DISSERTATIONES BIOLOGICAE UNIVERSITATIS TARTUENSIS
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ELE VAHTMÄE

Mapping benthic habitat with remote sensing in optically complex coastal environments

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LIST OF ORIGINAL PUBLICATIONS

This Thesis is based on the following original papers that will be referred to by their Roman numerals in the text:

I Kutser, T., Vahtmäe, E., Metsamaa, L. (2006). Spectral library of macroalgae and benthic substrates in Estonian coastal waters. *Proceedings of Estonian Academy of Sciences. Biology-Ecology*, 55, 4, 329–340.

II Vahtmäe, E., Kutser, T., Martin, G., Kotta, J. (2006). Feasibility of hyperspectral remote sensing for mapping benthic macroalgal cover in turbid coastal waters – a Baltic Sea case study. *Remote Sensing of Environment,* 101, 342–351.

III Kutser, T., Vahtmäe, E., Martin, G. (2006). Assessing suitability of multispectral satellites for mapping benthic macroalgal cover in turbid coastal waters by means of model simulations. *Estuarine, Coastal and Shelf Science,* 67, 521–529.

IV Vahtmäe, E., Kutser, T. (2007). Mapping bottom type and water depth in shallow coastal waters with satellite and airborne remote sensing. *Journal of Coastal Research, SI50, 185–189.*

Author's contribution:

Publication I: Tiit Kutser was the principal author of this paper**.** Ele Vahtmäe took part in field work and participated in data collection. She also processed the data and participated in writing the paper. Liisa Metsamaa took part in field work.

Publication II: The bio-optical model used in this study was developed by Tiit Kutser. Ele Vahtmäe carried out the model simulations and data analysis. She was also the principal author of the manuscript. Georg Martin and Jonne Kotta contributed in the preparation of the manuscript with their expertise on macrovegetation.

Publication III: The idea of the study belongs to Tiit Kutser. He was also the principal author of the manuscript. Ele Vahtmäe made model simulations and analysis of the results and was also involved in the preparation of the manuscript. Georg Martin contributed in the preparation of the manuscript with his expertise on macrovegetation.

Publication IV: Ele Vahtmäe took part in field work in West-Estonian archipelago, conducted data analysis and image analysis. She was also the principal author of the manuscript. Tiit Kutser made some part of these analyses and he was also involved in the preparation of the manuscript.

Paper:	**I**	**II**	**III**	**IV**
Original idea:	TK, EV	TK	TK	EV, TK
Study design:	TK, EV	TK, EV	TK, EV	EV, TK
Data collection:	TK, EV, LM	TK, EV	TK, EV	EV, TK
Data analysis:	TK, EV	EV	EV	EV, TK
Manuscript preparation:	TK, EV	EV, TK, GM, JK	TK, EV, GM	EV, TK

EV – Ele Vahtmäe
TK – Tiit Kutser
LM – Liisa Metsamaa
GM – Georg Martin
JK – Jonne Kotta

1. INTRODUCTION

Coastal zone is the region with a high population density, urban development's, economic activities and tourist facilities, being therefore among the most exploited and developed regions in the world. It receives all land discharges, including freshwater, sewage and erosion products, and it is affected by a number of marine processes such as the wave action and tidal currents, as well as storm surges. At the same time the coastal region is valuable in terms of biodiversity and marine resources as many benthic communities and ecosystems in coastal waters possess commercial and ecological value.

Benthic vegetation is an important component of coastal zone ecosystem. It contributes to the primary production in coastal areas, supporting grazing, as well as detrital food webs. Submerged aquatic vegetation provides important habitats as feeding, spawning and nursery grounds for many fish and invertebrate species. It also helps to prevent coastal erosion by binding sediments and reduces nutrient loading and other forms of pollution.

The health and survival of these submerged plant communities in coastal waters depend on suitable environmental conditions. Submerged aquatic vegetation requires light for photosynthesis, and its growth, survival and depth penetration is directly related to light availability (Dennison, 1987). The minimal light requirement of a particular species of submersed aquatic vegetation determines the maximal water depth at which it can survive (Dennison et al. 1993). The eutrophication, or nutrient enrichment, of coastal waters as a result of human's activities is now widely recognized as a major, world-wide pollution threat (Schramm and Nienhuis, 1996) and is considered one of the greatest threats for submerged macrovegetation (Phillips et al., 1978). With increasing eutrophication specific changes in benthic vegetation communities have been observed: 1) decline or disappearance of certain perennial plant communities, often replaced by annual, fast growing forms (e.g. folious green algae or filamentous algae); 2) reduced diversity of the flora; 3) mass development (blooms) of short-lived annual forms; 4) changing depth distribution of benthic algae owing to the reduced light transmittance through the water column (Schramm and Nienhuis, 1996).

Europe's marine environment is deteriorating rapidly and existing measures to reverse the situation are clearly insufficient. Current study is concentrated on the Baltic Sea, which is considered one of the most polluted seas in the world. For example the amounts of nutrients in the Baltic Sea have increased several times during the last century, with severe ecological effect on the biota (Rönnberg and Bonsdorff, 2004; Berger et al., 2004; Schories et al., 2009).

Therefore, the EU Marine Strategy takes a new ecosystem-based approach and the ultimate objective of proposed Strategy is to achieve a good environmental state of the European marine environments by the year 2021. The concept of the HELCOM Baltic Sea Action Plan (BSAP) is regarded as a pilot project for European seas in the context of the proposed EU Marine

Strategy Directive. At the heart of the BSAP lies the importance of improving knowledge, assessment and monitoring of the marine environment. One of the quality components that is used to evaluate ecological status of the marine environment are aquatic macrophytes.

Because of the direct relationships between submerged aquatic vegetation and water quality, trends in changes of algal cover are indicators of water state in coastal areas; hence we can consider benthic vegetation as an indicator of ecosystem health. The objective of monitoring benthic algal cover in coastal areas is to observe short- and long-term changes in species distribution and structure of coastal benthic substrate constituents. Quantitative analysis of coastal marine benthic communities enables adequately estimate coastal marine environmental state, provide better evidence for environmental changes and describe processes that are conditioned by anthropogenic forces.

Knowledge on the distribution of marine habitats is very fragmented today. In order to enable a sustainable coastal zone management, we need to increase knowledge on the Baltic Sea marine habitats, communities and species, which demands large-scale habitat classification and mapping. Quantifying the areal coverage of benthic macroalgae at a point in time allows researchers to identify the current state of the benthic community. The next step is to establish monitoring programs, which enable identifying changes in species distribution and structure.

In recent years the need for accurate mapping and monitoring of marine vegetation has become increasingly obvious together with rising concern over the impact of human activities in coastal areas. Aquatic vegetation abundance and diversity are important indicators of the health of the water body, but accurate maps and data are difficult to acquire. Mapping benthic algal cover with conventional methods (diving) provides great accuracy and high resolution (Werdell & Roesler, 2003) yet is very expensive and is limited by the time and manpower necessary to monitor large bodies of water and long stretches of coastline. Furthermore, in some regions, inclement weather through a portion of the year may prohibit diver observation of seasonal changes (Wittlinger & Zimmerman, 2000). In contrast, remote sensing from aircraft and space-based platforms offers unique large-scale synoptic data to address the complex nature of coastal waters (Richardson and LeDrew, 2006). Typically, field surveys provide accurate and precise measurements at a limited number of key sites, while remote sensing data provide extensive spatial coverage of the study area but slightly lower accuracy (Phinn et al., 2005). Remote sensing based mapping has significant advantage over traditional techniques, as it is spatially comprehensive (Dekker et al., 2001). Mapping via remote sensing using aerial and satellite sensors has been shown to be more cost-effective than fieldwork (Mumby et al., 1999). At the same time remote sensing approach without extensive field survey is shown to be too inaccurate, therefore remote sensing has been recommended as a complementary technology, which makes field survey more cost-effective (Green et al., 2000).

Mapping of substrate cover types and their biophysical properties based on their reflectance properties has been carried out successfully in optically clear waters (Phinn et al., 2005). Majority of remote sensing studies carried out in clear oceanic waters have been concentrated in reflectance properties of general benthic habitat types (e.g. sand, seagrass, corals, hard substrates) in coral reef environments (Holden & LeDrew, 1999; Lubin et al., 2001; Holden & LeDrew, 2002; Hochberg & Atkinson, 2003; Kutser et al., 2003; Karpouzli et al., 2004; Mishra et al., 2007; Bertels et al., 2008). Many studies have successfully accomplished in mapping seagrass communities (Fyfe, 2003; Dekker et al., 2005; Gullström et al., 2005; Pasqualini et al., 2005; Fornes et al., 2006; Phinn et al., 2008). Although comparatively fewer studies have been carried out in order to map benthic algal communities, spectral signatures of various algal types are now relatively well known. Published reflectance spectra of benthic algae are presented for example in Maritorena et al. (1994), Wittlinger and Zimmerman (2000), Andrefouët et al. (2004a), Kutser et al. (2006).

Remote sensing observations can be carried out from many different satellite and airborne platforms, which cover a wide range of spatial and spectral resolutions. While dealing with relatively large-scale benthic habitat structures (10–30m), the sensors with medium spatial resolution (such as LANDSAT, SPOT) can be used (Andrefouët et al., 2001; Call et al., 2003; Schweizer et al., 2005; Gullström et al., 2005; Phinn et al., 2005; Dekker et al., 2005; Pasqualini et al., 2005). However, the 20–30 m pixel sizes are often of a similar or larger scale to the size of the habitat patches causing problems related to mixed pixels (Mumby et al., 1999). This relatively coarse spatial resolution incurs high probability that the reflective value of a pixel is the result of a mixture of reflectance signals from different bottom types (Luczkovich et al., 1993). Sensors with spatial resolution better than 10 m, such as those provided by IKONOS or QuickBird (0,6–4 m) should reduce this hindrance (Holden & LeDrew, 2002). Increasingly, researchers are using higher spatial resolution data to map sub-surface features (Mumby & Edwards, 2002; Andrefouët et al., 2003; Sawaya et al., 2003; Malthus and Karpouzli, 2003; Riegl and Purkis, 2005; Wolter et al., 2005).

Although high spatial resolution multispectral satellites offer considerable promise for monitoring spatial changes in marine habitats, they often lack the sensitivity to discriminate spectra because they have only few water-penetrating bands (Mumby & Edwards, 2002). For example Malthus & Karpouzli (2003) demonstarted the limitation of three visible and fairly broad bands alone to classify targets such as seagrass and algal species, which typically were shown to be relatively dark and with only subtle spectral differences. Hochberg & Atkinson (2003) conclude that as spectral resolution decreases among the various sensors, so does the spectral separation between coral and algae. In contrast to multispectral sensors, hyperspectral instruments provide much greater spectral detail, and thus improved ability to extract multiple layers of information from an optically complex environment (Goodman & Ustin, 2007).

The progression from multispectral to hyperspectral data provides the capability to distinguish between closely related bottom types (Mishra et al., 2007).

However, those satellite systems that provide more spectral information usually have poorer spatial resolution (Hochberg et al., 2003a). For example, QuickBird has high spatial resolution of 2,4 m, but low spectral resolution (three bands at water penetrating wavelengths). This sensor has the ability to spatially resolve different bottom types, but its wavebands are not optimised for bottom type spectral discrimination. On the other hand, Hyperion provides continuous spectral information in visible and near infrared part of spectrum with 10 nm resolution, but its spatial resolution is only 30 m, which precludes the use of this sensor for spatially heterogeneous environments. The delineation of coastal zone features is thus largely dictated by the characteristics and capabilities of specific sensors (Malthus & Mumby, 2003).

Airborne sensors usually have higher spatial and spectral resolution than satellite sensors, providing more spectral information on more pure targets, and thus greater accuracy in detailed benthic habitat mapping (Mumby et al., 1997). Hochberg and Atkinson (2003) confirmed that narrowband hyperspectral sensors (AAHIS and AVIRIS) provide better spectral separation than broadband multispectral sensors. Programmable, imaging spectrometers, like the Compact Airborne Spectrographic Imager (CASI), can provide very high-resolution measurements in both the spatial and spectral domain (George and Malthus, 2001). Although airborne remote sensing is quite expensive and its use will be limited in operational monitoring of large areas (Koponen et al., 2002), hyperspectral imagery (e.g., AVIRIS, AISA, CASI, HYMAP, PHILLS) is rapidly becoming more available and more cost effective (Goodman & Ustin, 2007).

Remote sensing studies have generally been conducted in ocean waters where the water is clear. For example the research for applications of satellite imagery to coral reef science and management has been almost exhaustive (Mumby et al., 1997). However, the full potential of remote sensing is still to be exploited, particularly in temperate, sublittoral environments, where under certain situations, the strong attenuating influence of the water column has been a limiting factor (Malthus and Karpouzli, 2003). There is a need to expand the application of coral reef remote sensing to other biogeographical regions that have different combinations of marine habitats to examine the wider application of the sensors currently available (Benfield et al., 2007). Baltic Sea represents a water body with high concentration of colored dissolved organic matter, and suspended particles as well as frequent phytoplankton blooms. This thesis is aiming at exploring the possibilities to map benthic habitat in such optically complex water bodies.

2. OBJECTIVES

The aim of this thesis was to study optical properties of key algal species and bottom types in the Baltic Sea and to determine how the spectral reflectance of different benthic habitats is translated into remote sensing reflectance in such optically complex water body. The specific objectives of the study were to:

- Collect a spectral library of bottom types present in Estonian coastal waters concentrating foremost on the optical properties of the species *Fucus vesiculosus, Cladophora glomerata* selected by HELCOM as indicator species for the Baltic Sea and *Furcellaria lumbricalis,* which is commercially harvested for galactants (Paper I).
- Study by means of model simulations whether or not are green-, brown- and red algae separable from each other, sandy bottom or deep water with hyperspectral remote sensing sensors and to estimate the maximum depths at which the various substrates still have a measurable influence on the remotely sensed reflectance in different coastal water types (Paper II)
- Evaluate by means of model simulation the capability of multispectral satellite sensors for mapping the Baltic Sea algal cover (Paper III)
- Study advantages and limitations of multispectral and hyperspectral satellite data in mapping water depth and bottom type in the Baltic Sea (Paper IV)

3. PASSIVE OPTICAL REMOTE SENSING

3.1. Light in shallow water

Aquatic remote sensing is limited to the visible wavelengths between 400 and 700 nm, since visible radiation is the only portion of the electromagnetic spectrum that penetrates the water column and can be reflected back to a sensor. Many authors have described the light journey through the atmosphere to the aquatic environment and characterized the processes happening with the light within the aquatic medium (Dekker et al., 2001; Kirk, 2003; Miller et al., 2005). Reviews of the status of submerged aquatic remote sensing can be found in Holden & LeDrew (1998), Green et al. (2000), Dekker et al. (2005).

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 & Kiefer, 1999). Remote sensing sensor in an airplane or satellite, pointed down at the water body can receive light consisting of four separate components (Fig.1): light reaching the sensor after scattering of photons by the atmosphere; light reaching the sensor after specular reflection of direct sunlight at the sea surface; light upwelling from the sea surface after backscattering in water; light reflected off the bottom of a water body (provided the water is sufficiently shallow and the water is sufficiently clear) (Sathyendranath, 2000).

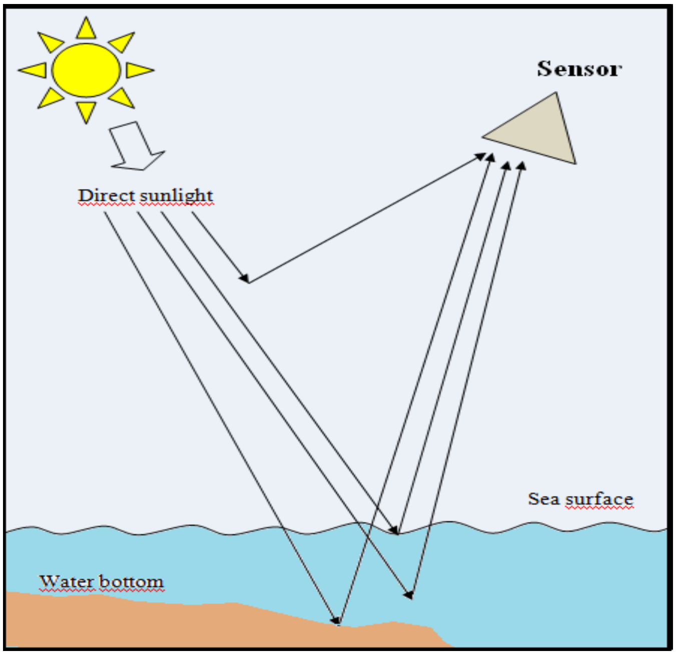

Figure1. Formation of the signal detectable by remote sensing instruments

Only last two of these four light fluxes contain information about the underwater light field, carrying thus useful information about the water body and the aquatic benthic habitat. The atmospheric contributions and specular reflection at the sea surface constitute noise in this context, and have to be corrected for (Sathyendranath, 2000). In case of oceanic remote sensing, the total signal received at the satellite altitude is dominated by radiance contributed by atmospheric scattering processes and only 0 to 20 percent of the signal corresponds to the oceanic reflectance (Kirk, 2003). The majority of waters reflect between 2 and 6% of downwelling irradiance (Dekker et al., 2001). Even small errors in estimating the atmospheric contribution can lead to significant errors in the estimation of the water component. Therefore, we have to be very precise estimating atmospheric contribution and techniques for atmospheric correction form a very important component of remote sensing of aquatic environment (Andrefouët et al., 2004a; Mishra et al., 2006; Bertels et al., 2008).

In addition to the atmospheric contribution, the presence of sun glint may impede the estimation of water leaving signal. When water surface is not flat, the direct radiance originating from the sun can be reflected on the crests or slopes of waves. The reflected radiance does not contain any information about the water constituents and benthic features. Sun glint effect is often a factor in wide-field-of-view acquisition airborne or satellite missions, despite acquisition time and solar/viewing geometry optimized to avoid glint (Hochberg et al., 2003b). Having the sensor flown towards or away from the sun may reduce contribution from glint, but it is not always possible due to the characteristics of a field site or scheduling (Mustard et al., 2001). Therefore, the ability to recognise and remove contributions from sun glint is required. Different sun glint removal methods have been proposed by Hochberg et al. (2003b), Hedley et al. (2005) and Kutser et al. (submitted).

When focusing on the water-leaving signal, we can see that it is influenced by several factors. The colour of water is determined by scattering and absorption of visible light by optically active substances present in the water. These optically active substances are pure water itself, phytoplankton, coloured dissolved organic matter (CDOM) and particulate matter. Furthermore, in shallow water, a significant part of the light from the sun may reach the bottom, and in that case the bottom also influences the water colour. The spectrum of light emanating from the sea surface in shallow waters contains information on the optical properties of the seawater constituents and the benthic substrate (Werdell & Roesler, 2003). For the bottom contribution to be retrieved by a sensor, the water column contributions have to be removed and the optical properties of the water column have to be known or at least be derivable (Mishra et al., 2006). One problem with remote sensing of shallow water substrates is the difficulty in separating the water column signal from the substrate signal (Holden & LeDrew, 1998), although the physics based analytical methods (Kutser et al., 2006, Lesser & Mobley, 2007) allow simultaneous mapping of water depth and bottom type.

In turbid coastal waters, spectral scattering and absorption by phytoplankton, suspended organic and inorganic matter and dissolved organic substances restrict the light passing to, and reflected from the benthos (Dekker et al., 2001). Mishra et al. (2007) showed that specific spectral features (e.g., pigment absorption) of different bottom types are generally overshadowed by significant water absorption, which makes benthic habitat mapping a difficult task. In highly turbid coastal waters, where the amount of water constituents is high and the depth of light penetration may be only in centimetres, the bottom would not be visible and it would not have any influence on reflectance spectrum. Turbid waters are possibly the greatest constraint to any coastal habitat-mapping programme utilising optical remote-sensing methods (Mumby et al., 1997).

The subsurface light field in shallow water is not only a function of the properties of the water mixture, but also of the depth and properties of the sea floor (Ackleson, 2003). One of the most commonly cited difficulties with remote sensing of underwater environments is the confounding influence of variable depth on bottom reflectance (Mumby et al.,1998) i.e. it is hard to separate whether the reflectance changed due to changes in water depth or bottom type. Depth correction method, eliminating the change in reflectance attributable to variable depth, has been proposed by Lyzenga (1981) and its variations have been suggested by other authors (Mishra et al., 2006; Benfield et al., 2007, Mishra et al., 2007). Nevertheless Andrefouët et al. (2004a) emphasize that accurate bathymetric correction of reflectance data in the 0 to 3 m range of depth is not strictly necessary. However, beyond 3 m, it is likely that water correction will be required to improve classification results (Purkis and Pasterkamp, 2004).

Altogether, mapping benthic habitats with remote sensing method is complicated by water column properties, varying water depth and the complex mosaics of bottom types. Increasing water turbidity and depth decrease the influence of the bottom reflection on the above-water spectra (Carder et al., 2003), making the habitat mapping less feasible.

3.2 Remote sensing sensors for assessment of the coastal zone

Remote-sensing instruments are usually located on either an airborne or space-borne platform. A remote sensing sensor has a field-of-view such that at any moment in time, it is viewing a part of Earth’s surface and recording how much radiation is being reflected from that part (Philipson, 2003). The characteristics of a remote sensing sensor are described by its radiometric, spatial, temporal and spectral resolution.

The radiometric resolution of a sensor refers to the possible number of grey levels in the image describing the sensor’s sensitivity. Many older sensors have a 8-bit radiometric resolution i.e. the measured signal is divided into 256 grey levels. More advanced sensors have 11-bit or up to 16-bit (65 536 grey levels) radiometric resolution.

The spatial resolution of the sensor describes the size of the ground area corresponding to one pixel in the image (Philipson, 2003). Different sensors cover a wide range of spatial resolutions ranging from one-kilometre to less than a meter. A higher spatial resolution will increase the sensors possibility to record spatial detail.

The temporal resolution of the sensor or the time between revisiting the same place is governed by a combination of the orbit characteristics and the swath width **(**Robinson, 2000). In general there is a trade-off between spatial and temporal resolution of sensors, the lower the spatial resolution, the higher the revisit rate. For example the spatial resolution of the Moderate Resolution Imaging Spectrometer (MODIS) sensor is quite coarse, 250–1000 m, at the same time it is designed to permit nearly daily global coverage (Peterson et al. 2003).

Finally, remote sensing sensors vary in the number and bandwidth of their spectral channels i.e. the spectral resolutions. Traditional satellite-flown multispectral instruments do not generate a reflectance spectrum; they generate a signal in each of a small number of very broad bands (Cracknell, 1999). Most multispectral satellites have only 2–4, quite broad bands in the visible part of the spectrum. A hyperspectral scanning system, or an imaging spectrometer as it is sometimes called, provides the intensity of the radiation received in each of a very large number very narrow bands so that one obtains what is, in effect, a continuous spectrum (Cracknell, 1999). Fig. 2 illustrates the difference between a hyperspectral sensor (Hyperion) and a multispectral sensor (ALI, spectral bands almost identical to sensors like Landsat, IKONOS and QuickBird).

The number of classes (categories) distinguishable by remote sensing depends on many factors including, the platform (satellite, airborne, towed instrument, handheld instrument), type of sensor (spectral, spatial and temporal resolution), atmospheric clarity, surface roughness, water clarity and water depth (Mumby et al., 2004a).

Mapping of submerged benthic vegetation with satellites largely depends on the characteristics and capabilities of the specific sensor. The limitations are caused by sensors poor spatial resolution, limited spectral capabilities and low temporal resolution. ”Conventional” space borne optical sensors (e.g. Landsat 7) are designed for mapping of relatively bright land surfaces. For example Landsat offers spatial resolution of 30 m, poor radiometric resolution (256 measured radiance levels) and limited spectral resolution, thus limiting its use for mapping and monitoring coastal habitats with reliability (Malthus & Karpouzli, 2003).

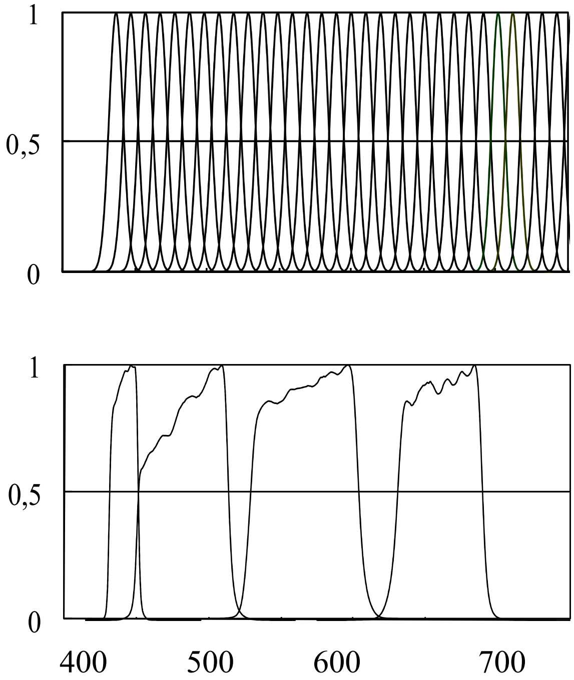

Figure 2. Normalised spectral response functions of a hyperspectral satellite sensor (Hyperion) and a multispectral satellite sensor (ALI) in visible part of spectrum.

High spatial resolution satellites, such as IKONOS and QuickBird, offer data at high spatial (0,6–4 m) and radiometric resolution and offer considerable promise for monitoring spatial changes in marine habitats (Malthus & Karpouzli, 2003). These sensors have enhanced spatial resolution that should minimize the spectral mixing problem, but the limited spectral capacities (three visible wavebands) may still be a limitation for vegetation mapping in heterogeneous environments (Andrefouët et al., 2004b). Another disadvantage of high spatial resolution sensors might be the low signal-to-noise ratio of measured reflectance. In this case less light is collected and the high ratio of pixel perimeter to area allows ”nuisance” light, originating from outside the pixel, to exert a relatively large influence on the signal (Mumby et al., 2004b).

Most multispectral satellite sensors (IKONOS, QuickBird) lack the sensitivity to discriminate spectra because they have a limited number of water-penetrating bands (Mumby and Edwards, 2002). Where distinguishable minima and maxima exist within the water-penetrating spectrum, satellite bands may be too broad to distinguish them (Mumby et al., 1997). A waveband might be so wide that it obscures a spectral response, which might have been detectable had the waveband been narrower (Holden & LeDrew, 1998). Higher spectral resolution is needed to perceive the subtle differences between various bottom types. Hyperspectral system may resolve this problem, since hyperspectral remote sensing instrument acquires data in tens to hundreds of spectral bands.

The first civilian hyperspectral sensor in space, Hyperion, was launched in the end of 2000. Hyperion has 240 10 nm wide spectral bands i.e. it is measuring continuous spectrum in visible and near infrared part of spectrum. It has been shown (Kutser et al., 2006) that Hyperion can be used to map different benthic types in shallow water coral reef environments. However, Hyperion is a technical demonstration satellite with short lifetime and very limited amount of spatial coverage that can be sensed each day. Therefore, we have to use satellite sensors with considerably purer spectral resolution for mapping benthic algal cover until next generation of hyperspectral sensors in space will be operational.

In addition to a great spectral resolution, airborne hyperspectral remote sensing sensors such as the Compact Airborne Spectrographic Imager (CASI), Airborne Imaging Spectrometer for Applications (AISA), HyMap Airborne Hyperspectral Scanner and the Airborne Visible Infrared Imager (AVIRIS) usually have a better spatial resolution than satellite sensors. Image data acquired from airborne platforms typically have spatial resolutions of 0,5–3 m. Such data provide smaller area coverage than that acquired from satellites. The cost of airborne data per unit of area is higher than that of satellites. Airborne sensors are expensive to run for large and/or remote regions. In these cases, space born sensors are considerably more cost effective if the spatial resolution is adequate (Kutser et al., 2003).

4. MATERIAL AND METHODS

4.1. In situ measurements of benthic reflectance spectra

The spectral irradiance reflectance *R* (implicitly a function of wavelength) of a material is defined as the ratio of spectral upwelling to downwelling plane irradiance (Mobley, 1994). *In situ* reflectance spectra of the typical aquatic benthic types of Estonian coastal waters were collected (**Paper I**). We concentrated on the specimens of the most typical green, brown and red benthic macroalgae – *Cladophora glomerata*, *Fucus vesiculosus* and *Furcellaria lumbricalis*. *C. glomerata* (green algae) and *F. vesiculosus* (brown algae) are considered as key species to monitor the effect of eutrophication in the Baltic Sea monitoring program carried out by HELCOM (www.helcom.fi). *Furcellaria lumbricalis* is commercially harvested for galactants, but is also important habitat for juvenile fish.

Reflectance spectra of benthic macroalgae and bare substrate were measured using handheld GER1500 spectroradiometer. Spectral range of the instrument is 300–1100 nm. Spectra are sampled with 1.5 nm intervals and spectral resolution of the GER1500 spectroradiometer is 3 nm. Reflectance is calculated as a ratio of radiance from algae against the radiance of standard Spectralon panel.

Reflectance measurements of wet algae were carried out on the shore immediately after landing of the boat or on board of the boat. Reflectance spectra of wet and dry sand, gravel, and some other material washed out to the shore were measured at their location.

4.2. Water samples collection

Water samples were collected at different locations from Estonian coastal waters, filtrated and analyzed to retrieve concentrations of phytoplankton, total suspended matter and colored dissolved organic matter. Filtration and laboratory analyses were carried out using methods described by Paavel (2008). Results of the water sample analysis gave as an estimate of the concentrations of the optically active constituents present in the water column of Estonian coastal waters. This information was used as input information in our bio-optical model.

4.3. Modelling

In situ benthic reflectance spectra were used to model the bottom-types as the different sensors would “see” them. A simple model, proposed by Maritorena et al. (1994), was used to simulate diffuse reflectance just below the water surface:

$$R(0-, H) = R_\infty + (R_b - R_\infty)\exp(-2KH),$$

where R(0–, H) is reflectance just below the water surface, *H* is water depth, R_b is bottom reflectance, R_∞ is reflectance of optically deep water, and *K* is diffuse attenuation coefficient of the water. Maritorena et al. (1994) have also shown that vertical attenuation coefficient for downwelling irradiance, K_d, is a good approximation for *K*.

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:

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

where a(λ) is the total absorption coefficient, $b_b(\lambda)$is the total backscattering coefficient, and λ is wavelength. The detailed description of the model has been given in **Paper II** and **Paper III.**

The modelling was carried out for three distinctly different water types: (1) CDOM-rich waters – resembling situation near a river estuary, (2) coastal waters not directly impacted by high CDOM discharge from rivers but with high concentration of cyanobacteria i.e archipelago waters during cyanobacterial bloom, (3) open Baltic Sea waters. Concentrations of optically active substances in these three water types are shown in Table 1. The concentrations were taken from real measurements.

Table 1. Concentrations of optically active substances used in model simulations. C_{Chl} and C_{SM} are concentrations of chlorophyll-a and total suspended matter respectively and $a_{CDOM}(400)$ is absorption by CDOM at wavelength 400 nm.

Water type	C_{Chl}	C_{SM}	$a_{CDOM}(400)$
1	6	6	15
2	10	5	3
3	2	2	1.5
	mg/m^3	mg/l	m^{-1}

Shallow water reflectance spectra were calculated with 0.5 m water column increments for each and water type. The R(0−) of optically deep water was calculated for each water type. Differences between all substrates in various water depths were calculated by subtracting the reflectance of one substrate from the reflectance of another substrate at the same depth. It was assumed that the substrates are separable from each other by a particular sensor in case the difference between the substrates was higher than the signal to noise ratio (SNR) of this sensor. SNR's of different sensors are characterised below.

4.4. Remote sensing sensors under investigation

The present study includes bio-optical modelling and image analysis. First we assessed by means of model simulations whether or not satellite and airborne imagery can be used for mapping benthic habitat in the Baltic Sea before purchasing actual image data. After that we conducted image analysis with the real imagery to study sensors capabilities to map benthic habitat in our waters.

In our modelling part of the study, the technical parameters of different remote sensing sensors (e.g spectral resolution, signal to noise ratio) were investigated in order to define theoretical discriminative limits of different sensors. First of all it was important to test whether the spectral resolution of different hyperspectral and multispectral sensors is sufficient for discriminating different bottom types. Secondly the sensitivity (SNR ratios) of different sensors was tested.

Hyperspectral sensors provide continuous spectral information, therefore the reflectance spectra of different bottom types were modelled with 10 nm intervals to define whether the benthic types can be discriminated based on the continuous spectral information. The 10 nm spectral resolution is a good approximation of most airborne imagers (e.g. AVIRIS, CASI, AISA) and resembles that of hyperspactral satellite Hyperion. The SNR specifications currently attainable by hyperspectral airborne remote sensing systems such as **AVIRIS** and **CASI**, flown under ideal circumstances, are about 1000:1 (Dekker et al., 2001).

In case of multispectral sensors, sensor-specific reflectance spectra were created by applying each sensor's relative spectral response to the high-resolution (10 nm) spectra and tested, whether the spectral information provided by few wavebands is sufficient to discriminate different benthic types. The sensors under investigation were following:

MERIS (Medium Resolution Imaging Spectrometer) is a medium spatial resolution, medium to high temporal resolution and has a high number (15) of narrow spectral bands. MERIS has a spatial resolution of 300 m in full resolution mode and 1.2 km in reduced resolution mode acquired routinely. It has nine visible wavebands covering the visible spectral range (410–710 nm). MERIS signal to noise ratio (SNR) decreases from 1400:1 in blue part of spectrum to 600:1 in red part of spectrum. Since most of the differences between reflectance spectra of different macroalgae and sand occur in green and red part of spectrum, we used SNR 600:1 to study capability of MERIS for separating different benthic macroalgae. Doerffer et al. (1999) gives a good overview of the MERIS instrument focusing on the specifications that make this sensor especially beneficial to the research of coastal areas.

The first **Landsat** series satellite was launched in 1972 and they have been used for mapping benthic cover since the mid-eighties (Jupp et al. 1985). **ALI** is an improved version of the Landsat series sensors and a possible precursor of Landsat 8 (Kutser et al. 2003). ALI and Landsat series sensors have three visible wavebands covering the visible spectral range (between 400–700 nm), these instruments offer coarse spatial resolution (30 m). Landsat SNR was taken 100:1 and ALI SNR was taken 250:1, which is equal to instrumental signal to noise provided by the satellite manufacturers.

IKONOS images provide four spectral bands in the blue, green, red and near-infrared (NIR) parts of the spectrum and enhanced spatial resolution (4 m). IKONOS SNR was taken 100:1.

SNR ratios for above mentioned instruments are given for above water signal. However, the model computes subsurface irradiance reflectance R(0–). About 48% of just below the water surface upwelling irradiance is reflected back into the water column (Dekker et al., 2001). Thus, the SNR in terms of just below the water surface reflectance, R(0–), can be approximately half that of the real remote sensing instruments when we study capability of these instruments to detect differences in reflectance spectra (Dekker et al,. 2001). For example in case of hyperspectral airborne remote sensing systems (AVIRIS, CASI), we assumed that two substrates are separable from each other if their spectral difference is higher than 0.2% which is equal to SNR 500:1 in terms of underwater reflectance.

After completing the modelling part of the study and several field campaigns in the study area we found that high spectral and spatial resolution is needed to map benthic algal cover in Estonian coastal waters. As there is no space borne sensor that provides both high spectral and spatial resolution we decided to order data of two satellites: QuickBird and Hyperion. The first one has the highest spatial resolution currently available and the latter provides the highest spectra resolution. Having data of two such different sensors allowed to study should we prefer high spatial or high spectral resolution if both of them are not available simultaneously.

QuickBird is a high spatial resolution instrument (2.4 m), with 4 bands in visible and near-infrared part of the spectrum similar to ALI, Landsat and IKONOS. We decided to use QuickBird instead of IKONOS as it provides higher spatial resolution while the spectral resolution is nearly identical. Wavelength ranges of the QuickBird bands are following: blue: 450–520 nm, green: 520–600 nm, red: 630–690, and near-infrared: 760–900 nm. Dynamic range of the instrument is 11 bits.

Hyperion has spectral resolution of 10 nm and around 200 usable spectral bands in visible and near infrared part of spectrum. Spatial resolution of the sensor is 30 m.

4.5. Image analysis

The study area for image analysis was selected between Islands Hiiumaa and Saaremaa in Western Estonian Archipelago, eastern part of the Baltic Sea (Fig. 3). The area is characterized in **Paper IV**. QuickBird image was acquired from the study site on August 22, 2005. Scene used in the present study was 10x10 km in size. Hyperion image acquired on September 1, 2005 was used for comparisons with the QuickBird image.

The fieldwork was conducted in August and September 2005. A photo record of bottom type and water depth was taken together with GPS coordinates in more than hundred sites. This data was used for classifying satellite imagery.

The image processing and analysis was made using ENVI software. The near infrared (NIR) band was used to mask out the land and clouds (in QuickBird image). Radiance values of the NIR band were used to prepare the binary mask which was subsequently applied to all bands. Additional areas, such as cloud shadows, not excluded using this mask, were removed manually. Geometric correction for QuickBird image was performed by image provider (DigitalGlobe Inc.), Hyperion image was geocorrected based on the corner coordinates provided by image provider (U.S. Geological Survey).

Atmospheric correction of Hyperion was performed using FLAASH. The FLAASH module in ENVI incorporates MODTRAN 4 radiation transfer code with all MODTRAN atmosphere and aerosol types to calculate a unique solution for each image. FLAASH also includes a correction for the "adjacency effect", provides an option to compute a scene-average visibility (aerosol/haze amount), and utilizes the most advanced techniques for handling particularly stressing atmospheric conditions (such as clouds). Sub-arctic summer atmosphere model with maritime aerosol was used.

Atmospheric correction of the QuickBird image was performed using an empirical line approach (Moran et al., 2001 and references within) utilising reflectance spectra measured by GER1500 spectrometer, which were recalculated to match with QuickBird spectral bands.

After some experimentation minimum distance supervised classification technique was selected and applied on the QuickBird image. Classes used in the analysis correspond to the bottom types of measurement points where we carried out the fieldwork.

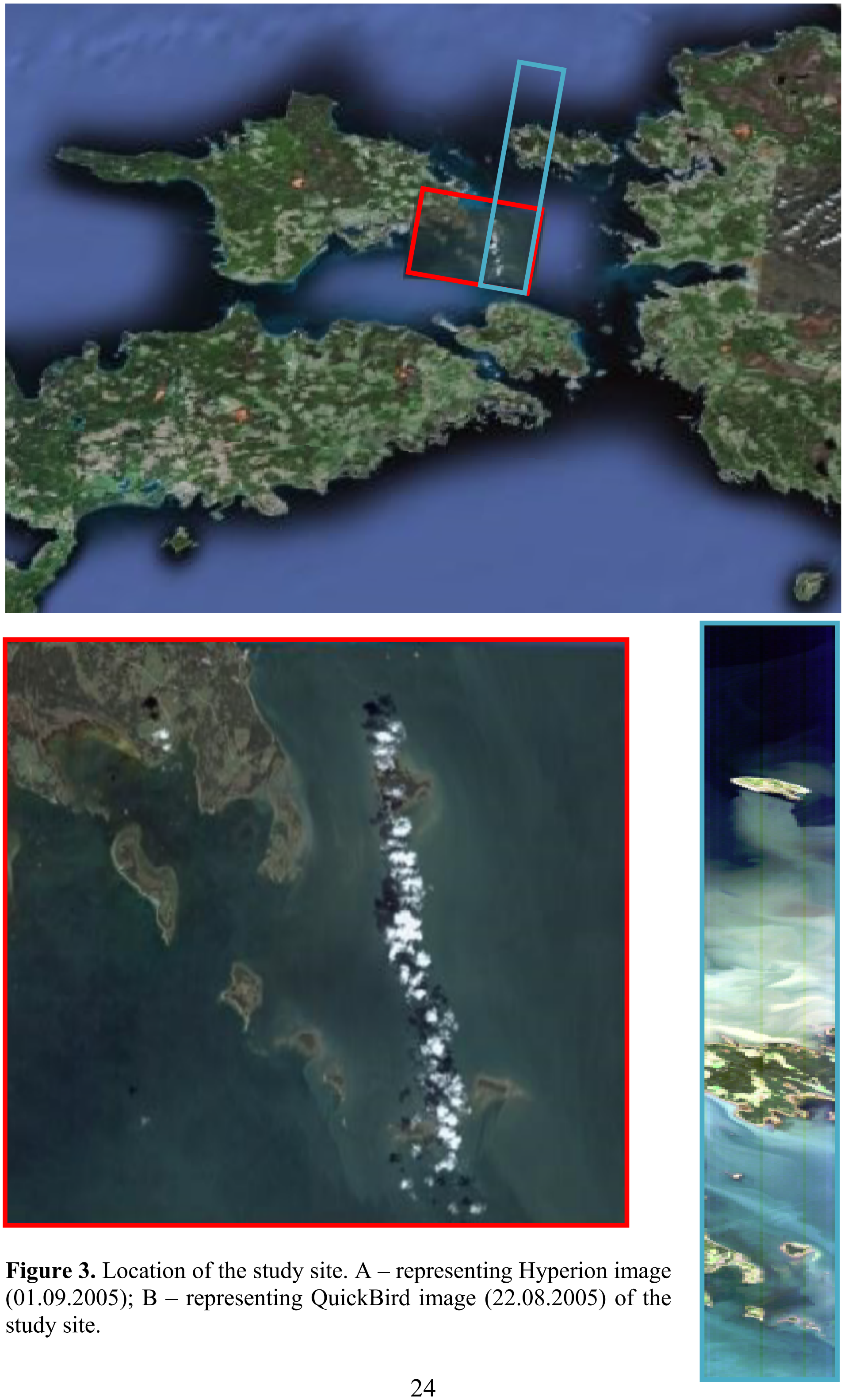

Figure 3. Location of the study site. A – representing Hyperion image (01.09.2005); B – representing QuickBird image (22.08.2005) of the study site.

5. RESULTS AND DISCUSSION

According to our objectives, the following results are presented: First, the spectral reflectance of different aquatic benthic types of Estonian waters were measured to determine the differences in their reflectance and to create the spectral library of the bottom types present in Estonian coastal waters. Then the measured reflectance spectra of three most typical green, brown and red benthic macroalgae were used in the model simulations to study whether these algae are optically distinguishable from each other, from sandy bottom and from optically deep water in such a complex water body as the Baltic Sea. Model simulations were also used in order to assess the capability of multispectral satellite sensors to map different benthic substrates. Finally, images taken by QuickBird and Hyperion satellite sensors were analysed to study advantages and limitations of multispectral and hyperspectral satellite data in mapping water depth and bottom type in the Baltic Sea

5.1. Spectral library of bottom types present in Estonian coastal waters

Identifying different aquatic bottom types using remote sensing method has been recommended as a possible mean to map large scale benthic coverage. It can be done if different bottom types are separable from each other based on their optical signature. To determine this, we collected a spectral library of different bottom types present in Estonian coastal waters.

The material present near the shoreline of Estonian coast may be quite variable: sandy beaches, belts of broken shells, areas covered with pebble, washed out algae and higher plants both in wet stage floating near the water line or dried in the sun on the shore. Measured reflectance spectra of these materials found on the shore are shown in **Paper I, figure 1** and **2**.

While doing our measurements, we concentrated on the different submerged substrates, including bare substrates and aquatic vegetation. Reflectance spectra of differently coloured pebble and sand were measured through the water column of 5 cm (Fig. 4A). Pebble may consist of stones of different origin. Reflectance spectra of granite (red, brown, black) were relatively dark (below 9%) as seen in Figure 4A. The reflectance of greyish limestone pebble was up to 15% and that of whiter sand- or limestone rocks reached 36%. Most of the pebble reflectance spectra were collected within 0.5 m radius. This means that the reflectance spectrum collected with an instrument which spatial resolution is greater than a few centimetres would be a mixture of spectral signatures from the differently coloured pebble. It must be noted that nearly all sand and pebble spectra had a chlorophyll absorption feature near 680–690 nm, which indicated presence of an algal cover on submerged material. It is typical for aquatic environments that even small sand particles are covered with microalgal communities (Stephens et al. 2003) and reflectance of all „abiotic" substrates contains chlorophyll signal.

Reflectance spectra of brown algae *Fucus vesiculosus* were consistent in shape (Fig. 4B), but variable in reflectance values. Reflectance values of dark brown parts of one *Fucus* specimen reached only 2% in the visible part of the spectrum whereas the maximum reflectance of top branches of the same specimen was between 5% and 9%. The shape of the *F. vesiculosus* reflectance spectra is analogous to other brown algae and many corals (containing symbiotic brown algae) measured in different parts of the world (Kutser & Jupp 2006; Hochberg et al. 2004), i.e. there are peaks near 600 and 650 nm and a shoulder near 580 nm.

Reflectance spectra of red algae *Furcellaria lumbricalis* (Fig. 4C) also resemble the reflectance spectra of other red algae collected in different parts of world oceans (Dekker et al., 2005; Hochberg et al., 2003a; Kutser et al., 2003; Maritorena et al., 1994) i.e. there are two main peaks in their reflectance spectra, near 600 and 650 nm. Spectrum 1 was measured above a *Furcellaria* patch, which was rinsed in seawater before the measurement. Spectra 2 and 3 were collected above another sample, which was covered by fine sediment and slime of decaying algae. This is probably the reason why these spectra are smoother than spectrum 1. The upper layer of the sample (spectrum 2) had turned greenish due to extensive sunlight in the shallow water where the sample was collected. The bottom side of the same sample (spectrum 3) was darker. However, the typical double peak is seen in all reflectance spectra even if the algae appear visually greenish.

Reflectance spectra of three different species of green algae were collected – *Chara* sp., *Enteromorpha* sp., and *Cladophora glomerata*. Reflectance spectra of these species are shown in Fig. 4D together with the reflectance spectrum of a seagrass *Zostera marina*.

Comparison of the results with reflectance spectra collected in different parts of the world indicates that the reflectance of red, green, and brown macroalgae is similar within each algae group (Maritorena et al., 1994; Anstee et al., 2000; Kutser et al., 2003; Dekker et al., 2005).

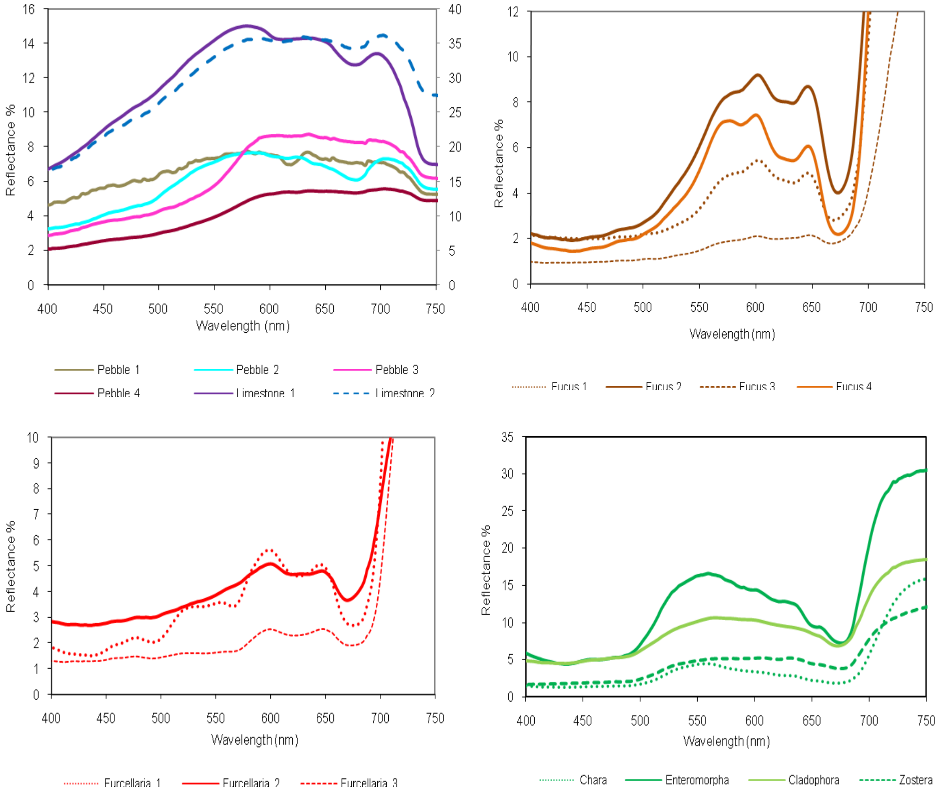

Figure 4. Reflectance spectra of different bottom types: A – differently coloured pebble measured through a water layer of 5 cm (reflectance values of white limestone (dashed line) is indicated on the right axis.); B – different specimens of the brown macroalga *Fucus vesiculosus*; C – different speciemens of the red macroalga *Furcellaria lumbricalis*; D – green macroalgae *Chara* sp., *Enteromorpha* sp., *Cladophora glomerata* and the seagrass *Zostera marina*.

5.2. Separability of green-, brown- and red algae from each other, sandy bottom and deep water with hyperspectral remote sensing sensors

Measured reflectance spectra of sand, green-, brown- and red benthic macroalgae were used in our model simulations to determine the separability of three important macroalgae species from each other, from sandy bottom and optically deep water. Green macroalgae were represented by a reflectance spectrum of *C. glomerata*, red macroalgae by unattached form of *F. lumbricalis*, and brown macroalgae by *F. vesiculosus*.

Figure 5A shows the spectral reflectance for each benthic vegetation species and for sandy bottom. All substrates have high reflectance in the near-infrared part of the spectrum. Sand has higher reflectance spectra than algae in visible part of spectrum. Green algae reflectance is higher than that of other measured algae. Reflectance values of *Fucus* and *Furcellaria* are very similar. However, there are differences in shape of their reflectance spectra. *Furcellaria* has a double peak near 600 and 650 nm. *Fucus* has a maximum in its reflectance spectrum near 600 nm and two “shoulders” near 570 and 650 nm similar to most living corals and many brown algae (Kutser & Jupp, 2006; Hochberg et al., 2004).

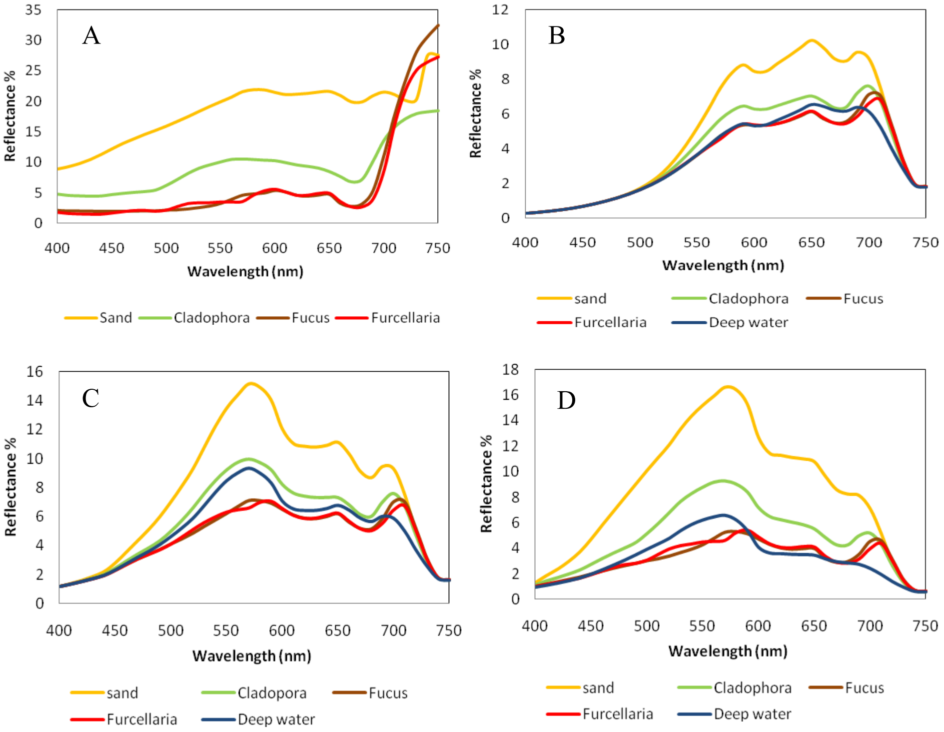

Figure 5. Reflectance spectra of studied benthic macroalgae and sand measured without overlaying water column (A). Simulated reflectance spectra of various substrates for 1 m deep water in water type 1 (B), water type 2 (C), and water type 3 (D). Reflectance spectrum of optically deep water (referred as deep water) for each water type is also added to the graphs.

We evaluated the effects of water column on remotely sensed spectra by simulating bottom-reflected light through different depths of water column for given concentrations of optically active substances. Figure 5B-D represents reflectance spectra of various substrates just below the water surface in 1 m deep water for three different water types. Optically deep water reflectance spectra of the same water types were added to the figures. The deep water spectrum in each graph was calculated using the same concentrations of optically active substances as the shallow water spectra in the same graph. The concentrations of optically active substances for each water type are shown in Table 1 and are characterized in **Paper II** and **Paper III.**

Majority of macroalgal cover in the Baltic Sea occurs in conditions similar to the type 3 water of our study. Cyanobacterial blooms (represented by water type 2) occur only during short time. Although the blooms may make mapping of benthic habitat impossible, they are avoidable with careful planning of field experiments. CDOM-rich waters (represented by water type 1) are located only near some river mouths. Benthic vegetation is practically missing in very CDOM-rich areas as there is not enough light at the sea bottom. Plumes of very CDOM-rich waters may also reach out of estuaries, but the duration of such blooms is usually short. Therefore, we concentrated on estimating the potential (e.g. the maximum depth penetration) of remote sensing to map benthic algal cover in the clearest water type.

5.2.1. Spectral differences between substrates and deep water

Shallow water reflectance spectra were calculated with 0.5 m increments for each bottom type. Differences between the R(0–) of optically deep water and shallow water reflectance spectra were calculated by subtracting one from another. It was assumed that the substrate is separable from deep water if the reflectance difference is higher than the SNR of hyperspectral instruments (AVIRIS, CASI) e.g. we assumed that two substrates are separable from each other if their spectral difference is higher than 0.2% which is equal to SNR 500:1 in terms of just below the water surface reflectance, R(0–).

Figure 6 shows the simulated spectral differences between reflectance of different bottom types and reflectance of our type 3 (open Baltic) deep water. Results of the simulations show that the maximum depth at which sandy bottom can be separated from type 3 optically deep water is 10 m (Fig. 6A). Green alga (*Cladophora glomerata*) is spectrally different from optically deep water, but the difference is not as high as for sand (Fig. 6B). The differences between green algae and deep water are seen in waters up to 7 m deep near 550–580 nm. According to Martin and Torn (2004) *C. glomerata* forms monodominant belts near the shore and does not occur in belts at depth greater than 3.5 m in Estonian coastal waters. Thus, it is relatively easy to separate *Cladophora* belts from optically deep water areas as remote sensing could potentially permit detecting it in depths that are greater than the depths where it grows in nature.

Figure 6C simulates the spectral difference between reflectance of brown algae *Fucus vesiculosus* at different depths and reflectance of optically deep water. *Fucus* has a relatively low reflectance and differences between algae and optically deep water reflectance spectra are small, except near 710 nm. The differences between brown algae and optically deep water are detectable in waters up to 6 m deep in the wavelength range 540–560 nm in the type 3 waters. Six meters is also the maximum depth where the *F. vesiculosus* grows in belts in Estonian coastal waters as individual colonies can be found in deeper waters (Martin and Torn, 2004). Thus, mapping the extent of *F. vesiculosus* belts with remote sensing should not be a problem when hyperspectral instruments are used.

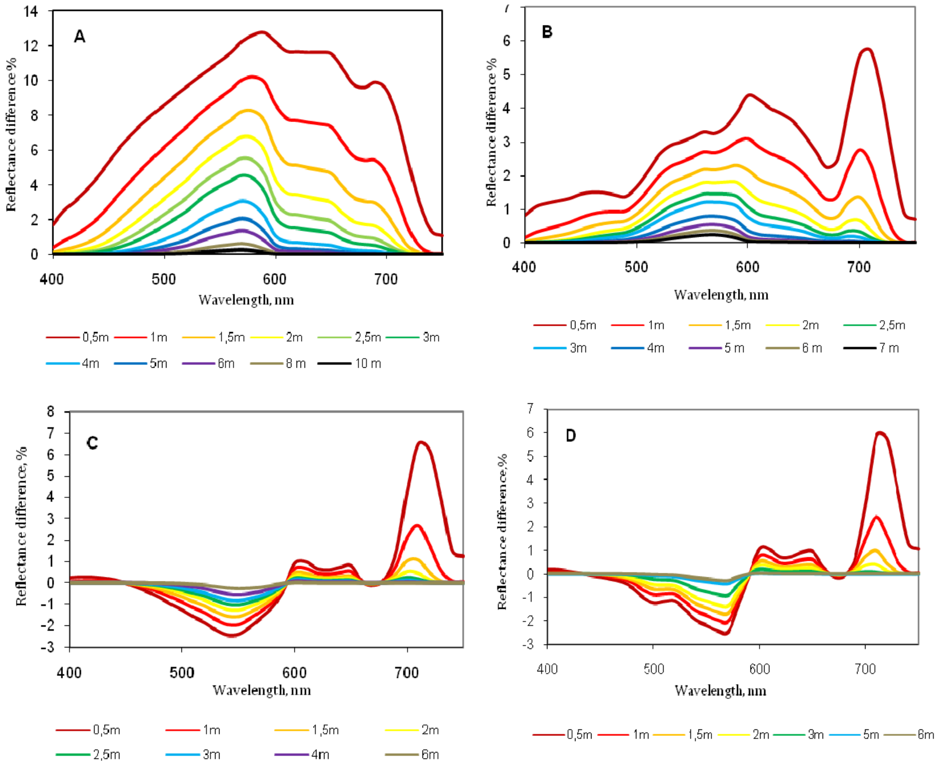

Figure 6. Spectral differences between simulated reflectance spectra (A) sand and optically deep water. (B) Green algae (*Gladophora glomerata*) and optically deep water. (C) Brown algae (*Fucus vesiculosus*) and optically deep water. (D) Red algae (*Furcellaria lumbricalis*) and optically deep water. Calculations are made for various water depths indicated in the legend.

Figure 6D shows the spectral difference between reflectance of red algae *Furcellaria lumbricalis* and reflectance of optically deep water. The spectral differences between *Furcellaria* and optically deep water are detectable in waters up to 6.5 m deep in the wavelength range 560–570 nm. Unattached *F. lumbricalis* may grow at depths down to 10 m deep in Estonian coastal waters (Martin and Torn, 2004). However, the commercially harvestable community occurs at depths of 5–7 m in the West Estonian Archipelago. Thus, most of the commercial stock of *F. lumbricalis* is in depths where it is potentially detectable by hyperspectral remote sensing sensors.

5.2.2. Spectral differences between algal species in different depths

Reflectance differences between different algae were calculated subtracting the reflectance of one species from the reflectance of another species at the same depth. Examples of spectral differences between the studied macroalgae are shown in **Paper II**, **figure 2**.

Spectral differences between sandy bottom and all three algal species are relatively high. The difference between sand and red or brown algae reflectance spectra is particularly high as *Fucus* and *Furcellaria* are relatively dark substrates compared to sand. The differences between sand and green algae *Cladophora* are detectable in waters up to 10 m deep. The differences between reflectance of sand and reflectance of red or brown algae are detectable in waters up to 11 m in wavelengths near 570 nm.

Our simulations show that the difference between reflectance of green algae and brown algae and between green algae and red algae are also comparatively high. The maximum detectable depth at which those species can be separated is 8 m and for that we can use the wavelength range 550–570 nm.

Both red algae *Furcellaria* and brown algae *Fucus* have relatively low reflectance values. Considerable differences between those two substrates appear in wavelengths near 520 nm, 570 nm and 700 nm. Difference near 570 nm is the greatest and this wavelength can be used to differentiate brown algae from red algae at depth up to 4 m.

Natural conditions in the Baltic Sea favour in several ways using of remote sensing in mapping of benthic algal cover. For example *C. glomerata* and *F. vesiculosus* form almost mono-dominant belts which are easier to map with remote sensing than mixed benthic communities. The studied algae prefer different water depths i.e. *Cladophora* belts occur in very shallow (generally less than 1 m) water, commercially harvestable stock of *Furcellaria* is at depths of 5–7 m and *Fucus* belts are mainly located between those two depth zones. The unattached *Furcellaria* is floating above sandy bottom. Most macroalgae require hard bottom where to fix themselves. Therefore, *Furcellaria* has to be optically separable only from sand and deep water to allow mapping its extent with remote sensing methods.

5.3. Capability of multispectral satellite sensors for mapping the Baltic Sea algal cover

Figure 7 illustrates how the sensors under investigation would detect reflectance spectra of studied bottom types without overlaying water column. It is seen in Fig. 7A that the difference between the substrates are mainly in reflectance values rather than in shape if sensors with three water penetrating bands, like ALI, Landsat or IKONOS, are used. MERIS bands are narrower (10 nm) and are located in spectral regions needed for example to separate brown algae from red algae (see Fig. 7B). However, the effect of water column has to be taken into account before deciding is MERIS suitable for discriminating between the optically similar substrates.

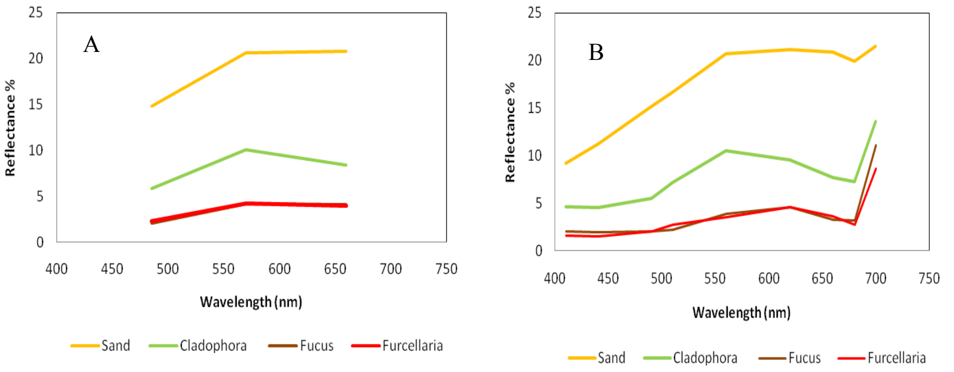

Figure 7. Reflectance spectra of sand and studied benthic algae species resampled for spectral resolution of multispectral sensors (A) Landsat, ALI, and IKONOS, (B) MERIS.

5.3.1. Simulated ALI, Landsat 7ETM and IKONOS performance in detecting benthic macroalgal cover

Shallow water reflectance spectra were calculated with 0.5 m increments for each bottom type and the expected values in multispectral sensors bands 1, 2 and 3 were derived. Differences between the R(0–) of optically deep water and shallow water reflectance spectra were calculated. The SNR of both Landsat 7 and IKONOS is about 100:1, the SNR of ALI is 250:1. About 50% of just below the water surface upwelling irradiance is reflected back into the water column. Therefore, the SNR in terms of just below the water surface reflectance, has to be 50:1 for Landsat 7 and IKONOS (which is equal to 2 %) and 125:1 for ALI (which is equal to 0,8%) to be able to differentiate between two bottom types.

Figure 8A indicates that all three bands can be used in separating sand from optically deep water in waters up to 3 m deep with ALI (SNR marked with blue dashed line) and in waters up to 2 m deep with Landsat and IKONOS (SNR marked with red dashed line). The second band near 560 nm can be used in differentiating sand and optically deep water in waters up to 5 m deep with ALI and in waters up to 4 m deep with Landsat and IKONOS. The characteristic spectral reflectance feature of sand is its brightness, and the brightness is so characteristic that even multispectral sensors with their limited spectral responses have no trouble discriminating sand from deep water.

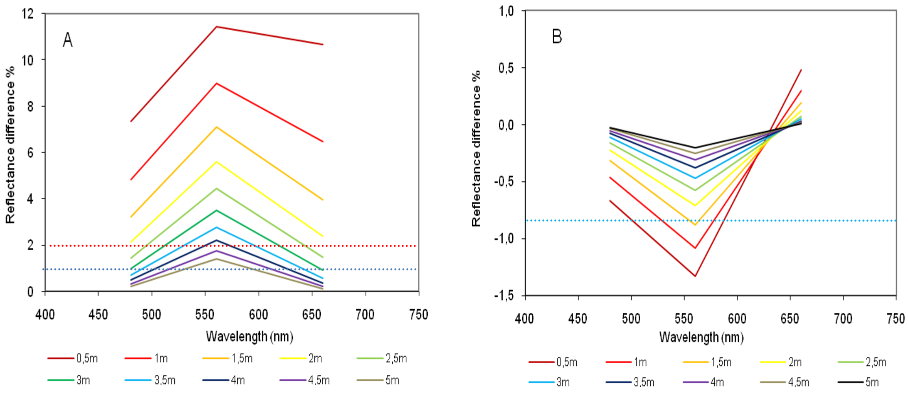

Figure 8. Spectral differences between simulated reflectance spectra (A) sand and deep water, (B) red macroalgae and deep water. Calculations are made for various water depths indicated in the legend. Each marker represents the central wavelength of a multispectral sensor band (ALI, Landsat, IKONOS). SNR of Landsat and IKONOS is marked with red dashed line, SNR of ALI is marked with blue dashed line.

Model simulations show (**Paper III, figure 3**) that the difference between green algae *Cladophora glomerata* and deep water is becoming undetectable in water deeper than 3 m when ALI is used. Landsat 7 and IKONOS are not capable of separating green algae and deep water at depths deeper than 1.5 m deep. Although *C. glomerata* can grow at depths 3.5 m in Estonian coastal waters, it usually grows on hard substratum surrounded by sandy bottom. It means that in most cases *Cladophora* belts have to be separated from shallow sandy bottom.

Optically dark marine habitats, such as brown and red algae, are spectrally similar to each other and to deep water when multispectral sensors are used. Figures 8B shows the difference between red algae and optically deep water. Landsat 7 and IKONOS are not capable of detecting these differences at all. ALI is capable of detecting the differences. Both brown and red macroalgae can be separated from deep water if the water depth does not exceed 1 m.

On the basis of the three visible bands available in the multispectral sensors dataset, sand was well differentiated from algal cover. Sand has a higher albedo than any algal substrate in ALI, Landsat7 and IKONOS bands 1, 2 and 3. Submerged feature brightness appears to be strongest attribute for separating substrate type. If there is a high degree of difference in the brightness of substrate types, features can be easily separated (Call et al 2003).

Since the differences between reflectance values of green algae and brown algae and green algae and red algae are small, multispectral satellites are hardly able to discriminate between these algal types based on their spectral signature.

As brown and red algae have similar spectral reflectance values. Broad-band sensors like ALI, Landsat7 and IKONOS are incapable of discriminating the two substrates from each other.

5.3.2. Simulated MERIS performance for detecting benthic algal cover

Unattached community of red algae *Furcellaria lumbricalis* occurs between the two biggest Estonian islands Saaremaa and Hiiumaa where it is trapped inside a circular current. Spatial scale of the area (hundreds of square kilometres) suggests that MERIS sensor with more coarse spatial resolution than the multispectral sensors, discussed above, could be used to map the extent of *Furcellaria* stock in this region. MERIS SNR was taken 600:1. In just below the water surface reflectance terms it means that the SNR has to be 300:1, which means that difference between two bottom types has to be 0.3% to be detectable by MERIS.

Figure 9A shows the simulated spectral differences between reflectance of red algae and reflectance of optically deep water. Difference is the greatest in ninth band near 700 nm, but these differences are above the instrument SNR level only in waters shallower than 2 m due to strong absorption of light at these wavelengths by water molecules. The next peak in the spectral difference spectra is in fifth band near 560 nm and these differences are detectable by MERIS in waters shallower than 5 m. The differences are detectable also in third and fourth bands in waters not deeper than 1 m.

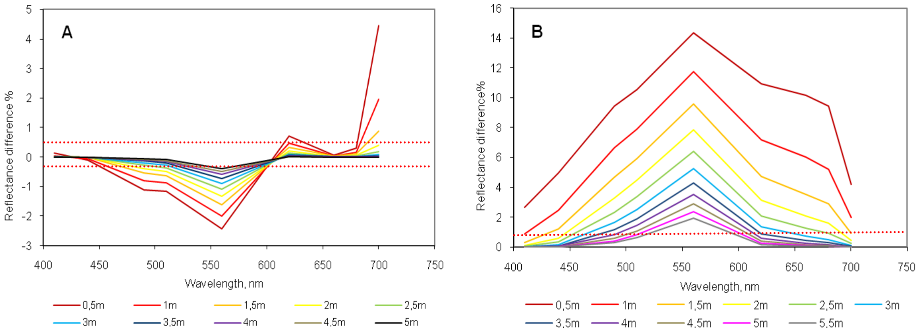

Figure 9. Spectral differences between simulated reflectance spectra (A) red macroalgae and optically deep water, (B) red macroalgae and sand. Calculations are made for various water depths indicated in the legend. Each marker represents the central wavelength of a MERIS band. SNR of MERIS is marked with red dashed line.

Figure 9B shows that the difference between sand and red algae is relatively high as *Furcellaria* is considerably darker substrate compared to sand. The difference is greatest in fifth band near 560 nm and this difference is detectable at least in waters up to 6 m.

The unattached *Furcellaria* is floating usually above sandy bottom practically not covered with other vegetation. Sand and *Furcellaria* are optically separable from each other by MERIS sensor in waters up to 6 m deep. It means that part of the commercial stock of *Furcellaria lumbricalis* could be mapped by MERIS in ideal circumstances (algal patches larger than MERIS spatial resolution, good illumination and weather conditions). Usually the *Furcellaria* mat is continuoes over the area it is covering. It means that the total area covered by Furcellaria can be mapped if we can detect outer boarder of the Furcellaria area. This can be done as the water is shallower there and sandy bottom is relatively bright background to the dark Furcellaria mat.

It must be noted that the modelling simulations were carried out for ideal circumstances i.e. relatively clear (for the Baltic Sea) water, calm water surface, pure substrates and using instrumental SNR provided by the satellite manufacturers. From this perspective, the results of this study represent the best possible case for each sensor.

5.4. Advantages and limitations of multispectral and hyperspectral satellite data in mapping water depth and bottom type in the Baltic Sea

A hyperspectral satellite image (Hyperion) and a multispectral satellite image (QuickBird) were tested to study, which of these sensors is most suitable for mapping bottom type and water depth in the Baltic Sea coastal waters. The modelling study carried out for the Baltic Sea conditions (**Paper II**) indicated that the main macroalgae groups are separable from each other also in relatively turbid waters of the Baltic Sea. On the other hand our field measurements and modelling results (**Paper I, II, III**) indicate that spectral resolution of multispectral sensors like QuickBird is not sufficient to separate red macroalgae from brown macroalgae based on their spectral signatures even if the macroalgae are not covered with water. The situation is more complicated if the vegetation is submerged.

Hyperion bands are narrow and enable differentiating between green-, red-, and brown macroalgae based on the shape of their reflectance spectra (**Paper II**). Another advantage of hyperspectral sensors is possibility of using analytical methods in mapping water depth and bottom type. These methods use measured or modelled spectral libraries to classify image data (Kutser et al. 2006, Lesser and Mobley 2007). There is no need to carry out field measurements simultaneously with image acquisition and to collect large amount of in situ data as the analytical methods are based on physics rather than spatial statistics of imagery and use optical properties of different bottom types and water column. This data may be collected at any time and from locations that are not necessarily in the imaged area. However, comparing Hyperion and QuickBird images (Figure 10) of our site it became obvious that spatial resolution of Hyperion is not adequate in such spatially heterogeneous environment like our study site. Therefore, we decided to concentrate our effort on the QuickBird image.

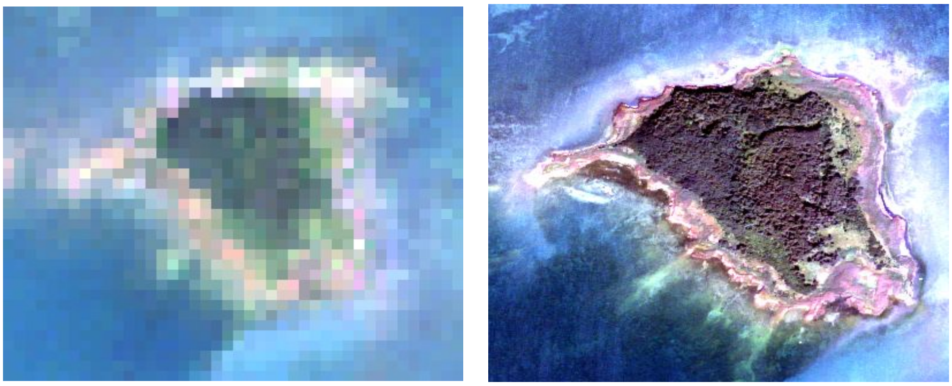

Figure 10. An islet Vareslaid in Western Estonian Archipelago imaged by (A) QuickBird satellite with 2.4 m spatial resolution (B) Hyperion satellite with 30 m spatial resolution

After some experimentation the Minimum Distance method was selected to classify the image. As indicated by Green et al. (2000), there is no best classification method, i.e. the different methods should be judged in terms of their cost and accuracy. The classification results for a sandy bay are shown in Figure 11. There were underwater sand dunes in this study area. We measured water depth in this area. Occurred, that water depth differences of 10 cm are clearly detectable in the QuickBird image. Another dominant feature in this study area is a belt of green filamentous macroalgae *Cladophora glomerata* covering areas with hard substratum (pebble). This was also correctly classified with the Minimum Distance method. There is also one misclassification in the imaged area. One of the sand areas is classified as “Turbid water with sandy bottom, 1.4 m deep”. Water depth in the area is classified correctly but seems that reflectance spectrum of sandy bottom through this particular water depth was identical to turbid water spectrum leading to the misclassification. This kind of misclassification is easy to understand in the case of multispectral data as there are only three spectral bands to use. Water with certain amount of resuspended sand has obviously similar reflectance spectrum than sandy bottom at certain depth in clear water.

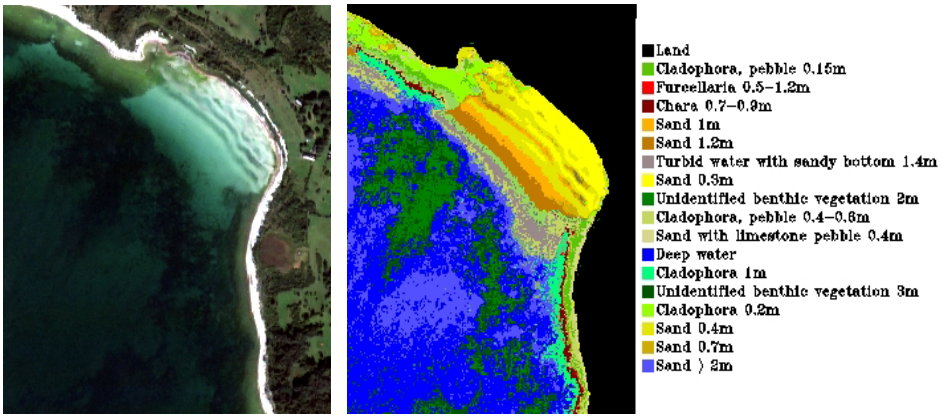

Figure 11. QuickBird true colour image (A) of a sandy bay and bottom classification map (B) obtained using the Minimum Distance supervised classification method with *in situ* bottom type and water depth data.

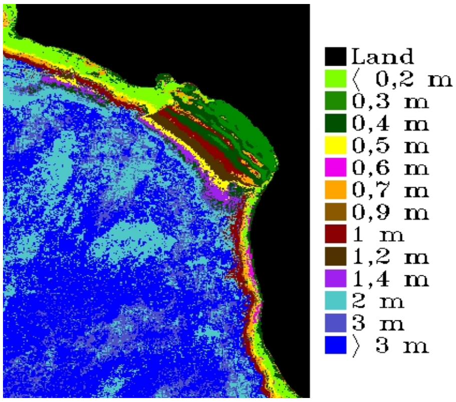

Figure 12. Depth map of the sandy bay shown in Figure 11.

It is relatively straightforward to produce water depth maps from the bottom classification map if each class contains substrate and depth information. This requires joining all classes representing different substrates at a certain depth into one depth class. Resulting depth map for the area shown in Figure 11 is presented in Figure 12.

The results obtained for a single QuickBird image show that mapping bottom type and water depth is relatively straightforward in shallow water areas if *in situ* data is available. However, our modelling results (**Paper II**) and results of this study show that different bottom types at different water depths may have identical optical signatures even in very shallow (1–2 m) water when multispectral sensors are used. Contextual editing (Mumby et al. 1998) i.e. taking into account preliminary knowledge of water depth and using knowledge about depth zones where dominant macroalgal species occur, should improve the macroalgae classification results. The situation is favourable for contextual editing in Estonian coastal waters where the two main environmental indicator species (*Cladophora glomerata* and *Fucus vesiculosus*) are known to form almost mono-species belts at different water depths (Martin and Torn, 2004). For example the green filamentous macroalgae *Cladophora glomerata* is present only in waters less than 2 m deep and forms mono-species belts in waters less than 1 m deep (Martin and Torn, 2004). On the other hand the important environmental indicator species *Fucus vesiculosus* (brown macroalgae) forms mono-species belts in deeper waters (2–5 m). Thus, taking into account the water depth information we can exclude possible sources of misclassification.

6. CONCLUSIONS

Based on the results of this study it could be concluded that:

- The reflectance spectra of macroalgae of the same species collected from the Baltic Sea are consistent in shape, but may be variable in absolute values.
- Comparison of the results with reflectance spectra collected in different parts of the world indicates that the reflectance of red-, green-, and brown macroalgae are similar within each algae group.
- The results of this study indicate that macroalgae can most likely be identified by remote sensing on three broad group level (red-, green- and brown macroalgae). High within species variability in reflectance values suggests that it cannot be done on species level.
- Modelling results indicate that the reflectance spectra of representatives of green algae (*C. Glomerata*), red algae (*F. Lumbricalis*) and brown algae (*F. Vesiculosus*) differ from each other and from sand and deep water reflectance spectra. The differences are detectable by remote sensing instruments which spectral resolution is at least as good as spectral resolution of our model (10 nm).
- The maximum depths where hyperspectral remote sensing instruments could potentially detect the spectral differences between the studied substrates are greater than the depths where the studied algae actually occur (at least in Estonian coastal waters) if the sensor's SNR is better than 1000:1.
- Modelling results also indicate that to some extent it is possible to map green, red and brown algae (*Cladophora glomerata*, *Furcellaria lumbricalis* and *Fucus vesiculosus)* with multispectral satellite sensors in turbid waters, which optical properties resemble those of the open Baltic Sea, but the depths where the macroalgae can be detected are usually shallower than the maximum depths where these macroalgae grow.
- Using of multispectral satellite data with high spatial resolution is preferable to using of hyperspectral medium resolution data in mapping benthic macroalgal cover in areas where the spatial heterogeneity is very high.
- In case of a single image and availability of *in situ* data multispectral sensors with high spatial resolution (QuickBird) can provide more detailed information about the benthic cover than was assumed based on the shape of reflectance spectra of different bottom types and spectral resolution of the sensor. However, lack of *in situ* data or using of multiple images may complicate the situation.

Taking into account the need in high spatial resolution data for mapping bottom types and water depth in shallow coastal water and advantages of hyperspectral information compared to multispectral data one can assume that hyperspectral airborne imagery is the most suitable data for that purpose.

REFERENCES

Ackleson, S. G. (2003) Light in shallow waters: A brief research review. *Limnology and Oceanography*, 48, 323–328.

Andrefouët, S., Muller-Karger, F.E., Hochberg, E.J., Hu, C., Carder, K.L. (2001) Change detection in shallow coral reef environments using Landsat 7 ETM+ data. *Remote Sensing of Environmnet,* 78, 150–162.

Andrefouët, S., Kramer, P., Torres-Pulliza, D., Joyce, K. E., Hochberg, E. J., Garza-Perez, R., Mumby, P. J., Riegl, B., Yamano, H., White, W.H., Zubia, M., Brock, J.C., Phinn, S. R., Naseer, A., Hatcher, B. G., Muller-Karger, F.E. (2003). Multi-site evaluation of IKONOS data for classification of tropical coral reef environments. *Remote Sensing of Environment*, 88, 128–143.

Andrefouët, S., Payri, C., Hochberg, E., Hu, C., Atkinson, M., Muller-Karger, F.E. (2004a) Use of in situ and airborne reflectance for scaling-up spectral discrimination of coral reef macroalgae from species to communities. *Marine Ecology Progress Series,* 283, 161–177.

Andrefouët, S., Zubia, M., Payri, C. (2004b) Mapping and biomass estimation of the invasive brown algae *Turbinaria ornata* (Turner) J. Agardh and *Sargassum mangarevense* (Grunow) Setchell on heterogeneous Tahitian coral reefs using 4-meter resolution IKONOS satellite data. *Coral Reefs,* 23, 26–38.

Anstee, J., Dekker, A., Byrne, G., Daniel, P., Held, A. & Miller, J. (2000) Use of hyperspectral Imaging for benthic species mapping in South Australian coastal waters. In *10th Australasian Remote Sensing and Photogrammetry Conference, Adelaide*, 1051–1061.

Benfield, S.L., Guzman, H. M., Mair, J. M., Young, J.A.T. (2007) Mapping the distribution of coral reefs and associated sublittoral habitats in Pacific Panama: a comparison of optical satellite sensors and classification methodologies. *International Journal of Remote Sensing,* 28 (22), 5047–5070.

Berger, R., Bergström, L., Granéli, E. & Kautsky, L. (2004) How does eutrophication affect different life stages of Fucus vesiculosus in the Baltic Sea? – a conceptual model. *Hydrobiologia*, 514, 243–248.

Bertels, L., Vanderstraete, T., Van Coillie, S., Knaeps, E., Sterckx, S., Goossens, R. And Deronde, B. (2008) Mapping of coral reefs using hyperspectral CASI data; a case study: Fordata, Tanimbar, Indonesia. *International Journal of Remote Sensing,* 29 (8), 2359–2391.

Call, K.A., Hardy, J.T., Wallin, D.O. (2003) Coral reef habitat discrimination using multivariate spectral analysis and satellite remote sensing. *International Journal of Remote Sensing*, 24 (13), 2627–2639.

Carder, K. L., Liu, C., Lee, Z., English, D. C., Patten, J., Chen, F. R., Ivey, J. E. (2003) Illumination and turbidity effects on observing faceted bottom elements with uniform Lambertian albedos. *Limnology and Oceanography*, 48, 355–363.

Cracknell, A.P. (1999). Remote sensing techniques in estuaries and coastal zones – an update. *International Journal of Remote Sensing,* 19, 485–496.

Dekker, A. G., Brando, V.E., Anstee, J. M., Pinnel, N., Kutser, T., Hoogenboom, E. J., Peters, S., Pasterkamp, R., Vos, R., Olbert, C. and Malthus, T.J.M. (2001) Imaging Spectrometry of water. In *Imaging Spectrometry,* F. D. Van der Meer and S. M. De Jong (Eds.), pp 307–359.

Dekker, A. G., Brando, V. E., Anstee, J. M. (2005). Retrospective seagrass change detection in a shallow coastal tidal Australian lake. *Remote Sensing of Environment*, 97, 415–433.

Dennison, W.C. (1987) Effect of light on seagrass photosynthesis, growth and depth distribution. *Aquatic Botany*, 27, 15–26.

Dennison, W.C., Orth, K.A., Moore, R.J., Stevenson, J.C., Carter, V., Kollar, S., Bergstrom, P.W., Batiuk, R.A. (1993) Assessing water quality with submersed aquatic vegetation. *Bioscience*, 43, 86–94.

Doerffer, R., Sørensen, K., Aiken, J. (1999) MERIS potential for coastal zone applications. *International Journal of Remote Sensing,* 9, 1809–1818.

Fyfe, S.K. (2003) Spatial and temporal variation in spectral reflectance: Are seagrass species spectrally distinct? *Limnology and Oceanography,* 48, 464–479.

Fornes, A., Basterretxea, G., Orfila, A., Jordi, A., Alvarez, A., Tintore, J. (2006) Mapping Posidonia oceanica from IKONOS. *ISPRS Journal of Photogrammetry & Remote Sensing*, 60, 315–322.

George, D. G., Malthus, T. J. (2001) Using a compact airborne spectrographic imager to monitor phytoplankton biomass in a series of lakes in north Wales. *The Science of the Total Environment,* 268, 215–226.

Goodman, J. A., Ustin, S.L. (2007) Classification of benthic composition in a coral reef environment using spectral unmixing. *Journal of Applied Remote Sensing,* 1, 011501.

Gordon, H. R., Brown, O. B., & Jacobs, M. M. (1975). Computed relationships between the inherent and apparent optical properties of a flat, homogenous ocean. Applied Optics, 14, 417−427.

Green, E.P., Mumby, P.J., Edwards, A.J. and Clark, C.D. (2000) Remote Sensing Handbook for Tropical Coastal Management. A.J. Edwards (Eds.) Coastal Management Sourcebooks 3, UNESCO, Paris.

Gullström, M., Lunden, B., Bodin, M., Kangwe, J., Öhman, M. C., Mtolera, M.S.P., Björk, M. (2005) Assessment of changes in the seagrass-dominated submerged vegetation of tropical Chawka Bay (Zanzibar) using satellite remote sensing. *Estuarine, Coastal and Shelf Science,* 67, 399–408.

Hedley, J.D., Harborne, A.R., Mumby, P.J. (2005) Simple and robust removal of sun glint for mapping shallow-water benthos. *International Journal of Remote Sensing,* 26 (10), 2107–2112.

Hochberg, E.J. and Atkinson, M.J. (2003) Capabilities of remote sensors to classify coral, algae and sand as pure and mixed spectra. *Remote Sensing of Environment*. 85, 174–189.

Hochberg, E.J., Atkinson, M.J., Andrefouët, S. (2003a) Spectral reflectance of coral reef bottom-types worldwide and implications for coral reef remote sensing. *Remote Sensing of Environment,* 85, 159–173.

Hochberg, E. J., Andrefouet, S., & Tyler, M. R. (2003b) Sea surface correction of high spatial resolution IKONOS images to improve bottom mapping in near-shore environments. *IEEE Transactions on geoscience and remote sensing,* 41, 1724–1729.

Hochberg, E. J., Atkinson, M. J., Apprill, A., Andrefouët, S. (2004) Spectral reflectance of coral. *Coral Reefs*, 23, 84–95.

Holden, H. and LeDrew, E. (1998) The scientific issues surrounding remote detection of submerged coral ecosystems. *Progress in Physical Geography,* 22 (2), 190–221.

Holden, H. and LeDrew, E. (1999) Hyperspectral identification of coral reef features. *International Journal of Remote Sensing,* 20 (13), 2545–2563.

Holden, H. and LeDrew, E. (2002) Measuring and modeling water column effects on hyperspectral reflectance in a coral reef environment. *Remote Sensing of Environment*, 81, 300–308.

Jupp, D.L.B., K.K. Mayo, D.A. Kuchler, and D.V.R. Classen. (1985) Remote sensing for planning and managing the Great Barrier Reef of Australia. *Photogrammetria,* 40, 21–52.

Karpouzli, E., Malthus, T.J., Place, C.J. (2004) Hyperspectral discrimination of coral reef benthic communities in the western Caribbean. *Coral Reefs,* 23, 141–151.

Kirk, J.T.O. (1984) Dependence of relationship between inherent and apparent optical properties of water on solar altitude. Limnology and Oceanography, 29, 350–356.

Kirk, J.T.O. (2003) *Light and Photosynthesis in aquatic ecosystems*. Second Edition. Cambridge, UK, Cambridge University Press.

Koponen, S., Pulliainen, J., Kallio, K., Hallikainen, M. (2002) Lake water quality classification with airborne hyperspectral spectrometer and simulated MERIS data. *Remote Sensing of Environment,* 79, 51–59.

Kutser, T., Dekker, A., Skirving, W. (2003) Modeling spectral discrimination of Great Barrier Reef benthic communities by remote sensing instruments. *Limnology and Oceanography,* 48, 497–510.

Kutser, T. (2004) Quantitative detection of chlorophyll in cyanobacterial blooms by satellite remote sensing. *Limnology and Oceanography,*49, 2179–2189.

Kutser, T. and Jupp, D.L.B. (2006) On the possibility of mapping living corals to the species level based on their optical signatures. *Estuarine, Coastal and Shelf Science*, 69, 607–614.

Kutser, T., Miller, I., Jupp, D.L.B. (2006) Mapping coral reef benthic substrates using hyperspectral space-borne images and spectral libraries. *Estuaries, Coastal and Shelf Science,* 70, 449–460.

Kutser, T., Vahtmäe, E. (submitted). A sun glint correction method for hyperspectral imagery containing areas with non-negligible NIR signal (very shallow water, floating plants and blooms). *Remote Sensing of Environment*.

Lesser, M.P., & Mobley, C.D. (2007) Bathymetry, water optical properties, and benthic classification of coral reefs using hyperspectral remote sensing imagery. *Coral Reefs*, 26, 819–829.

Lillesand, T., Kiefer, R. (1999) Remote Sensing and Image Interpretation. 4th Edition, John Wiley & Sons Inc., ISBN 0-417-25515-7.

Lubin, D., Li, W., Dustan, P., Mazel, C. H., Stamnes, K. (2001) Spectral signatures of coral reefs: features from space. *Remote Sensing of Environment*, 75, 127–137.

Luczkovich, J.J., Wagner, T.W., Michalek, J.L., Stoffle, R.W. (1993) Discrimination of coral reefs, seagrass meadows, and sand bottom types from space: a Dominican Republic case study. *Photogrammetric Engineering and Remote Sensing,* 59, 385–389.

Lyzenga, D.R. (1981). Remote sensing of bottom reflectance and water attenuation parameters in shallow water using aircraft and Landsat data. *International Journal of Remote Sensing,* 2, 71–82.

Malthus, T. J. and Karpouzli, E. (2003) Integrating field and high spatial resolution satellite-based methods for monitoring shallow submersed aquatic habitats in the Sound of Eriskay, Scotland, UK. *International Journal of Remote Sensing*, 24 (13), 2585–2593.

Malthus, T.J. and Mumby, P. (2003) Remote sensing of the coastal zone: an overview and priorities for future research. *International Journal of Remote Sensing,* 24 (13), 2805–2815.

Maritorena, S., Morel, A., and Gentili B. (1994) Diffuse reflectance of oceanic shallow waters: Influence of water depth and bottom albedo. *Limnology and Oceanography*, 39, 1689–1703.

Martin, G., and Torn, K. (2004) Classification and description of phytobenthic communities in the waters of the West-Estonian Archipelago Sea. *Hydrobiologia*, 514, 151−162.

Miller, R.L., Del Castillo, C.E. and McKee, B.A. (Eds.). (2005). Remote Sensing of Coastal Aqcuatic Environments. Springer

Mishra, D.R., Narumalani, S., Rundquist, D., Lawson, M. (2006) Benthic habitat mapping in tropical marine environments using QuickBird multispectral data. *Photogrammetric Engineering & Remote Sensing*, 72 (9), 1037–1048.

Mishra, D.R., Narumalani, S., Rundquist, D., Lawson, M., Perk, R. (2007) Enhancing the detection and classification of coral reef and associated benthic habitats: A hyperspectral remote sensing approach. *Journal of Geophysical Research*, 112, C08014, doi:10.1029/2006JC003892.

Mobley, C.D. (1994) Light and Water. Radiative Transfer in Natural Waters. Academic Press.

Moran, M.S, Bryant, R., Thome, K., Nouvellon, W.N.Y., Gonzales-Dugo, M.P., Qi, J., Clarke, T.R. (2001) A refined empirical line approach for reflectance factor retrieval from Landsat-5 TM and Landsat-7 ETM+. *Remote Sensing of Environment*, 78, 71–82.

Mumby, P. J., Green, E. P., Edwards, A. J., Clark, C. D. (1997) Coral reef habitat mapping: how much detail can remote sensing provide? *Marine Biology,* 130, 193–202.

Mumby, P.J., Clark, C.D., Green, E.P., Edwards, A.J. (1998) Benefits of water column correction and contextual editing for mapping coral reefs. *International Journal of Remote Sensing,* 19 (1), 203–210.

Mumby, P. J., Green, E. P., Edwards, A. J., Clark, C. D. (1999) The cost-effectiveness of remonte sensing for tropical coastal resources assessment and management. *Journal of Environmental Management,* 55, 157–166.

Mumby, P. J., Edwards, A. J. (2002) Mapping marine environments with IKONOS imagery: enhanced spatial resolution can deliver greater thematic accuracy. *Remote Sensing of Environment*, 82, 248–257.

Mumby, P.J., Skirving, W., Strong, A. E., Hardy, J.T., LeDrew, E.F., Hochberg, E.J., Stumpf, R.P., David, L.T. (2004a) Remote sensing of coral reefs and their physical environment. *Marine Pollution Bulletin,* 48, 219–228.

Mumby, P. J., Hedley, J. D., Chisholm, J. R. M., Clark, C. D., Ripley, H., Jaubert, J. (2004b)

The cover of living and dead corals from airborn remote sensing. *Coral Reefs*, 23, 171–183.

Mustard, J.F., Staid, M.I., & Fripp, W.J. (2001) A semianalytical approach to the calibration of AVIRIS data to reflectance over water application in a temperate estuary. *Remote Sensing of Environment,* 75, 335–349.

Paavel, P. (2008) Bio-optical properties of turbid lakes. Dissertationes Biologicae Universitatis Tartuensis, Tartu.

Pasqualini, V., Pergent-Martini, C., Pergent, G., Agreil, M., Skoufas, G., Sourbes, L., Tsirika, A. (2005) Use of SPOT 5 for mapping seagrasses: An application to Posidonia oceanica. *Remote Sensing of Environment*, 94, 39–45.

Peterson, D.L., Brass, J.A., Smith, W.H., Langford, G., Wegener, S., Dunagan, S., Hammer, P., Snook, K. (2003) Platform options of free-flying satellites, UAVs or the International Space Station for remote sensing assessment of the littoral zone. *International Journal of Remote Sensing,* 24 (13), 2785–2804.

Philipson, P. (2003) Environmental Applications of Aquatic Remote Sensing. Acta Universitatis Upsaliensis, Uppsala.

Phillips G. L., Eminson, D. & Moss, B. (1978) A mechanism to account for macrophyte decline in progressive eutrophicated freshwater. *Aquatic Botany*, 4, 103–126.

Phinn, S. R., Dekker, A. G., Brando, V.E., Roelfsema, C. M. (2005) Mapping water quality and substrate cover in optically complex coastal and reef waters: an integrated approach. *Marine Pollution Bulletin*, 51, 459–469.

Phinn, S.R., Roelfsema, C.M., Dekker, A.G., Brando, V.E., Anstee, J. (2008) Mapping seagrass species, cover and biomass in shallow waters: An assessment of satellite multi-spectral and airborne hyper-spectral imaging systems in Moreton Bay (Australia). *Remote sensing of Environment,* 112, 3413–3425.

Purkis, S., Pasterkamp, R. (2004) Integrating in situ reef top reflectance spectra with Landsat TM imagery to aid shallow tropical benthic habitat mapping. *Coral Reefs,* 23, 5–20.

Richardson, L.L. and LeDrew, E.F. (Eds.) (2006) Remote Sensing of Aquatic Coastal Ecosystem Processes. Springer.

Riegl, B. M., Purkis, S. J. (2005) Detection of shallow subtidal corals from IKONOS satellite and QTC View (50, 200 kHz) single-beam sonar data (Arabian Gulf, Dubai, UAE). *Remote Sensing of Environment*, 95, 96–114.

Robinson, I.S. (2000) Space techniques for remote sensing of environmental risks in seas and oceans. *Surveys in Geophysics*, 21, 317–328.

Rönnberg, C. and Bonsdorff, E. (2004) Baltic Sea eutrophication: area-specific ecological consequences*. Hydrobiologia*, 514, 227–241.

Sathyendranath, S. (2000). Remote Sensing of Ocean Colour in Coastal and Other Optically Complex Waters. Reports of the International Ocean-Colour Coordinating Group 3.

Sawaya, K.E., Olmanson, L.G., Heinert, N.J., Brezonik, P.L., Bauer, M.E. (2003) Extending satellite remote sensing to local scales: land and water resource monitoring using high-resolution imagery. *Remote sensing of Environment*, 88, 144–156.

Schories, D., Pehlke, C., Selig, U. (2009). Depth distribution of Fucus vesiculosus L. and Zostera marina L. as classification parameters for implementing the European Water Framework Directive on the German Baltic coast. *Ecological Indicators*, 9, 670–680.

Schramm, W. and Nienhuis, P.H. (Eds.). (1996) Marine Benthic Vegetation. Recent changes and the Effects of Eutrophication. Ecological Studies, Vol. 123. Springer.

Schweizer, D., Armstrong, R.A., Posada, J. (2005) Remote sensing characterization of benthic habitat and submerged vegetation biomass in Los Roques Archipelago National Park, Venezuela. *International Journal of Remote Sensing,* 26 (12), 2657–2667.

Stephens F.C., Louchard E.M., Reid R.P., Maffione R.A. (2003) Effect of microalgal communities on reflectance spectra of carbonate sediments in subtidal optically shallow marine Environments. *Limnology and Oceanography*, 48, 535–546.

Werdell, P. J., Roesler, C. S. (2003) Remote assessment of benthic substrate composition in shallow waters using multispectral reflectance. *Limnology and Oceanography*, 48, 557–567.

Wittlinger, S.K., Zimmermann, R.C. (2000) Hyperspectral remonte sensing of subtidal macroalgal assemblages in optically shallow waters. Proc. Ocean Optics XV. SD-ROM.

Wolter, P.T., Johnston, C.A., Niemi, G.J. (2005). Mapping submerged aquatic vegetation in the US Great Lakes using Quickbird satellite data. *International Journal of Remote Sensing,* 26 (23), 5255–5274.

SUMMARY IN ESTONIAN

Merepõhja elupaikade kaardistamine optiliselt keerukates rannikuvetes kaugseire meetodil

Rannikualad on maailmas ühed enim arenenud piirkonnad ning sinna on koondunud suur osa inimtegevusest. Samas on rannikualad väärtuslikud ka bioloogilise mitmekesisuse ning loodusressursside poolest ning paljud sealsed ökosüsteemid omavad nii majanduslikku kui ka ökoloogilist väärtust.

Põhjataimestik on rannikualade ökosüsteemide tähtis komponent, omades suurt tähtsust aine- ja energiaringes. Põhjataimestiku vöönd on oluline elupaik mereorganismidele, tagades paljudele nii paikse kui liikuva eluviisiga mereorganismidele toidubaasi ning elupaiga. Samuti on põhjataimestikul suur tähtsus ka paljude tööndusllike kalade kudesubstraadina.

Põhjataimestiku levik sõltub keskkonnatingimustest. Fotosünteesiks vajavad nad valgust ning nende kasv, ellujäämine ning sügavuslevik on otseselt seotud valgustingimustega. Käesoleval ajal on Läänemeri inimtegevuse poolt tugevasti mõjutatud. Inimtegevusest põhjustatud eutrofeerumine e. veekogude toitainetesisalduse suurenemine on üheks suurimaks ohuks Läänemere põhjataimestikule. Eutrofeerumise suurenedes halvenevad valgustingimused ning see toob omakorda kaasa muutused põhjakooslustes.

Põhjataimestik on veekeskkonna ökoloogilise seisundi indikaator ning muutused põhjakoosluste ruumilises levikus ning liigilises koosseisus aitavad hinnata rannikumere keskkonna seisundit. Senini on põhjataimestikku Läänemeres kaardistatud sukeldumismeetodil, mis on aga suhteliselt kallis, aeganõudev ning uuritava ala suurus on väga väike võrreldes Eesti rannikuvete kogupindalaga. Kaugseiremeetod võimaldaks kaardistada laialdasemaid alasid võrreldes sukeldumismeetodiga.

Käesoleva dissertatsiooni põhieesmärkideks olid: (1) koostada spektriteek Eesti rannikualade peamiste merepõhja tüüpide (liiv, kruus, savi, muda, rohevetikad, pruunvetikad, punavetikad) heleduskoefitsendi spektritest ning erinevate makrovetikaliikide puhul uurida liigisisest heleduskoefitsendi spektrite varieeruvust ; (2) mudelarvutuste teel uurida, kas ja kui sügavas vees on kaugseire meetodil võimalik Läänemere peamisi vetikarühmasid (puna-, rohe- ja pruunvetikad) üksteisest, liivast ja optiliselt sügavast veest optiliselt erinevates rannavetes eristada; (3) mudelarvutuste teel uurida multispektraalsete sensorite võimekust kaardistada erinevaid põhjatüüpe Läänemere tingimustes; (4) uurida suure ruumilise ja väikse spektraalse lahutusvõime ning keskmise ruumilise ja suure spektraalse lahutusvõimega satelliitide sobivust Läänemere rannikupiirkondade põhjataimestiku kaardistamiseks.

Töö tulemusena leiti järgmist:

Sama vetikaliigi heleduskoefitsendi spektrid on kuju poolest sarnased, kuid võivad varieeruda absoluutväärtuste poolest. See tähendab, et tõenäoliselt saab kaugseire meetodil makrovetikaid identifitseerida kolme vetikarühma tasemel, mitte aga liigi tasemel. Võrreldes meie poolt Läänemeres mõõdetud heleduskoefitsendi spektreid mujal maailmas teostatud mõõtmistega, selgus, et rohe-, pruun- ja punavetikate heleduskoefitsendi spektrid on vetikarühmade tasandil üksteisega sarnased.

Modelleerimise tulemused näitavad, et rohe-, pruun- ja punavetikate (mida esindasid vastavalt C*ladophora glomerata*, *Fucus vesiculosus* ja *Furcellaria lumbricalis)* heleduskoefitsendi spektrid erinevad üksteisest, liivast ning sügava vee heleduskoefitsiendi spektritest. Kaugseire sensorid, mille spektraalne lahutus on vähemalt sama hea nagu meie mudelil (10 nm) ning signaali ja müra suhe vähemalt 1000:1 (praegused lennuvahenditel paiknevad sensorid), suudavad neid põhjatüüpe üksteisest eristada. Seejuures on maksimaalne sügavus, kus see eristamine on võimalik, sügavamal kui nende vetikate esinemissügavus Eesti rannavetes.

Modelleerimistulemustele toetudes võib öelda, et Läänemere tingimustes on multispektraalsete sensoritega (nagu ALI, Landsat 7, QuickBird ja IKONOS) mingil määral võimalik kaardistada rohevetikaid *Cladophora glomerata*, punavetikaid *Furcellaria lumbricalis* ja pruunvetikaid *Fucus vesiculosus*. Sellegipoolest on sügavus, milleni multispektraasled riistad on võimelised vetikaid eristama madalam, kui maksimaalne sügavus, kus need vetikad Eesti rannikuvetes kasvavad.

Põhjataimestiku suure ruumilise varieeruvuse tõttu on Eesti rannikumere põhjatüüpide kaardistamisel eelistatum suure ruumilise lahutusvõimega sensorid, nagu QuickBird (2,4 m). 30-meetrise ruumilise lahutusvõimega Hyperion on Eesti rannikumere põhjatüüpide kaardistamiseks ebarahuldav, kuna erinevate põhjatüüpide varieeruvus ühe pikseli piires on suur.

Suure ruumilise lahutusvõimega multispektraalne sensor QuickBird oli võimeline Eesti rannikumere põhjatüüpe eristama paremini, kui seda võis eeldada modelleerimistulemuste põhjal. Siiski ei ole sellise sensori spektraalne lahutusvõime mitmete oluliste põhjatüüpide eristamiseks piisav ning seetõttu võib järeldada, et optimaalseim riist põhjataimestiku ulatuse ja tüübi ning vee sügavuse kaardistamiseks Eesti rannavetes on lennuvahendil paiknev suure ruumilise ja spektraalse lahutusvõimega spektromeeter.

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PUBLICATIONS

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Kutser, T., Vahtmäe, E., Martin, G. (2006). Assessing suitability of multispectral satellites for mapping benthic macroalgal cover in turbid coastal waters by means of model simulations. *Estuarine, Coastal and Shelf Science,* 67, 521–529.

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Kutser, T., Vahtmäe, E., Metsamaa, L. (2006). Spectral library of macroalgae and benthic substrates in Estonian coastal waters. *Proceedings of Estonian Academy of Sciences*. *Biology-Ecology*, 55, 4, 329–340.

Kutser, T., Metsamaa, L., Vahtmäe, E., Strömbeck, N. (2006). Suitability of MODIS 250 m resolution band data for quantitative mapping of cyanobacterial blooms. *Proceedings of Estonian Academy of Sciences. Biology-Ecology*, 55, 4, 318–328.

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