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DETECTING CYANOBACTERIAL BLOOMS BY PASSIVE OPTICAL REMOTE SENSING. THE BALTIC SEA CASE STUDY.

M.Sc. Thesis (in hydrobiology)

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Tartu 2005

CONTENTS

INTRODUCTION

Cyanobacteria are potentially one of the most interesting organisms in ecological and phycological studies. Not only do they belong to the oldest organisms on the planet (Golubic & Lee, 1999; Lotter, 2001), but they also are extremely important primary producers (Waterbury *et al.*, 1979; Ting *et al.*, 2002). Moreover, many of them are potentially toxic and thus are often nuisance organisms as candidates for aquatic algal blooms (Carmichael, 2001; Codd *et al.*, 1999). Reliable mapping of the cyanobacterial blooms is important in the case of the Baltic Sea region, because the cyanobacterial blooms occur every summer covering areas of more than 100 000 km^2 (Kahru, 1997), affecting recreation, ecosystem integrity, and human and animal health.

Aquatic research is expensive and often limited by the time it takes research vessels to travel between sampling sites. Aquatic systems are not stationary, and phytoplankton blooms are often both spatially and temporally transient. Because data sets are acquired over periods of hours to days, they may not accurately reflect the variability in conditions that can occur over such time periods. For example, wind can significantly move surface volumes in short periods of time (Richardson, 1996). Remote sensing, however, reveals the conditions present in the entire region at a single point in time. Remote sensing instruments include hyperspectral (i.e., many narrow bands) imaging spectrometers (Goetz *et al.*, 1985). These sensors provide both image data, in which a scene is shown in a photographic-like presentation at the spatial resolution of the sensor, and spectra (derived from a large number of narrow, contiguous bands) (Richardson, 1996).

Aim of the present thesis is to study optical properties of algae present in the Baltic Sea and to estimate using model simulations weather or not cyanobacteria are separable from other algae species based on their reflectance spectra. Second important objective is to estimate spectral resolution of multispectral sensors adequate for quantitative mapping of cyanobacteria, can they be used to separate potentially harmful blooms from blooms of other algae and to estimate sensitivity of

the sensors i.e. what are the minimum concentration changes of chlorophyll when cyanobacterial dominance in the water becomes identifiable by those satellites.

1. LITERATURE OVERVIEW

1.1. Introduction to cyanobacterial blooms

Cyanobacteria are common inhabitants of pristine aquatic and terrestrial environments on a global scale and natural populations of these organisms can occur away from human influence. These organisms also respond to cultural eutrophication by the development of massive populations, including blooms, scums and mats (Fogg *et al*., 1973; Sutcliffe & Jones, 1992) (Fig. 1.). Such mass populations are increasingly attracting the attention of environment agencies, water authorities, and human and animal health organizations, since cyanobacteria can present a range of amenity, water quality and treatment problems, and hazards to human and animal health (NRA, 1990; Ferguson *et al*., 1996).

Figure 1. Cyanobacterial bloom in the Baltic Sea in July 1997. Photo: Inga Lips, Estonian Marine Institute.

1.1.1. Health issues and economic losses

There are various health issues associated with more than 60 identified toxins of cyanobacteria which are regarded as neurotoxins, hepatotoxins, cytototoxins, skin irritants and gastrointestinal toxins. These categories are entirely appropriate for the anatoxins and cyanobacterial paralytic shellfish poisoning (PSP) toxin. Anatoxin-*a* and methylated form, homoanatoxin-*a*, are postsynaptic cholinergic nicotine agonists which act as neuromuscular blocking agents. These alkaloids cause staggering, gasping, muscle fasciculation's and cyanosis in animals, plus in birds, with death by

respiratory arrest. The guanidine methyl phosphate ester, in anatoxin-*a* (s), is a potent inhibitor of cholinesterases. It causes hypersalivation, diarrhea and ataxia with rapid death in domestic animals. The potent hepatotoxins, microcystins and nodularins cause severe disruption of liver architecture and function. Death occurs due to pooling of blood in the liver and respiratory arrest. Cylindrospermopsin, a crytotoxic guanidine alkaloid, is an inhibitor of protein synthesis and causes necrotic injury to the liver, kidneys, adrenals, lungs and intestine. Skin-irritation toxins include tumor-promoting protein kinas activators (Codd, 1998).

Toxins enter the food chain as the phytoplanktons are filtered from the water as food by shellfish such as clams, mussels, oysters, or scallops, which gradually accumulate the algal toxins eventually reaching levels that, are potentially lethal to humans or other consumers (Codd, 1998). That and the incidence of dying blooms washing upon beaches during the peak of the summer holiday season has resulted in economic loss and considerable public interest in this phenomenon (Subramaniam *et al*., 2000).

It is difficult to assess the full economic losses associated with a harmful phytoplankton bloom events; either the level of the losses is not made available to the public or the “knock on” effects are never considered. The loss of markets and tourism are one indication, but the potential collapse of local communities and social structure through a local resource being damaged or destroyed cannot always be fully accounted for (Cracknell *et al*., 2001).

1.1.2. Detection problems

Cyanobacterial blooms may be detected using a range of techniques, including laboratory, field and remote sensing observations (Cracknell *et al*., 2001). It has been shown (Rantajärvi *et al.*, 1998) that spatial and temporal frequencies of conventional water-sampling programs are not adequate to report changes in phytoplankton biomass, especially during bloom conditions, when spatial and temporal variability in phytoplankton density is particularly high. The use of unattended flow-through systems on ship-of-opportunity (Leppänen *et al*., 1995; Rantajärvi *et al*., 1998) and

airborne (Dekker *et al*., 1992; Jupp *et al*., 1994) and satellite remote sensing (Kahru *et al*., 1993, 2000; Kahru 1997; Kutser, 2004) have been recommended to provide more reliable information about the extent of the cyanobacterial blooms than the conventional monitoring programs can provide.

The autonomous flow through-systems on ship-of-opportunity only map chlorophyll content along their routs. Moreover, they take water from a fixed depth. It is assumed that the top water layer is well mixed and that the concentration of chlorophyll is constant in the upper mixed layer. This assumption is true in the case of "normal conditions," when algae that cannot control their vertical movement dominate the waters. Cyanobacteria, however, can regulate their buoyancy and in calm weather tend to keep themselves close to the water surface, quite often forming very dense accumulations just below the water surface and surface scum's (Pearl and Ustach, 1982; Sellner, 1997). The same problem occurs while sampling from research vessels if special precaution has not been taken to collect aggregations of cyanobacteria from layer just below the water surface or mats of cyanobacteria floating on the surface. However, Kutser (2004) has shown that quantitative mapping of cyanobacteria is possible with hyperspectral sensors that have adequate spatial resolution.

1.2. Remote sensing

Remote sensing is the science of obtaining information about an object, area or phenomenon through the analysis of data acquired by a sensor that is not in contact with the object, area or phenomenon (Lillesand and Kiefer, 1999). Usually, this object is located on or in close proximity to the earth's surface and sensor is located in an aircraft or on a satellite platform (Philipson, 2003).

1.2.1. Electromagnetic radiation and spectral reflectance

The data recorded by a remote sensing sensor is a measure of the electromagnetic radiation or energy (EMR) reflected by the object and the sun is the most obvious source of radiation. A part of this radiation is what we usually call visible light and it is the same radiation that our eyes, our sensors, can register and process in the brain in order to make us observe the world around us. Remote sensing sensors can also be constructed to record other types of EMR, e.g., ultra-violet light, infrared radiation (including thermal radiation) and microwaves, and therefore provide us with information that is invisible to the human eye (Philipson, 2003).

When electromagnetic energy is incident on any object on the earth's surface, three different interactions between the radiation and the object are possible. The radiation will either be reflected by the object, absorbed by the object or transmitted through the object (Fig. 2.). Remote sensing sensors can measure the intensity and properties of the radiation reflected by the object.

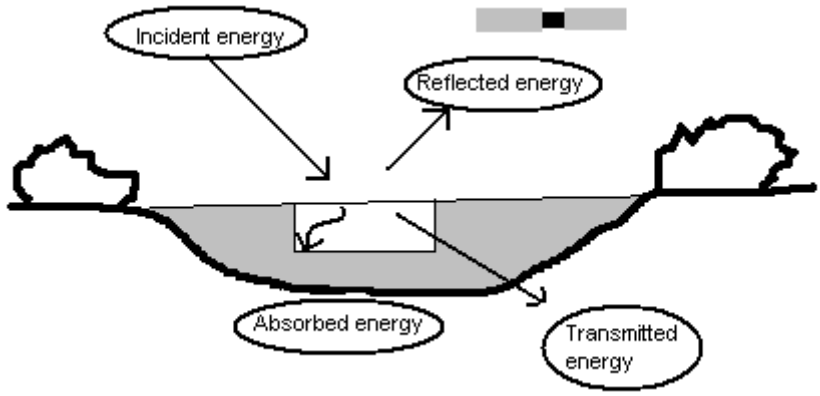

Figure 2. Basic energy interactions between the incoming radiation and the object. Reproduced from Lillesand and Kiefer, 1999.

The proportion of radiation that are reflected, absorbed or transmitted will vary for different objects, depending on the condition and type of material and are also dependant on wavelength. These variations, called spectral variations, can be used

to distinguish different objects from each other. In terms of visible light, these spectral variations result in the visual effect called color (Philipson, 2003).

The reflectance characteristics of an object can be quantified by measuring the portion of incident radiation that is reflected. This is measured as a function of wavelength and is called spectral reflectance (Philipson, 2003).

1.2.2. Remote sensing sensors

Most remote sensing sensors (instruments) are designed to measure photons. The fundamental principle underlying sensor operation centers on what happens in a critical component - the detector. This is the concept of the photoelectric effect. This, simply stated, says that there will be an emission of negative particles (electrons) when a negatively charged plate of some appropriate light-sensitive material is subjected to a beam of photons. The electrons can then be made to flow from the plate, collected, and counted as a signal. A key point is that the magnitude of the electric current produced (number of photoelectrons per unit time) is directly proportional to the light intensity. Thus, changes in the electric current can be used to measure changes in the photons (numbers; intensity) that strike the plate (detector) during a given time interval. The kinetic energy of the released photoelectrons varies with frequency (or wavelength) of the impinging radiation. But, different materials undergo photoelectric effect release of electrons over different wavelength intervals; each has a threshold wavelength at which the phenomenon begins and a longer wavelength at which it ceases (Nicholas— http://rst.gsfc.nasa.gov).

The characteristics of remote sensing sensors are described by its spatial and spectral radiometric resolution. The spatial resolution of the sensor describes the size of the ground area corresponding to one pixel in the image, e.g. 20x20 meters. The best satellite sensors available today have a spatial resolution better than one meter. The spatial resolution depends on the field-of-view of the sensor, the altitude and speed of the satellite or aircraft and the scan rate. Satellite sensors have a

predefined spatial resolution but the resolution of airborne sensors can be adjusted from one registration to another by changing the altitude and speed of the aircraft. A higher spatial resolution will increase the sensors possibility to record spatial detail (Philipson, 2003).

The spectral resolution describes the ability of a sensor to define fine wavelength intervals, i.e., the width of the spectral bands in the sensor. Usually, the number of bands and the position of the bands are also mentioned in connection with the spectral resolution. Most satellite sensors have 2-4, quite broad bands, in the visible (blue, green and red) and 1-3 in the near-infrared, mid-infrared or thermal part of the spectrum (Lillesand and Kiefer, 1999).

1.3. Aquatic remote sensing

The requirements and objectives for mapping the water environment are usually different from those for the mapping of land surfaces. The land applications are often focused on classification problems, i.e., identification of features in an image. Additionally, the spectral characteristics of a certain object are fairly constant between years, with the exception of seasonal changes. The spectral characteristics of a water mass, on the other hand, are highly variable and may be changing very rapidly and the water mass is seldom analyzed in the same way as a land surface (Östlund, 1999).

In the case of the water body only the upwelling light from below the sea surface carries useful information about the water properties (Fig. 3.). The atmospheric contributions and specular reflection at the sea surface constitute noise in this context, and have to be corrected for. Often, satellite sensors for water color have the capability to orient the detector to avoid specular reflection from the sun, but there are no ways to prevent some of the flux scattered by the atmosphere from reaching the sensor. In fact, at the altitude of satellite sensor, more than 80 % the light

reaching the detector may have an atmospheric origin (Morel,1980), and small errors in estimating the atmospheric contribution can cause significant biases in the estimation of the water. Furthermore, the upwelling component from the water has to be processed to evaluate what the water-leaving component would have been, if there were no atmosphere in between the sensor and the water body. Techniques for atmospheric correction therefore form a very important component of remote sensing of water color (Gordon and Morel, 1983; Stürm, 1993; Gordon and Wang, 1994; Gordon, 1997).

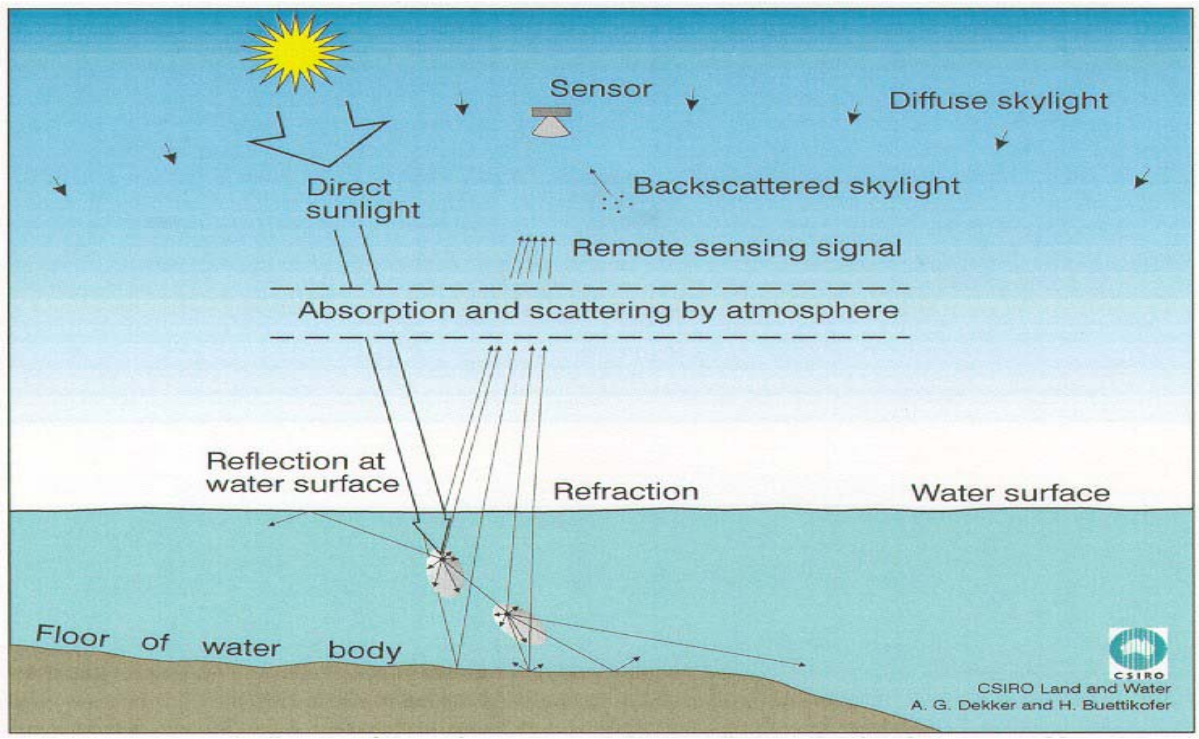

Figure 3. A schematic diagram of the various processes that contribute to the signal as measured by a remote sensor in an optically shallow water where the substrate has a significant effect on the water leaving radiance at the water surface (Dekker *et al.*, 2001).

In the open ocean, it is mainly the phytoplankton and pure water itself that affect the attenuation and scattering of radiation. In fresh water and in the costal zone, phytoplankton and water are acting together with other dissolved substances and particulate matter, which originate from land, e.g., resuspension of the bottom and terrestrial run-off (Dekker, 1993). From a practical, optical, perspective, there can be recognized three components, in addition to pure water itself:

- Phytoplankton. This component is taken to include phytoplankton and other microscopic organisms. But for convenience, there are called this the “phytoplankton” component, in recognition of their major influence on optical properties.
- Suspended material (inorganic). Even though microscopic organisms are also “suspended” material.
- Yellow substances. These are colored, dissolved organic substances (CDOM). This component includes also “detrital” particulate material, which generally has absorption characteristics to yellow substances.

It is important to recognize that this somewhat unorthodox partitioning is adopted for convenience from an optical point of view. The nomenclature identifies only the major components in each category, but each category includes other minor players. One can think of other ways for portioning, which would involve assigning independent categories to some of the minor players, or regrouping the components differently. But the important thing is to be consistent, and to ensure that nothing that plays an optically-significant role is left out, and nothing is accounted for twice (IOCCG, 2000).

1.3.1. Remote sensing of cyanobacteria

Thousands of phytoplankton species, with characteristic size, shapes and physiological properties, are known to exist in the aquatic environment, and their species composition and concentration can change with time and space. The concentration of the main phytoplankton pigment, chlorophyll-*a*, is often taken as an index of phytoplankton biomass. However, it is important to recognize that chlorophyll-*a* is accompanied by number of auxiliary pigments in the phytoplankton cells (IOCCG, 2000).

The last few decades has seen rapid advantages in two technology-based approaches to the study of phytoplankton biology: the use of remote sensing, which quantitatively measures light reflected from the surface of the earth, as a tool to study

regional-scale aquatic ecosystem dynamics, and the refinement of techniques to identify and quantify algal pigments. Although research in remote sensing has been driven by the ongoing development of new sensors, advanced in pigment analysis have essentially evolved from continual research in phytoplankton population dynamics, ecology, and physiology (Richardson, 1996).

Innovative results in both disciplines have developed from following parallel premises with roots in the fields of phytoplankton taxonomy and optics. In essence, the overall line of reasoning is as follows. Many phytoplankton accessory pigments are taxonomically significant (Bjørnland and Liaaen-Jensen, 1989; Rowan 1989). Therefore, detection of specific accessory pigments in aquatic systems can reveal the type(s) of phytoplankton present (Gieskes, 1991; Millie *et al*., 1993). Because each individual pigment is characterized by unique light absorbance features (Floppen, 1971, Morton, 1975), detection of specific optical features can discriminate individual pigments and thus allow assessment of phytoplankton population.

Accumulation of aggregations of cyanobacterial cells just below the water surface and surface scum's are so distinct that the extent of the blooms can be mapped using almost any remote sensing instrument. For example broadband sensors like AVHRR (Kahru et al., 1993; Håkanson and Moberg, 1994), multispectral sensors such as CZCS (Siegel et al., 1999) and SeaWiFS (Joint and Groom, 2000; Siegel and Gerth, 2000), and synthetic aperture radars (Svejkovsky and Shandley, 2001) have been used to map the extent of cyanobacterial blooms. Quantitative mapping of cyanobacteria with above mentioned instruments is practically impossible with radars and hardly achievable with above mentioned sensors due to pure spectral and spatial resolution of the instruments.

The concentration of chlorophyll *a* (Chl *a*) as a general indicator for plankton biomass can be assessed in clear oceanic waters using imagery from a wide range of air- and space born sensors (Vos *et al*., 2003). However, the standard chlorophyll retrieval algorithm fails in coastal and inland waters. For example, SeaWiFS and MODIS (Fig. 4.) standard algorithms overestimate Chl *a* in the Baltic Sea by 200% during non-

bloom condition (Darecki and Stramski, 2004). On the other hand it has been shown (Kutser, 2004) that the Chl *a* may be underestimated by up to two orders of magnitude even by in situ methods when extensive cyanobacterial blooms occur.

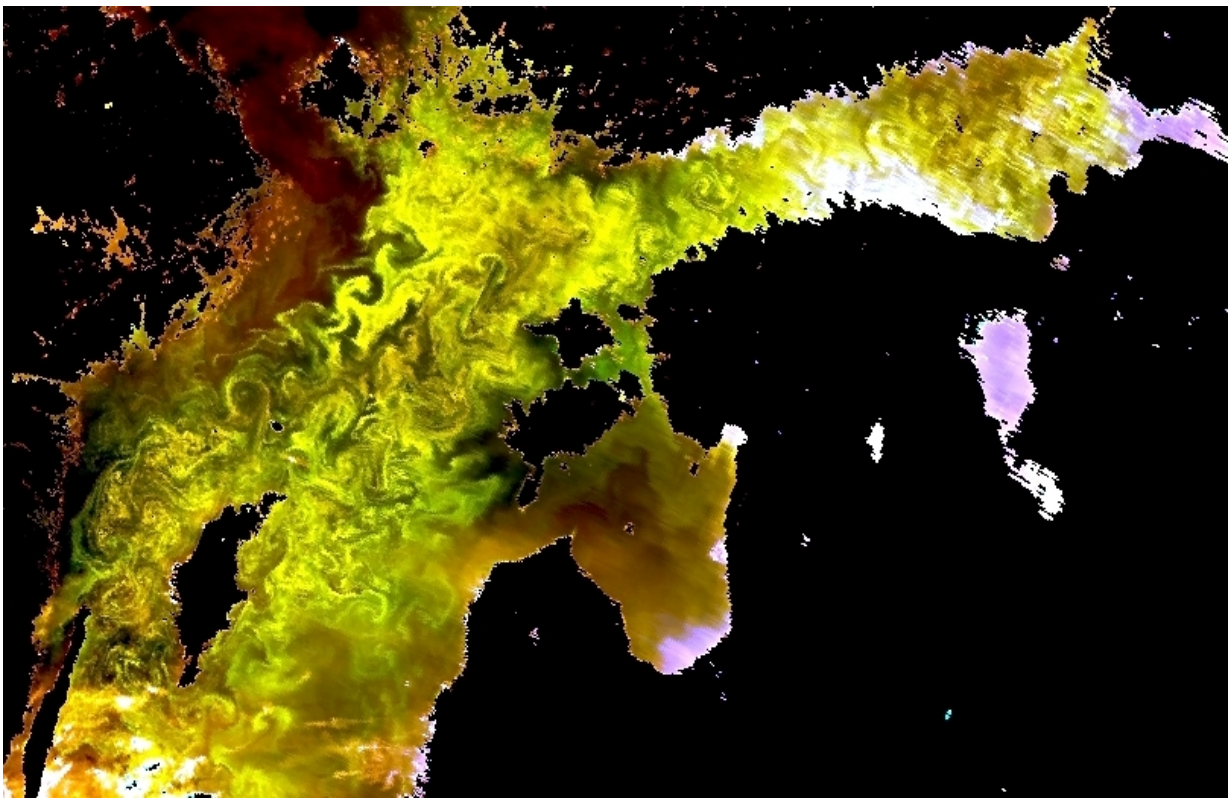

Figure 4. MODIS 1 km resolution image of cyanobacterial bloom in the Baltic Sea in 17th July 2002. Tiit Kutser, Estonian Marine Institute.

Recent advances in space born remote sensing technology broaden the perspectives of monitoring toward the identification and quantification of plankton groups. Algorithms for the retrieval of Chl *a* from turbid water reflectance were already being developed (Gons *et al*., 2002; Kutser, 2004). Now, the retrieval of the pigments phycocyanin and phycoerythrin, which are characteristic of the presence of cyanobacterial, are being attempted. It is known that the presence of phycocyanin can be detected from spectral reflectance (Dekker *et al*., 1991; Gons *et al*., 1992; Jupp *et al*., 1994). However, empirical relationships that have been devised to quantify cyanobacterial phycocyanin from the spectral reflectance of turbid water (Dekker, 1993; Schalles & Yacobi 2000; Simis et al., 2005) required more spectral information than provided by satellites with global coverage. Hyperion and MERIS have sufficient spectral resolution to enable mapping of phycocyanin from space. The

problem is that phycocyanin and phycoerythrin are not routinely measured from water samples, and there is no information available about phycocyanin and phycoerythrin concentrations in the Baltic Sea cyanobacteria. Moreover, Simis et al. (2005) have found that the specific absorption coefficient of phycocyanin is rather variable.

2. MATERIAL AND METHODS

2.1 Laboratory measurements of optical properties of algae

There is very few information available about absorption, scattering and backscattering properties of different algae species. The most comprehensive study has been published by Ahn *et al*. (1992), but it did not contain species present in the Baltic Sea area. Nilas Strömbeck from University of Uppsala carried out the laboratory measurements described in Chapter 2.1 which were used in paper Metsamaa *et al.* (2005) (see appendix 1), and in this thesis.

2.1.1. Phytoplankton cultures

Six different phytoplankton species were grown in batch cultures at low light (c:a 25 µE) in a 16/8 hour light/dark cycle at 25 °C; the cyanobacteria *Aphanizomenon flos-aquae var. "baltica", Anabaena circinalis and Nodularia spumigena*, the diatom *Cyclotella cryptica* and the chlorophyte *Scenedesmus obliqus*. The species were chosen both to match the dominating and bloom-forming groups of the three largest Swedish lakes and the Baltic Sea (Table. 1).

About two weeks before the IOP (inherent optical properties)-measurements, new batch cultures of the different phytoplankton was set up and their optical density was measured semi-daily in order to monitor their growth rate. When the growth rates were determined, a third set of new batches was set for the IOP-measurements. Finally, when all IOP-measurements were made, the chlorophyll *a* + phaeophytine *a* concentration of all batches was measured spectrophotometrically after extraction in ethanol (ISO 10 260). By backward interpolation using the measured growth rates, chlorophyll concentrations for each IOP-measurement could be estimated and subsequently chlorophyll-specific IOP-s.

Table 1. Characteristics of the different phytoplankton species. CCAP is short for CCAP Culture Collection of Algae and Protozoa, SAMS Research Services Ltd, Dunstaffnage Marine Laboratory, Scotland, SU is short for Stockholm University, Department of Botany, Sweden and UU is the abbreviation of Uppsala University, Limnology/Department of Ecology and Evolution, Evolutionary Biology Centre, Sweden.

Phytoplankton	Representative for	Origin	Provider	Medium
Cyclotella cryptica	Lakes Vättern & Mälaren	River Ouse, England	CCAP	DM
Aphanizomenon flos-aquae	Lakes Mälaren & Vättern	Queen Elizabeth Reservoir, England	CCAP	JM
Aphanizomenon flos-aquae	Baltic Sea	Rivermouth in Baltic Sea, Finland	SU, Sara Jonasson	JM
Anabaena circinalis	-	Lough Henney, N. Ireland	CCAP	JM
Nodularia spumigena	Baltic Sea	Baltic Sea	SU, Sara Jonasson	Z8XSalt
Scenedesmus obliqus	-	-	UU, Gunnel Ahlgren	Z8

2.1.2 Absorption of phytoplankton

The optical density $OD(\lambda)$ was measured over the range 350-750 nm, using a Perkin-Elmer Lambda 900 spectrophotometer equipped with a Spectralon integrating sphere (150 mm in diameter) at Dep. of Solid State Physics, Uppsala University, Sweden. A 1-cm quartz cell was placed right in front of the entrance of the integrating sphere, and the optical density, $OD_{tot}(\lambda)$ of the phytoplankton batch cultures was measured. Then the batch cultures were filtered through 0.22 μm Millipore membrane filters, and the optical density of their filtrates $OD_{CDOM}(\lambda)$ was measured. For all measurements, 0.22 μm Millipore membrane filtered, UV-treated Milli-Q water, was used as reference.

To obtain the spectral absorption coefficients for the different phytoplankton species, $a_{ph}(\lambda)$ the following calculations were made:

$$a_{tot}(\lambda) = 2.303\ OD_{tot}(\lambda) / 0.01\ \text{m} \quad (1)$$

$$a_{CDOM}(\lambda) = 2.303\ OD_{CDOM}(\lambda) / 0.01\ \text{m} \quad (2)$$

$$a_{ph}(\lambda) = a_{tot}(\lambda) - a_{CDOM}(\lambda) \quad (3)$$

For avoiding multiple scattering and thus an overestimation of the absorption coefficient, the optical thickness, τ, should be kept below 0.3 (Bricaud *et al.*, 1988).

$$\tau = c\ l \quad (4)$$

where c is the beam attenuation (see below) and l is the pathlength of the measurement cell (here 0.01 m). Three of the six samples in this study had τ lower than 0.3 and all samples were below 0.6. Thus, multiple scattering could not totally be neglected. However, at the most, 20 % of the incident photons undergo multiple scattering (Bricaud, *et al.*, 1983), and then in the forward direction, and therefore no correction was applied to the measurements.

The average acceptance half angle of the spectrophotometer with this setup was 48.2 °, resulting in that at least 90 % of the scattered light was detected (Davies-Colley, *et. al.*, 1986), and possibly up to 99.5 % (Bricaud *et al.*, 1983). Therefore, no scattering correction of the measurements was made.

2.1.3. Beam attenuation and scattering of phytoplankton

The beam attenuation was measured using the same equipment as above, but this time the 1-cm quarts cell was placed 25 cm away from the entrance of the sphere. Additionally, the entrance of the sphere was decreased to about 2 times 2 mm. In this way the acceptance half angle became about 0.11 °. Measurements and calculations were then made analogously of those above, resulting in spectral beam attenuation coefficients for the different phytoplankton batch cultures, $c_{ph}(\lambda)$. No correction for scattering errors was made, as the low half angle should only allow an error of less than 3 % (Ahn *et al.*, 1992).

The spectral phytoplankton scattering coefficient was simply calculated as the difference between the beam attenuation and absorption coefficients of phytoplankton:

$$b_{ph}(\lambda) = c_{ph}(\lambda) - a_{ph}(\lambda). \quad (5)$$

2.1.4. Backscattering of phytoplankton

Backscattering was measured using the six-channel HydroScat-6 (HS-6) backscattering sensor (Maffione and Dana, 1997) from HOBI Labs. The HS-6 was originally designed as a field instrument, and supposed to be used in open water. However, it is also possible to use the instrument in the laboratory (Vaillancourt, 2004) or field (Lindfors, 2005) inside a tank, if proper precautions are taken. In this experiment a tank of approximately 30 l especially developed for the HS-6, was filled up with pure water (UV-treated Milli-Q water). The inner walls of the tanks are black, and the bottom is convex in order to minimize any bottom effects. A small submergible pump is placed inside the tank, ensuring total mixing of the water. While the tank was filled with pure water, background backscattering possibly related to tank effects and particles in the water passing the purification system was measured. Then at subsequent regular intervals (e.g. 2 min), a small amount of phytoplankton batch culture (10-100 ml depending on culture) of known chlorophyll concentration was added to the tank. The backscattered signal was measured as soon as the signal became stable. After proper care had been taken in correcting the backscattered signals using the total absorption and scattering coefficients (HOBILabs, 2000), spectra of the backscattering coefficient were obtained. However, by keeping chlorophyll concentrations relatively low in the tank during the measurements, the effects of the corrections were small, generally in the order of a few percent. By subtraction of background backscattering from the recorded backscattering after each addition of phytoplankton and then division by chlorophyll concentration, chlorophyll-specific phytoplankton backscattering could finally be calculated. Reported values were based on averages of three-five spectra.

2.2. Bio-optical modelling

Reflectance spectra of the optically deep water were calculated using a semi-empirical model described in detail by Kutser (2004). The model is based on the results of Monte Carlo studies by Gordon *et al*. (1975) and Kirk (1984) and is expressed with equation

$$R_\infty(0-,\lambda) = (-0.629\mu_0 + 0.975)\frac{b_b(\lambda)}{a(\lambda)+b_b(\lambda)}, \quad (6)$$

where $a(\lambda)$ is the total absorption coefficient, $b_b(\lambda)$is the total backscattering coefficient, and λ is wavelength. The μ_0 was taken equal to 0.85 according to solar zenith angle in mid-summer at the latitude of the central Baltic Sea.

As the light passes through the water-air interface it undergoes refraction that increases its angle to the vertical. Combining these effects with the effect of internal reflection, Austin (1980) proposed the factor of 0.544 for relating radiance just above the surface with radiance just below the surface. Thus we can calculate the diffuse component of remote sensing reflectance just above the water surface:

$$r(0+\lambda) = 0.544(-0.629\mu_0 + 0.975)\frac{b_b(\lambda)}{a(\lambda)+b_b(\lambda)}. \quad (7)$$

It is assumed that there are three optically active components in the water: phytoplankton, colored dissolved organic matter (CDOM), and suspended matter. Under these conditions the total spectral absorption coefficient, $a(\lambda)$, is described by:

$$a(\lambda) = a_w(\lambda) + a^*_{Ph}(\lambda)C_{Chl} + a_{CDOM}(\lambda) + a^*_{SM}(\lambda)C_{SM}, \quad (8)$$

where a_w is the absorption coefficient of pure water, $a^*_{Ph}(\lambda)$ is the chlorophyll-specific spectral absorption coefficient of phytoplankton, $a_{CDOM}(\lambda)$ is the spectral absorption coefficient of CDOM, and $a^*_{SM}(\lambda)$ is the specific absorption coefficient of suspended matter. C_{Chl} and C_{SM} are concentrations of chlorophyll *a* and total suspended matter.

The total spectral backscattering coefficient $b_b(\lambda)$ can be described:

$$b_b(\lambda) = 0.5b_w(\lambda) + b^*_{b,Ph}(\lambda)C_{Chl} + b^*_{b,SM}(\lambda)C_{SM}, \quad (9)$$

where b_w is the scattering coefficient of pure water and it is assumed that the backscattering probability is 50% in pure water. $b^*_{b,Ph}$ is chlorophyll-specific backscattering coefficient of phytoplankton and $b^*_{b,SM}$ is suspended sediment specific spectral backscattering coefficient of suspended matter.

In this model the values of absorption and scattering coefficients of pure water were taken from Smith and Baker (1981). The absorption by CDOM is expressed as a function of the absorption coefficient of filtered water sample at wavelength 400 nm, $a_{CDOM}(400)$, and slope factor, S, by following formula:

$$a_{CDOM}(\lambda) = a_{CDOM}(400)\exp[-S(\lambda - 400)]. \quad (10)$$

According to estimations by Mäekivi and Arst (1996) S=0.017 gives the best result in case of the Baltic Sea, Estonian and Finnish lakes. Specific absorption coefficient of suspended matter was taken from Kutser (1997), and specific scattering coefficients of suspended matter, as well as backscattering probabilities (backscattering to scattering ratio), were taken from study by Kutser *et al.* (2001).

The modeling was carried out for two distinctly different water types: 1) CDOM-rich waters near a river estuary, 2) open Baltic Sea waters (Table 2).

Table 2. The description of water types used in this thesis. Water type 1 is CDOM rich waters near a river estuary and water type 2 is open Baltic Sea water. The suspended matter and CDOM values were selected based on in situ measurements.

	Suspended matter (C_{SM}) (mg/l)	Yellow substances ($a_{CDOM}(400)$) (m^{-1})	Chlorophyll *a* concentration (mg/m^3)
Water type 1	6	15	from 1 to 300
Water type 2	2	1,5	from 1 to 300

In both cases the chlorophyll *a* values between 1 mg/m^3 to 300 mg/m^3 were used in model stimulation. However, the increment used for different chlorophyll a concentration ranges varied. Increment of 1 mg/m^3 was used for chlorophyll *a* range 1-10 mg/m^3, increment 2 mg/m^3 was used for range 10-20 mg/m^3 , increment 5 mg/m^3 for range 20-50 mg/m^3, increment 10 mg/m^3 for chlorophyll *a* range 50-300 mg/m^3.

The modeling was carried out with specific absorption and backscattering coefficients of 13 algae species. Optical properties of eight species (including two species of cyanobacteria) were taken from paper by Ahn *et al.* (1992). Optical properties of five cultured species (including three species of cyanobacteria) were investigated as described in Chapter 2.1.

2.3. Technical characteristics of satellite sensors under investigation

Landsat series satellites have been used for mapping of cyanobacterial blooms (Galat and Verdin, 1989; Vincent et al., 2004). 16 days revisit time of Landsat does not allow using this sensor for operative monitoring of cyanobacterial blooms. However, in certain circumstances it may be useful to use sensors with good spatial resolution for studying of cyanobacterial blooms. ALI is a prototype of the next-generation Landsat sensor with improved spectral and radiometric resolution and substantial mass, volume and cost savings. ALI spectral bands in the visible part of the spectrum are practically identical to other multispectral sensors like Landsat ETM and IKONOS. ALI has ten bands: a panchromatic (480-690 nm) band with 10 m spatial resolution and nine spectral bands (see http://eo1.usgs.gov/instru/ali.asp) with 30 m spatial resolution. Spectral range of the first three ALI bands used in this study are: 450-515 nm, 525-605 nm, and 630-690 nm. ALI signal-to-noise-ratio is 250 and the radiometric resolution is 16 bit. The ALI footprint is 37x185 km.

MODIS has 13 visible and near-infrared bands that could potentially be used in aquatic remote sensing. Bands 1 and 2 are with 250 m spatial resolution, bands 3

and 4 are with 500 m resolution and bands 8-16 are with 1000 m spatial resolution. Spectral bands of MODIS and MERIS are shown in Table 3. Full spatial resolution of MERIS sensor is 300 m.

Table 3. Wavelength ranges of MODIS and MERIS bands that can be used for mapping cyanobacterial blooms.

	MODIS	MERIS
Band	wavelengths, nm	wavelengths, nm
1	620-670	407.5-417.5
2	841-876	437.5-447.5
3	459-479	485-495
4	545-565	505-515
5		555-565
6		615-625
7		660-670
8	405-420	677.5-685
9	438-448	703.75-713.75
10	483-493	750-757.5
11	526-536	
12	546-556	771.25-786.25
13	662-672	855-875
14	673-683	880-890
15	743-753	895-905
16	862-877	

3. RESULTS AND DISCUSSION

Summer blooms nitrogen-fixing cyanobacteria: *Aphanizomenon flos-aquae*, *Nodularia spumigena* and *Anabaena ssp*., are regular phenomena in the Baltic Sea (Öström, 1976; Niemistö *et al*., 1989). These bloom-forming species are toxic or potentially toxic (Sivonen *et al*., 1989). There were three cyanobacteria species *Aphanizomenon flos-aquae*, *Nodularia spumigena* and *Anabaena* circinalis among the species studied by N. Strömbeck (Metsamaa *et al*., 2005). Chlorophyll-specific absorption coefficient spectra of these species are shown in the Fig. 5., together with specific absorption spectra of *Cyclotella cryptica* (*Diatomophyceae*) and *Scenedesmus obliqus* (*Chlorophyceae*). This results were compared with specific absorption coefficient spectra of eight different algae species (including two species of cyanobacteria) taken from paper by Ahn *et al.* (1992). The absorption spectra of these eight algae species are shown in Fig. 6. One can see that values of the specific absorption coefficient spectra of cyanobacteria measured by N. Strömbeck are in the same range than values of non-cyanobacterial species measured by Ahn *et al.* (1992), whereas values of the specific absorption coefficient of cyanobacteria measured by Ahn *et al*. (1992) are often higher than those of other species. Phycocyanin absorption feature (max near 630 nm) is clearly seen in specific absorption coefficient spectra of all cyanobacteria suggesting that it may also be detectable in reflectance spectra measured by remote sensing instruments.

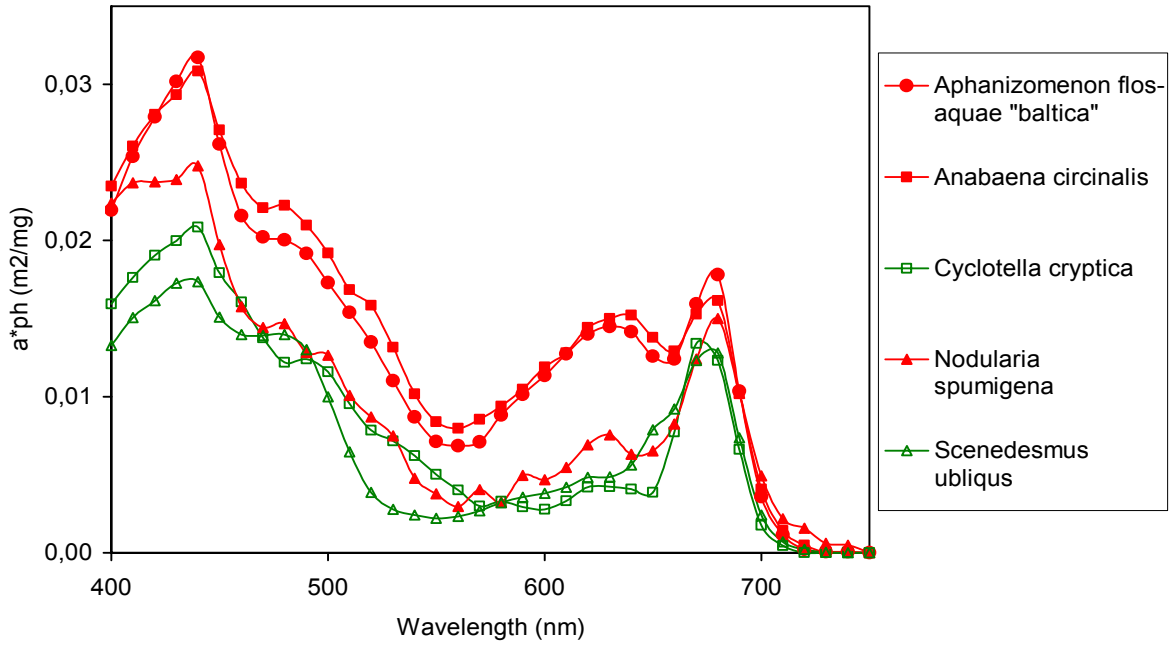

Figure 5. Measured chlorophyll-specific absorption coefficient spectra of different algae species. Absorption spectra of cyanobacteria are shown with red line and reflectance spectra of other algae with green line.

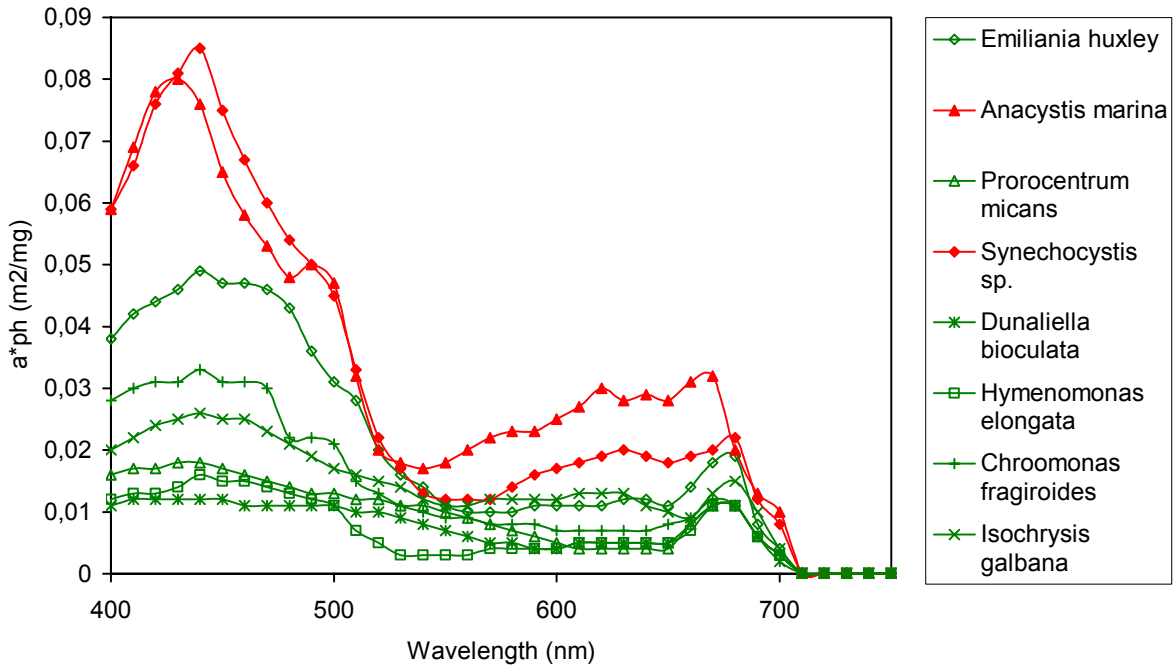

Figure 6. Measured chlorophyll-specific absorption coefficient spectra of different algae species taken from paper by Ahn *et.al.* (1992) Absorption spectra of cyanobacteria are shown with red line and reflectance spectra of other algae with green line.

Figure 7. shows the chlorophyll-specific backscattering coefficient of phytoplankton species studied by N. Strömbeck.

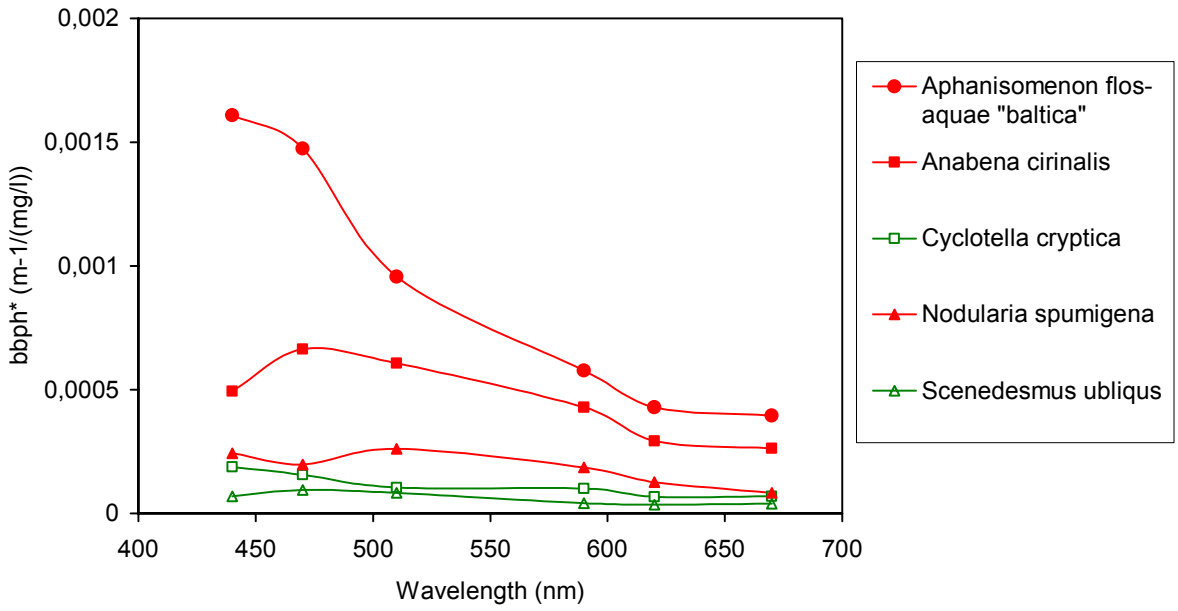

Figure 7. Measured chlorophyll-specific backscattering coefficient spectra of different algae species. Backscattering spectra of cyanobacteria are shown with red line and reflectance spectra of other algae with green line.

In work Metsamaa *et al*. (2005) and study by Ahn *et al.* (1992) the specific absorption and backscattering coefficients were measured in the case on pure algae cultures. It has been shown before that chlorophyll *a* absorption coefficient varies with cell morphology and photo adaptive responses (Sathyendranath *et al*., 1987; Staehr *et al*., 2002) but a cyanobacterial species response to changing environmental conditions and that can cause also variability between phycocyanin absorption values in cultures and in natural assemblages. Phycocyanin is an accessory pigment that can efficiently increase the light harvesting capacity in the “green gap” of Chl *a* (Britton, 1983). The cellular pigment concentration of phycocyanin can be expected to fluctuate more than chlorophyll *a* dose for changing nutrient and light environments (Tandeau de Marsac, 1977). It has been proposed that phycobilioproteins (including phycocyanin) might be broken down during nitrogen shortage, to recycle amino acids (Bogorad 1975). Such mechanisms imply high variability in cellular phycocyanin content and specific absorption coefficient of phycocyanin (Simis et al., 2005).

Bio-optical model simulations were carried out for two different waters types- CDOM-rich coastal and open Baltic Sea waters to study weather or not are cyanobacteria separable from other algae by remote sensing and what have to be the minimum concentrations of cyanobacteria allowing this. Just above the water surface reflectance r(0+) (Eg. 6.) spectra were calculated for chlorophyll *a* concentrations from 1 mg/m^3 to 300 mg/m^3, with different increments described in chapter 2.2., using measured absorption− and backscattering coefficients from all algae species studied by N. Strömbeck and presented in the paper by Ahn *et al*. (1992).

Figures 8. and 9. illustrate the difference in optical properties of the two different water types. Concentration of chlorophyll *a* is 30 mg/m^3 in both cases to amplify the between-species difference in reflectance spectra. There is some between-species difference in reflectance spectra in type 1 (CDOM-rich) water (Fig. 8). However, the shape of the spectra is relatively similar. All the reflectance spectra contain minima between 590-650 nm. It is probably caused by combined effect of absorption by CDOM and phytoplankton pigments and backscattering by the phytoplankton cells rather than by phycocyanin absorption as some of the species do not contain phycocyanin. The phycocyanin absorption feature is clearly seen in reflectance spectra of cyanobacteria in type 2 waters (Fig. 9).

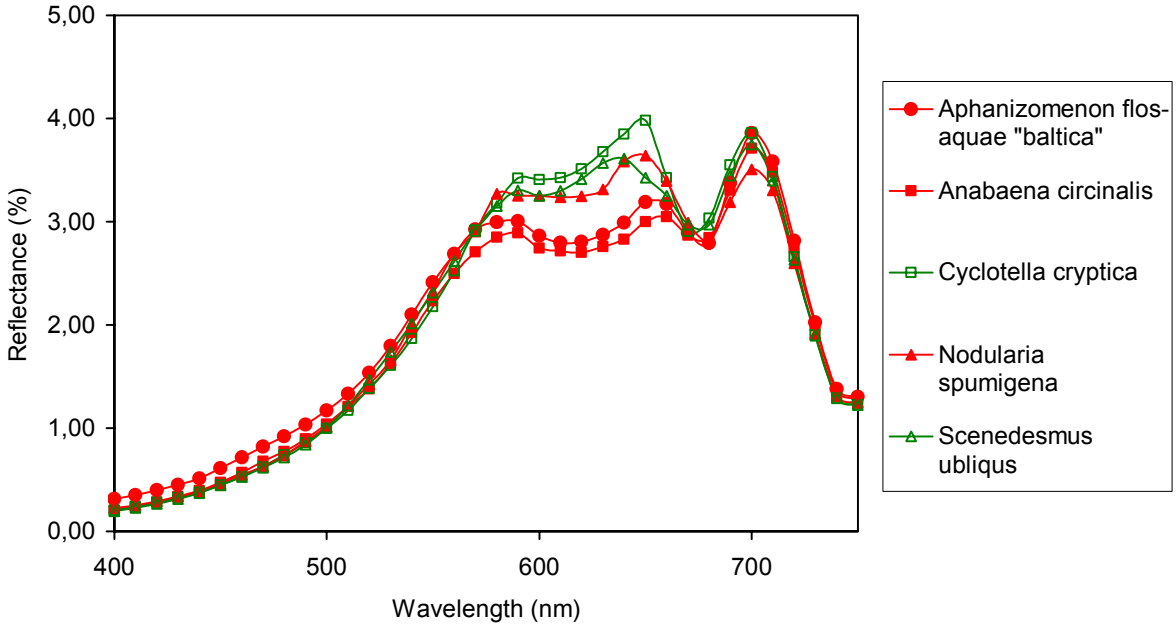

Figure 8. Modelled reflectance spectra of different algae species in CDOM-rich coastal waters. Chlorophyll concentration was 30 mg/m^3 in all simulations. Reflectance spectra of cyanobacteria are shown with red line and reflectance spectra of other algae with green line.

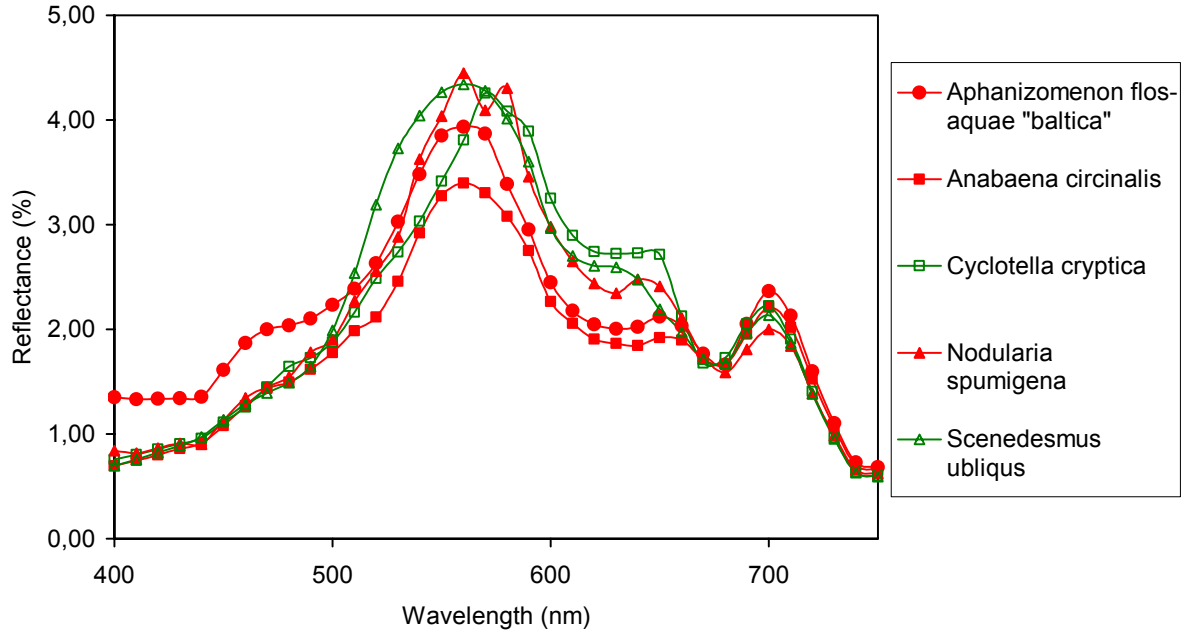

Figure 9. Modelled reflectance spectra of different algae species in open Baltic Sea waters. Chlorophyll concentration was 30 mg/m^3 in all simulations. Reflectance spectra of cyanobacteria are shown with red line and reflectance spectra of other algae with green line.

These modelling results showed that reflectance spectra of cyanobacteria are different from those of other algae species, especially in case of higher chlorophyll *a* concentrations. However, an exception among all studied algae was *Isochrysis galbana* (*Prymnesiophyceae*). Reflectance spectrum of this species is similar to those of cyanobacteria i.e. there is absorption feature near 630 nm. This is probably caused by chlorophylls c_1 and c_2, which are the major pigments (> 10%) of the total chlorophylls in the algal class prymnesiophyceae. Chlrophylls c_1 and c_2 have absorption peaks near 628 and 630 nm correspondingly (Jeffrey and Vesk, 1996). Most prymnesiophyceae are planktonic marine unicells, either flagellate or with flagellate stages in the life history. Prymnesiophyceae are found mostly in tropical and subtropical oceans with few abundant in polar waters. *Emiliania huxley* and *Hymenomonas elogata* belong also to prymnesiophyceae. However, there was no significant absorption feature near 630 nm in modelled reflectance spectra of these species. It can be assumed that Prymnesiophyceae do not present a challenge in recognising cyanobacteria based on their optical signatures as those alga groups occur in different aquatic environments.

Present modelling results indicate that in the type 2 waters the phycocyanin absorption feature becomes noticeable in the reflectance spectra when chlorophyll *a* concentration is 8-10 mg/m^3. In the Baltic Sea, chlorophyll *a* concentrations of 4 mg/m^3 and higher are considered as bloom condition. This result indicates that it will most probably not be possible to recognize cyanobacterial blooms in very early stages as the reflectance spectra of waters dominated by cyanobacteria are similar to waters dominated by other algae species. It must be noted that the phycocyanin to chlorophyll absorption ratio was fixed in case of all cyanobacteria as the absorption spectra were measured for one particular culture. The phycocyanin absorption feature may be seen at slightly different chlorophyll values if the phycocyanin to chlorophyll ratio is different.

The signal to noise ratio (SNR) specifications currently attainable by airborne remote sensing systems such as AVIRIS and CASI, flown under ideal circumstances, are about 1000:1 (Dekker et al., 2001). Thus, the difference between two reflectance spectra has to be at least 0.1% to be detectable by such remote sensing sensors.

Differences between reflectance spectra of *Aphanisomenon flos-aquae* were calculated in the case of water type 2 (open Baltic waters) to estimate what are the minimum concentration differences that can be recognized by remote sensing instruments mentioned above.

For chlorophyll *a* concentrations around 20 mg/m^3 the difference has to be at least 4 mg/m^3 before the reflectance spectra are separable from each other. The biggest difference occurs between 700 and 720 nm. The same wavelength range is most useful for recognizing changes in chlorophyll *a* concentrations also in more dense blooms. For example if chlorophyll *a* concentrations are around 100 mg/m^3 then 10 mg/m^3 differences in chlorophyll *a* are recognizable in the same wavelength range by the instruments which SNR = 1000:1. Situation is the same when chlorophyll *a* values increase to 200 mg/m^3. The smallest concentration change when noticeable differences occur in reflectance spectra may be also interpreted as the accuracy in chlorophyll *a* estimation achievable with remote sensing instruments. Thus for below 10 mg/m^3 values the estimation accuracy is 3 mg/m^3, for chlorophyll *a* values around 20 mg/m^3 it is 4 mg/m^3 and for chlorophyll *a* concentrations from 100-200 mg/m^3 it is 10 mg/m^3. Thus, the relative error in mapping water chlorophyll *a* content is higher (33%) in case of low concentrations of phytoplankton and drops to 5% in case of higher concentrations.

ALI technical characteristic were used to simulate how the reflectance spectra will look like in case of different algae species. Modelled reflectance spectra of ALI are shown in Fig.10. There is small difference between reflectance spectra of cyanobacteria and other algae in CDOM-rich coastal waters as is seen in Fig. 10A. The band 2 and band 3 ratios is slightly different for those two algae groups. In more clear waters there is practically no difference in shape of reflectance spectra of cyanobacteria and other algae. The between species variability is mainly in reflectance values rather than in shape and the differences are amplified by relatively high concentration of chlorophyll *a* (30 mg/m^3) used in modelling the reflectance spectra shown in Fig. 10B.

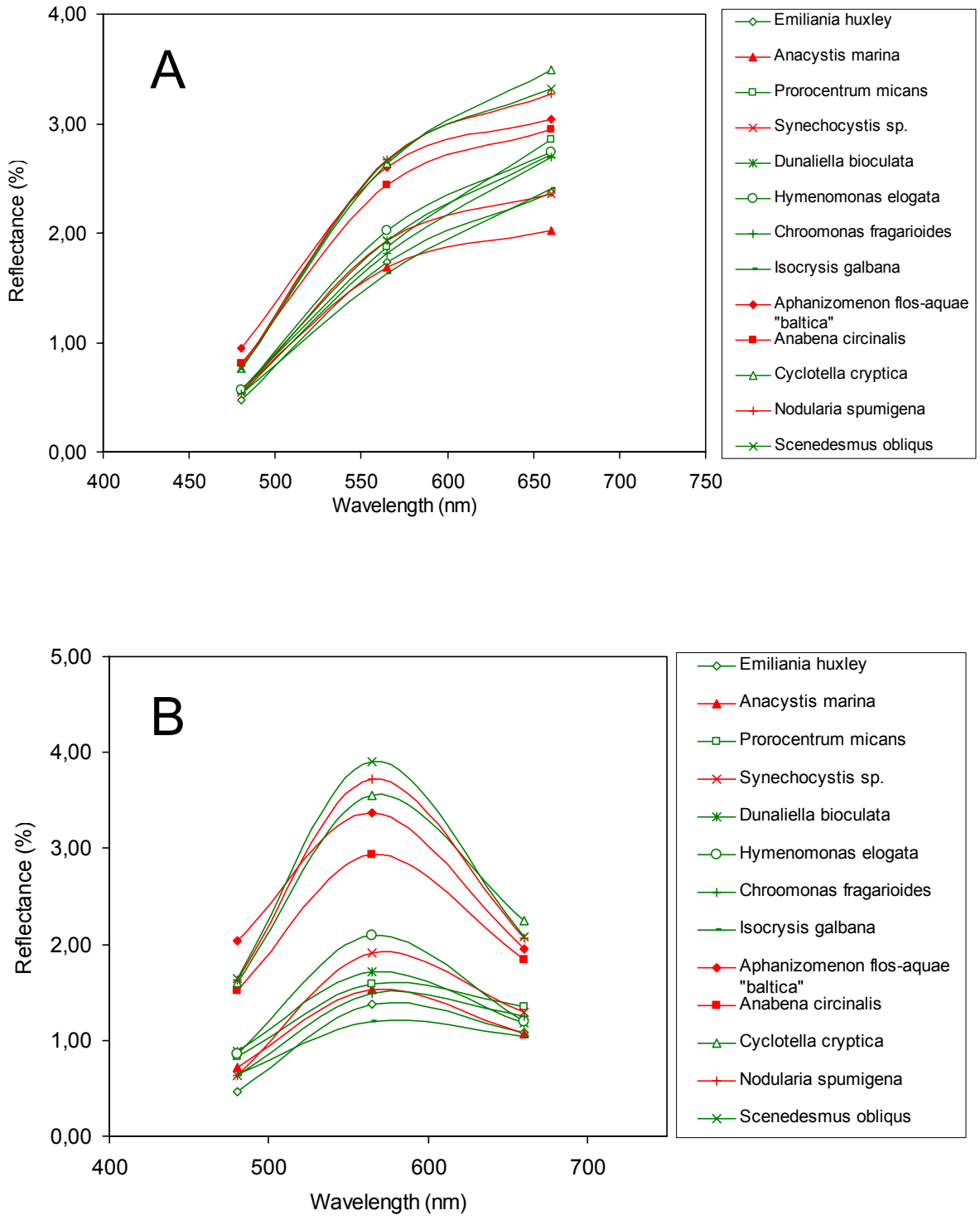

Figure 10. Modelled reflectance spectra of different algae species in CDOM-rich coastal waters (A) and open Baltic Sea waters (B) resampled to spectral bands of multispectral sensors (ALI, Landsat, IKONOS). Chlorophyll concentration was 30 mg/m^3 in all simulations. Reflectance spectra of cyanobacteria are shown with red line and reflectance spectra of other algae with green line.

It is not possible to detect presence of phycocyanin using multispectral sensors like ALI or Landsat. Half of the phycocyanin absorption feature is outside band 2 (630-690nm). Present modelling results show that increase in amount of cyanobacteria in the water causes bigger increase in reflectance values near 650 nm than decrease in reflectance near 630 nm. Those two effects compensate each other in wavelength range of band 2. Thus, the effect of increased amount of cyanobacteria (and consequently the concentration of phycocyanin) has often almost negligible effect in band two. Vincent *et al*. (2004) showed that it is possible to map phycocyanin contestation in lake waters using Landsat. The results of Vincent *et al*. (2004) can be explained with correlation of concentration of phycocyanin with some other water characteristic (e.g. transparency) which is in correlation with Landsat data. The similar effects may occur also in other cases. For example Kutser *et al.* (1995) have shown that it is possible to estimate concentration of total phosphorus in lake water using remote sensing despite phosphorus does not have any effects on reflectance spectra. The total phosphorus is often just in correlation with water turbidity which has effect on reflectance.

Fig. 11 shows that between species differences in reflectance spectra are also mainly in reflectance values not in shape of the reflectance when MODIS bands are used. Variable illumination or atmospheric conditions or variations in the amount of suspended matter may cause similar variability in MODIS data. Band configuration of MODIS is more suitable for Case I waters as there are five band in spectral region 400-550 nm where most of variability in reflectance spectra occurs in that case. In Case II waters the maxima in reflectance spectra is shifting towards longer wavelengths with increasing turbidity. Thus, the reflectance maximum often occurs in wavelength range 550-670 nm where MODIS does not have any spectral bands. Important wavelengths for potential detecting of cyanobacteria are near 630 nm where the phycocyanin absorption feature occurs and near 650 nm where there is a peak in reflectance spectra of cyanobacteria (probably due to high backscattering). MODIS does not provide any information from this spectral region. Therefore it is highly unlikely that MODIS can be used to identify potentially harmful cyanobacterial blooms from blooms of other algae.

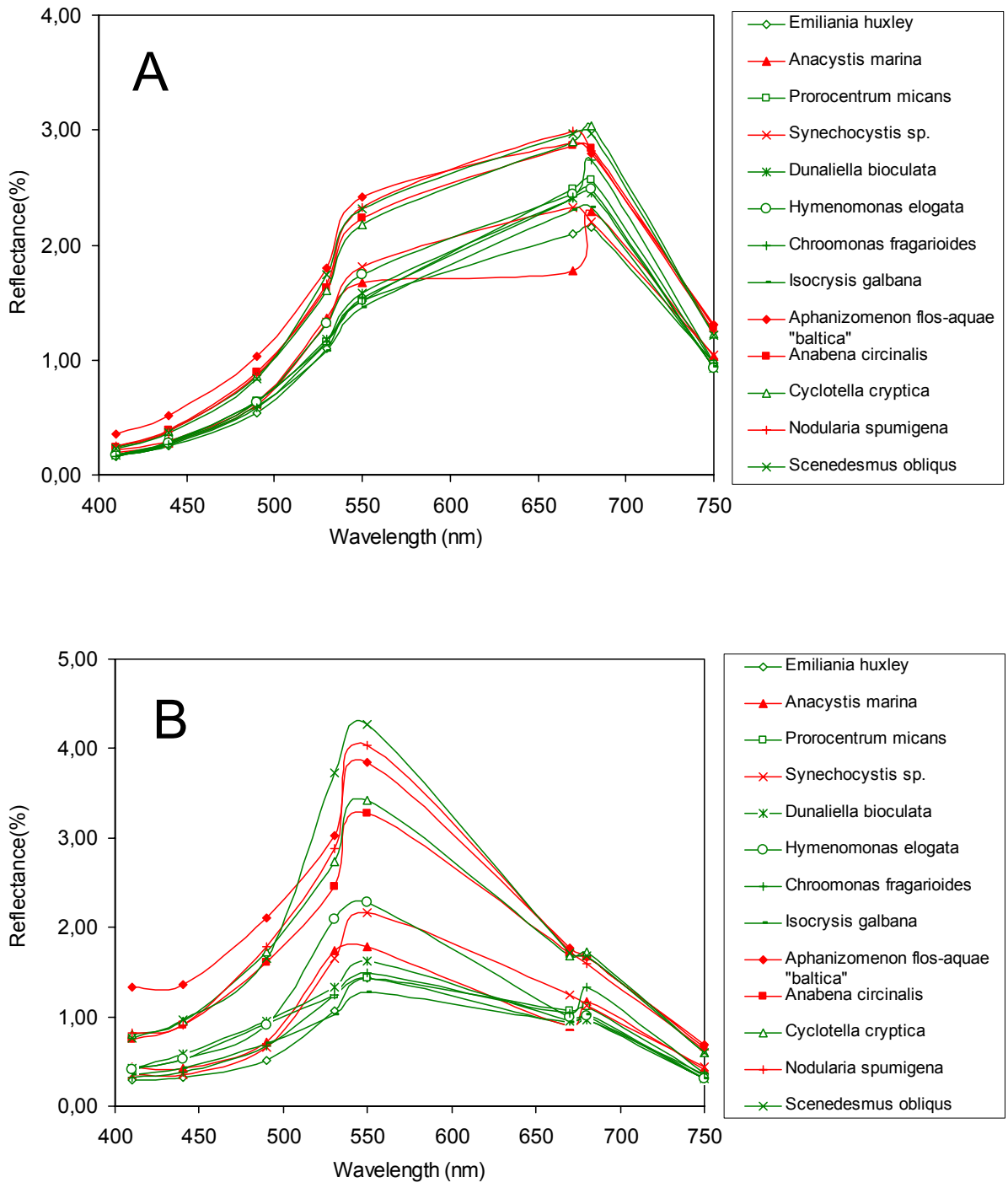

Figure 11. Modelled reflectance spectra of different algae species in CDOM-rich coastal waters (A) and open Baltic Sea waters (B) resampled to spectral bands of MODIS. Chlorophyll concentration was 30 mg/m^3 in all simulations. Reflectance spectra of cyanobacteria are shown with red line and reflectance spectra of other algae with green line.

Fig. 12 shows that MERIS band configuration is more appropriate for turbid coastal waters. It is seen both in case of CDOM-rich coastal waters (Fig. 12A) and open Baltic Sea waters (Fig. 12B) that MERIS bands 6 and 7 can be used to separate between cyanobacteria and other algae if the concentration of chlorophyll is high (30 mg/m^3 in case of Fig. 12). The best wavelength configuration for that purpose should be with central wavelengths at 630 nm and 650 nm, but the MERIS bands 6 and 7 (see wavelengths in Table 3) are quite close to the ideal. Other MERIS bands useful for detecting phytoplankton are bands 8 at wavelengths where chlorophyll *a* absorption feature occurs in water reflectance spectra and band 9 at wavelengths where there is often peak in reflectance spectra of waters which contain high amount of phytoplankton.

Fig. 13 illustrates how the increasing amount of chlorophyll *a* influences the reflectance detected by MERIS in case of two algae species *Cyclotella cryptica* (Fig. 13A) and a cyanobacterium *Nodularia spumigena* (Fig. 13B). The phycocyanin absorption feature is not so clearly seen in reflectance spectra of *Nodularia spumigena* as it is in case of other cyanobacteria (see Fig. 12). However, behaviour of band 6 and band 7 ratio is different even in case of *Nodularia* as it is seen in Fig. 12. It is also seen that reflectance spectra of these two species are fairly similar in case of lower chlorophyll concentrations. In the Baltic Sea chlorophyll values above 4 mg/m^3 are considered as bloom condition. Reflectance spectra of waters with different dominant algal species are fairly similar for chlorophyll concentrations below the “bloom limit”. Therefore, it is highly unlikely that MERIS can be used to detect emerging potentially harmful blooms of cyanobacteria in very early stages of the bloom.

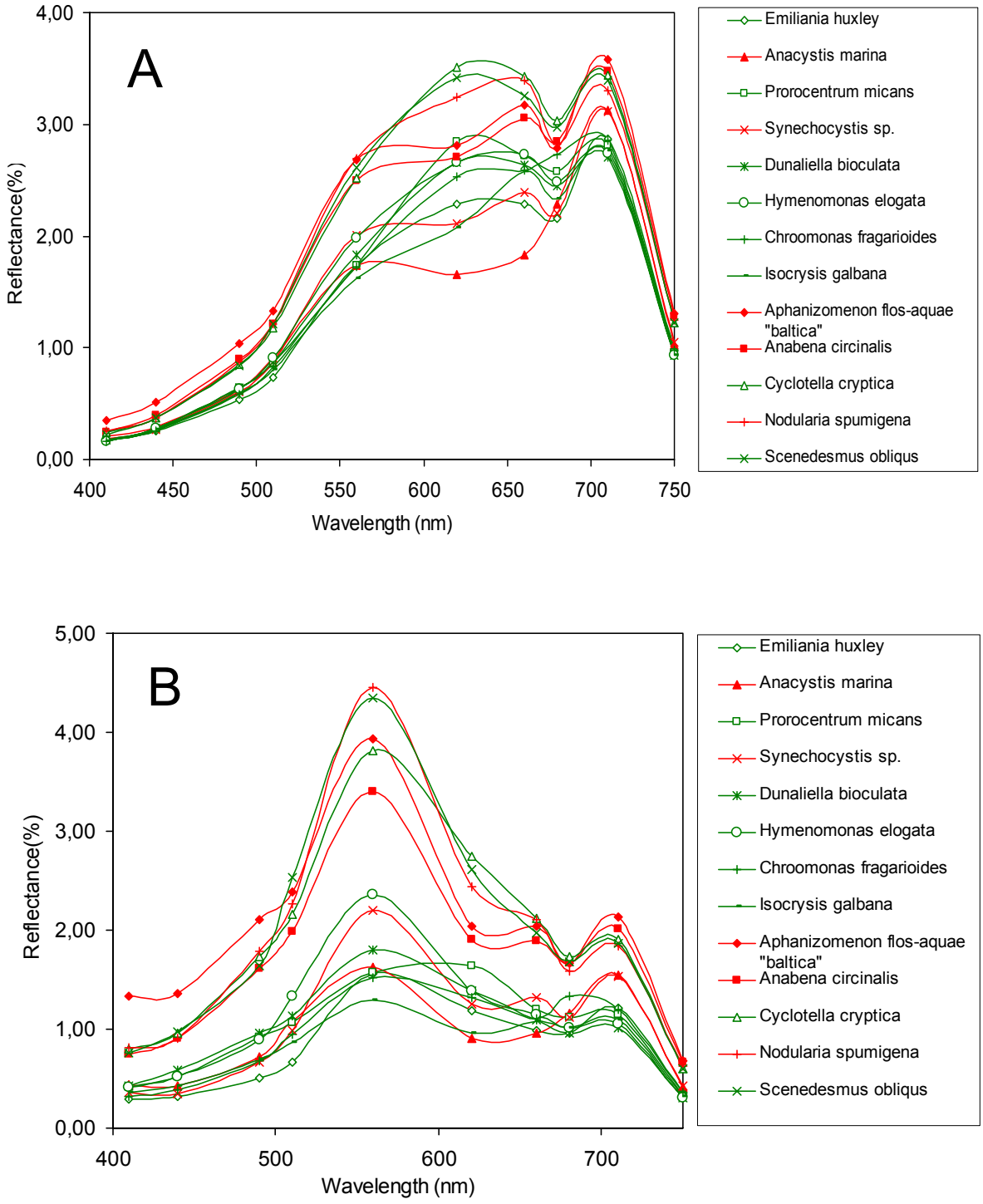

Figure 12. Modelled reflectance spectra of different algae species in CDOM-rich coastal waters (A) and open Baltic Sea waters (B) resampled to spectral bands of MERIS. Chlorophyll concentration was 30 mg/m^3 in all simulations. Reflectance spectra of cyanobacteria are shown with red line and reflectance spectra of other algae with green line.

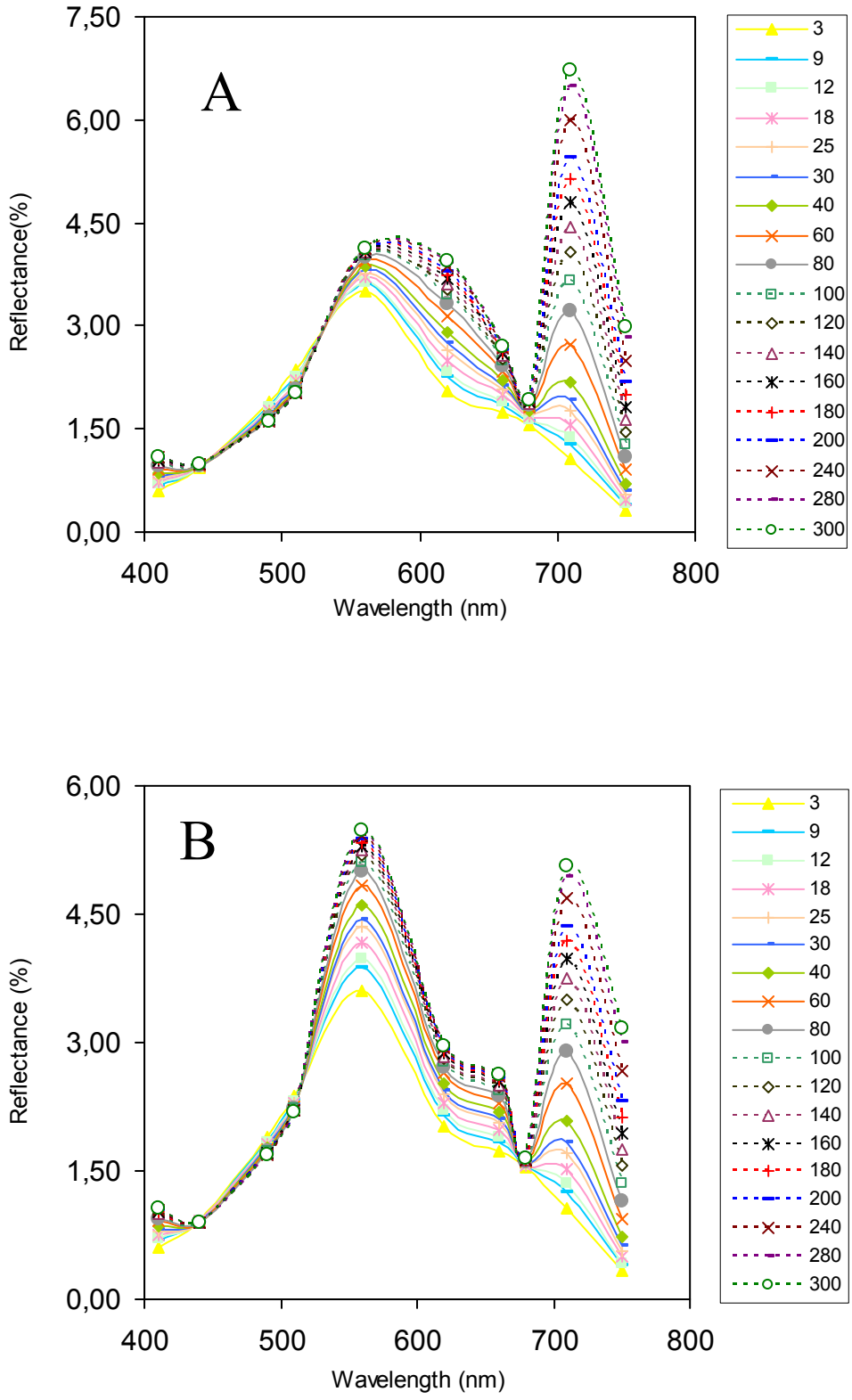

Figure 13. Modelled reflectance spectra of *Cyclotella cryptica* (A) and a cyanobacterium *Nodularia spumigena* (B) resampled for MERIS bands. Concentrations of chlorophyll (in mg/m^3) are shown in the legend. Modelling was carried out using optical properties of the open Baltic Sea waters.

Mapping of cyanobacterial bloom has been based on assumption that any other reason cannot cause increased signal from offshore regions of the Baltic Sea in the middle of summer than bloom of cyanobacteria. It has been shown that multispectral sensors like ALI, Landsat or MODIS cannot be used to differentiate between waters dominated by cyanobacteria and water dominated by other algae. Results of present work indicate that MERIS is capable of recognising cyanobacterial blooms. However, detecting of emerging blooms is not possible whereas the phycocyanin absorption feature becomes detectable by MERIS when chlorophyll a values have reached values around 10-30 mg/m^3 (depending on species) which are much higher that the level of chlorophyll which is considered as bloom condition in the Baltic Sea (4 mg/m^3).

It is possible to use also ALI, Landsat or MODIS for quantitative monitoring of cyanobacteria during bloom conditions despite they cannot recognise cyanobacteria. These sensors can detect changes in reflectance values caused by variable amount of cyanobacteria in the water if we assume that elevated water leaving radiance can be explained solely by presence of cyanobacteria. Certain amount of in situ data is needed to find the relationship between satellite signal and the amount of cyanobacteria. However, the results have to be taken with certain precaution. First of all the in situ chlorophyll *a* values used for developing the remote sensing algorithms and validating satellite maps do not represent the situation satellites are detecting unless special methods have been used to collect the cyanobacteria from subsurface layer or surface scum. This kind of sampling is possible only from small boats and all routinely collected chlorophyll *a* data has to be neglected while calibrating satellite images collected during cyanobacterial blooms. It must also be noted that the chlorophyll retrieval algorithms obtained for the multispectral sensors with just a few bands are image specific and not automatically applicable in different locations or on other images of the same site. The reason is that intensity of the signal in those one to two bands that can give information about the water properties may vary due to other reasons like changes in illumination or optical water properties.

The other problem is related with spatial resolution of MERIS or MODIS. Kutser (2004) has shown that chlorophyll *a* concentration may vary by two orders of magnitude within one MERIS pixel. Thus, specially designed in situ experiments are

needed to collect chlorophyll data that can be used for validating cyanobacterial bloom images as the within pixel variability of phytoplankton has to be studied. This kind of in situ data is not available at present.

More detailed information about optical properties and concentrations of chlorophyll *a* in surface scum and dense subsurface layers of cyanobacteria are needed to improve performance of the bio-optical model and consequently the accuracy of chlorophyll *a* retrieval from remote sensing data. This is the aim of future research.

CONCLUSIONS

Remote sensing instruments with sufficient spectral resolution (10 nm or better) and high radiometric sensitivity can be used for recognition and quantitative mapping of cyanobacteria as absorption by phycocyanin is causing absorption feature in reflectance spectra that is typical to cyanobacteria only. Some algal species (*Prymnesiophyceae*) may contain chlorophylls c_1 and c_2 that may cause similar absorption feature in reflectance spectra. However, cyanobacteria and *Prymnesiophyceae* usually do not occur in similar aquatic environments. Therefore, separating of cyanobacterial blooms from waters dominated by other algae should not be a problem provided the amount of cyanobacteria is high enough.

Estimation for the open Baltic Sea waters shows that concentration of chlorophyll has to be 8-10 mg/m^3 before the phycocyanin absorption feature becomes detectable in reflectance spectra of hyperspectral instruments with sufficient SNR. Therefore, it is highly unlikely that remote sensing can be used for early warning of emerging potentially harmful blooms as chlorophyll concentrations higher than 4 mg/m^3 are already considered as bloom.

Accuracy of remote sensing estimates of the chlorophyll *a* concentration from hyperspectral data is variable. It is around 3 mg/m^3 for chlorophyll *a* concentrations below 10 mg/m^3, rises to 4 mg/m^3 for chlorophyll *a* range between and 10 mg/m^3 and 20 mg/m^3 and increases to 10 mg/m^3 when chlorophyll *a* values are around 100-200 mg/m^3. Thus, we may say that relative error in mapping of chlorophyll *a* concentration in such CDOM-dominated waters like the Baltic Sea is high in case of smaller chlorophyll *a* concentrations and is decreasing towards higher concentrations.

The modelling results show also that multispectral sensors like ALI, Landsat or MODIS are not capable of separating waters dominated by cyanobacteria from waters dominated by other algae species as their spectral band configuration does not allow detecting absorption features caused by phycocyanin or any other spectral features that are characteristic to cyanobacteria only. MERIS bands 6 and 7 allow detecting phycocyanin absorption feature near 630 nm and a small peak in

reflectance spectra near 650 nm characteristic to only cyanobacteria. Thus, MERIS can be used in detecting cyanobacteria if they occur in bloom quantities.

Appendix 1 and appendix 2 contain manuscripts which are based on results of this thesis and have been submitted to two pre-reviewed journals.

KOKKUVÕTE (Summary in Estonian)

Tsüanobakterite tuvastamine kaugseire meetodite abil, Läänemere näitel.

Liisa Metsamaa

Tsüanobakterite toksiinid võivad põhjustada erinevat tüüpi vaevusi inimestel ning isegi surma kalade ja kariloomade puhul. Seetõttu on potentsiaalselt toksiliste tsüanobakteriõitsengute avastamine ja seire olulise tähtsusega. Käesoleval ajal tugineb Eesti rannikumere seire veeproovide võtmisel 9 seirejaamast Tallinna, Pärnu ja Narva lahtedes kahel korral kuus (suveperioodil). Nii harvade ja väheste mõõtmistega ei ole võimalik tsüanobakteriõitsenguid avastada ega nende liikumist seirata. Praktiliselt ainsaks võimaluseks oleks kaugseire meetodite kasutuselevõtt. Antud magistritöö eesmärgiks oli välja selgitada, kas tsüanobaktereid on võimalik kaugseire meetoditega eristada teistest fütoplanktoni liikidest vee heleduskoefitsiendi spektrite järgi, kui suur peaks sellisel juhul olema tsüanobakterite hulk vees ja millise spektraalse ning ruumilise lahutusvõimega peaksid olema selleks kasutatavad kaugseire sensorid?

Töö tulemusena leiti, et piisava spektraalse lahutusvõimega (10 nm või vähem) ja kõrge tundlikkusega kaugseire instrumendid võimaldavad tsüanobakterite tuvastamist ainult tsüanobakteritele omase pigmendi, fükotsüaniini, kaudu kuna fükotsüaniin neelab kitsaste lainepikkuste vahemikus (630 nm) ning tekitab vee heleduskoefitsiendi spektris lokaalse miinimumi. Mõned fütoplanktoni liigid (*Prymnesiophyceae*) võivad aga sisaldada klorofülli c_1 ja c_2, mis põhjustavad vee heleduskoefitsiendi spektris muutusi, mis on sarnased fükotsüaniini mõjuga. Samas aga on teada, et tsüanobakterid ja *Prymnesiphyceae* liigid tavaliselt ühes ja samas looduslikus keskkonnas ei esine. Seega ei tohiks tsüanobakterite tuvastamine kaugseire meetoditega võimatu olla, kuid tsüanobakterite hulk peab selleks piisav olema.

Läänemere avaosa kohta tehtud mudelarvutused näitavad, et klorofüll *a* kontsentratsioon peab olema vähemalt 8-10 mg/m^3, et fükotsüaniini neeldumine oleks vee heleduskoefitsiendi spektris hüperspektraalsete instrumentidega tuvastatav. Kuna Läänemeres loetakse kokkuleppeliselt õitsenguks klorofüll *a* kontsentratsioone alates 4 mg/m^3, siis tõenäoliselt ei ole kaugseire instrumentidega võimalik potentsiaalselt toksilise tsüanobakterite õitsengu varane identifitseerimine see tähendab õitsengu ulatus on küll kaugseire abil kaardistatav, aga kas tegu on tsüanobakteritega või mitte, pole võimalik veel määrata.

Täpsus, millega on võimalik tsüanobakterite olemasolu vees hinnata, sõltub tsüanobakteritete hulgast vees (mida iseloomustatakse klorofüll *a* kontsentratsiooni kaudu). Näiteks kui klorofüll *a* kontsentratsioon on alla 10 mg/m^3, siis peab klorofülli *a* kontsentratsioon muutuma vähemalt 3 mg/m^3, et muutus oleks mõõdetav ka kaugseire riistadega. See tähendab, et klorofüll *a* hindamise viga on 30 %. Kui klorofüll *a* hulk on 10 mg/m^3 ja 20 mg/m^3 vahel, siis on klorofüll *a* hindamise viga 4 mg/m^3 ning kui klorofüll *a* hulk on 100-200 mg/m^3, siis on hindamise viga 10 mg/m^3. See tähendab, et sellistes hägustes vetes, nagu seda on Läänemeri, on tsüanobakterite hulga hindamise suhteline viga suur kui vetikate hulk on väike ning suhteline viga väheneb kontsentratsiooni kasvades.

Modelleerimise tulemused näitasid ka, et multispektraalsed sensorid nagu ALI, Landsat ja MODIS ei ole võimelised teiste fütoplanktoni liikide hulgast tsüanobaktereid eristama, kuna spektrikanalite laius ja hulk ei võimalda fükotsüaniini neeldumise avastamist või muude vaid tsüanobakteritele omaste tunnuste tuvastamist vee heleduskoefitsiendi spektritest. MERIS-e spektrikanalid 6 ja 7 on võimelised fükotsüaniini neeldumist tuvastama 630 nm juures ning vaid tsüanobakteritele omase väikse heleduskoefitsiendi tõusu tuvastamiseks 650 nm juures. Seega on MERIS tsüanobakterite tuvastamiseks potentsiaalselt kasutatav instrument kui tsüanobaktereid esineb vees piisavas koguses.

Töö autor tänab siinkohal oma magistritöö juhendajat PhD Tiit Kutserit sisuliste nõuannete ja suure abi eest. Tänan ka Niklas Strömbecki, kes teostas fütoplanktoni liikide optiliste parameetrite laboratoorsed mõõtmised.

ACKNOWLEDGEMENTS

The author of this thesis thanks PhD Tiit Kutser for his valuable comments on the manuscript. Niklas Strömbeck are acknowledged for providing the laboratory measurements of optical properties of algae.

The laboratory analysis on inherent optical properties of different algae species were supported by Swedish National Space Board grant 131/03. Author scholarship was funded from the Estonian Science Foundation grant 6051 and the study in general was funded from research grant 0712699s05 from Estonian Ministry of Education and Research.

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APPENDEX 1

Recognising cyanobacterial blooms based on their optical signature

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Abstract

Mass populations of cyanobacteria are increasingly attracting the attention of environment agencies, water authorities, and human and animal health organizations, since they can present a range of amenity, water quality ant treatment problems, and hazards to human and animal health. The problem is especially actual in the Baltic Sea where the cyanobacterial blooms occur every summer covering areas of more than 100 000 km^2. We studied optical properties of several algae species (including cyanobacteria) present in the Baltic Sea region. The measurements results were used in a bio-optical model together with optical properties of other algal species available in literature. Our results show that remote sensing instruments with sufficient spectral resolution (10 nm or better) and high radiometric sensitivity can be used for recognition and quantitative mapping of cyanobacteria as absorption by phycocyanin is causing absorption feature in reflectance spectra that is typical to cyanobacteria only. Some algal species (Prymesiophyceae) may contain chlorophylls c_1 and c_2 that cause similar absorption feature in reflectance spectra. However, cyanobacteria and Prymesiophyceae usually do not occur in similar aquatic environments. Therefore, separating of cyanobacterial blooms from waters dominated by other algae should not be a problem provided the amount of cyanobacteria is high enough. Our estimation for the open Baltic Sea waters shows that concentration of chlorophyll has to be 8-10 mg/m^3 before the phycocyanin absorption feature becomes detectable in reflectance spectra.

Therefore, it is highly unlikely that remote sensing can be used for early warning of emerging potentially harmful blooms as chlorophyll concentrations higher than 4 mg/m^3 are already considered as bloom. We also estimated accuracy of chlorophyll estimates for the open Baltic Sea waters in case of variable concentration of cyanobacteria.

1. Introduction

Cyanobacteria are common inhabitants of pristine aquatic and terrestrial environments on a global scale and natural populations of these organisms can occur away from human influence. These organisms also respond to cultural eutrophication by the development of massive populations, including blooms, scums and mats (Fogg *et al*., 1973; Sutcliffe & Jones, 1992). Such mass populations are increasingly attracting the attention of environment agencies, water authorities, and human and animal health organizations, since cyanobacteria can present a range of amenity, water quality ant treatment problems, and hazards to human and animal health (NRA, 1990; Ferguson *et al*., 1996).

There are various health issues associated with more than 60 identified toxins of cyanobacteria which are regarded as neurotoxins, hepatotoxins, cytototoxins, skin irritants and gastrointestinal toxins. Toxins enter the food chain as the phytoplanktons are filtered from the water as food by shellfish such as clams, mussels, oysters, or scallops, which gradually accumulate the algal toxins eventually reaching levels that, are potentially lethal to humans or other consumers (Codd, 1998). That and the incidence of dying blooms washing upon beaches during the peak of the summer holiday season has resulted in economic loss and considerable public interest in this phenomenon (Subramaniam *et al*., 2000).

It has been shown (Rantajärvi *et al*., 1998) that spatial and temporal frequencies of conventional water-sampling programs are not adequate to report changes in phytoplankton biomass, especially during bloom conditions, when spatial and temporal variability in phytoplankton density is particularly high. The use of unattended flow-through systems on ship-of-opportunity (Leppänen *et al*., 1995; Rantajärvi *et al*., 1998) and airborne (Dekker *et al*., 1992; Jupp *et al*., 1994) and satellite remote sensing (Kahru *et al*., 1993, 2000; Kahru 1997; Kutser, 2004) have

been recommended to provide more reliable information about the extent of the cyanobacterial blooms than the conventional monitoring programs can provide.

The autonomous flow-through systems on ship-of –opportunity only map chlorophyll content along their routs. Moreover, they take water from a fixed depth. It is assumed that the top water layer is well mixed and that the concentration of chlorophyll is constant in the upper mixed layer. This assumption is true in the case of "normal conditions," when algae that cannot control their vertical movement dominate the waters. Cyanobacteria, however, can regulate their buoyancy and in calm weather tend to keep themselves close to the water surface, quite often forming very dense accumulations just below the water surface and surface scum's (Pearl and Ustach, 1982; Sellner, 1997).

Accumulation of aggregations of cyanobacterial cells just below the water surface and surface scums are so distinct that the extent of the blooms can be mapped using almost any remote sensing instrument. For example broadband sensors like AVHRR (Kahru et al., 1993; Håkanson and Moberg, 1994), multispectral sensors such as CZCS (Siegel et al., 1999) and SeaWiFS (Joint and Groom, 2000; Siegel and Gerth, 2000), and synthetic aperture radars (Svejkovsky and Shandley, 2001) have been used to map the extent of cyanobacterial blooms. Quantitative mapping of cyanobacteria with above mentioned instruments is practically impossible with radars and hardly achievable with above mentioned sensors due to pure spectral and spatial resolution of the instruments. However, Kutser (2004) has shown that quantitative mapping of cyanobacteria is possible with hyperspectral sensors that have adequate spatial resolution.

The concentration of chlorophyll *a* (C_{Chl}) as a general indicator for plankton biomass can be assessed in clear oceanic waters using imagery from a wide range of air- and space born sensors (Vos *et al*., 2003). However, the standard chlorophyll retrieval algorithm fail in coastal and inland waters. For example, SeaWiFS and MODIS standard algorithms overestimate C_{Chl} in the Baltic Sea by 200% during non-bloom condition (Darecki and Stramski, 2004). On the other hand it has been shown (Kutser, 2004) that the C_{Chl} may be underestimated by up to two orders of magnitude even by in situ methods when extensive cyanobacterial blooms occur.

Recent advances in space born remote sensing technology broaden the perspectives of monitoring toward the identification and quantification of plankton

groups. Algorithms for the retrieval of Chl *a* from turbid water reflectance were already being developed (Gons *et al*., 2002; Kutser, 2004). Now, the retrieval of the pigments phycocyanin and phycoerythrin, which are characteristic of the presence of cyanobacterial, are being attempted. It is known that the presence of CPC can be detected from spectral reflectance (Dekker *et al*., 1991; Gons *et al*., 1992; Jupp *et al*., 1994). However, empirical relationships that have been devised to quantify cyanobacterial phycocyanin from the spectral reflectance of turbid water (Dekker, 1993; Schalles & Yacobi 2000; Simis et al., 2005) required more spectral information than provided by satellite remote with global coverage. Hyperion and MERIS have sufficient spectral resolution to enable mapping of phycocyanin from space. The problem is that phycocyanin and phycoerythrin are not routinely measured from water samples, and there is no information available about phycocyanin and phycoerythrin concentrations in the Baltic Sea cyanobacteria. Moreover, Simis et al. (2005) have found that the specific absorption coefficient of phycocyanin is rather variable.

Aim of the present paper is to study optical properties of algae present in the Baltic Sea and surrounding lakes and to estimate using model simulations weather or not cyanobacteria are separable from other algae species based on their reflectance spectra. Kutser (2004) showed that it is possible to estimate chlorophyll concentration during cyanobacterial blooms provided hyperspectral remote sensing imagery with adequate spatial resolution is available. However, Kutser (2004) used rather crude classification where chlorophyll concentrations used were 1, 2, 4, 8, 16, 32, 64, 128, 256, 512 and 1024 mg/m3. In the present study we attempt to estimate what could be the minimum concentration of chlorophyll when cyanobacterial dominance in the water becomes identifiable by remote sensing instruments and what could be the accuracy of chlorophyll estimation in case of cyanobacterial blooms.

2. Methods

2.1 Laboratory measurements of optical properties of algae

2.1.1 Phytoplankton cultures

Six different phytoplankton species were grown in batch cultures at low light (c:a 25 µE) in a 16/8 hour light/dark cycle at 25 °C; the cyanobacteria *Aphanizomenon flos-aquae var. "baltica", Anabaena circinalis and Nodularia spumigena*, the diatom *Cyclotella cryptica* and the chlorophyte *Scenedesmus obliqus*. The species were chosen both to match the dominating and bloom-forming groups of the three largest Swedish lakes and the Baltic Sea (table. 1).

About two weeks before the IOP-measurements, new batch cultures of the different phytoplankton was set up and their optical density was measured semi-daily in order to monitor their growth rate. When the growth rates were determined, a third set of new batches was set for the IOP-measurements. Finally, when all IOP-measurements were made, the chlorophyll *a* + phaeophytine *a* concentration of all batches was measured spectrophotometrically after extraction in ethanol (ISO 10 260). By backward interpolation using the measured growth rates, chlorophyll concentrations for each IOP-measurement could be estimated and subsequently chlorophyll-specific IOP:s.

2.1.2Absorption of phytoplankton

The optical density $OD(\lambda)$ was measured over the range 350-750 nm, using a Perkin-Elmer Lambda 900 spectrophotometer equipped with a Spectralon integrating sphere (150 mm in diameter) at Dep. of Solid State Physics, Uppsala University, Sweden. A 1-cm quartz cell was placed right in front of the entrance of the integrating sphere, and the optical density, $OD_{tot}(\lambda)$ of the phytoplankton batch cultures was measured. Then the batch cultures were filtered through 0.22 µm Millipore membrane filters, and the optical density of their filtrates $OD_{CDOM}(\lambda)$ was measured. For all measurements, 0.22 µm Millipore membrane filtered, UV-treated Milli-Q water, was used as reference.

To obtain the spectral absorption coefficients for the different phytoplankton species, $a_{ph}(\lambda)$ the following calculations were made:

$$a_{tot}(\lambda) = 2.303\ OD_{tot}(\lambda) / 0.01\ \text{m} \quad (1)$$

$$a_{CDOM}(\lambda) = 2.303\ OD_{CDOM}(\lambda) / 0.01\ \text{m} \quad (2)$$

$$a_{ph}(\lambda) = a_{tot}(\lambda) - a_{CDOM}(\lambda) \quad (3)$$

For avoiding multiple scattering and thus an overestimation of the absorption coefficient, the optical thickness, τ, should be kept below 0.3 (Bricaud et al., 1988).

$$\tau = c\, l \quad (4)$$

where c is the beam attenuation (se below) and l is the pathlength of the measurement cell (here 0.01 m). Three of the six samples in this study had τ lower than 0.3 and all samples were below 0.6. Thus, multiple scattering could not totally be neglected. However, at the most, 20 % of the incident photons undergo multiple scattering (Bricaud, et al., 1983), and then in the forward direction, and therefore no correction was applied to the measurements.

The average acceptance half angle of the spectrophotometer with this setup was 48.2 °, resulting in that at least 90 % of the scattered light was detected (Davies-Colley, al., 1986), and possibly up to 99.5 % (Bricaud et al., 1983). Therefore, no scattering correction of the measurements was made.

2.1.3 Scattering and backscattering of phytoplankton

The beam attenuation was measured using the same equipment as above, but this time the 1-cm quarts cell was placed 25 cm away from the entrance of the sphere. Additionally, the entrance of the sphere was decreased to about 2 times 2 mm. In this way the acceptance half angle became about 0.11 °. Measurements and calculations were then made analogously of those above, resulting in spectral beam attenuation coefficients for the different phytoplankton batch cultures, $c_{ph}(\lambda)$. No correction for scattering errors was made, as the low half angle should only allow an error of less than 3 % (Ahn et al., 1992).

The spectral phytoplankton scattering coefficient was simply calculated as the difference between the beam attenuation and absorption coefficients of phytoplankton:

$$b_{ph}(\lambda) = c_{ph}(\lambda) - a_{ph}(\lambda). \quad (5)$$

2.1.4 Backscattering of Phytoplankton

Backscattering was measured using the six-channel HydroScat-6 (HS-6) backscattering sensor (Maffione and Dana 1997) from HOBI Labs. The HS-6 was originally designed as a field instrument, and supposed to be used in open water. However, it is also possible to use the instrument in the laboratory (Vaillancourt, 2004) or field (Lindfors, 2005) inside a tank, if proper precautions are taken. In this experiment a tank of approximately 30 l especially developed for the HS-6, was filled up with pure water (UV-treated Milli-Q water). The inner walls of the tanks are black, and the bottom is convex in order to minimize any bottom effects. A small submergible pump is placed inside the tank, ensuring total mixing of the water. While the tank was filled with pure water, background backscattering possibly related to tank effects and particles in the water passing the purification system was measured. Then at subsequent regular intervals (e.g. 2 min), a small amount of phytoplankton batch culture (10-100 ml depending on culture) of known chlorophyll concentration was added to the tank. The backscattered signal was measured as soon as the signal became stable. After proper care had been taken in correcting the backscattered signals using the total absorption and scattering coefficients (HOBILabs 2000), spectra of the backscattering coefficient were obtained. However, by keeping chlorophyll concentrations relatively low in the tank during the measurements, the effects of the corrections were small, generally in the order of a few percent. By subtraction of background backscattering from the recorded backscattering after each addition of phytoplankton and then division by chlorophyll concentration, chlorophyll-specific phytoplankton backscattering could finally be calculated. Reported values were based on averages of three-five spectra.

2.2 Bio-optical modelling

Reflectance spectra of the optically deep water were calculated using a semi-empirical model described in detail by Kutser (2004). The model is based on the results of Monte Carlo studies by Gordon et al. (1975) and Kirk (1984) and is expressed with equation

$$R_{\infty}(0-,\lambda) = (-0.629\mu_0 + 0.975)\frac{b_b(\lambda)}{a(\lambda)+b_b(\lambda)}, \qquad (6)$$

where $a(\lambda)$ is the total absorption coefficient, $b_b(\lambda)$is the total backscattering coefficient, and λ is wavelength. The μ_0 was taken equal to 0.85 according to solar zenith angle in mid-summer at the latitude of the central Baltic Sea.

We assumed that there are three optically active components in the water: phytoplankton, coloured dissolved organic matter (CDOM), and suspended matter. Under these conditions the total spectral absorption coefficient, $a(\lambda)$, is described by:

$$a(\lambda) = a_w(\lambda) + a^*_{Ph}(\lambda)C_{Chl} + a_{CDOM}(\lambda) + a^*_{SM}(\lambda)C_{SM}, \quad (7)$$

where a_w is the absorption coefficient of pure water, $a^*_{Ph}(\lambda)$ is the chlorophyll-specific spectral absorption coefficient of phytoplankton, $a_{CDOM}(\lambda)$ is the spectral absorption coefficient of CDOM, and $a^*_{SM}(\lambda)$ is the specific absorption coefficient of suspended matter. C_{Chl} and C_{SM} are concentrations of chlorophyll-*a* and total suspended matter.

The total spectral backscattering coefficient $b_b(\lambda)$ can be described:

$$b_b(\lambda) = 0.5b_w(\lambda) + b^*_{b,Ph}(\lambda)C_{Chl} + b^*_{b,SM}(\lambda)C_{SM}, \quad (8)$$

where b_w is the scattering coefficient of pure water and it is assumed that the backscattering probability is 50% in pure water. $b^*_{b,Ph}$ is chlorophyll-specific backscattering coefficient of phytoplankton and $b^*_{b,SM}$ is suspended sediment specific spectral backscattering coefficient of suspended matter.

In our model the values of absorption and scattering coefficients of pure water were taken from Smith and Baker (1981). The absorption by CDOM is expressed as a function of the absorption coefficient of filtered water sample at wavelength 400 nm, $a_{CDOM}(400)$, and slope factor, *S*, by following formula:

$$a_{CDOM}(\lambda) = a_{CDOM}(400)\exp[-S(\lambda - 400)]. \quad (9)$$

According to estimations by Mäekivi and Arst (1996) S=0.017 gives the best result in case of the Baltic Sea, Estonian and Finnish lakes. Specific absorption coefficient of suspended matter was taken from Kutser (1997), and specific scattering coefficients of suspended matter, as well as backscattering probabilities (backscattering to scattering ratio), were taken from study by Kutser et al. (2001).

The modelling was carried out for two distinctly different water types: 1) CDOM-rich waters near river an estuary, 2) open Baltic Sea waters. For the first water type the concentration of suspended matter was taken 6 mg/l and $a_{CDOM}(400)$=15 m^{-1}. For the open Baltic Sea waters we took C_{SM}=2 mg/l and $a_{CDOM}(400)$=1.5 m^{-1}. The suspended matter and CDOM values are based on our measurements. Model

simulations were varied out with large variety of chlorophyll concentrations from 1 mg/m^3 to 300 mg/m^3. However, the increment used for different concentration ranges varied. Increment of 1 mg/m^3 was used for chlorophyll range 1-10 mg/m^3, increment 2 mg/m^3 was used for range 10-20 mg/m^3 , increment 5 mg/m^3 for range 20-50 mg/m^3, increment 10 mg/m^3 for chlorophyll range 50-300 mg/m^3.

The modelling was carried out with specific absorption and backscattering (or scattering) coefficients of 14 algae species. Optical properties of nine species (including three species of cyanobacteria) were taken from paper by Ahn et al. (1992). Optical properties of five cultured species (including three species of cyanobacteria) were investigated as described in Chapter 2.1.

3. Results and discussions

Summer blooms nitrogen-fixing cyanobacteria: *Aphanizomenon flos-aquae*, *Nodularia spumigena* and *Anabaena ssp*., are regular phenomena in the Baltic Sea (Öström, 1976; Niemistö *et al*., 1989). These bloom-forming species are toxic or potentially toxic (Sivonen *et al*., 1989). We studied optical properties of three cyanobacteria species *Aphanizomenon flos-aquae*, *Nodularia spumigena* and *Anabaena circinalis*. Chlorophyll-specific absorption coefficient spectra of these species are shown in the Fig. 1, together with specific absorption spectra of *Cyclotella cryptica* (Diatomophyceae) and *Scenedesmus obliqus* (Chlorophyceae). We compared our results with specific absorption coefficient spectra of nine different algae species (including three species of cyanobacteria) taken from paper by Ahn et al. (1992). The absorption spectra of these nine algae species are shown in Fig. 2. One can see that values of the specific absorption coefficient spectra of cyanobacteria measured by us are in the same range than values of non-cyanobacterial species measured by Ahn et al. (1992), whereas values of the specific absorption coefficient of cyanobacteria measured by Ahn et al. (1992) are often higher than those of other species. Phycocyanin absorption feature (max near 630 nm) is clearly seen in specific absorption coefficient spectra of all cyanobacteria suggesting that it may also be detectable in reflectance spectra measured by remote sensing instruments.

Figure 3 shows the chlorophyll-specific backscattering coefficient of phytoplankton species studied by us.

In our work and results of Ahn et al. (1992) the specific absorption and backscattering coefficients are measured in the case on pure algae cultures. But a cyanobacterial species response to changing environmental conditions and that can cause also variability of phycocyanin absorption values. It has been shown before that chlorophyll a absorption coefficient varies with cell morphology and photo adaptive responses (Sathyendranath et al., 1987; Staehr et al., 2002). Phycocyanin is an accessory pigment that can efficiently increase the light harvesting capacity in the "green gap" of chl a (Britton, 1983). The cellular pigment concentration of phycocyanin can be expected to fluctuate more than chlorophyll a dose for changing nutrient and light environments (Tandeau de Marsac, 1977). It has been proposed that phycobilioproteins (including phycocyanin) might be broken down during nitrogen shortage, to recycle amino acids (Bogorad 1975). Such mechanisms imply high variability in cellular phycocyanin content and specific absorption coefficient of phycocyanin (Simis et al., 2005).

We carried of bio-optical model simulations for two different waters types - CDOM-rich coastal and open Baltic Sea waters to study weather or not are cyanobacteria separable from other algae by remote sensing and what have to be the minimum concentrations of cyanobacteria allowing this. Just above the water surface reflectance R(0+) spectra were calculated for chlorophyll *a* concentrations from 1 mg/m^3 to 300 mg/m^3, with different increments described in chapter 2.2., using measured absorption− and backscattering coefficients from all algae species studied by us and presented in the paper by Ahn et al. (1992).

Figures 4 and 5 illustrate the difference in optical properties of the two different water types. Concentration of chlorophyll *a* is 30 mg/m^3 in both cases to amplify the between-species difference in reflectance spectra. There is some between-species difference in reflectance spectra in type 1 (CDOM-rich) water (Fig. 4). However, the shape of the spectra is very similar. All the reflectance spectra contain minima between 590-650 nm. It is probably caused by combined effect of absorption by CDOM and phytoplankton pigments and backscattering by the phytoplankton cells rather than by phycocyanin absorption as some of the species do not contain

phycocyanin. The phycocyanin absorption feature is clearly seen in reflectance spectra cyanobacteria in type 2 waters (Fig. 5).

Our modelling results showed that reflectance spectra of cyanobacteria are different from those of other algae species, especially in case of higher chlorophyll concentrations. However, an exception among all studied algae was *Isochrysis galbana* (Prymnesiophyceae). Reflectance spectrum of this species is similar to those of cyanobacteria i.e. there is absorption feature near 630 nm. This is caused by chlorophylls c_1 and c_2, which are the major pigments (> 10%) of the total chlorophylls in the algal class prymnesiophyceae. Chlrophylls c_1 and c_2 have absorption peaks near 628 and 630 nm correspondingly (Jeffrey and Vesk, 1996). Most prymesiophyceae are planktonic marine unicells, either flagellate or with flagellate stages in the life history. Prymesiophyceae are found mostly in tropical and subtropical oceans with few abundant in polar waters. *E. huxley* and *H. elogata* belong also to prymesiophyceae. However, there was no significant absorption feature near 630 nm in modelled reflectance spectra of these species. We may assume that Prymesiophyceae do not present a challenge in recognising cyanobacteria based on their optical signatures as those alga groups occur in different aquatic environments.

Our modelling results indicate that the type 2 waters the phycocyanin absorption feature becomes noticeable in the reflectance spectra when chlorophyll concentration is 8-10 mg/m^3. In general, chlorophyll concentrations of 4 mg/m^3 and higher are considered as bloom condition. This result indicates that it will most probably not be possible to recognise cyanobacterial blooms in very early stages as the reflectance spectra of waters dominated by cyanobacteria are similar to waters dominated by other algae species. It must be noted that the phycocyanin to chlorophyll absorption ratio was fixed in case of all our cyanobacteria as the absorption spectra were measured for one particular culture. The phycocyanin absorption feature may be seen at slightly different chlorophyll values if the phycocyanin to chlorophyll ratio is different.

The signal to noise ratio (SNR) specifications currently attainable by airborne remote sensing systems such as AVIRIS and CASI, flown under ideal circumstances, are about 1000:1 (Dekker et al., 2001). Thus, the difference between two reflectance spectra has to be at least 0.1% to be detectable by such remote sensing sensors.

We calculated differences between reflectance spectra of *Aphanisomenon flos-aquae* in the water type 2 (open Baltic waters) to estimate what are the minimum concentration differences that can be recognised by above mentioned remote sensing instruments.

For chlorophyll concentrations around 20 mg/m^3 the difference has to be at least 4 mg/m^3 before the reflectance spectra are separable from each other. The biggest difference occurs between 700 and 720 nm. The same wavelength range is most useful for recognising changes in chlorophyll concentrations also in more dense blooms. For example if chlorophyll concentrations are around 100 mg/m^3 then 10 mg/m^3 differences in chlorophyll are recognisable in the same wavelength range by the instruments which SNR = 1000:1. The same is situation when chlorophyll values increase to 200 mg/m^3. The smallest concentration change when noticeable differences occur in reflectance spectra may be also interpreted as the accuracy in chlorophyll estimation we may achieve with remote sensing instruments. Thus for below 10 mg/m^3 values the estimation accuracy is 3 mg/m^3, for chlorophyll values around 20 mg/m^3 it is 4 mg/m^3 and for chlorophyll concentrations from 100-200 mg/m^3 it is 10 mg/m^3. Thus, the relative error in mapping water chlorophyll content is higher (33%) in case of low concentrations of phytoplankton and drops to 5% in case of higher concentrations.

3. Conclusions

Remote sensing instruments with sufficient spectral resolution (10 nm or better) and high radiometric sensitivity can be used for recognition and quantitative mapping of cyanobacteria as absorption by phycocyanin is causing absorption feature in reflectance spectra that is typical to cyanobacteria only. Some algal species (Prymesiophyceae) may contain chlorophylls c_1 and c_2 that cause similar absorption feature in reflectance spectra. However, cyanobacteria and Prymesiophyceae usually do not occur in similar aquatic environments. Therefore, separating of cyanobacterial blooms from waters dominated by other algae should not be a problem provided the amount of cyanobacteria is high enough.

Our estimation for the open Baltic Sea waters shows that concentration of chlorophyll has to be 8-10 mg/m^3 before the phycocyanin absorption feature becomes detectable in reflectance spectra. Therefore, it is highly unlikely that remote

sensing can be used for early warning of emerging potentially harmful blooms as chlorophyll concentrations higher than 4 mg/m^3 are already considered as bloom.

Accuracy of remote sensing estimates of the chlorophyll concentration is variable. It is around 3 mg/m^3 for chlorophyll concentrations below 10 mg/m^3, rises to 4 mg/m^3 for chlorophyll range between and 10 mg/m^3 and 20 mg/m^3 and increases to 10 mg/m^3 when chlorophyll values are around 100-200 mg/m^3. Thus, we may say that relative error in mapping of chlorophyll concentration in such CDOM-dominated waters like the Baltic Sea is high in case of smaller chlorophyll concentrations and is decreasing towards higher concentrations.

4. Acknowledgements

The laboratory analysis on inherent optical properties of different algae species were supported by Swedish National Space Board grant 131/03. Liisa Metsamaa's scholarship was funded from the Estonian Science Foundation grant 6051 and the study in general was funded from research grant 0712699s05 from Estonian Ministry of Education and Research.

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APPENDEX 1 Recognising cyanobacterial blooms based on their optical signature. *Harmful Algae* (submitted)

Table 1. Characteristics of the different phytoplankton species. CCAP is short for CCAP Culture Collection of Algae and Protozoa, SAMS Research Services Ltd, Dunstaffnage Marine Laboratory, Scotland, SU is short for Stockholm University, Department of Botany, Sweden and UU is the abbreviation of Uppsala University, Limnology/Department of Ecology and Evolution, Evolutionary Biology Centre, Sweden.

Phytoplankton	Representative for	Origin	Provider	Medium
Cyclotella cryptica	Lakes Vättern & Mälaren	River Ouse, England	CCAP	DM
Aphanizomenon flos-aquae	Lakes Mälaren & Vättern	Queen Elizabeth Reservoir, England	CCAP	JM
Aphanizomenon flos-aquae	Baltic Sea	Rivermouth in Baltic Sea, Finland	SU, Sara Jonasson	JM
Anabaena circinalis	-	Lough Henney, N. Ireland	CCAP	JM
Nodularia spumigena	Baltic Sea	Baltic Sea	SU, Sara Jonasson	Z8XSalt
Scenedesmus obliqus	-	-	UU, Gunnel Ahlgren	Z8

APPENDIX 1 Recognising cyanobacterial blooms based on their optical signature. *Harmful Algae* (submitted)

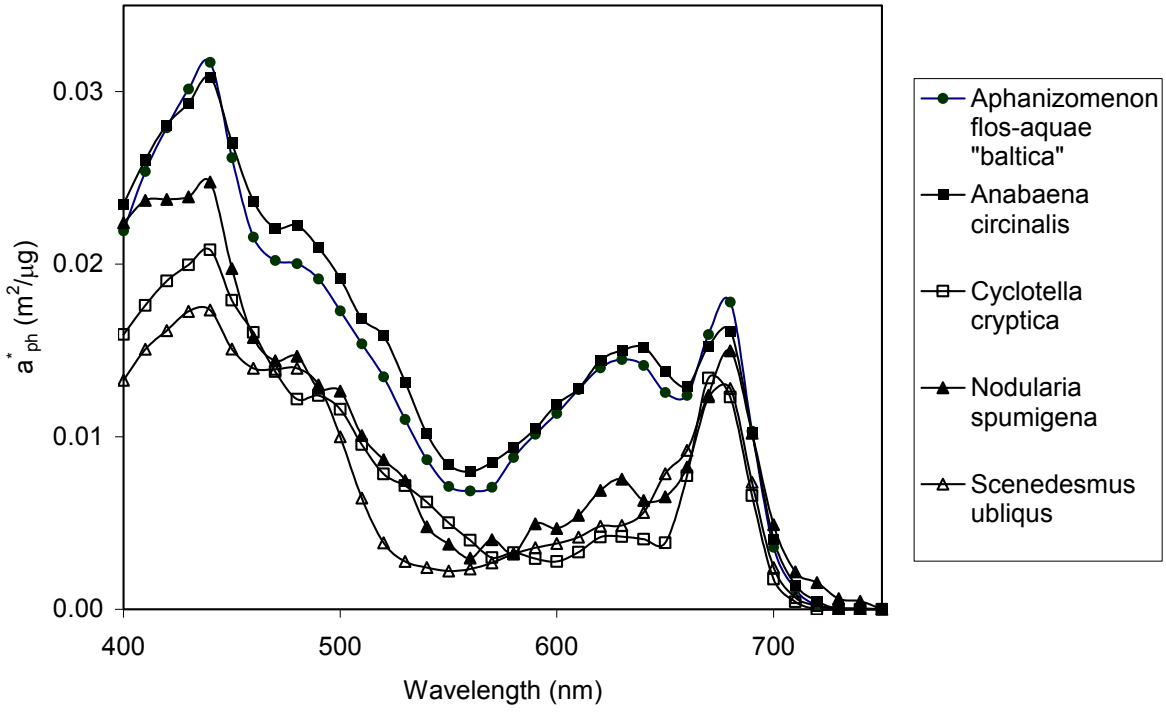

Fig 1.

APPENDEX 1 Recognising cyanobacterial blooms based on their optical signature. *Harmful Algae* (submitted)

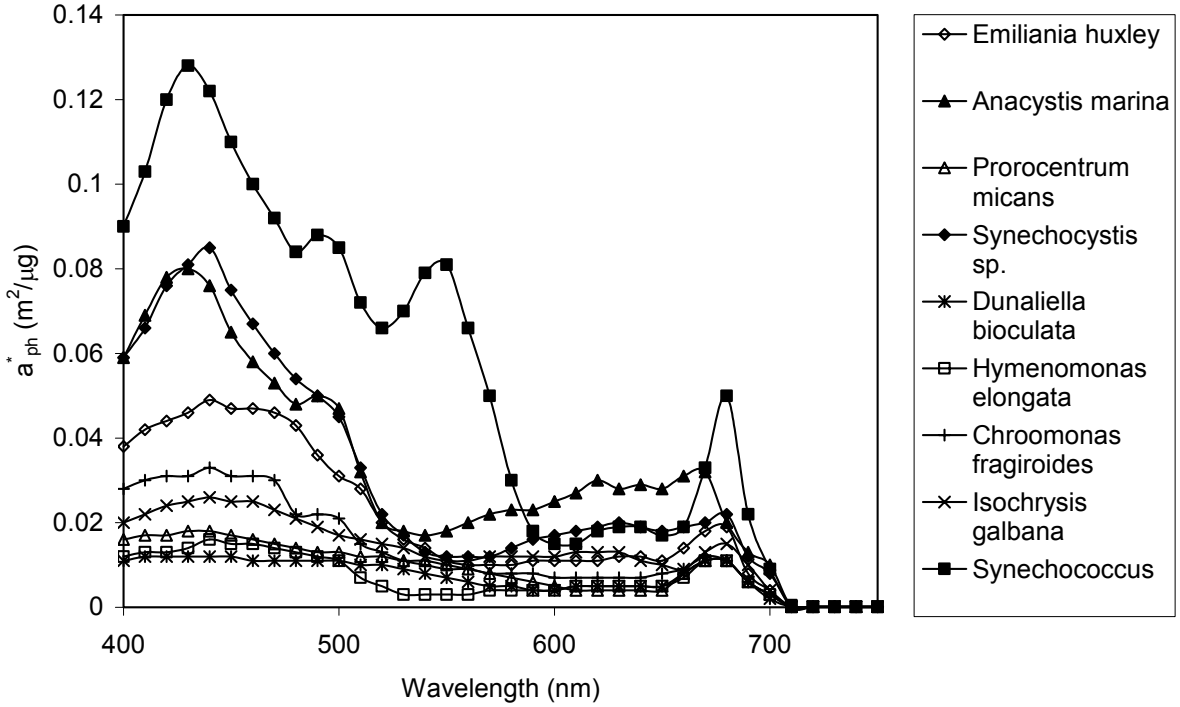

Fig. 2

APPENDEX 1 Recognising cyanobacterial blooms based on their optical signature. *Harmful Algae* (submitted)

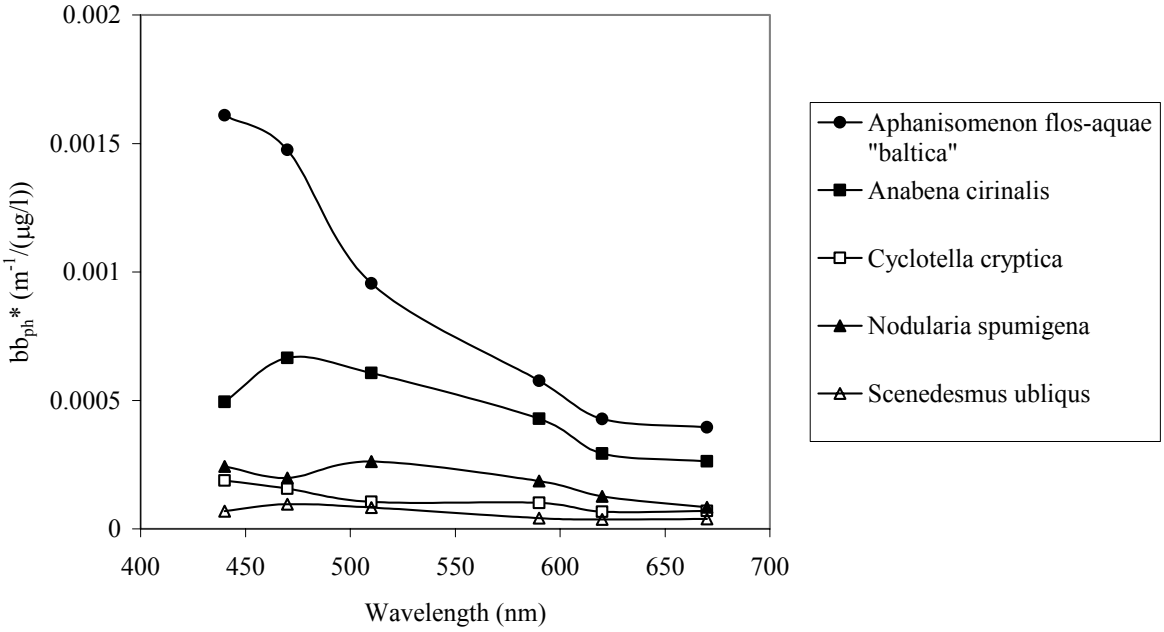

Fig. 3

APPENDIX 1 Recognising cyanobacterial blooms based on their optical signature. *Harmful Algae* (submitted)

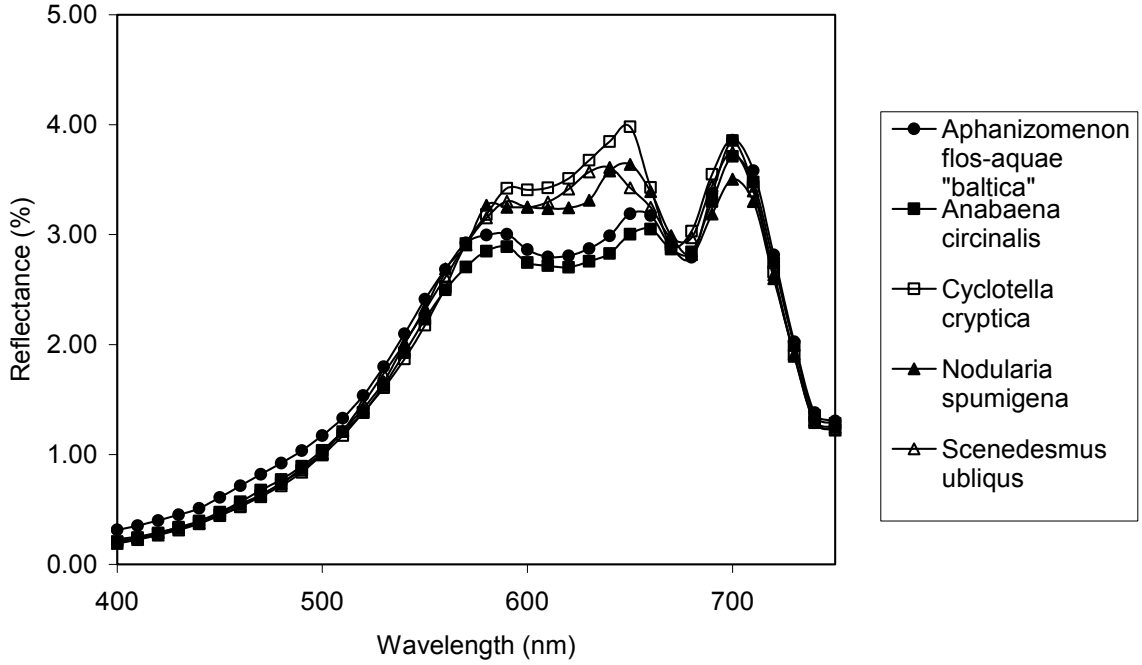

Fig. 4

APPENDEX 1 Recognising cyanobacterial blooms based on their optical signature. *Harmful Algae* (submitted)

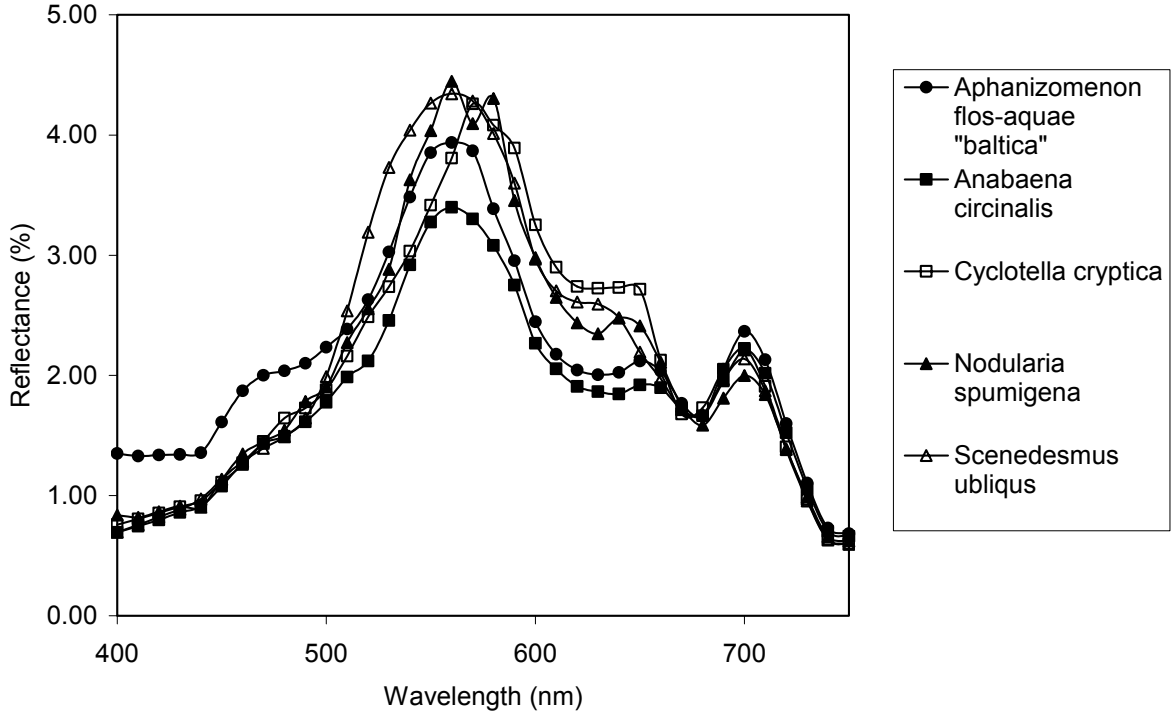

Fig. 5

APPENDIX 2

Monitoring cyanobacterial blooms by satellite remote sensing

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Abstract

Cyanobacterial blooms are increasingly attracting the attention of environment agencies, water authorities, and human and animal health organizations, since they can present a range of amenity, water quality ant treatment problems, and hazards to human and animal health. The problem is especially actual in the Baltic Sea where the cyanobacterial blooms occur every summer covering areas of more than 100 000 km^2. It has been shown that quantitative mapping of cyanobacteria during bloom conditions is possible with hyperspectral instruments. However, those sensors cannot provide spatial coverage and high revisit times needed for near real time monitoring of potentially harmful blooms. Our aim was to estimate is spectral resolution of multispectral sensors, which can provide needed coverage, adequate for quantitative mapping of cyanobacteria and is it possible to separate potentially harmful blooms from blooms of other algae using ocean colour satellites. Our modelling results show that multispectral sensors like ALI, Landsat or MODIS are not capable of separating waters dominated by cyanobacteria from waters dominated by other algae species as their spectral band configuration does not allow detecting absorption features caused by phycocyanin (present only in cyanobacteria) or any other spectral features that are characteristic to cyanobacteria only. MERIS bands 6 and 7 allow detecting phycocyanin absorption feature near 630 nm and a small peak in reflectance spectra near 650 nm characteristic to only cyanobacteria. Thus, MERIS can be used in detecting cyanobacteria if they are present in relatively high quantities. Unfortunately it is not possible to use MERIS for early warning of

emerging potentially harmful blooms as the minimum concentration of chlorophyll needed to cause features in reflectance spectra typical to cyanobacteria only occur at much higher concentrations than the level of chlorophyll already considered as bloom.

1. Introduction

Cyanobacteria are potentially one of the most interesting organisms in ecological and phycological studies. Not only do they belong to the oldest organisms on the planet (Golubic & Lee, 1999; Lotter, 2001), but they also are extremely important primary producers (Waterbury *et al.*, 1979; Ting *et al.*, 2002). Moreover, many of them are potentially toxic and thus are often nuisance organisms as candidates for aquatic algal blooms (Carmichael, 2001; Codd *et al.*, 1999). There are various health issues associated with more than 60 identified toxins of cyanobacteria which are regarded as neurotoxins, hepatotoxins, cytototoxins, skin irritants and gastrointestinal toxins. Toxins enter the food chain as the phytoplankton is filtered from the water as food by shellfish such as clams, mussels, oysters, or scallops, which gradually accumulate the algal toxins eventually reaching levels that, are potentially lethal to humans or other consumers (Codd, 1998). That, and the incidence of dying blooms washing upon beaches during the peak of the summer holiday season, has resulted in economic loss and considerable public interest in this phenomenon (Subramaniam *et al.*, 2000). The problem is especially actual in the Baltic Sea region where the cyanobacterial blooms occur every summer covering areas of more than 100 000 km^2 (Kahru, 1997).

Cyanobacterial blooms are extremely patchy. Therefore they often remain unobserved by current monitoring programs. It has been shown (Rantajärvi *et al.*, 1998) that spatial and temporal frequencies of conventional water-sampling programs are not adequate to report changes in phytoplankton biomass, especially during bloom conditions, when spatial and temporal variability in phytoplankton density is particularly high. The use of unattended flow-through systems on ship-of-opportunity (Leppänen *et al.*, 1995; Rantajärvi *et al.*, 1998), airborne (Dekker *et al.*, 1992; Jupp *et al.*, 1994) as well as satellite remote sensing (Kahru *et al.*, 1993, 2000; Kahru 1997; Kutser 2004) have been recommended to provide more reliable

information about the extent of the cyanobacterial blooms than the conventional monitoring programs can provide. However, Kutser (2004) has shown that it is not possible to collect water samples that give adequate chlorophyll concentrations from flow-through systems as the ships destroy natural spatial distribution of the bloom. In such systems water is taken for sampling from one fixed depth. Unlike other algae cyanobacteria are capable of regulating their buoyancy and in calm weather are tend to form subsurface accumulations and surface scum instead of being uniformly mixed in the water column (Pearl and Ustach, 1982; Sellner, 1997). It means that the flow through systems often collect water from depth where there is just a very small amount of cyanobacteria compared to their concentration near the water surface. The same problem occurs while sampling from research vessels if special precaution has not been taken to collect aggregations of cyanobacteria from layer just below the water surface or mats of cyanobacteria floating on the surface. Remote sensing estimates of chlorophyll are also incorrect as they are validated against the in situ results which are not representing the real situation in the bloom. Therefore, Kutser (2004) recommended using of bio-optical modeling instead of water sampling for quantitative mapping of cyanobacteria by remote sensing in bloom conditions. However, the sensor used for demonstration of this method was Hyperion. Hyperion is the first civilian hyperspectral sensor in space and provides much more detailed spectral information (10 nm resolution) than other satellites. Spatial resolution of Hyperion (30 m) is also much better than that of ocean colour sensors like MODIS, MERIS or SeaWiFS. On the other hand spatial and temporal coverage of Hyperion does not allow using it in regular monitoring of potentially harmful cyanobacterial blooms. Ocean colour sensors with wide spatial coverage and daily revisit times have to be used in near real time monitoring.

Aim of our study is to estimate is spectral resolution of multispectral sensors adequate for quantitative mapping of cyanobacteria, is it possible to separate potentially harmful blooms from blooms of other algae using ocean colour satellites, and to estimate sensitivity of the sensors i.e. what are the minimum concentration changes those satellites can detect. A bio-optical model (Kutser, 2004) was used to simulate just above the water surface reflectance spectra for two different water types and different concentrations of chlorophyll. The spectra were resampled to

spectral resolution of different satellite sensors to be able to answer the above mentioned questions.

2. Methods

2.1 Bio-optical modelling

Reflectance spectra of the optically deep water were calculated using a semi-empirical model described in detail by Kutser (2004). The model is based on the results of Monte Carlo studies by Gordon et al. (1975) and Kirk (1984) and is expressed with equation

$$R\ (0-,\lambda) = (-0.629\mu_0 + 0.975)\frac{b_b(\lambda)}{a(\lambda) + b_b(\lambda)}, \qquad (1)$$

where $R(0-,\lambda)$ is irradiance reflectance just below the water surface, $a(\lambda)$ is the total absorption coefficient, $b_b(\lambda)$is the total backscattering coefficient, and λ is wavelength. The cosine of the incident photons just below the surface, μ_0, was taken equal to 0.85 according to solar zenith angle in mid-summer at the latitude of the central Baltic Sea.

We assumed that there are three optically active components in the water: phytoplankton, coloured dissolved organic matter (CDOM), and suspended matter. Under these conditions the total spectral absorption coefficient, $a(\lambda)$, is described by:

$$a(\lambda) = a_w(\lambda) + a^*_{Ph}(\lambda)C_{Chl} + a_{CDOM}(\lambda) + a^*_{SM}(\lambda)C_{SM}, \qquad (2)$$

where a_w is the absorption coefficient of pure water, $a^*_{Ph}(\lambda)$ is the chlorophyll-specific spectral absorption coefficient of phytoplankton, $a_{CDOM}(\lambda)$ is the spectral absorption coefficient of CDOM, and $a^*_{SM}(\lambda)$ is the specific absorption coefficient of suspended matter. C_{Chl} and C_{SM} are concentrations of chlorophyll-*a* and total suspended matter.

The total spectral backscattering coefficient $b_b(\lambda)$ can be described with equation:

$$b_b(\lambda) = 0.5b_w(\lambda) + b^*_{b,Ph}(\lambda)C_{Chl} + b^*_{b,SM}(\lambda)C_{SM}, \qquad (3)$$

where b_w is the scattering coefficient of pure water and it is assumed that the backscattering probability is 50% in pure water. $b^*_{b,Ph}$ is chlorophyll-specific backscattering coefficient of phytoplankton and $b^*_{b,SM}$ is suspended sediment specific spectral backscattering coefficient of suspended matter.

In our model the values of absorption and scattering coefficients of pure water were taken from Smith and Baker (1981). The absorption by CDOM is expressed as a function of the absorption coefficient of filtered water sample at wavelength 400 nm, $a_{CDOM}(400)$, and slope factor, S, by following formula:

$$a_{CDOM}(\lambda) = a_{CDOM}(400)\exp[-S(\lambda - 400)]. \quad (4)$$

According to estimations by Mäekivi and Arst (1996) S=0.017 gives the best result in case of the Baltic Sea, Estonian and Finnish lakes. Specific absorption coefficient of suspended matter was taken from Kutser (1997), and specific scattering coefficients of suspended matter, as well as backscattering probabilities (backscattering to scattering ratio), were taken from study by Kutser et al. (2001).

The modelling was carried out for two distinctly different water types: 1) CDOM-rich waters near a river estuary, 2) open Baltic Sea waters. For the first water type the concentration of suspended matter was taken 6 mg/l and $a_{CDOM}(400)$=15 m^{-1}. For the open Baltic Sea waters we took C_{SM}=2 mg/l and $a_{CDOM}(400)$=1.5 m^{-1}. The suspended matter and CDOM values are based on our measurements in Estonian coastal waters. Model simulations were carried out with large variety of chlorophyll concentrations from 1 mg/m^3 to 300 mg/m^3. However, the increment used for different concentration ranges varied. Increment of 1 mg/m^3 was used for chlorophyll range 1-10 mg/m^3, increment 2 mg/m^3 was used for range 10-20 mg/m^3 , increment 5 for range 20-50 mg/m^3, increment 10 mg/m^3 for chlorophyll range 50-300 mg/m^3.

The modelling was carried out with specific absorption and backscattering (or scattering) coefficients of 13 algae species. Optical properties of eight species (including three species of cyanobacteria) were taken prom paper by Ahn et al. (1992). Optical properties of five cultured species (including three species of cyanobacteria) were taken from (Metsamaa et al., 2005).

2.2 Technical characteristics of satellite sensors under investigation

Landsat series satellites have been used for mapping of cyanobacterial blooms (Galat and Verdin, 1989; Vincent et al., 2004). 16 days revisit time of Landsat does not allow to use this sensor for operative monitoring of cyanobacterial blooms. However, in certain circumstances it may be useful to use sensors with good spatial

resolution for studying of cyanobacterial blooms. ALI is a prototype of the next-generation Landsat sensor with improved spectral and radiometric resolution and substantial mass, volume and cost savings. ALI spectral bands in the visible part of the spectrum are practically identical to other multispectral sensors like Landsat ETM and IKONOS. ALI has ten bands: a panchromatic (480-690 nm) band with 10 m spatial resolution and nine spectral bands (see http://eo1.usgs.gov/instru/ali.asp) with 30 m spatial resolution. Spectral range of the first three ALI bands used in this study are: 450-515 nm, 525-605 nm, and 630-690 nm. ALI signal-to-noise-ratio is 250 and the radiometric resolution is 16 bit. The ALI footprint is 37x185 km.

MODIS has 13 visible and near-infrared bands that could potentially be used in aquatic remote sensing. Bands 1 and 2 are with 250 m spatial resolution, bands 3 and 4 are with 500 m resolution and bands 8-16 are with 1000 m spatial resolution. Spectral ranges of used MODIS bands are shown in Table 1. Full spatial resolution of MERIS sensor is 300 m. Spectral bands of MERIS instrument are shown in Table 1.

3. Results and discussions

Dekker (1993) has shown that it is possible to estimate concentration of phycocyanin in the water using remote sensing methods. Phycocyanin is a pigment that is present only in cyanobacteria and can be used as an indicator of cyanobacteria. However, phycocyanin is not routinely measured from water samples. Moreover, Simis et al. (2005) have shown that the specific absorption coefficient of phycocyanin is variable. Chlorophyll concentration is routinely measured in many monitoring programs and is used as a proxy of the amount of phytoplankton. Therefore we used concentration of chlorophyll as a variable in our model in attempt to estimate is it possible to separate cyanobacteria from other algal species based on remote sensing reflectance.

In our previous study (Metsamaa et al., 2005) we showed that cyanobacteria can be separated from other algae based on their reflectance spectra provided hyperspectral instruments with at least 10 nm spectral resolution and high (1000:1) signal to noise ratio (SNR) are available. If the concentration of cyanobacteria is sufficiently high (chlorophyll concentration at least 8-10 mg/m^3) then phycocyanin absorption feature in reflectance spectra near 630 nm can be used to recognise domination of cyanobacteria in the water. On the other hand Vincent et al. (2004)

have shown that even multispectral sensors like Landsat can be used for mapping phycocyanin in lake waters. Therefore we used technical characteristics of ALI (spectral bands identical to Landsat, SNR 2.5 times better) and simulated how the reflectance spectra will look like in case of different algae species. Modelled reflectance spectra of ALI are shown in Fig.1. There is small difference between reflectance spectra of cyanobacteria and other algae in CDOM-rich coastal waters as is seen in Fig. 1A. The band 2 and band 3 ratio is slightly different for those two algae groups. In more clear waters there is practically no difference in shape of reflectance spectra of cyanobacteria and other algae. The between species variability is mainly in reflectance values rather than in shape and the differences are amplified by relatively high concentration of chlorophyll (30 mg/m^3) used in modelling the reflectance spectra shown in Fig. 1.

It is not possible to detect presence of phycocyanin using multispectral sensors like ALI or Landsat. Half of the phycocyanin absorption feature is outside band 2 (630-690nm). Our modelling results show that increase in amount of cyanobacteria in the water causes bigger increase in reflectance values near 650 nm than decrease in reflectance near 630 nm. Those two effects compensate each other in wavelength range of band 2. Thus, the effect of increased amount of cyanobacteria (and consequently the concentration of phycocyanin) has often almost negligible effect in band two. The results of Vincent et al. (2004) can be explained with correlation of concentration of phycocyanin with some other water characteristic (e.g. transparency) which is in correlation with Landsat data. The similar effects may occur also in other cases. For example Kutser et al. (1995) have shown that it is possible to estimate concentration of total phosphorus in lake water using remote sensing despite phosphorus does not have any effects on reflectance spectra. The total phosphorus is often just in correlation with water turbidity which has effect on reflectance.

Fig. 2 shows that between species differences in reflectance spectra are also mainly in reflectance values not in shape of the reflectance when MODIS bands are used. Variable illumination or atmospheric conditions or variations in the amount of suspended matter may cause similar variability in MODIS data. Band configuration of MODIS is more suitable for Case I waters as there are five band in spectral region 400-550 nm where most of variability in reflectance spectra occurs in that case. In Case II waters the maxima in reflectance spectra is shifting towards longer

wavelengths with increasing turbidity. Thus, the reflectancer maxima often occurs in wavelength range 550-670 nm where MODIS does not have any spectral bands. Important wavelengths for potential detecting of cyanobacteria are near 630 nm where the phycocyanin absorption feature occurs and near 650 nm where there is a peak in reflectance spectra of cyanobacteria (probably due to high backscattering). MODIS does not provide any information from this spectral region. Therefore we may conclude that it is highly unlikely that MODIS can be used to identify potentially harmful cyanobacterial blooms.

Fig. 3 shows that MERIS band configuration is more appropriate for turbid coastal waters. It is seen both in case of CDOM-rich coastal waters (Fig. 3A) and open Baltic Sea waters (Fig. 3B) that MERIS bands 6 and 7 can be used to separate between cyanobacteria and other algae if the concentration of chlorophyll is high (30 mg/m3 in case of Fig. 3). The best wavelength configuration for that purpose should be with central wavelengths at 630 nm and 650 nm, but the MERIS bands 6 and 7 (see wavelengths in Table 1) are quite close to the ideal. Other MERIS bands useful for detecting phytoplankton are bands 8 at wavelengths where chlorophyll a absorption feature occurs in water reflectance spectra and band 9 at wavelengths where there is often peak in reflectance spectra of waters which contain high amount of phytoplankton.

Fig. 4 illustrates how the increasing amount of chlorophyll a influences the reflectance detected by MERIS in case of two algae species *Cyclotella cryptica* (Fig. 4A) and a cyanobacterium *Nodularia spumigena* (Fig. 4B). The phycocyanin absorption feature is not so clearly seen in reflectance spectra of *Nodularia spumigena* as it is in case of other cyanobacteria (see Fig. 3). However, behaviour of band 6 and band 7 ratio is different even in case *Nodularia* as is seen in Fig. 4. It is also seen that reflectance spectra of these two species are fairly similar in case of lower chlorophyll concentrations. In the Baltic Sea chlorophyll values above 4 mg/m^3 are considered as bloom condition. Reflectance spectra of waters with different dominant algal species are fairly similar for chlorophyll concentrations below the "bloom limit". Therefore, it is highly unlikely that MERIS can be used to detect emerging potentially harmful blooms of cyanobacteria in very early stages of the bloom.

Accumulation of aggregations of cyanobacterial cells just below the water surface and surface scum are so distinct that the extent of the blooms can be mapped using

almost any remote sensing instrument. For example broadband sensors like AVHRR (Kahru et al., 1993; Håkanson and Moberg, 1994), multispectral sensors such as CZCS (Siegel et al., 1999) and SeaWiFS (Joint and Groom, 2000; Siegel and Gerth, 2000), and synthetic aperture radars (Svejkovsky and Shandley, 2001) have been used to map the extent of cyanobacterial blooms. Radar beam cannot penetrate the water surface. AVHRR has only one broad spectral band that covers the whole visible part of spectrum. This kind of instruments cannot be used to differentiate between increased water leaving signal caused by suspended matter or algal bloom. Mapping of cyanobacterial bloom has been based on assumption that any other reason cannot cause increased signal from offshore regions of the Baltic Sea in the middle of summer than bloom of cyanobacteria. We have shown that multispectral sensors like ALI, Landsat or MODIS cannot be used to differentiate between waters dominated by cyanobacteria and water dominated by other algae. Our results indicate that MERIS is capable of recognising cyanobacterial blooms. However, detecting of emerging blooms is not possible whereas the phycocyanin absorption feature becomes detectable by MERIS when chlorophyll a values have reached values around 10-30 mg/m^3 (depending on species) which are much higher that the level of chlorophyll which is considered as bloom condition in the Baltic Sea (4 mg/m^3).

It is possible to use also ALI, Landsat or MODIS for quantitative monitoring of cyanobacteria during bloom conditions despite they cannot recognise cyanobacteria. These sensors can detect changes in reflectance values caused by variable amount of cyanobacteria in the water if we assume that elevated water leaving radiance can be explained solely by presence of cyanobacteria. Certain amount of in situ data is needed to find the relationship between satellite signal and the amount of cyanobacteria. However, the results have to be taken with certain precaution. First of all the in situ chlorophyll values used for developing the remote sensing algorithms and validating satellite maps do not represent the situation satellites are detecting unless special methods have been used to collect the cyanobacteria from subsurface layer or surface scum. This kind of sampling is possible only from small boats and all routinely collected chlorophyll data has to be neglected while calibrating satellite images collected during cyanobacterial blooms. It must also be noted that the chlorophyll retrieval algorithms obtained for the multispectral sensors with just a few bands are image specific and not automatically applicable in different locations or on

other images of the same site. The reason is that intensity of the signal in those one to two bands that can give information about the water properties may vary due to other reasons like changes in illumination or optical water properties.

The other problem is related with spatial resolution of MERIS or MODIS. Kutser (2004) has shown that chlorophyll concentration may vary by two orders of magnitude within one MERIS pixel. Thus, specially designed in situ experiments are needed to collect chlorophyll data that can be used for validating cyanobacterial bloom images as the within pixel variability of phytoplankton has to be studied. This kind of in situ data is not available at present.

More detailed information about optical properties and concentrations of chlorophyll in surface scum and dense subsurface layers of cyanobacteria are needed to improve performance of the bio-optical model and consequently the accuracy of chlorophyll retrieval from remote sensing data. This is the aim of our future research.

4. Conclusions

Our modelling results show that multispectral sensors like ALI, Landsat or MODIS are not capable of separating waters dominated by cyanobacteria from waters dominated by other algae species as their spectral band configuration does not allow detecting absorption features caused by phycocyanin (present only in cyanobacteria) or any other spectral features that are characteristic to cyanobacteria only. MERIS bands 6 and 7 allow detecting phycocyanin absorption feature near 630 nm and a small peak in reflectance spectra near 650 nm characteristic to only cyanobacteria. Thus, MERIS can be used in detecting cyanobacteria if they are present in relatively high quantities. Unfortunately it is not possible to use MERIS for early warning of emerging potentially harmful blooms as the minimum concentration of chlorophyll needed to cause features in reflectance spectra typical to cyanobacteria only occur at much higher concentrations than the level of chlorophyll already considered as bloom.

5. Acknowledgements

Liisa Metsamaa's scholarship was funded from the Estonian Science Foundation grant 6051 and the study in general was funded from research grant 0712699s05 from Estonian Ministry of Education and Research.

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Captions to figures

Fig. 1. Modelled reflectance spectra of different algae species in CDOM-rich coastal waters (A) and open Baltic Sea waters (B) resampled to spectral bands of multispectral sensors (ALI, Landsat, IKONOS). Chlorophyll concentration was 30 mg/m^3 in all simulations. Reflectance spectra of cyanobacteria are shown with solid line and reflectance spectra of other algae with dashed line.

Fig. 2. Modelled reflectance spectra of different algae species in CDOM-rich coastal waters (A) and open Baltic Sea waters (B) resampled to spectral bands of MODIS. Chlorophyll concentration was 30 mg/m^3 in all simulations. Reflectance spectra of cyanobacteria are shown with solid line and reflectance spectra of other algae with dashed line.

Fig. 3. Modelled reflectance spectra of different algae species in CDOM-rich coastal waters (A) and open Baltic Sea waters (B) resampled to spectral bands of MERIS. Chlorophyll concentration was 30 mg/m^3 in all simulations. Reflectance spectra of cyanobacteria are shown with solid line and reflectance spectra of other algae with dashed line.

Fig. 4. Modelled reflectance spectra of *Cyclotella cryptica* (A) and a cyanobacterium *Nodularia spumigena* (B) resampled for MERIS bands. Concentrations of chlorophyll (in mg/m3) are shown in the legend. Modelling was carried out using optical properties of the open Baltic Sea waters.

APPENDEX 2 Monitoring cyanobacterial blooms by satellite remote sensing. *Estuarine, Coastal and Shelf Science* submitted.

Table 1. Wavelength ranges of MODIS and MERIS bands that can be used for mapping cyanobacterial blooms

	MODIS	MERIS
Band	wavelengths, nm	wavelengths, nm
1	620-670	407.5-417.5
2	841-876	437.5-447.5
3	459-479	485-495
4	545-565	505-515
5		555-565
6		615-625
7		660-670
8	405-420	677.5-685
9	438-448	703.75-713.75
10	483-493	750-757.5
11	526-536	
12	546-556	771.25-786.25
13	662-672	855-875
14	673-683	880-890
15	743-753	895-905
16	862-877	

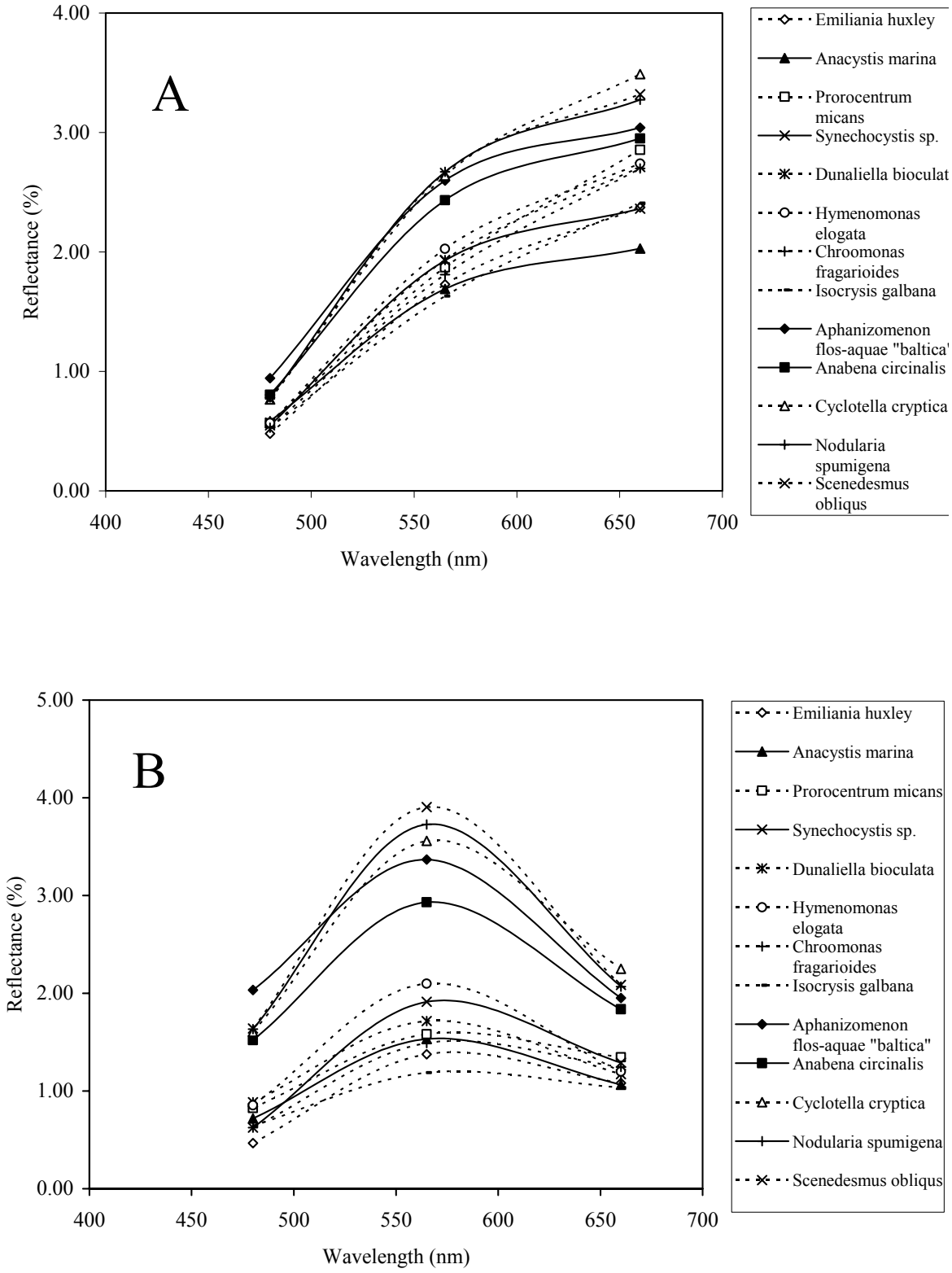
A
B
Reflectance (%)
Wavelength (nm)
4.00
3.00
2.00
1.00
0.00
5.00
400
450
500
550
600
650
700
Emiliania huxley
Anacystis marina
Prorocentrum micans
Synechocystis sp.
Dunaliella bioculat
Dunaliella bioculata
Hymenomonas elogata
Chroomonas fragarioides
Isocrysis galbana
Aphanizomenon flos-aquae "baltica"
Anabena circinalis
Cyclotella cryptica
Nodularia spumigena
Scenedesmus obliqus

Fig. 1

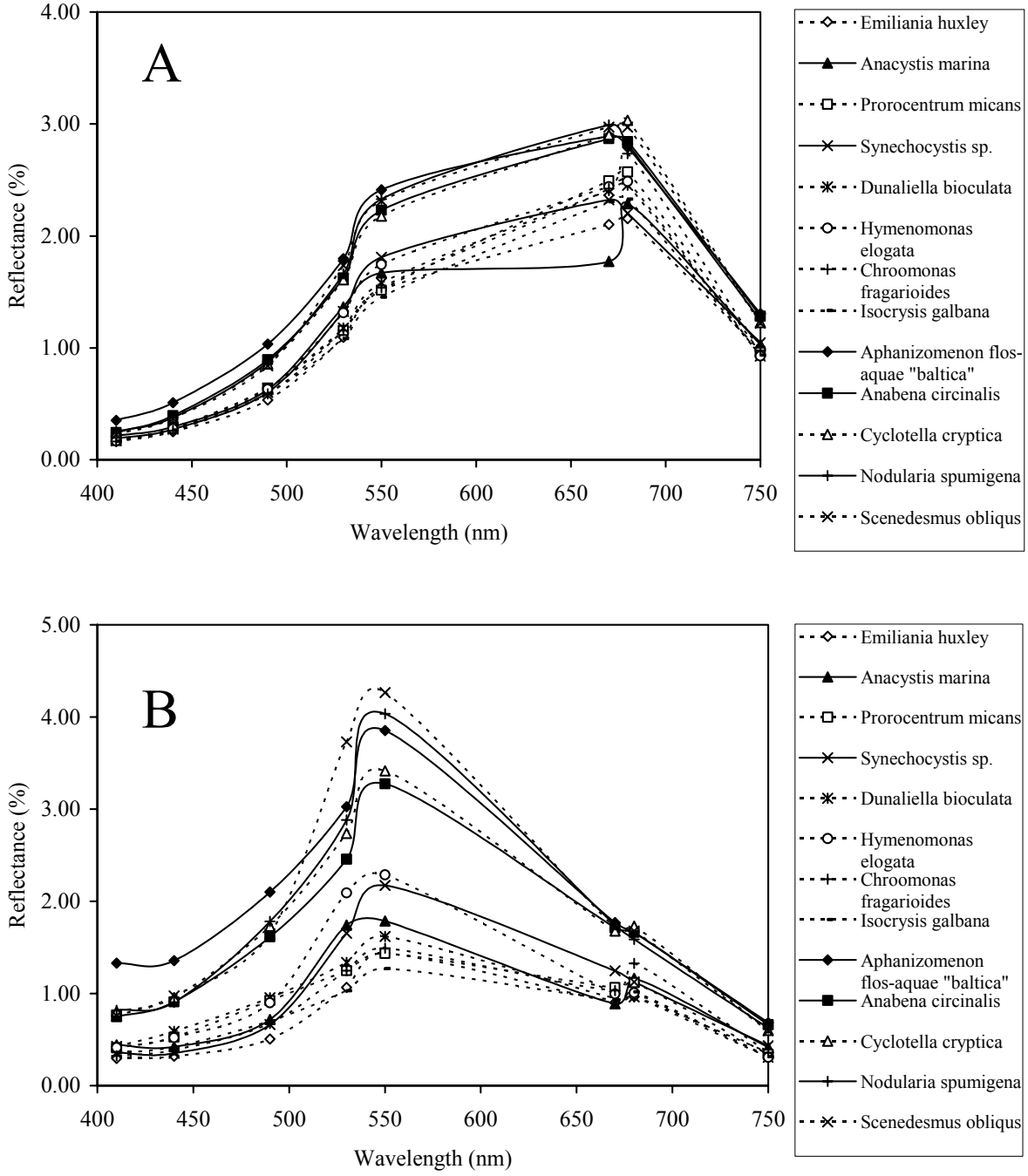
A
B
Reflectance (%)
Wavelength (nm)
Emiliania huxley
Anacystis marina
Prorocentrum micans
Synechocystis sp.
Dunaliella bioculata
Hymenomonas elogata
Chroomonas fragarioides
Isocrysis galbana
Aphanizomenon flos-aquae "baltica"
Anabena circinalis
Cyclotella cryptica
Nodularia spumigena
Scenedesmus obliqus

Fig. 2

APPENDIX 2 Monitoring cyanobacterial blooms by satellite remote sensing. *Estuarine, Coastal and Shelf Science* submitted.

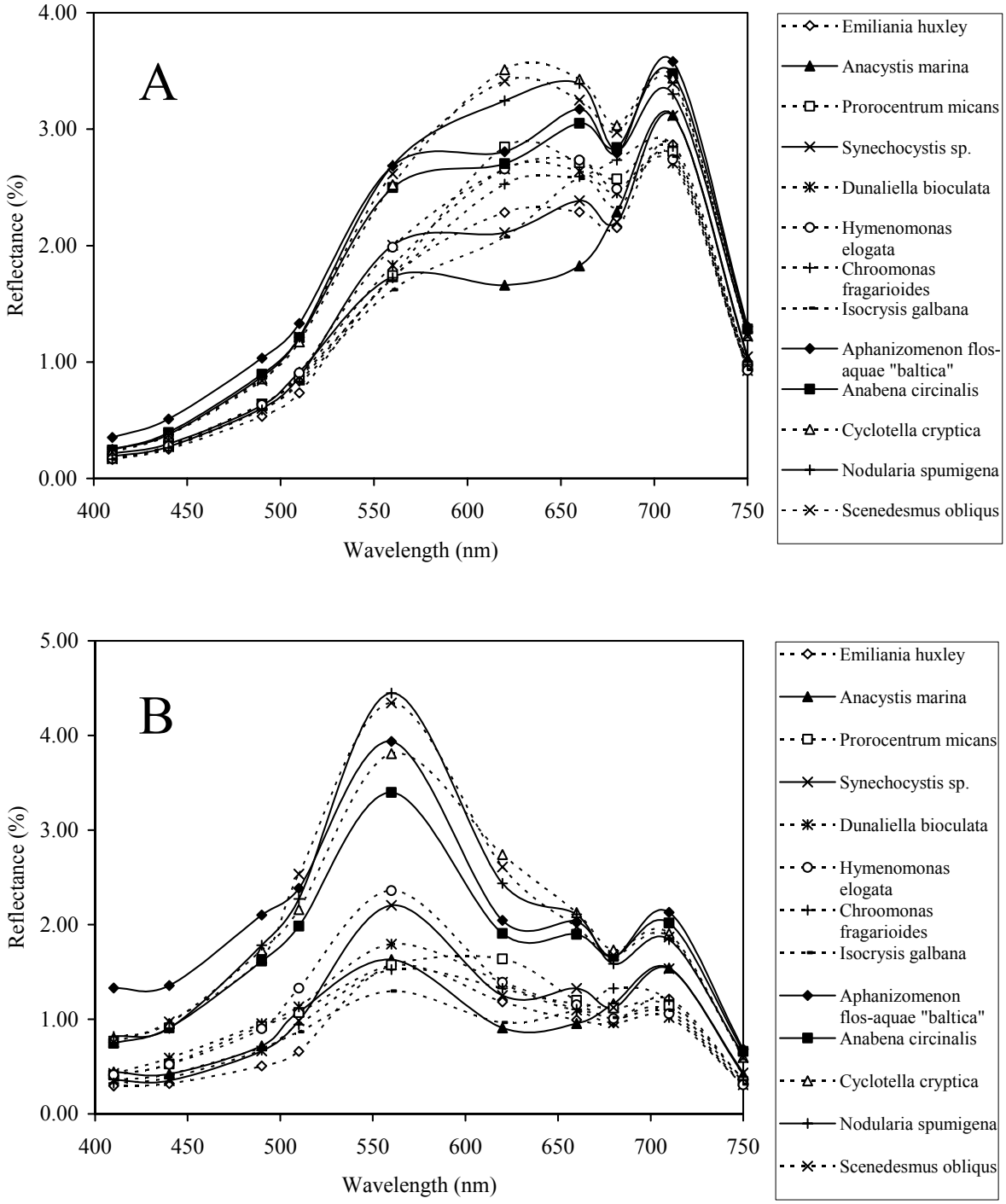

Fig.3

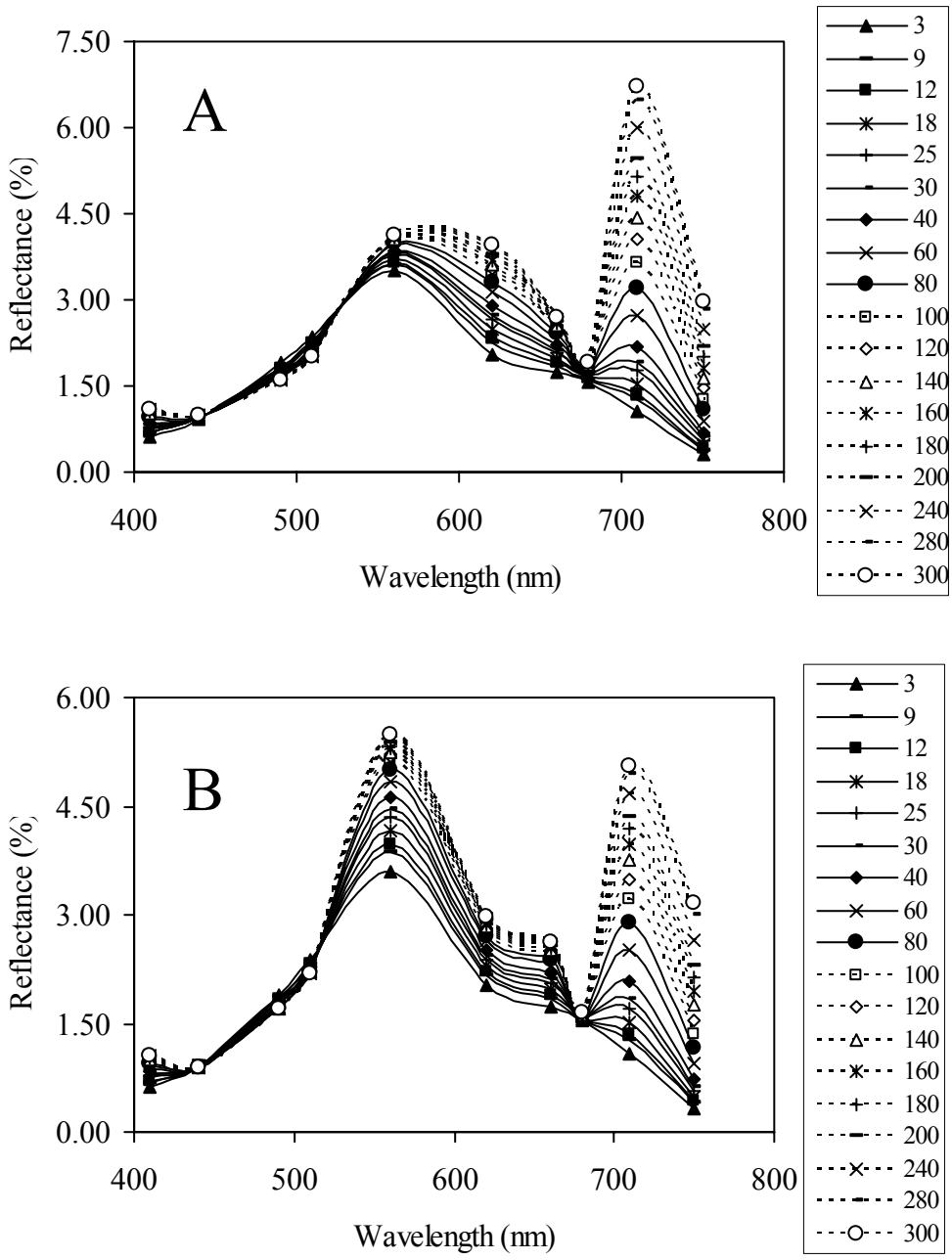
A
B
Reflectance (%)
Wavelength (nm)
7.50
6.00
4.50
3.00
1.50
0.00
400
500
600
700
800
3
9
12
18
25
30
40
60
80
100
120
140
160
180
200
240
280
300

Fig. 4