. 2006).

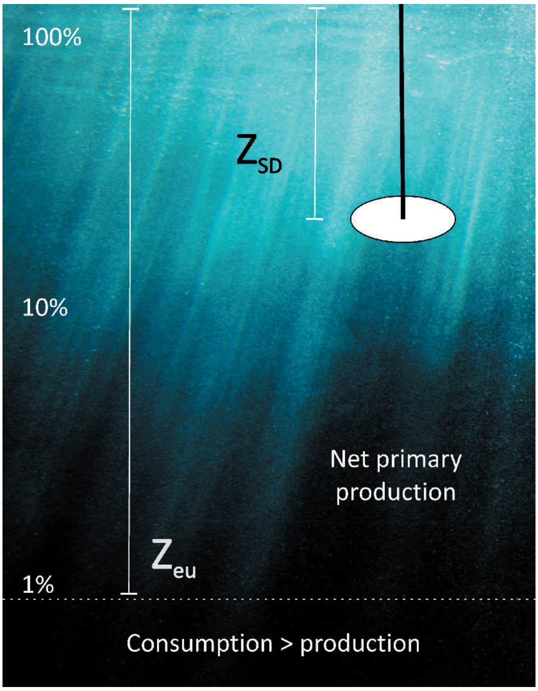

Figure 4. Illustration of the two commonly utilised parameters of underwater illumination. The number scale of relative values refers to the proportion of underwater PAR that remains in comparison to the value measured just below the sea surface. The euphotic depth (Z_{eu}) is commonly defined as the depth of 1% PAR penetration. Most of the aquatic photosynthesis occurs within this water layer. The Secchi depth (Z_{SD}) provides a visual measure of water transparency and is usually conducted by lowering a white disc into the water and recording the depth at its disappearance.

It is widely regarded that during the phytoplankton growth season, the compensation depth falls approximately at the 1% PAR penetration depth (Tett 1990; Reinart et al. 2001). The challenge regarding this rule is that the depth is based on relative irradiance readings. If there are great differences in the incoming solar radiation levels, the amount of light photons at the 1% depth varies notably. For example, Reinart et al. (2000) assessed definitions of euphotic depths in Finnish and Estonian lakes with varying optical properties. They concluded that the 1% depth rather well represents that depth where primary production approaches zero. However, the positive net production, or compensation depth, corresponded to somewhat higher levels of illumination. Moreover, they could not state any constant irradiance level that would consistently correspond to the compensation depth (Reinart et al. 2000).

As well as estimating depths of 1% PAR penetration, irradiance measurements can be processed into vertical attenuation coefficients to illustrate the efficiency of attenuation in water (Dera and Woźniak 2010). By calculating a rate of change with depth (m^{-1}), a characterisation of the medium is gained without an influence of light intensity itself (Woźniak and Dera 2007). Coefficients are commonly calculated either for the entire PAR spectrum, K(PAR), or for selected wavelengths, e.g. K(490), and consider either scalar irradiance or solely downward (or upward) radiation (Kirk 2011). It is common to derive attenuation coefficients separately for absorption and scattering processes (Woźniak and Dera 2007).

The traditional Secchi disc measurements are conducted by lowering a white disc vertically into the water until it disappears from sight (Fig. 4) (e.g. Tyler 1968; Preisendorfer 1986). The depth of Secchi disc disappearance is given in metres. The oldest records that describe water transparency date back to the 17th century and various investigations had already been executed using white discs during the 19th (for a history review, see Wernand 2010). However, Angelo Secchi was the first to give an extensive and detailed description of the method in the 1860s (e.g. Aarup 2002; Wernand 2010). Therefore, the white plates still used today for estimating water transparency are called Secchi discs and the consequent depths of measurements are referred to as Secchi depths. In the Baltic Sea, these measurements have more than a century long history (Aarup 2002; Dupont and Aksnes 2013). The data provide extremely valuable information on the optical properties of the sea since it is not possible to acquire a similar time series through any modern study methods.

The method is inexpensive, straightforward, and easy-to-use, which is why measurements are still commonly conducted in marine surveys of various research interests (Walker 1982; Hou et al. 2007; Lee et al. 2015). Consequently, their frequency greatly surpasses underwater PAR measurements – particularly in the past but very likely also in the future. Secchi measurements have been seen as an indirect estimate of many water quality parameters, such as eutrophication, turbidity, or chlorophyll content (Preisendorfer 1986; Aas et al. 2014). Moreover, Secchi depths are often linked to euphotic depth by calculating the ratio of these two optical parameters. The conversion coefficient between the depths varies according to local water properties. For example, while Holmes (1970) has regarded a factor of 3 to be suitable in turbid waters, the total range of coefficients has been suggested to range from 1 to 10 (Koenings and Edmundson 1991). Conversion coefficients are discussed in more detail in Paper III.

2.1.4 Optical classification systems of water masses

Optical classification systems have been created to categorise waters according to their optical properties. Such categorisations are especially important for ocean colour remote sensing. The most utilised and applied classification system is probably the one presented by Morel and Prieur (1977), who divided marine waters into two distinctive categories and identified these categories as Case 1 and Case 2. In Case 1 waters, light attenuation is, apart from the water itself, dominated by photosynthetic pigments and can be linked to concentrations of phytoplankton (Morel and Prieur 1977). Other associated substances, such as phytoplankton degradation products, may be present in water but they either only absorb light to an insignificant extent compared to chlorophyll *a* and other pigments, or their absorption abilities covary with the pigments (Antoine et al. 2014). By contrast, absorption in Case 2 waters is dominated by optically active substances that do not correlate with chlorophyll *a*, even though chlorophyll *a* itself may still contribute to attenuation in varying degrees (Morel and Prieur 1977). The latter category is highly variable, including a range of water types from turbid waters with high inorganic particle concentrations, to dark waters with high levels of humic substances. From a global perspective, the pelagic waters in open oceans are regarded as representing Case 1 waters, whereas those of Case 2 typically characterise coastal and shallow water areas. Nevertheless, this dichotomy is not that clear as pelagic waters can also reflect properties of Case 2 and coastal waters Case 1 (Mobley et al. 2004; Woźniak and Dera 2007; Antoine et al. 2014).

Another commonly mentioned classification system, based on the vertical attenuation of spectral irradiance, had been developed by Jerlov already in the 1950s (e.g. Johnsen 2011; Aas et al. 2013). His system included 14 categories, five types of oceanic waters (originally I–III, with Ia and Ib added later) and nine types representing coastal waters (originally 1–9, later reduced to 1, 3, and 5) (Lüning 1981; Aas et al. 2013). The main division is similar to that of Morel and Prieur (1977): in the oceanic types, the low attenuation is mainly caused by chlorophyll absorption, and in the coastal types, attenuation is dominated by CDOM and both absorption and scattering may occur to a high degree (Johnsen 2011). In general, these types are ranked according to the decreasing overall water transparency and simultaneously, to the increasing wavelength of peak transmission (Lüning 1981; Johnsen 2011).

Besides global classifications, there are also systems optimised for local conditions. For instance, in their studies of Estonian and Finnish lakes, Reinart et al. (2003) divided waters into five classes. The classes were C (clear), M (moderate), T (turbid), V (very turbid), and B (brown), each having their own criteria in their optical properties. In comparison to the Estonian–Finnish system, Koenings and Edmundson (1991) classified Alaskan lakes into categories of clear, stained, and turbid. These lake classifications may be relevant with respect to the Baltic Sea, since coastal waters, particularly in small bays, are optically more comparable to lake waters than open ocean waters (Reinart et al. 2003).

In addition to classification systems focusing on optical properties, the data of underwater light availability, in one form or another, have been utilised as a part of more general environmental classification systems. For example, the EU Water Framework Directive (WFD), which ultimately aims to protect and enhance the status of water quality of all types of waters in the EU Member States, unifies water bodies with similar characteristics. The parameters utilised for coastal and transitional waters include a variety of biological elements as well as hydro-morphological, chemical, and physico-chemical variables as supporting elements. To reach the "high status" in the ecological status classification, water transparency, as one of the physico-chemical elements, should not show signs of anthropogenic disturbance and should remain within the ranges normally associated with undisturbed conditions (European Commission 2000). Moreover, the European Environment Agency's EUNIS Habitat Classification System (European Nature Information System) and its local derivative, known as the HELCOM HUB (HELCOM Underwater Biotope and Habitat Classification) provide international frameworks for defining biotopes. The biotope types are created in a standardised and structured way by relying on hierarchical split rules, one of which divides datasets according to a photic–aphotic dichotomy (HELCOM 2013).

2.2 The Baltic Sea and the Archipelago Sea

2.2.1 Characteristics and physical properties

The Baltic Sea is a marginal, almost landlocked sea located in northern Europe. It lies approximately along the latitudes of 54–66°N and longitudes of 10–30°E. With these dimensions it is the world's second largest brackish water basin with a surface area of 393,000 km^2. Since the sea is relatively shallow, with an average depth of approximately 54 m, its volume is only 21,000 km^3 (Leppäranta and Myrberg 2009). The sea has nine riparian countries (Denmark, Estonia, Finland, Germany, Latvia, Lithuania, Poland, The Russian Federation, and Sweden). If including all the countries lying fully or partially within its drainage basin, the number of Baltic Sea countries increases to 14. The total drainage basin covers an area that is more than four times larger than the area of the sea itself. The area populates more than 85 million inhabitants with higher population density in the southern area (Sweitzer et al. 1996). Human pressures on the sea are evident as most of the major cities, such as St. Petersburg, Copenhagen, Stockholm, Riga, Helsinki, and Gdańsk, have a coastal location.

The relatively young sea has a complex geological history, which includes a sequence of stages from the Baltic Ice-Lake, though the Yoldian Sea and Ancylus Lake, to the Littorina Sea and finally to the present-day Baltic Sea (Winterhalter et al. 1981; Björck 1995). Moreover, past events still affect the Baltic Sea through ongoing post-glacial rebound and the consequent slow but continuous appearance of new land areas. This phenomenon is particularly prevalent in the northern part of the Baltic Sea, where the isostatic land uplift is up to 9 mm per year, while in the south, the uplift is practically negligible (e.g. Ekman 1996; Fjeldskaar et al. 2000). The coastal regions vary also in their geomorphology and topography, the northern part generally being more complex than the southern side (Winterhalter et al. 1981; Kaskela et al. 2012).

As a semi-enclosed sea basin, the Baltic Sea has limited water exchange with the North Sea through the Danish Straits. The two sills separating the Baltic Proper and the North Sea are very shallow: the Darss and Drogden sills are 18 and 8 m in depth, respectively (e.g. Stigebrandt 2001; Stanev et al. 2015). Besides restricting the water flow, these shallow transition areas act as a low-pass filter damping tidal oscillations that originate from the Atlantic Ocean (Stanev et al. 2015). Consequently, tidal activity is negligible within the Baltic Sea Basin. Sea level changes over longer periods are nevertheless caused by wind and air pressure differences (approximately one day to several weeks), as well as changes in seawater density (months) (Leppäranta and Myrberg 2009).

In the main basins of the Baltic Sea, the surface water circulation is generally counter-clockwise. As a rule, water flows northwards at the eastern margin and southwards at the western margin of the Baltic Proper and the Gulf of Bothnia, as well as eastward at the Estonian coast and westward at the Finnish coast of the Gulf of Finland (Myrberg and Andrejev 2006; Leppäranta and Myrberg 2009). The currents are weak but their persistency is relatively strong (Kullenberg 1981; Leppäranta and Myrberg 2009). Below the surface layer, water circulation patterns are rather different since they are impacted by the bathymetric characteristics of the basin (Leppäranta and Myrberg 2009). The intrusion of deep water to the surface layer through the vertical movement of water masses, i.e. upwelling events, can take place anywhere in the Baltic Sea where the conditions are suitable (Lehmann and Myrberg 2008). Coastal upwelling occurrences are most frequently found along the Swedish east coast and Finnish coast of the Gulf of Finland (Lehmann et al. 2012).

Owing to its location in the northern high latitudes, seasonality is a dominant feature in the Baltic Sea. Furthermore, the long meridional extension of the sea (>1300 km) causes profound differences in the climatic conditions of northern and southern localities. The northern areas are generally colder and receive less precipitation than the southern part (Bergström et al. 2001). Although the Baltic Sea is ice-covered at least partially every winter, the ice extent varies notably between years: the inter-annual variability in ice cover ranges from 10% to 100% of the total sea surface area (Tinz 1996; Leppäranta and Myrberg 2009). The temporal extent of the ice period reaches up to six months in the Bay of Bothnia, whereas the open Baltic Proper freezes entirely only during the most severe winters (Granskog et al. 2006).

Seasonality affects also water column stratification. During summers and winters, surface waters are separated from deeper waters by water temperature differences, which lead to density stratification. In spring and autumn, these thermoclines disappear due to mixing in the water column, initiated by changes in water temperature (e.g. Horne and Goldman 1994; Wetzel 2001). In the Baltic Sea, thermoclines are usually found at depths ranging from 15 to 20 m (Kullenberg 1981). Another feature restricting the full mixing of water column is related to the vertical salinity gradient. The halocline, which lies at about 40–80 m depth in the Baltic Sea, isolates deep water from the well-mixed uniformly saline surface water layer (Kullenberg 1981; Stigebrandt 2001; Leppäranta and Myrberg 2009).

The Baltic Sea receives freshwater from two main sources: river runoff and net precipitation, where precipitation exceeds evaporation (Omstedt and Rutgersson 2000; Stigebrandt 2001). Saline water is mainly introduced by salt water intrusions, which are sudden and intensive but occur rarely (Ehlin 1981; Lehmann and Post 2015). The latest major occurrence that replenished the deep waters was recorded during the winter of 2014–2015, 12 years after the previous notable intrusion (Mohrholz et al. 2015). The North Sea environment is, in turn, affected by the outflow of less saline water from the Baltic Sea (Hänninen et al. 2015). In general, if comparing the amount of water that is flowing in and out of the Baltic Sea, the outflow is larger than the inflow (Kullenberg and Jacobsen 1981; Omstedt and Rutgersson 2000). Salinity decreases from near oceanic conditions in the Danish straits to almost complete freshwater conditions at the ends of the two northern bays (Samuelsson 1996; Leppäranta and Myrberg 2009). Salinity, among other features such as temperature and ice cover, provides an illustrative example of why the Baltic Sea is sometimes characterised as a sea of gradients.

2.2.2 Optical and biological properties

Optically, the entire Baltic Sea can be classified as a Case 2 water body (e.g. Darecki and Stramski 2004; Kratzer et al. 2008) and according to Siegel et al. (2005), it covers the full range of coastal water types (1–9) of the Jerlov classification. Its optical properties are complex and highly variable in space and time. This differentiates the Baltic Sea from the great oceans and many other sea areas in the world and consequently, many optical models or remote sensing algorithms developed elsewhere are not applicable as such (Kratzer et al. 2003). The Baltic Sea has very high concentration of CDOM (e.g. Ferrari and Dowell 1998; Kowalczuk et al. 2005), the seasonal variation of which typically reflects changes in river runoff (Kowalczuk et al. 2010; Asmala et al. 2012). SPM is mostly either terrigenous in origin or resuspended from the seafloor (Håkanson and Eckhéll 2005), while concentrations of photosynthetically active pigments show spatio-temporal variation (Siegel et al. 2005; Suominen et al. 2010a).

Phytoplankton succession is an important contributor to underwater illumination dynamics, both spatially and temporally. In waters of high latitudes, while phytoplankton species diversity and biomass abundance may vary greatly within a season, these variations are relatively constant between years (Wetzel 2001). The following seasonal development is regulated by the biogeochemical cycles of nutrients. First, nitrogen is exploited during the spring bloom, mainly by diatoms and dinoflagellates. The resulting nitrogen limitation causes a phytoplankton minimum in early summer, which lasts until nitrogen-fixing cyanobacteria start to bloom in high summer (Hällfors et al. 1981). Sometimes a third phytoplankton bloom still occurs in autumn (Wasmund and Uhlig 2003). These seasonal patterns are usually disturbed only by human influences (Wetzel 2001).

The characteristics of the Baltic Sea make it a sensitive and vulnerable ecosystem, which is susceptible to environmental loading and high pressure of use. In fact, the environmental state of the sea has already declined in the past century. Eutrophication, which has resulted from increased nutrient concentrations in the seawater, is commonly regarded as one of the main threats to the Baltic Sea (Bonsdorff et al. 2002; HELCOM 2009; Elmgren et al. 2015). Even though the external nutrient loads to the sea started to decrease already in the 1980s, internal fluxes from the seafloor sediments still retain high concentrations (Gustafsson et al. 2012). The relationship between the concentrations of nitrogen and phosphorus exhibits some variability within the Baltic Sea, since nutrient limitation patterns show both geographical and seasonal variations. In general, the majority of the sea area is nitrogen limited at least partially during the growing season, whereas phosphorus limitation mostly occurs in the areas that are least affected by eutrophication (Tamminen and Andersen 2007).

Eutrophication development has been strongly linked to diminished water transparency (HELCOM 2009), as Secchi depths have decreased alarmingly in the whole Baltic Sea area during the last century (Sandén and Håkansson 1996; Dupont and Aksnes 2013). The most pronounced decrease has been observed in the northern Baltic Proper, where Secchi depth averages have almost halved from 9.4 m to 5.4 m in a century (Fleming-Lehtinen and Laamanen 2012). Over a long time scale, these trends have been similar in other Baltic Sea subregions also. However, during the last decades, the decrease in water transparency has stopped in some regions, while Secchi depths have even started to increase again in others (HELCOM 2009; Fleming-Lehtinen and Laamanen 2012).

Apart from drifting micro-organisms, i.e. phytoplankton, aquatic primary production also occurs in macrophytes, which refers to various groups of conspicuous aquatic plants (Wetzel 2001). The global distribution of macrophyte species has been reported to be strongly impacted by salinity (e.g. Twilley and Barko 1990; Shaw et al. 2000; Rinne et al. 2011; Antunes et al. 2012). In the brackish waters of the Baltic Sea, the influence of the salinity gradient is highly important as the vegetation populating the sea is a mixture of species of both marine and freshwater origins. In general, species richness is regarded as low because viable species need to have a wide salinity tolerance to be able to survive in low saline waters (Hällfors et al. 1981). More locally, other factors, such as bottom substrate type, wave exposure, water transparency, and temperature may also have an important role in regulating the structure of macrophyte communities (e.g. Kautsky and van der Maarel 1990; Kiirikki 1996; Rinne et al. 2011). Moreover, the dispersal abilities of macrophyte species are varied and depend on multiple factors, such as wave exposure, diaspore mass and shape, cover of established vegetation, nutrient level, and water depth (Kautsky 1988; Steinhardt and Selig 2007).

Similarly, the vertical distribution of macrophytes is regulated by a variety of factors. In the Baltic Sea, the species distribution at the surface water layer is typically limited by exposure, mainly caused by wave and ice disturbance (e.g. Kiirikki 1996; Kotta et al. 2014). The lower depth limit of macrophyte distribution is strongly regulated by the photosynthetic properties of the species. Species that are adapted to low light levels can populate deeper water depths than those that require greater irradiance, referring to lower and higher compensation irradiances respectively (e.g. Dring 1981; Ramus 1981;

Johansson and Snoeijs 2002). Furthermore, the spectral composition of light has an impact on the light-harvesting capacity of species and individuals because of variability in their photosynthetic pigment contents (Dring 1990). In general, if comparing the phylogenetic groups, green algae typically inhabit the upper layers and brown algae intermediate depths, whereas the proportion of red algae tends to increase with depth (Pedersén and Snoeijs 2001). Conversely, exposure to excessive PAR and/or ultraviolet radiation can negatively influence the photosynthetic activities in the upper water column (Franklin and Forster 1997; Häder and Figueroa 1997). During the last century, eutrophication and the consequent decrease in water transparency has strongly affected the distribution of many macrophyte species. For example, the depth penetration of bladderwrack (*Fucus vesiculosus*) – one of the key macrophyte species in the Baltic Sea – has declined alarmingly along the Baltic coasts during the past decades (e.g. Kautsky et al. 1986; Eriksson et al. 1998; Torn et al. 2006; Snickars et al. 2014).

2.2.3 Intrinsic characteristics of the SW-Finnish archipelago

One specific feature of the Baltic Sea is its large archipelagoes. The most notable is the archipelago continuum that includes the coastal archipelago of south-western Finland and the Åland Islands and its surrounding archipelago area (Fig. 5). This region is, with somewhat varying delimitations, referred to as the Archipelago Sea. It includes tens of thousands of islands and thus, forms one of the largest archipelagoes in the world if counted by the number of islands and islets (Granö et al. 1999). The Archipelago Sea is located at the intersection of three major regions of the Baltic Sea: the Gulf of Finland, the Gulf of Bothnia, and the northern Baltic Proper. It acts as a filter between the basins of the Gotland Sea and the Sea of Bothnia, as well as between the coastline and the open sea in general (Leppäranta and Myrberg 2009).

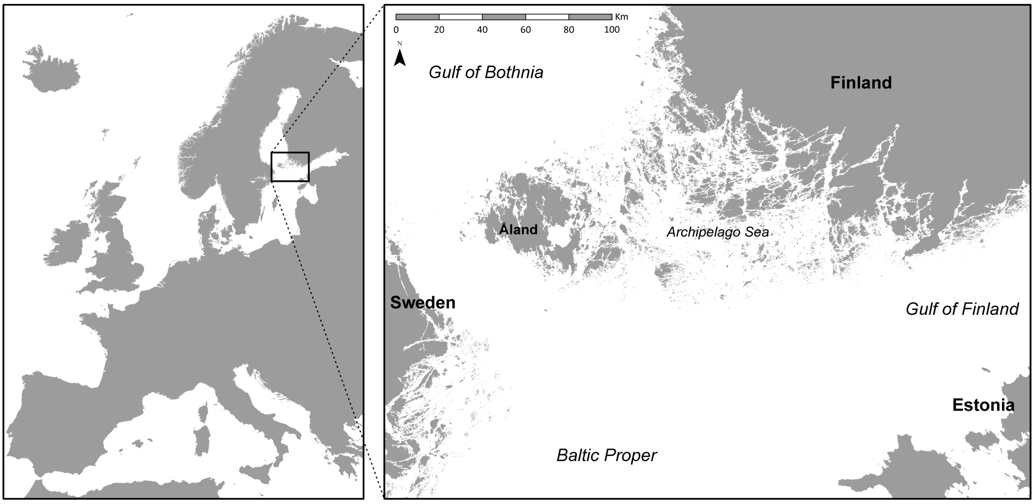

Figure 5. The archipelago area between Finland and Sweden is comprised of the archipelago of Åland islands and the coastal archipelago of south-western Finland.

The south-western Finnish archipelago, the main study area of this thesis, is a relatively shallow sea area with an average depth of approximately 20 metres. The deepest points nevertheless exceed 100 metres in depth. In general, the bathymetry is highly variable and forms a complex structure of sub-basins and thresholds (sills). The complexity of the archipelago environment restricts efficient water exchange (Erkkilä and Kalliola 2004; Myrberg and Andrejev 2006). Although the archipelago area is with a high probability ice-covered every winter (Granskog et al. 2006; Leppäranta and Myrberg 2009), the timing of the freezing as well as the length of the ice period vary annually.

The archipelago area is often divided into zones, which are referred to as inner, middle, and outer archipelago. The size of islands typically decreases from the inner archipelago towards the outer archipelago and simultaneously, the sea surface openness increases towards the open sea (e.g. Granö et al. 1999). The transition from the vicinity of the mainland towards the open sea is characteristic to the area also in the form of various water quality features (e.g. Hänninen et al. 2000; Erkkilä and Kalliola 2004; Suominen et al. 2010a). For example, the salinity of the south-western Finnish archipelago increases gradually seawards, with an approximate range of 5.0–6.5. However, the transition is not always uniform and the exact ranges vary during the ice-free season (Suominen et al. 2010b). The surface water temperatures, which are somewhat higher in the inner archipelago than in the outer zone, reach up to 20°C during summer seasons (Suominen et al. 2010a). It is noteworthy that short time scale differences in water quality are common because of winds, local water movements, and sea level changes (Erkkilä and Kalliola 2004; Suominen 2015).

3 MATERIAL AND METHODS

3.1 Field work and data preparation

The papers of this thesis are strongly founded on *in situ* underwater PAR measurements and hence, remotely derived satellite data lie beyond the scope and method selection of this work. The majority of the data originate from own *in situ* measurements that have been conducted in the south-western Finnish archipelago, in addition to which, data from external sources have been applied as supporting material (Table 1). The main datasets are derived from two fieldwork campaigns conducted in the summers of 2010 and 2011 (Fig. 6). Both sampling efforts are located in the north-eastern part of the Archipelago Sea, approximately at latitude 60°N and longitude 22°E. The area provides a gradual transition from the vicinity of the mainland towards the open sea to the Baltic Proper. This transition through the archipelago zones – inner, middle, and outer – provides variable conditions within relatively short distances. This complexity of environmental settings includes, among other things, shallow and deep waters, sheltered and exposed localities, and areas of high and low human influence.

Table 1. Summary of the main materials utilised in the papers of this thesis.

	Paper I	Paper II	Paper III	Paper IV
Field measurements				
PAR profiles (µmol s^{-1} m^{-2}, %)	x	x	x	x
Secchi depths (m)			x	
Water properties (e.g. chl fluorescence, turbidity)	x			x
External data sources				
Underwater habitat database				x

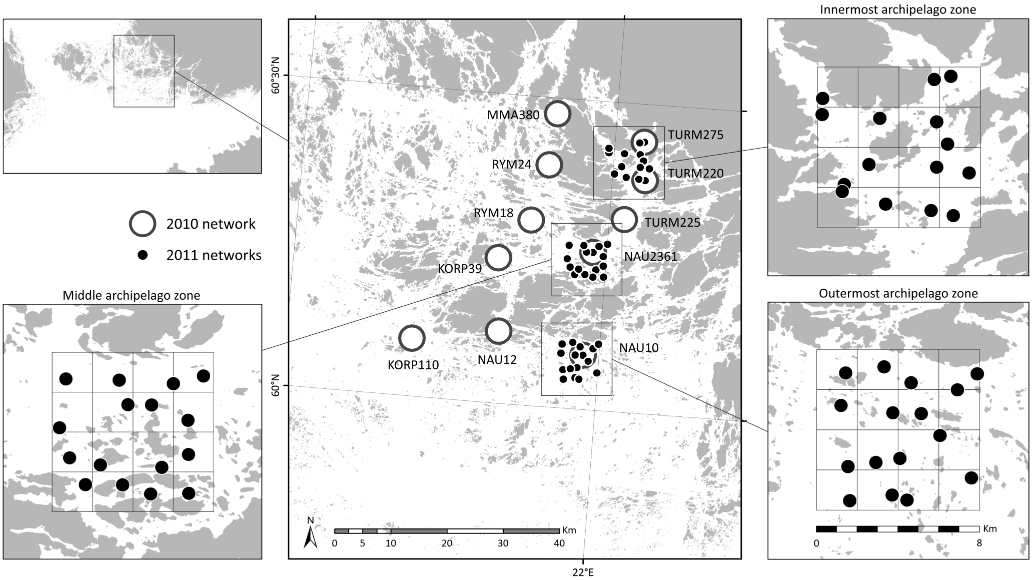

Figure 6. The study area and the sampling stations. In 2010, the larger sampling network was measured eight times during the growing season (weeks 17, 20, 23, 26, 31, 34, 37, 40). In 2011, the three denser networks were visited twice (weeks 23 and 31).

The first measurement campaign was organised in 2010 (papers I, II, III, and IV). The study area, 45 km by 40 km, included 11 sampling stations, with distances of 7–16 km separating adjacent stations (Fig. 6). The sampling stations coincided with the monitoring sites of the Finnish environmental authorities and also formed a part of a larger sampling routine conducted in 2007 (see also Suominen et al. 2010a; Suominen et al. 2010b; Tolvanen et al. 2013). The sampling routine covered the ice-free growing season period from late April to early October. On average, the stations were visited every third week, which resulted in eight measurement weeks for each station and 88 measurements in total. To allow the comparison of seasonal fluctuations in the area, the measurement weeks 17, 20, 23, 26, 31, 34, 37, and 40 were also synchronised to the campaign of 2007.

The second sampling routine consisted of three smaller study sites which were sampled more intensively (papers II and III). These denser networks included 15–16 sample stations, the locations of which were selected by stratified random sampling into study areas of 8 km by 8 km (Fig. 6). The study sites represented different locations in the archipelago transition and were therefore commonly referred to as the innermost, middle, and outermost network. The networks were visited in weeks 23 and 31, such that one study network was covered during one day. The measurement weeks fell on early June and early August 2011, corresponding to those times when high and low euphotic depth values were recorded in the campaign of 2010, respectively.

The field sampling was conducted in boats with outboard motors that were turned off during the measurements (Fig. 7). At each sampling station, light profiling took about 10 to 15 minutes and the boat was let to drift freely during that time. Anchoring would have been impossible in the deeper waters or would have caused unnecessary resuspension of material in shallow areas. In studying underwater light availability, it is crucially important not to hoard over-long field days. Extending the day either from the morning or the evening is not recommended as inappropriately low solar altitudes compromise the reliability of the data. At my study area, in rather high northern latitudes, the summer days are extremely long, which also allow long working hours close to midsummer. However, the days are notably shorter in April and October. Consequently, field days perfectly manageable in June may not be reasonable at the beginning or the end of the growing season. In this study, all the measurements were performed between 08:00 and 19:00 hrs, local daylight saving time, solar noon being around 13:30 hrs.

PAR was measured by LI-COR quantum sensors (LI-COR Biosciences, USA), which measure the amount of radiation as µmol s^{-1} m^{-2} in the 400–700 nm wavelength area. Underwater measurements were conducted by a spherical quantum sensor (model LI-193) that measures the scalar irradiance of PAR range from nearly all directions. Compared to the measurements of downwelling PAR, scalar measurements are less sensitive towards changes in the Sun's altitude (Stramska and Frye 1997) and are more suitable for studies whose interest is photosynthesis (Tett 1990; Arst 2010). Similarly, regarding photosynthesis, spectrally integrated information of the PAR waveband provides more useful information than narrow wavebands around certain wavelengths (Kirk 2011). Conversely, spectrally resolved irradiance would provide more detailed information on PAR quality than integrated values. Such detailed information nevertheless goes beyond the scope of this thesis as the study focus was on overall PAR availability dynamics through euphotic depth estimates, instead of the attenuation characteristics of specific wavelengths.

Underwater measurements were started just below the sea surface to find out how much irradiance is entering the water. These readings were measured as close to the surface as possible without breaking the surface layer. This could be done rather accurately from a small boat by holding the instrument set by hand, which allows balancing the position of the sensor in real time. Thereafter, measurements were made at one metre intervals starting from 1 m depth. Afterwards, outlier detection was conducted at all the measurement depths to remove values that deviated by more than 20% from the median of the particular depth. Some variability occurred in readings of the topmost water layer due to, for example, the focusing effect of irradiance (see e.g. Schubert et al. 2001). In deeper waters, the light levels remained considerably more stable. Although the maximum measurement depth was 20 m, many profiles were shorter owing to the shallowness of the sampling location. The shallowest profile measurement reached a depth of only 5 m.

Along with the underwater recordings, measurements above the sea surface were conducted simultaneously using a terrestrial quantum sensor, LI-190, to monitor the incoming radiant flux. Fluctuations were caused by rapidly changing weather conditions and cloud cover, e.g. when a single cloud occurs in an otherwise cloudless sky. Therefore, if the irradiance conditions were fluctuating whenever measurements were supposed to start, we waited for more stable conditions. Terrestrial measurements were normalised to a fixed level to allow the direct comparison of measurements depths. The amount of changes in incoming radiation was assumed to affect the underwater readings by the corresponding percentage. Thus, whenever the incoming radiation increased, the underwater readings were reduced in the same relation and vice versa. Each PAR profile was calibrated separately according to their surface measurements.

After outlier removal and normalisation of PAR levels, the corrected PAR readings were converted to relative values to express how much irradiance (%) is remaining at each measurement depth compared to the below-surface values. Euphotic depth could be then estimated from the profiles of relative PAR values according to the rule of 1% PAR penetration. The light attenuation was regarded as linear between each measurement depth, and euphotic depth was modelled with 0.1 m accuracy between the measurements above and below the exact 1% depth. For those stations that did not reach the 1% level, the euphotic depths were extrapolated according to the deepest existing measurements. Extrapolation was needed for *circa* 10% of the profiles. Euphotic depths were preferred as study variables as they illustrate the light availability conditions in shallow coastal waters more directly than, for example, more abstract attenuation coefficients and therefore, provide interesting environmental variables for studies related to primary production and in particular, macrophyte species distribution. K(PAR) attenuation coefficients and profiles were utilised as additional sources of information.

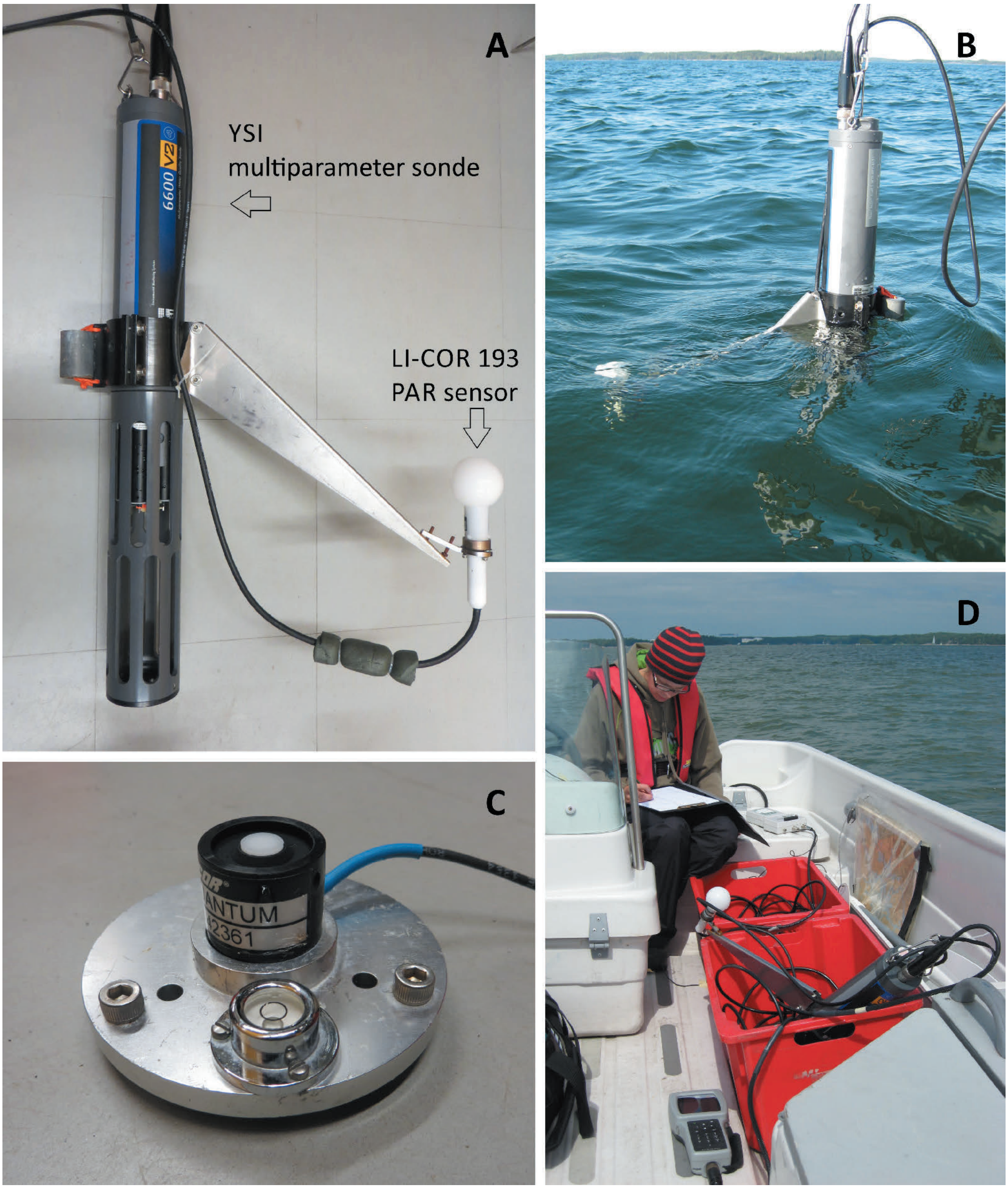

Figure 7. The instrument set including a YSI 6600 V2 multi-parameter sonde and underwater PAR sensor LI-COR 193, photographed out of operation (A) and in water, ready to operate (B). The light sensor is attached to the sonde with a fixed stand to minimise the effect of shading. The terrestrial PAR sensor LI-COR 190 was used to monitor incoming irradiance (C). The measurements were made from small boats to allow operability close to the sea surface (D).

The underwater PAR sensor was attached to a YSI 6600 V2 multiparameter sonde (YSI Inc., USA) by a fixed stand (Fig. 7). The pressure-based depth sensor of the YSI sonde allowed a much more accurate estimate of measurement depth than what would be derived simply by following how much cable had been lowered. Besides measuring temperature, salinity, and pH, the YSI sonde included optical sensors for chlorophyll fluorescence (RFU; sensor model YSI 6025) and turbidity (NTU; 6136). In addition to depth profiles, traditional Secchi disc measurements were also conducted at each station. Secchi depths were measured using white plates and were accurate to 0.1 m.

The underwater habitat dataset that was used in paper IV was gathered in August–September 2010 and is a small part of the extensive database collected under the VELMU programme (The Finnish Inventory Programme for the Underwater Marine Environment, see http://www.ymparisto.fi/en-US/VELMU). The data were collected in a standardised dive transect method by trained SCUBA divers. In paper IV, transects were divided into individual dive frames that were then utilised as sampling units. Besides macrophyte cover, the VELMU data also provided information on seafloor substrates and mussel cover.

3.2 Data processing and analyses

The *in situ* sampled data of this thesis formed a large database of unprocessed material. Therefore, systematic practises were needed: first, to organise and manage these datasets, and second, to process the primary data into more practical units. After extensive pre-processing efforts, the final sample sizes were relatively small and therefore, easier to manage. For instance, the total number of light profiles, and consequently euphotic depths, was 88 in 2010 and 94 in 2011. Data mining, which was always based on data coding, was either executed manually or sometimes using scripting language.

Table 2. Summary of means that have been used in the papers of this thesis to process and present data.

	Paper I	Paper II	Paper III	Paper IV
Data processing and analyses				
Data preparation by GIS tools		x		x
Data transformation / substantial re-processing		x	x	x
Descriptive statistics	x	x	x	x
Statistical analyses	x	x	x	x
Data visualisation and presentation of results				
Tables		x	x	x
Graphs	x	x	x	x
Maps	x	x	x	

Geographically, all the samples are presented in point form and each point has spatial information integrated within. While Geographical Information Systems (GIS) were utilised in the data handling, preparation, and visualisation, the majority of the actual analyses rely rather on statistical methods (Table 2). GIS applications have been used in creating buffers to select data for further analyses (papers II and IV), as well as computing the Euclidean distances between the sampling stations (papers II and IV). The main findings of the material and its subsamples are summarised by presenting descriptive statistics, such as minima, maxima, and averages (papers I, II, III, and IV). Basic statistics are also applied frequently, the most commonly applied statistical tests being correlation and regression analyses (papers I, II, III, and IV). For instance, they were utilised to compare and relate a set of euphotic depths to attenuating components or Secchi depths, or to euphotic depths derived elsewhere either in time or space.

Each paper (I–IV) presents a distinct perspective on the study subject and therefore, varying methodologies have been implemented based on their respective study needs and research approaches. In paper I, hierarchical cluster analysis was performed to cluster sampling stations to define the optical zonation of the south-western Finnish archipelago. In paper II, a number of statistical methods was incorporated to assess the representativeness of spot sampling. For example, all the possible combinations of sampling points were computed to assess the role of randomness in sampling. In addition, a procedure to detect spatio-temporal anomalies was modified according to the approach suggested by Cheng and Li (2006). In paper III, the performances of conversion procedures were evaluated based on three error indicators, i.e. mean absolute error (MAE), mean relative error (MRE), and relative root-mean-squared error (RRMSE). This paper also relies on modelling, where conversion methods are first calibrated with one dataset and then tested with another independent set of data. Finally in paper IV, variance partitioning was applied to quantify the importance of light availability to macrophyte community structures. This method required the datasets to be transformed into distance matrices.

As with deciding the methods of data processing, so too the selection of tools to present the research findings varied according to the studies in question. Visualisation of the results is very important, since the thesis aims to quantify and illustrate the variability in a phenomenon that has many dimensions. Thus, graphs – particularly bar charts, scatter plots, and box plots – are common and have been utilised in all the papers (Table 2). Many visualisations are combinations of different data presentation methods or present a series of results from different sampling occasions. Furthermore, large amounts of information were often summarised in tables (papers II, III, and IV).

Despite the wide selection of visualisation possibilities, the representation of multidimensional complexities in two-dimensional figures is always challenging. In this thesis, the spatial nature of the study subject has often been highlighted by visualising the results on a map background (Table 2). The map helps to perceive the geographical connections behind the individual spot sample results and provides non-spatial statistical analysis with a spatial reference. Consequently, the role of GIS has been particularly strong in the data presentations.

4 RESULTS AND DISCUSSION

4.1 The thickness of the euphotic layer is highly variable in the SW-Finnish archipelago

The overall range of euphotic depths, covering all measurements from the sampling campaign in 2010, was from 2.8 to 18.0 m, with an average depth of 9.6 m and a standard deviation of 3.5 m (paper I). This range includes manifold differences in underwater light availability over a multitude of dimensions. The first two spatial dimensions represent the geographical patterns: in my study setting the north-south direction approximates the transition from the mainland towards the open waters and the east-west direction reflects the cross-sectional line across the archipelago waters. The third spatial dimension was reached through vertical depth profiles, while the fourth refers to temporal changes within seasonal development.

The 2010 sampling regime in the south-western Finnish archipelago revealed great variability in the spatial distribution of euphotic depths. A clear gradual transition from the vicinity of the mainland towards the open sea was not surprising (paper I). Even though the results for the first time quantified the euphotic depth distribution to this extent, similar tendencies have also been reported by other methods. For example, Suominen et al. (2010a) reported an equivalent water clarity transition utilising Secchi disc measurements, while Erkkilä and Kalliola (2004) made similar conclusions from satellite-derived turbidity estimates. In south-western Finland, this gradual change is highly pronounced and the transition zone is relatively wide because of the large archipelago belt that hinders water mixing. Nevertheless, a transition of increasing water transparency from coastline towards the open sea is a typical phenomenon in various types of coastal environments despite their location and coastline type. Examples can be found from other subregions of the Baltic Sea (e.g. Wasmund et al. 2001; Kratzer and Tett 2009), as well as from more oceanic environments, such as the Gulf of Mexico (e.g. Højerslev and Aarup 2002; Lugo-Fernández et al. 2012) or the coast of southern California (e.g. Stevenson and Polski 1961; Aksnes and Ohman 2009). The water clarity transition is usually reported to be linked to terrestrial freshwater inputs, namely river runoff.

The impact of intra-annual seasonality is strong in the high latitudes of the Baltic Sea. Although the annual ice cover naturally has an important influence on the underwater light availability of the underlying aquatic environment (e.g. Schubert et al. 2001; Arst et al. 2006), annual rhythms also have visible influences on underwater nature during the ice-free period. The general seasonal development in illumination dynamics showed a distinctive periodicity that presumably follows seasonal phytoplankton dynamics, i.e. occurrences of spring and summer blooms of algae (paper I). The results were consistent with the findings of Suominen et al. (2010a). Gallegos et al. (2005) studied the temporal variability of optical properties in a sub-estuary of Chesapeake Bay, which is a turbid, eutrophic, and brackish water estuary resembling the coastal Baltic Sea. While their study methods were different, they reported similar fluctuations of clear water periods and the effects of phytoplankton blooms on light attenuation. Apart from the variability in concentrations of photosynthesising organisms, both the seasonal dynamics of river runoff and the consequent distribution of organic and inorganic material also affected the optical properties of coastal waters (Ehlin 1981; Walker 1982; Kowalczuk 1999).

Nevertheless, it should be noted that while the generalisations presented illustrate the overall patterns, they may hide a multitude of smaller scale fluctuations. A more detailed viewpoint was gained by investigating the denser networks that illustrated the euphotic depth variability within the 8 km by 8 km squares. The results showed that changes in water clarity can be very local (paper II). If the ratio between the maximum and minimum value of each week was approximately four for the larger network (paper I), the same was 1.5 for each of the smaller networks (Fig. 8). In absolute numbers, the differences are thus notably smaller for the smaller networks. However, if relating the ratios to the surface area or to the maximum sampling distances within the networks, variability seemed to be relatively greater at a more local scale than over a wider perspective.

Neither can the transition within the seasonal pattern of increasing and decreasing visibility be assumed to be straightforward and unidirectional in a temporal dimension. While a detailed quantification of the temporal variability would require more comprehensive sampling, the available example time series provided some illustration

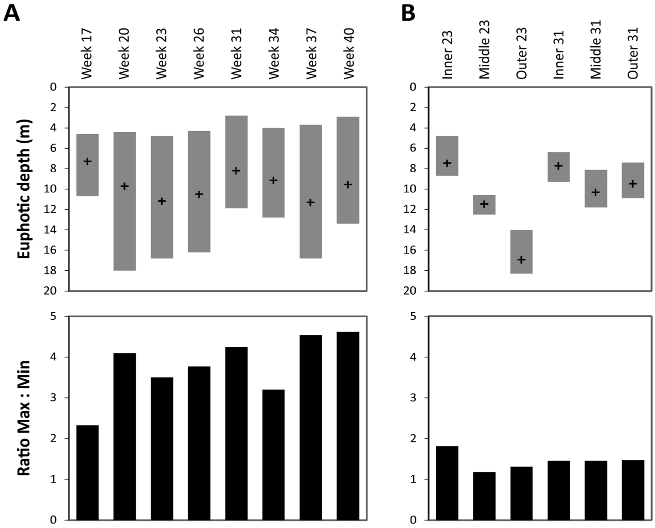

Figure 8. The ranges of euphotic depths (upper panels) and the ratios between the maximum and minimum euphotic depths (lower panels) calculated for each sampling week of the larger network (A), and for the denser networks (innermost, middle, and outermost network) for both the measurement weeks (week 23 and week 31) (B). Crosses in the upper panel indicate average euphotic depths of the respective sampling set.

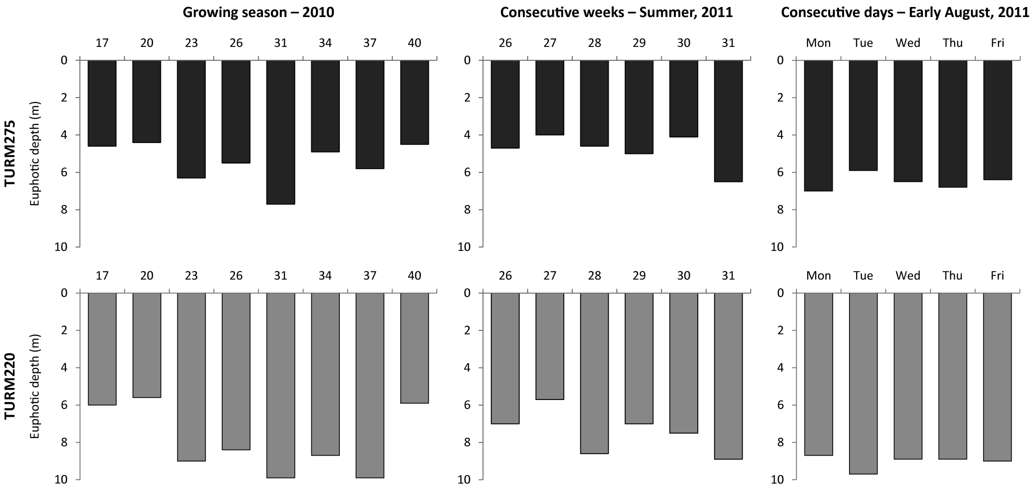

Figure 9. Example time series of euphotic depths from two inner archipelago sampling stations. Left: time series represent parts from the larger sampling campaign conducted in 2010. Middle: measurements from six consecutive weeks, starting from late June and ending in early August in 2011. Right: euphotic depths from five consecutive days measured in week 31. The measurement on Wednesday represents week 31 in the middle-most time series.

of the variability that can be encountered in relatively short time periods (Fig. 9). Two example stations were visited at six consecutive weeks over a time period from late June to early August, and similarly, over five consecutive days in early August, in 2011. In comparison to the overall variability measured during the growing season in 2010, 75% of the euphotic depth range was recorded already in six weeks and approximately one fourth was detected in just five days. This indicates that light availability not only follows the general seasonal cycles but that it also varies more locally and that short time scale fluctuations may also be marked. Lindström (2000), who has also reported on rapid changes in the optical properties of Finnish coastal waters, stated that the most remarkable fluctuations in light penetration are usually linked to changes in plankton biomass.

4.2 Underwater light field forms a spatio-temporally heterogeneous complexity

Although the spatial and temporal trends in euphotic depth dynamics were generally distinct and strongly pronounced, it was equally evident that in a complex archipelago, transitions from one state to another are not linear. Anomalies and deviations from the geographical transition and the seasonal development occurred frequently (papers I and II). By comparing the seasonal patterns of individual stations, it could be seen that the increases and decreases in light availability did not proceed simultaneously (Fig. 10). In other words, the timing of the euphotic depth maxima and minima varied within the study area (papers I and II).

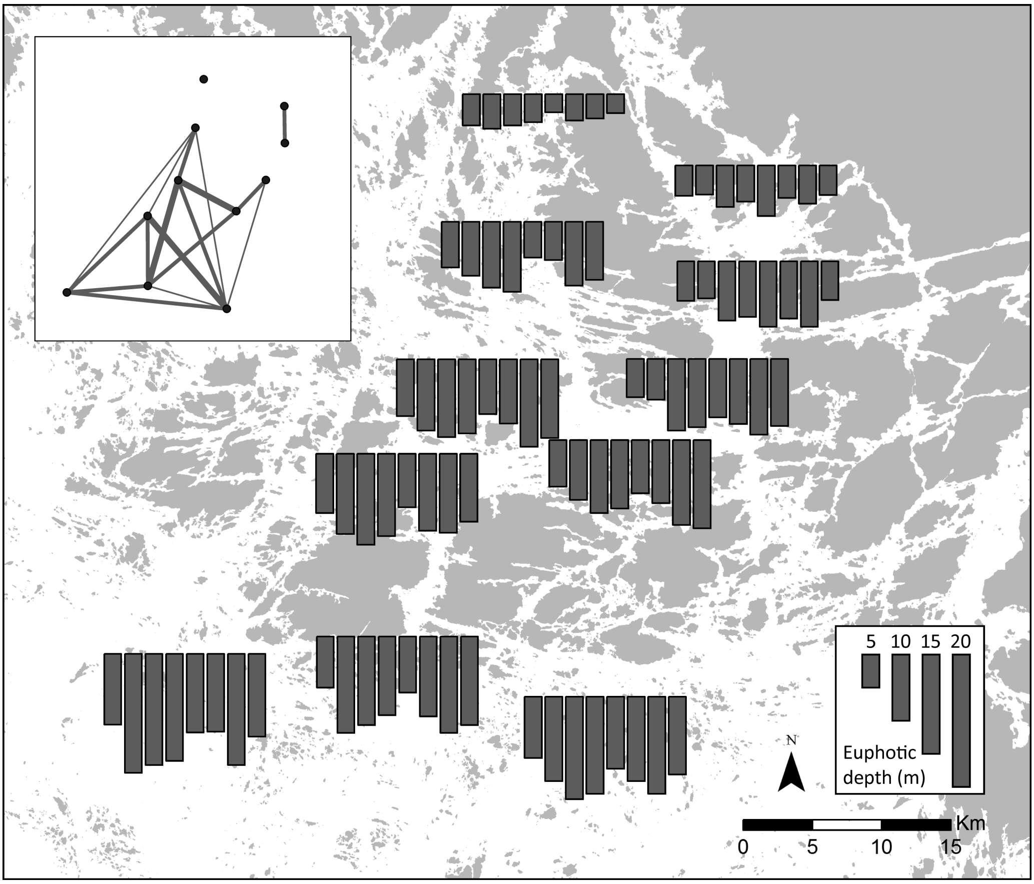

Figure 10. Spatio-temporal variation of euphotic depth, where individual measurements are plotted as time series graphs at the station locations (for exact station locations, see Figure 6). For each sampling location, the bars represent measurement weeks 17, 20, 23, 26, 31, 34, 37, and 40 in chronological order from left to right. In addition, the line illustration in the top-left corner shows which stations have similar seasonal patterns (see also Figure 4, in paper II). The stations that are statistically significantly correlated with each other (Pearson correlation, $p \leq 0.05$) are connected with lines, the thicknesses of which indicate the strength of correlation (ranging from 0.716 to 0.903).

The need to consider the underwater light field in the archipelago in terms of its spatio-temporal complexity was first noted in paper I, while in paper II the discussion continued by utilising statistical methods to assess the spatial and temporal patterns. It was confirmed that even though the transition between two sampling locations is not necessarily linear or straightforward, distant locations generally tend to differ more notably in their water quality than nearby locations. Consequently, neighbouring stations correlated more often than distant stations when temporal patterns of individual stations were compared by statistical analysis (Fig. 10). This is in line with the widely applied Tobler's first law of geography, where near things are stated to be more related to each other than distant things (Tobler 1970).

The divergences from the overall patterns highlight the heterogeneity and complexity of coastal illumination dynamics and strengthen the suggestion to regard euphotic depth development as a spatio-temporal process, instead of focusing on the two dimensions separately. If the geographical transition and seasonal fluctuations are treated as separate, parts of the overall variability in underwater light dynamics will remain unnoticed. Consequently, it is not advisable to map spatial patterns comprehensively from one occasion and then assume the same pattern to apply later at other occasions. Simply adjusting the euphotic depth level, i.e. increasing or decreasing the values according to seasonal fluctuations in light availability, does not fully represent the real spatio-temporal variability in a dynamic sea area. As Smyth (1998) has stated, it requires the representation of both geographic space and time to provide a realistic conception of the physical world.

Similar findings on the spatially divergent seasonal developments in water quality properties have been presented by Suominen (2015) in his doctoral thesis. According to Suominen, underwater light conditions are especially prone to spatial divergence because the factors influencing the light availability are complex and various. In wind-exposed, shallow water bodies, light attenuation has been estimated to be mostly affected by phytoplankton dynamics on a seasonal basis and by suspended material over shorter time scales (Van Duin et al. 2001). The interplay of these and other influencing factors may occur asynchronously in the sub-basins of the large archipelago area, which in turn causes great divergences in underwater light dynamics. In comparison, the spatio-temporal patterns of physico-chemical properties, such as temperature and salinity, are less complicated because these features interact with other variables and processes to a lesser extent (Suominen 2015).

The spatio-temporal heterogeneity in underwater light penetration extends to the vertical dimension as well. While the amount of radiation naturally decreases from the sea surface towards the seafloor, light attenuation efficiency can also vary with depth (Arst 2010; Kirk 2011). In paper I, different types of light attenuation profiles were identified. Here, less than half of the profiles indicated optical homogeneity by having a constant attenuation efficiency throughout the depth profile (paper I; Fig. 2). Walker (1982), who studied attenuation profiles in north-eastern Australia, had previously reported that profiles of clearer surface waters overlying more turbid waters were almost equally abundant than those with reverse layering. In the south-western Finnish archipelago, the attenuation efficiency was predominantly higher in surface waters than in the deeper layers (paper I). Thus, no geographical differences in water column structure were found based on light attenuation profiles. For a more detailed assessment, I would suggest vertically denser sampling of PAR profiles.

4.3 Representative data are needed but challenging to obtain in dynamic coastal waters

Because water bodies differ from each other in many aspects, new models and concepts cannot always be directly applied to new study areas. In ocean colour science, the utilisation of most models and algorithms is a major challenge in the Baltic Sea as the systems are developed for waters that are optically less complex (Darecki et al. 2005; Vepsäläinen et al.

2005). For example, the interpretation of satellite imagery is considerably complicated by the high concentration of coloured dissolved substances in the Baltic Sea waters (Darecki et al. 2005; Zibordi et al. 2009). The exceptionally large archipelago zone, in turn, differentiates the complex south-western Finnish coast from other Baltic coastal areas. Furthermore, the inner differences within the archipelago itself create a complexity where generalised and simplified information hardly applies everywhere (papers I, II, and III). Local information is therefore much needed in the Baltic Sea.

In the field of optical oceanography, the calibration of conversion coefficients is an obvious example to illustrate the need and requirement for local information (see e.g. Koenings and Edmundson 1991). In paper III, where the relationship between the euphotic and Secchi depths was investigated, the archipelago area was regarded to be so variable in its optical properties that it could not be adequately described using only a single fixed coefficient. Moreover, the tested coefficients that were fixed either in a certain location or time frame performed relatively poorly, indicating that the calibration procedure itself requires good spatial and temporal coverage to provide adequate spatio-temporal representativeness (paper III). In general, a temporally limited sampling may provide a false understanding of the local geographic patterns if the results are regarded to present prevailing features rather than momentary conditions. Over a narrow time frame, some changes in the background conditions, such as fluctuations in river runoff, events of water mixing, or the emergence of algal blooms, will always be incompletely defined.

While there is a great need for local data collection by *in situ* sampling, on the other hand the usability of such data should be critically reviewed. For example, the three denser networks revealed a high variability in euphotic depths despite the relatively short distances between the sampling stations (see chapter 4.1). The euphotic depths of neighbouring stations were almost never exactly the same and thus, a single spot sample cannot be seen to represent large areas around its surroundings (paper II). In such environments, finding a good sampling location can be a major challenge. Although acquiring prior knowledge of the area through feasibility measurements might help to perceive local patterns in an area, in highly fluctuating environments the usefulness of such action may be low owing to poor persistence of the local water quality patterns (Fig. 11). A station that satisfactorily illustrated the overall conditions of its surroundings on one occasion may behave very differently at another time (paper II).

While the euphotic depth time series from consecutive weeks and days provide only local examples, of which the ability to generalise patterns remains debatable, they nevertheless illustrate the possible level of the randomness effect on the underwater light measurements in the archipelago. In an extreme example from an inner archipelago site, a euphotic depth of 5.8 m was measured on Monday, 7.2 m on Tuesday, and 9.1 m on Wednesday. In just two days, the euphotic depth had increased 3.3 m, corresponding to an increase of 60%. According to Montes-Hugo et al. (2003), in even more extreme cases, water quality fluctuations may be so rapid that the usefulness of instantaneous local measurements becomes completely invalidated. Similarly, Ganju et al. (2014) warned that daily or weekly sampling may be too infrequent in estuarine conditions. In such situations, new data collection procedures are required.

In general, the more variable and dynamic the study area, the poorer is the representativeness of a single spot sample. As a consequence, environments which undergo strong fluctuations and high variability require more frequent sampling than areas of stable conditions (paper II; Murtojärvi et al. 2011). In addition, the magnitude of local variance may vary between the measurement occasions and therefore, the optimal number of sampling stations may change as well (paper II). As momentary anomalies and random irregularities are common in the water quality of the south-western Finnish archipelago (Erkkilä and Kalliola 2004), the likelihood of coinciding with these occurrences during measurements is high and need to be acknowledged. The low temporal representativeness of *in situ* spot sampling has implications also on ocean colour remote sensing through sea-truthing requirements. In highly fluctuating aquatic environments, the length of the acceptable time period for match-ups between satellite images and *in situ* sampling must be shorter than in more stable conditions.

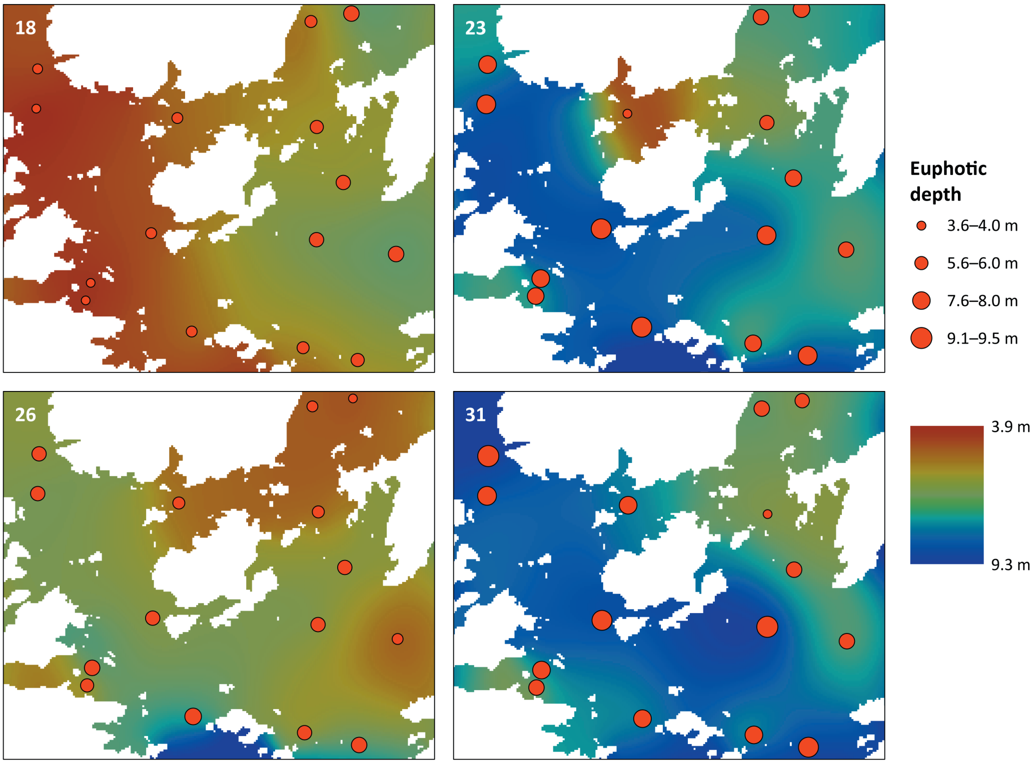

Figure 11. Examples of euphotic depth patterns at same coastal archipelago location from four occasions in summer 2011. The measurement week numbers are indicated in the corners of each map. The red points indicate sampling locations and their sizes represent the respective euphotic depth values. Interpolation surfaces in the background are provided to better illustrate the gradations. The symbol sizes and colours are synchronised among the maps.

4.4 Monitored Secchi depths provide limited view on underwater light dynamics

For decades environmental authorities have conducted water quality monitoring in the Finnish coastal waters. These monitoring measurements have included a variety of parameters, such as concentrations of chlorophyll *a* and nutrients. When it comes to underwater light, Secchi depths have been the standard method of providing an estimate of the overall water clarity. As a visual method, Secchi measurements are prone to subjectivity caused by differences in an individual's ability to detect the disc in water (Walker 1982). Small deviations may have also been caused by differences in equipment and details of the measurement technique (see Preisendorfer 1986). Nevertheless, these time series contribute valuable information of regional patterns and long-term water quality changes, as well as supplying a historical reference to new developments. However, the applicability of these water transparency time series to yield information on underwater light dynamics is limited owing to a multitude of reasons.

Parameters illustrating the general availability of underwater light, such as euphotic and Secchi depths, are composite measures that cover variability in the optically active substances. Differences in the underlying processes (absorption and scattering) are reflected in the output but cannot be separated from it. The balance between the processes is influenced by the relative concentrations of absorbing and scattering material, e.g. CDOM and SPM, in water (Kirk 2011). The Secchi disc visibility and underwater light sensors, in turn, react differently to changes in the absorption/scattering balance (Koenings and Edmundson 1991). Therefore, Secchi depths and euphotic depth are not fully interchangeable and the sole utilisation of Secchi depths in ecological modelling may provide a somewhat biased view on underwater light availability. Therefore, PAR measurements are appreciated over Secchi depths (Reinart et al. 2000). While it is possible to convert Secchi depths to euphotic depths or attenuation coefficients by utilising conversion coefficients or functions, neither of these methods are indisputable (paper III).

A major challenge in utilising long Secchi depth time series and monitoring data is the representativeness of such data. In paper II, the euphotic depths of reference points represented their local surroundings to a varying degree (see chapter 4.3). The challenge of poor local representativeness might be highlighted in monitoring programmes where sampling locations are chosen according to practical reasons rather than for the optimisation of research purposes. In many cases, monitoring stations which are located in deep waters and in open parts of the archipelago, may poorly reflect the water quality changes of shallow bays and other sheltered areas (ELY Centre of Southwest Finland 2011). However, for some study purposes, the latter environments are actually more relevant. For example, modelling benthic macrophyte communities is practical only in shallow waters where light availability is not limiting the growth possibilities.

Another, more profound issue in monitoring representativeness is related to the temporal coverage of the monitoring data. In Finnish coastal waters, monitoring efforts have traditionally been concentrated on a narrow time period during the high summer months (ELY Centre of Southwest Finland 2011; Murtojärvi et al. 2011). Although there are some more frequently sampled stations, most are visited only during high summer in July or August. This limited sampling naturally provides a poor view on the seasonal water quality changes within the growing seasons. Furthermore, it may provide a biased understanding of the overall water clarity (see chapter 4.2), as late summer measurements may reduce and early summer values emphasise the spatial divergences in the area (Suominen 2015).

4.5 Intra-annual variation in PAR availability ought to be included in ecological modelling

Underwater light is a crucial environmental variable for submerged vegetation (e.g. Dennison 1987; Koch 2001). Therefore, light availability is usually included in ecological modelling in one form or another. This kind of information is included also in the EUNIS and HELCOM HUB Habitat Classification Systems, which utilise hierarchical split rules in their biotope definitions (HELCOM 2013). The impact of light availability for habitat forming is highlighted in these classification systems, as illumination conditions are applied already at the first split-phase that regards in-water properties. The weakness of the splitting system is that the habitat classification relies on photic–aphotic dichotomies. In other words, the environment is strictly divided into zones where light is available and zones where there is not enough light for photosynthesis.

Regarding the results presented in this thesis, the excessive simplification of underwater light dynamics is very problematic. It is evident that in high latitude localities, the radiation level does not remain the same throughout the growing season, neither in absolute numbers nor in relation to surface values (papers I and II). Consequently, the surface area of seafloors with part-time illumination and part-time darkness is relatively large (Tolvanen et al. 2013). Many studies on photosynthesis and macrophyte growth have been executed in controlled environments and therefore, the influences of natural fluctuations in light availability are less noted (Sand-Jensen et al. 2007). In paper IV, the focus was on community level responses in natural surroundings. The results revealed some differences in relationships between light availability and the three algal types and the macrophyte life strategies.

Paper IV also tested the impact of light availability variation to macrophyte community formation. The dataset was derived from the 2010 measurements and thus, included illumination information from eight sampling occasions. The information was processed to three light variables, i.e. median, minimum, and range of relative PAR values. The internal importance of these light variables varied among the response variables, indicating differences in impacts of light variability to macrophyte types. Green algae cover, for example, was best determined by the PAR minimum, while the variability of brown algae cover was poorly explained by any of the variables in pure form. There were also differences in the responses of life strategies as annual macrophytes were more strongly linked to light variables than perennials (paper IV). Consequently, fluctuations in illumination conditions may have an impact

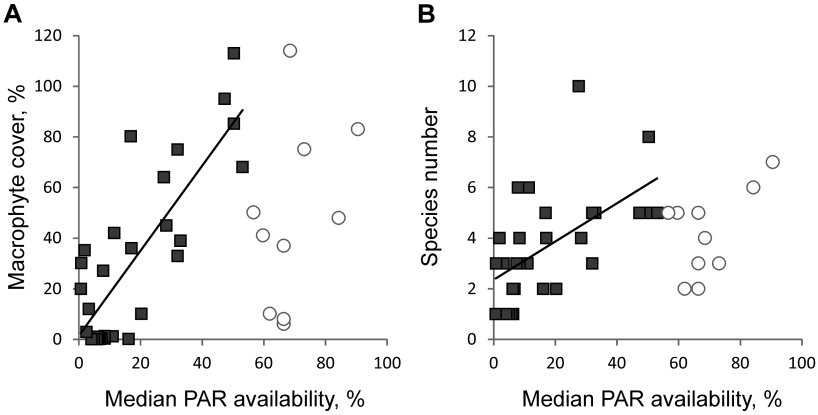

Figure 12. Macrophyte cover (A) and species number (B) in relation to median PAR availability. The black squares and trend line represent deep water data (n=30) and the light grey circles illustrate the shallow water (≤1.5 m) dive frames (n=10). The relationship between macrophyte variables and PAR availability clearly changes at the cut point.

on benthic habitat structures. For these reasons, it would be beneficial to include the seasonal variability to light availability outputs in habitat modelling. This is particularly important whenever there is a possibility that temporally limited sampling provokes misinterpretations about spatial divergences in euphotic depth dynamics (chapter 4.4).

Finally, the growing conditions are not equal in the vertical dimension either – not even within the euphotic zone. The quality and quantity of underwater radiation varies and photosynthetic organisms have differentiated in their tolerance and adaptation for these conditions (Dring 1990; Kirk 2011). While individuals in poor light conditions encounter light limitation, at the same time, species near the surface may suffer from photoinhibition (e.g. Powles 1984; Long et al. 1994). Furthermore, surface waters should be separated from deeper water masses because of external forces affecting the distribution of benthic vegetation. In deeper waters, where light availability is poorer, community formation is often light regulated. However, at the surface where light is abundant, macrophyte distribution is more exposure regulated, i.e. some potential habitats are disturbed by wave activity and ice scraping (Kiirikki 1996). In paper IV, the decision to exclude study frames located in shallow water up to 1.5 m depth was seen as successful (Fig. 12).

4.6 Utilisation of underwater light data requires compromises and great caution

The heterogeneity and complexity of the underwater light field is highlighted throughout this thesis. Chapters 4.1 and 4.2 illustrate the magnitude of variability in underwater light availability. Chapter 4.3 discusses the somewhat poor representativeness of spot sampling and at the same time highlights the need for local data collection. The usability of temporally-limited Secchi depth sampling is reflected in chapter 4.4, and chapter 4.5 urges the inclusion of variability in underwater light availability into ecological modelling. What is common with the statements is that the underwater light field undergoes great changes and that these dynamics should be both more thoroughly acknowledged and cautiously used.

The challenge lies in the availability of information and suitable datasets. In data collection, analysis, and visualisation, real world phenomena need to be simplified as the whole complexity in its all details and dimensions cannot be presented. For instance, a map showing the results of one measurement occasion, however accurate and precise information it may provide, displays only a snapshot of the phenomenon. Change detection based on snapshots is never complete (see Chrisman 1998). Water quality parameters, such as underwater light availability, can undergo variations over multiple scales: changes may be temporary or permanent, patterns may be very local or regional, as well as fluctuations periodic and regular or irregular and unpredictable (Suominen 2015). Quantifying all these changes would require continuous data collection in multiple dimensions. In reality, measuring all the aquatic features in all the spatial and temporal scales is practically impossible (Sathyendranath and Platt 1990).

In many cases, simplification is a prerequisite. However, it could be stated that some information is always lost when the amount of details is decreased. Averages, for example, may be reasonable for some purposes but they may also hide maximum and minimum values that may be highly relevant for other aims. Similarly, some studies utilise general trends while others have more interest in outliers and deviating patterns. In the latter, the interest can focus on either local or global outliers. The scale of changes may also be important, as high frequency fluctuations in water quality can, despite their lower amplitude, be more stressful for underwater vegetation than seasonal variations of greater amplitude and lower frequency (García-Sanchez et al. 2014). Data should cover aspects critical for the research question. For instance, in ecological modelling it was regarded worthwhile to include temporal variability in light availability estimates (paper IV). However, more research is needed to gain a more profound understanding of the data requirements.

Even though the purpose of the data collection should always define the data needs and the methods utilised (Sanders et al. 1983; Strobl and Robillard 2008), sometimes existing datasets guide the study possibilities instead of vice versa. It should always be assessed whether the available dataset really represents the phenomenon of interest because the same datasets and methods do not fulfil the needs of all research goals. For example, in chapter 4.4, Secchi depth data that have been collected during short-term monitoring periods were assessed to be unsuitable to represent the underwater light dynamics of the south-western Finnish archipelago. In water quality monitoring, the station networks and sampling schedules are often compromises that try to serve multiple purposes. Although high summer measurements may be optimal for other purposes, for underwater optics they are problematic.

Regarding illumination dynamics, new and more comprehensive data is clearly needed. Gathering an applicable and representative knowledge base is not straightforward and by no means an easy task. Increasing attention has been given to the vision where multiple data collection methods and sources are combined in a complementary manner (e.g. Kratzer et al. 2014; Harvey 2015; Suominen 2015). Here, the weaknesses of methods can be supplied and patched with the strong points of other data sources. Traditionally, water property measurements have been conducted by *in situ* spot sampling, which is relatively laborious, time consuming, and an expensive way to collect information. In recent advancements, attention has been increasingly given to remote sensing, which could, at least in optimal conditions, produce data extending over a superior geographic area, including a higher temporal frequency. Ocean colour science faces many challenges in the Baltic Sea, especially in its shallow coastal waters (e.g. Erkkilä and Kalliola 2004; Reinart and Kutser 2006; Zibordi et al. 2009; Mouw et al. 2015). Nevertheless, promising results of the usability of remote sensing in water quality monitoring have been already produced (e.g. Kutser 2004; Attila et al. 2013; Kratzer et al. 2014; Harvey et al. 2015b). Furthermore, automated and unmanned *in situ* measurement possibilities exist, such as vertical profilers, buoys, and ferry-box systems, which are less prone to climatic considerations (e.g. sea roughness or ice cover). Implementing new methodologies and combining them to the old ones requires a new kind of expert knowledge as the interoperability of the data sources needs to assured.

5 CONCLUSIONS

In this thesis, I have assessed the multidimensional dynamics of underwater light availability in the coastal archipelago of south-western Finland, in the Baltic Sea. The results revealed notable variability in euphotic depth, both in spatial and temporal dimensions. The general geographical pattern highlighted the expected transition of increasing light availability from the mainland towards the open sea. However, the seasonal development, which in general followed the cycle of phytoplankton blooms, was spatially divergent, creating strong spatio-temporal variability in overall light dynamics.

Besides quantifying the general trends, the study also revealed local anomalies and strong heterogeneity in the light field. This notable fluctuation in light availability was recorded over multiple scales and dimensions. Therefore, the complex archipelago environment is a challenging study location, where the need for local data collection is evident but where the optimisation of such efforts is difficult. The main findings of this thesis suggest sufficient sampling in both spatial and temporal dimension in order to avoid misinterpretations resulting from biased data collection. The results also imply that ecological modelling and habitat classification would gain from a more detailed understanding on the variability of underwater PAR availability.

This thesis provides new knowledge of the complexity of the underwater light field in the coastal Baltic Sea. This kind of information is greatly needed to improve the overall understanding of the coastal processes. The results also give tools for a more efficient application of the existing datasets and heightened awareness of new data needs in coastal research.

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