BALANCE Interim Report No. 3

Feasibility of hyperspectral remote sensing for mapping benthic macroalgal cover in turbid coastal waters of the Baltic Sea

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0 PREFACE

This report is a BALANCE product and focus on the potential use of hyperspectral remote sensing for mapping benthic macroalgae cover in turbid coastal waters of the Baltic Sea. More information about BALANCE can be found at http://www.balance-eu.org.

Quantitative analysis of coastal marine benthic communities enables adequately estimate the state of coastal marine environment, provide better evidence for environmental changes and describe processes that are conditioned by anthropogenic forces. Remote sensing could provide a tool for mapping bottom vegetation if the substrates are spectrally resolvable. We measured reflectance spectra of green- (*Cladophora glomerata*), red- (*Furcellaria lumbricalis*), and brown (*Fucus vesiculosus*) macroalgae and used a bio-optical model in estimating whether these algae distinguish optically from each other, from sandy bottom or deep water in turbid water conditions of the Baltic Sea. The simulation was carried out for three different water types: 1) CDOM-rich coastal water, 2) coastal waters not directly impacted by high CDOM discharge from rivers but with high concentration of cyanobacteria, 3) open Baltic waters. Our modelling results indicate that the reflectance spectra of *Cladophora glomerata*, *Furcellaria lumbricalis*, *Fucus vesiculosus* differ from each other and also from sand and deep water reflectance spectra. The differences are detectable by remote sensing instruments at spectral resolution of 10 nm and SNR better than 1000:1. Thus, the lowest depth limits where the studied macroalgae grow do not exceed the depth where such remote sensing instruments could potentially detect the spectral differences between the studied species. The BALANCE activities in the pilot areas shall lead to the development of generic tools and guidelines for marine spatial planning in the Baltic Sea. In a longer perspective, the management practices should improve in order to better safeguard and protect marine resources.

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1 INTRODUCTION

Sustainable management of coastal environments requires regular collection of accurate information on recognized ecosystem health indicators (Phinn et al., 2005). The objective of benthic algal monitoring 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 the state of coastal marine environment, provide good evidence for environmental changes and describe processes that are conditioned by anthropogenic forces. Distribution of macrophytes is largely determined by light (e.g. Duarte, 1991; Nielsen et al., 2002) and therefore also by parameters affecting the light climate. Increased nutrient concentrations stimulate the production of phytoplankton which reduce water clarity and consequently the depth penetration of macrophytes (Nielsen et al., 2002; Schramm, 1996). Therefore, the depth distribution of macrophytes should indirectly predict the state of eutrophication in coastal waters.

The ratio of annual to perennial macroalgae is considered as potential water quality indicator as high nutrient concentrations generally favour the growth of ephemeral flora (Sand-Jensen & Borum, 1991; Pedersen, 1995). According to the Baltic Sea Marine Environment Protection Commission (HELCOM, www.helcom.fi) *Cladophora glomerata* (green algae) and *Fucus vesiculosus* (brown algae) are considered as the key species to monitor the effect of eutrophication in the Baltic Sea. *Fucus vesiculosus* forms extensive belts in 1-2.5 m depth range in relatively clear waters. On the contrary mass occurrence of *Cladophora glomerata* is usually observed in eutrophic waters. Thus, shifts from *Fucus* to *Cladophora* may indicate increase in trophic status of the sea area.

Distribution of phytobenthic communities is determined by substrate availability, depth and light climate on local scale and salinity on the Baltic Sea scale (Kautsky, 1988; Martin, 2000). Green algae usually occur in the shallowest part of the littoral on hard substrate. *Cladophora glomerata* is wide spread over the Baltic Sea area and is not limited by salinity. It usually forms monodominant belts on the hard substrate close to the water edge (Söderström, 1963). Brown algae are presented by variety of species with morphological characteristics from ephemeral filamentous species to perennial species with large thalli. *Fucus vesiculosus* is the largest macroalgae found in the Baltic Sea. In areas with hard substrate with moderate exposure this species is very important as habitat forming element of coastal ecosystem, supporting high biodiversity along rocky shores of Western and NE Baltic. The brown alga is not found at salinities lower than 3-4 PSU. The third studied species is unattached form of the red alga *Furcellaria lumbricalis*. The species is found on sandy gravel surfaces in the waters of West Estonian Archipelago (Martin & Torn, 2004). It is commercially harvested for galactants, but is also important habitat for juvenile fish.

Mapping benthic algal cover with conventional diving methods provides great accuracy and high resolution (Werdell & Roesler, 2003) yet is very expensive and requires extensive time and manpower to cover large water bodies and long stretches of coastline. Remote sensing can potentially provide a tool for fast mapping of benthic algal cover provided the algal species are separable from each other based on their optical signatures.

Mapping of substrate cover types and their biophysical properties has been carried out successfully in optically clear, shallow coastal and reef waters (Anstee et al., 2000; Dekker et al., 2001; Lubin et al., 2001; Kutser & Jupp, 2002; Phinn et al., 2005). In comparison with the reflectance properties of coral reef benthic communities (Hochberg & Atkinson, 2000, 2003; Minghelli-Roman et al., 2002; Hochberg et al., 2003; Karpouzli et al., 2004) and seagrass communities (Fyfe, 2003; Louchard et al., 2003; Pasqualini et al., 1997), there are a few studies on the reflectance properties of algal communities. The algal spectral reflectance properties have been published in some of the coral reef benthic community studies (Hochberg & Atkinson, 2000; Kutser et al., 2000, 2003). Besides, a few published reflectance spectra of various algal types are presented by Siegel (1992), Maritorena et al. (1994), Anstee et al., (2000), Wittlinger & Zimmerman (2000), Hochberg et al., (2003) and some other publications.

Remote sensing techniques have been successfully applied for operational mapping of the biophysical properties of clear waters, but turbid waters continue to represent a challenge to remote sensing techniques (Phinn et al., 2005). The Baltic Sea waters are relatively turbid and there is a few information about optical properties of benthic algae in the Baltic Sea (Siegel, 1992; Kutser et al., 2006a). Baltic Sea is an intracontinental shallow marine environment under strong influence of human activities and terrestrial material. Baltic Sea waters are often dominated by coloured dissolved organic matter (CDOM). Large discharge from rivers, limited exchange with marine waters of the North Sea, and a relatively shallow sea floor significantly influence the optical properties of the Baltic (Darecki & Stramski, 2004).

The objective of this report is to show how the spectral reflectance of benthic algae is translated into remote sensing reflectance. In shallow water, where the depth is much less than the potential for light to penetrate, a large fraction of the subsurface light reaches the sea floor, where portions of the light energy are absorbed, reflected back into the overlying water column or re-emitted as fluorescence (Ackleson, 2003). In 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., 1992). Previous simulations to investigate the influence of water column depth indicate that much of the useful signal reflected from submersed plant material is rapidly attenuated with increasing depth of the water and bottom reflectance is diminished as it is filtered through the water column (Lyzenga, 1978; Maritorena et al. 1994; Wittlinger & Zimmermann, 2000; Holden and LeDrew, 2001; Lubin et al., 2001; Kutser et al., 2003).

Our aim was to demonstrate whether (1) the three important species of benthic macroalgae are separable from each other, from sandy bottom or deep water as well as (2) 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 of the Baltic Sea area.

2 METHODS

2.1 In situ measurements of benthic reflectance spectra

Reflectance spectra of benthic macroalgae 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 instrument is 3 nm. Reflectance was calculated as a ratio of radiance from algae to radiance from standard Spectralon panel.

Specimens of most typical green, brown and red benthic macroalgae – *Cladophora glomerata*, *Fucus vesiculosus*, and *Furcellaria lumbricalis* were studied. In deeper (2-5 m) areas the specimens were collected into water-filled plastic bags. Reflectance measurements of wet algae were carried out on the shore immediately after landing of the boat. In shallower waters the reflectance spectra were measured immediately on board of the boat. Three reflectance spectra of each specimen were measured and an average spectrum of a typical specimen of each species was used in following model simulations. Reflectance spectrum of wet mineral sand was used in the model analysis.

2.2 Bio-optical modelling

A simple model was used to simulate diffuse reflectance just below the water surface. It has been shown by Maritorena et al. (1994) that the diffuse reflectance of shallow waters just below the water surface can be calculated using following formula:

$$R(0-,z) = R_\infty + (R_b - R_\infty)\exp(-2Kz), \qquad (1)$$

where z is water depth, Rb 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, Kd, is a good approximation for K.

Kirk (1984) has demonstrated with Monte Carlo simulations that the Kd at the midpoint of euphotic zone, zm, can be expressed as a function of the absorption (a), and scattering (b) coefficients, and the cosine of the incident photons just below the surface (μ0) in accordance with

$$K_d(z_m) = \frac{1}{\mu_0}\left[a^2 + (0.473\mu_0 - 0.218)ab\right]^{1/2}. \qquad (2)$$

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

$$R_{\infty}(0-,\lambda) = (-0.629\mu_0 + 0.975)\frac{b_b(\lambda)}{a(\lambda)+b_b(\lambda)}, \quad (3)$$

where a(λ) is the total absorption coefficient, bb(λ)is the total backscattering coefficient, and λ is wavelength. Mapping of benthic algal cover is usually carried out in July-August period when the algal cover is at its maximum. On the other hand it is reasonable to carry out remote sensing measurements close to noon. Therefore, μ0 was taken equal to 0.85 to simulate the best case scenario for the Baltic Sea i.e. measurements are carried out around noon in the middle of summer and at the latitude of the central Baltic Sea.

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

$$a(\lambda) = a_w(\lambda) + a^*_{Ph}(\lambda)C_{Chl} + a_{CDOM}(\lambda) + a^*_{SM}(\lambda)C_{SM}, \quad (4)$$

where aw is the absorption coefficient of pure water, a*Ph(λ) is the chlorophyll-specific spectral absorption coefficient of phytoplankton, aCDOM(λ) is the spectral absorption coefficient of CDOM, and a*SM(λ) is the specific absorption coefficient of suspended matter. CChl and CSM are concentrations of chlorophyll-a and total suspended matter.

The total spectral backscattering coefficient bb(λ) can be described:

$$b_b(\lambda) = 0.5b_w(\lambda) + b^*_{b,Ph}(\lambda)C_{Chl} + b^*_{b,SM}(\lambda)C_{SM}, \quad (5)$$

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

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

$$a_{CDOM}(\lambda) = a_{CDOM}(400)\exp[-S(\lambda - 400)]. \quad (6)$$

According to estimations by Mäekivi and Arst (1996) S=0.017 gives the best result in case of the Baltic Sea, Estonian and Finnish lakes. Specific absorption coefficient of suspended matter was taken from Kutser (1997), and specific scattering coefficients of suspended matter, as well as backscattering probabilities (backscattering to scattering ratio), were taken from study by Kutser et al. (2001). Absorption and scattering coefficients as well as backscattering probability of a cyanobacterium *Aphanizomenon flos-aquae* (Kutser et al., 2006b) were used in the modelling as this species is often dominating Baltic Sea waters in July-August when algal mapping is normally carried out for monitoring purposes.

The modelling was carried out for three distinctly different water types: 1) CDOM-rich waters near a river estuary, 2) coastal waters not directly impacted by high CDOM discharge from rivers but with high concentration of cyanobacteria, 3) open Baltic waters. Concentrations of optically active substances in these three water types are shown in Table 1. The concentrations were taken from real measurements from a coastal area near a CDOM-rich river inflow, a bay with slightly elevated CDOM concentration caused by a creak with moderate CDOM concentrations, and from an offshore area near West-Estonian Archipelago where the concentrations of optically active substances resemble the values typical for the open Baltic Sea waters. Shallow water reflectance spectra were calculated with 0.5 m increments for each bottom type. The R(0-) of optically deep water was calculated for each water type.

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

The signal to noise ratio (SNR) specifications currently attainable by airborne remote sensing systems such as AVIRIS and CASI, flown under ideal circumstances, are about 1000:1 (Dekker et al., 2001). About 48% of just below the water surface upwelling irradiance is reflected back into the water column. Thus, the SNR in terms of just below the water surface reflectance, R(0-), has to be 500:1 to be able to detect differences in reflectance spectra by the above mentioned instruments (Dekker et al., 2001). In actual remote sensing environments there are sources of noise in the image data such as atmospheric variability, the air-water interface with swell, wave and wavelet induced reflections and refraction of the diffuse skylight and direct sunlight (Dekker at el., 2005). The environmental SNR can be estimated from image data using method proposed by Dekker & Peters (1993) and further developed by Brando & Dekker (2003) and Wettle et al. (2004). However, our aim was not testing the suitability of the particular instruments for mapping of benthic macroalgae. Therefore, for simplicity of calculations, 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.

3 RESULTS

We collected reflectance spectra of sand, green, brown and red benthic macroalgae, measured without an overlying water column. Green macroalgae were represented by a reflectance spectrum of *Cladophora glomerata*, red macroalgae by free floating form of *Furcellaria lumbricalis*, and brown macroalgae by *Fucus vesiculosus*. Figure 1a shows the spectral reflectance for each bottom type.

We evaluated the effects of water column on remotely sensed spectra by simulating bottom-reflected light through different depths of water column for a given concentrations of water column constituents. Figures 1b-1d represent reflectance spectra of various substrates just below the water surface in 1 m deep water for three different water types. The deep water spectrum was calculated using the same concentrations of optically active substances as the shallow water spectra.

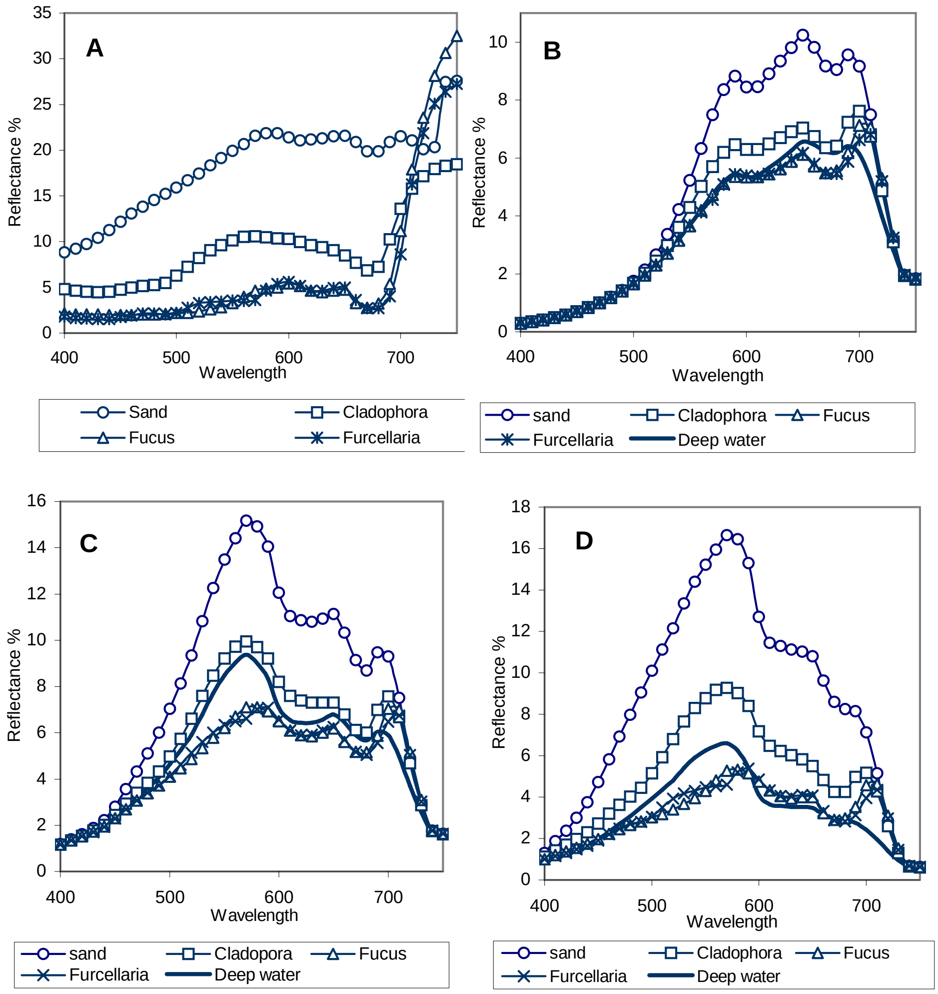

Fig. 1. *Just below the water surface reflectance spectra (A) Substrates measured without an overlaying water column. (B) Simulated reflectance spectra of various substrates and deep water at 1 m depth in water type 1. (C) Simulated reflectance spectra of various substrates and deep water at 1 m depth in water type 2. (D) Simulated reflectance spectra of various substrates and deep water at 1 m depth in water type 3.*

The amount of optically active water constituents was taken relatively high in the water type 1 (CChl=6 mg/m3, CSM=6 mg/l and aCDOM(400)=15 m-1. CDOM absorbs light strongly in the shorter wavelengths and even in 1 m deep water different substrates were not distinguishable at wavelengths shorter than 520 nm. Water itself absorbs light in the red and near-infrared region of the spectrum and thus the reflectance values at the longer wavelengths were dramatically decreased, and become almost identical for all substrates at wavelengths greater than 730 nm. Reflectance values of *Fucus and Furcellaria* at 1 m water depth were lower than that of deep water, but reflectance values of sand and *Cladophora* at 1 m water depth were higher than that of deep water.

The reflectance values are considerably higher in case of type 2 waters (CChl=10 mg/m3, CSM=5 mg/l and aCDOM(400)=3 m-1). The concentration of chlorophyll in type 2 waters was taken typical to mild bloom values. We used specific absorption and scattering coefficients of a typical Baltic Sea bloom-forming cyanobacterium *Aphanizomenon flos-aquae*. The species contains phycocyanin that absorbs light near 630 nm. The absorption of phycocyanin is quite strong in case of high chlorophyll concentrations as seen in reflectance spectrum of deep water. Except for green macroalgae all studied substrates also have the absorption feature near 630 nm. Thus, it is more complicated to recognize different benthic substrates during cyanobacterial blooms than in case of the dominance of other algae that do not contain phycocyanin.

The clearest water type (CChl=2 mg/m3, CSM=2 mg/l and aCDOM(400)=1.5 m-1) resembles the open Baltic Sea waters near West-Estonian Archipelago. CDOM has significant effect on reflectance spectra even in the open Baltic Sea waters. However, the effect was much smaller than in case of other water types and CDOM absorption made no differences between the reflectance of red and brown macroalgae at wavelengths 510-600 nm (in 1 m deep water).

3.1 Spectral differences between substrates and deep water

Majority of macroalgal cover in the Baltic Sea occurs in conditions similar to the type 3 water of our study as cyanobacterial blooms occur during short time and extremely CDOM-rich waters are located only near some river mouths. Therefore we concentrated on estimating the potential (e.g. the maximum depth penetration) of remote sensing to map benthic algal in this particular water type.

The maximum depth at which sandy bottom can be separated from the deep open Baltic water was 10 m if we assumed that the above water remote sensing instrument has 1000:1 SNR (Fig. 2a).

Green macroalgae are spectrally different from optically deep water, but the difference was not as high as in case of sand. Differences are largest near 710 nm, but these differences were above the hypothetical instrument SNR level only in waters shallower than 2.5 m. In shallower water (up to 1.5 m deep) the difference was also high near 600 nm. The differences between green macroalgae and deep water were seen in waters down to 7 m deep and the spectral region where these differences occurred was between 550-580 nm (Fig. 2b).

The reflectance signal of the brown macroalgae *Fucus vesiculosus* was lower than reflectance of deep water within wavelength ranges 450-590 nm and 660-680 nm. *Fucus* had a relatively low reflectance and the differences between algae and deep water reflectance spectra were small, except near 710 nm. However, these differences were above the hypothetical instrument SNR level only at depths above 2.5 m. The next peaks in the spectral difference spectra were near 540 nm, 610 nm and 650 nm. The differences between brown macroalgae and deep water were detectable in waters down to 6 m deep in the wavelength range 540-560 nm in the type 3 waters (Fig. 2c).

The spectra of the red macroalgae *Furcellaria lumbricalis* and deep water were different down to 6.5 m within spectral range 560-570 nm if a remote sensing sensor with 1000:1 SNR is used (Fig. 2d).

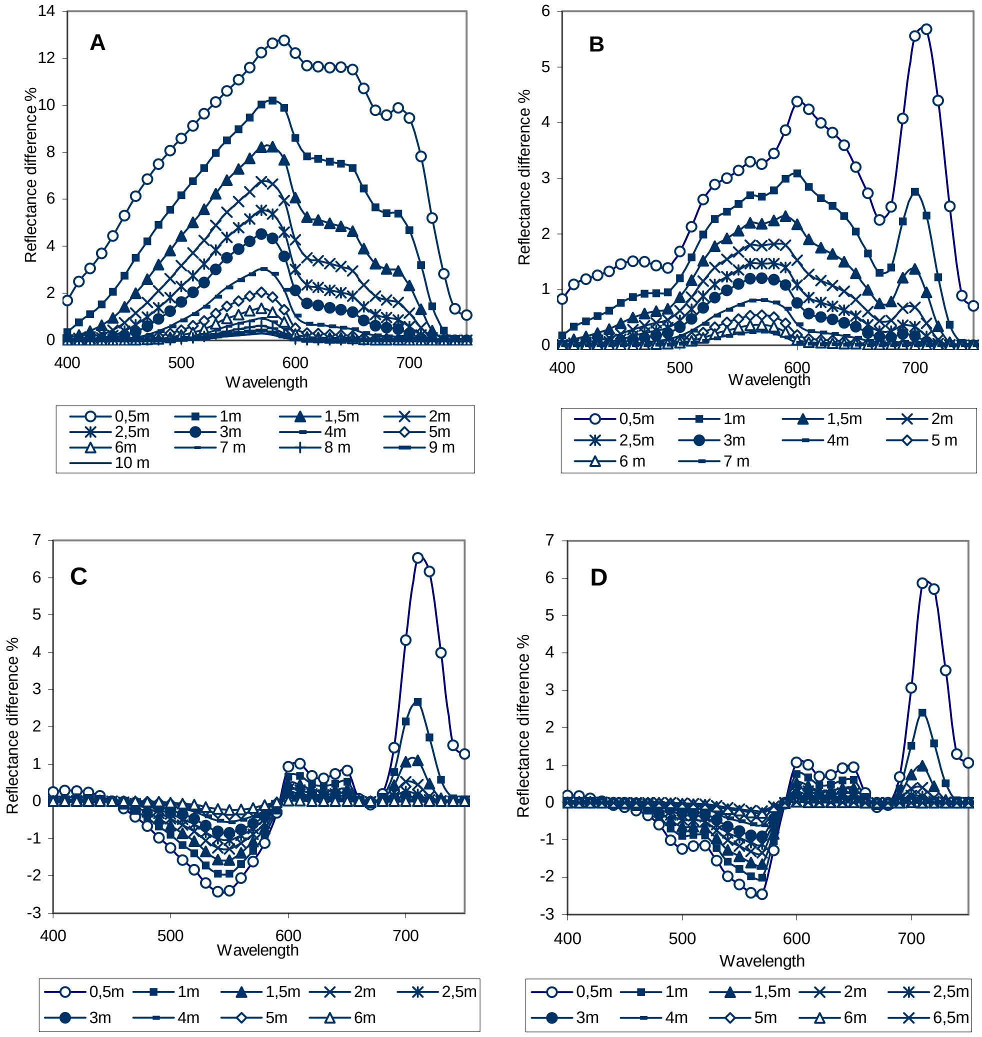

Fig.2. Spectral differences between simulated reflectance spectra (A) sand and deep water. (B) Green algae (Gladophora glomerata) and deep water. (C) Brown algae (Fucus vesiculosus) and deep water. (D) Red algae (Furcellaria lumbricalis) and deep water. Calculations are made for various water depths indicated in the legend.

3.2 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 (Fig 3). Spectral differences between sandy bottom and all three macroalgal species were relatively high. The differences between the reflectance spectra of sand and green algae were smaller than the differences between sand and red or brown macroalgae as *Fucus* and *Furcellaria* are relatively dark substrates compared to sand. The differences between sand and Cladophora were detectable in waters down to 10 m deep. The differences between reflectance of sand, and reflectance spectra of red or brown macroalgae were detectable down to 11 m at wavelengths near 570 nm.

The differences between reflectance of green and brown macroalgae were largest at 550 nm. *Fucus* had higher reflectance than *Cladophora* only in wavelengths greater than 710 nm, but those differences cannot be detected in waters deeper than 1 m. Our simulations show that the maximum depth at which those species can be separated by hyperspectral remote sensing is 8 m if the wavelength range 550-570 nm is used.

The differences between the reflectances of *Cladophora* and *Furcellaria* were largest at 570 nm. Some slight differences were detectable down to 8 m when remote sensing instruments with 1000:1 SNR are used.

Both *Furcellaria* and *Fucus* had relatively low reflectance values. Considerable differences appear in wavelengths near 520 nm, 570 nm and 700 nm being highest near 570 nm. Thus, the latter can be used to distinguish brown macroalgae from red macroalgae at depth down to 4 m. Difference near 520 nm can be used to differentiate these two substrate types at depth down to 2.5 m and difference near 700 nm can be used only in waters down to 1.5 m deep.

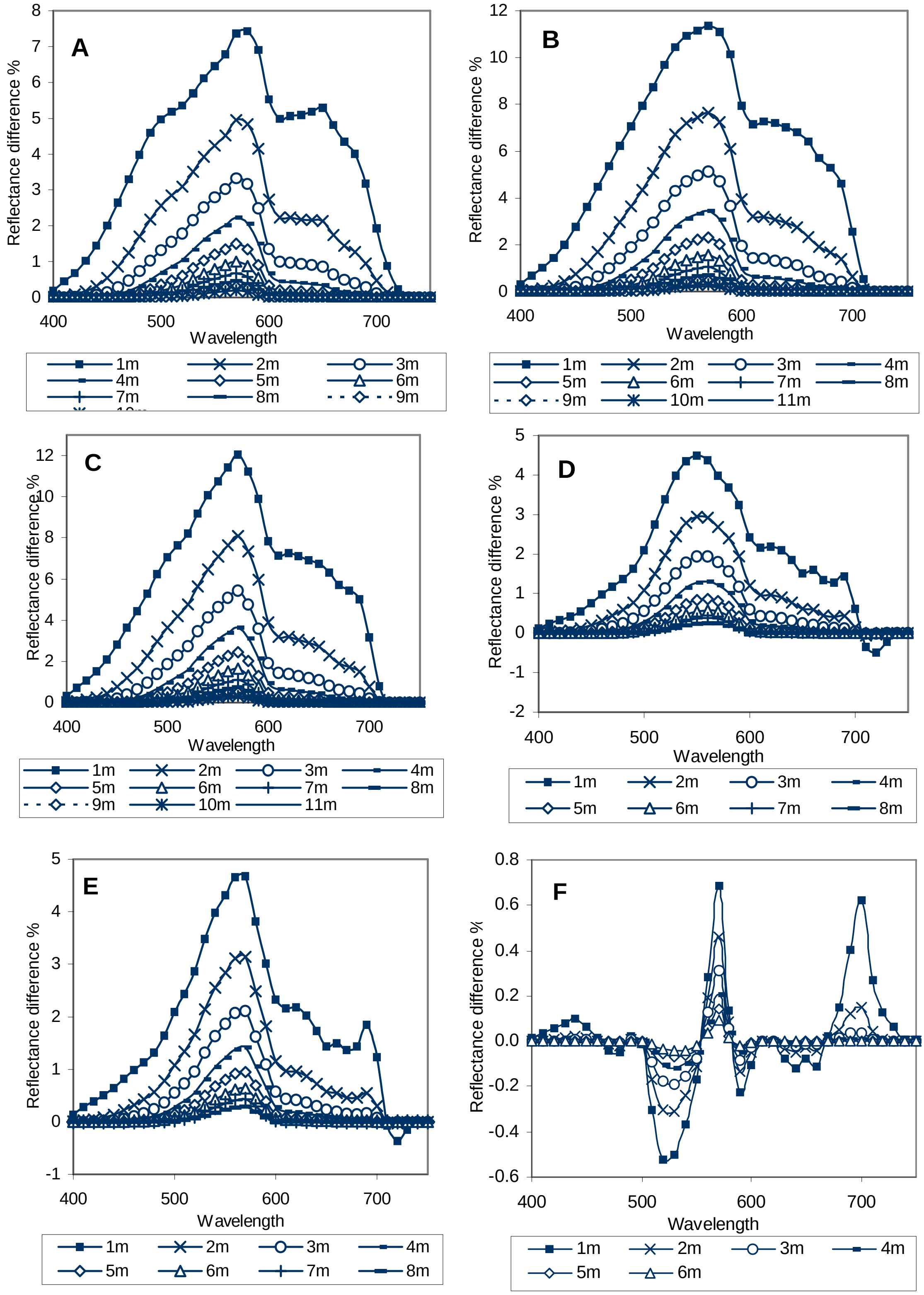

Fig.3. *Spectral differences between simulated reflectance spectra (A) Sand and green (Gladophora glomerata) algae. (B) Sand and brown algae (Fucus vesiculosus). (C) Sand and red algae. (D) Green algae (Gladophora glomerata) and brown algae (Fucus vesiculosus). (E) Green algae (Gladophora glomerata) and red algae (Furcellaria lumbricalis). (F) Brown algae (Fucus vesiculosus) and red algae (Furcellaria lumbricalis). Calculations are made for various water depths indicated in the legend.*

4 DISCUSSION

All studied substrates have high reflectance in the near-infrared part of the spectrum. Sand has higher reflectance spectra than algae in visible part of spectrum. The reflectance of green macroalgae is higher than that of other measured algae in visible part of spectrum. 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. The reflectance of other red algae measured in different parts of the World oceans by different authors (Maritorena et al., 1994; Kutser et al., 2003; Hochberg et al., 2003; Dekker et al., 2005; Kutser et al., 2006a) are similar to that of *Furcellaria*. *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 (Maritorena et al., 1994; Kutser et al., 2003; Hochberg et al., 2003; Dekker et al. 2005; Kutser et al., 2006a). Siegel (1992) has measured reflectance spectra of brown macroalgae *Fucus serratus* in the Baltic Sea. His results differ from our reflectance spectra of Fucus *vesiculosus* and the reflectance spectra measured by other above mentioned authors. The reason may be the method which was used by Siegel. He measured downwelling irradiance above the water surface and upwelling radiance just below the water surface. Distance from the upwelling radiance sensor to the bottom was not mentioned in his publication, but it seems that the water column between the macroalgae and the senor affected his measurements of benthic reflectance. Usually there is chlorophyll-a absorption feature near 680-690 nm even in case of “abiotic” substrates like sand and the feature is very distinctive in reflectance spectra of macroalgae and corals. However, the feature is missing in reflectance spectra measured by Siegel (1992). This indicates that the water column between benthic macroalgae and the sensor influenced Siegel’s measurements significantly in red part of spectrum where the absorption of light by water increases exponentially with increasing wavelength.

Reflectance spectra of green macroalgae are similar to the reflectance spectra of green algae and seagrasses measured in different parts of the world oceans (Siegel, 1992; Maritorena et al., 1994; Kutser et al., 2003; Hochberg et al., 2003; Dekker et al., 2005; Kutser et al., 2006a). This suggests that green algae and seagrasses may be hardly separable from each other based on their reflectance spectra. This statement, however, requires further studies.

The depth where sandy bottom can be detected in CDOM-rich estuaries (water type 1) is small (1-3 m). Different macroalgae are practically impossible to recognise in such waters. However, there is usually no bottom vegetation in these areas as the amount of light available for photosynthesis is not sufficient even in so shallow water. Exceptional river plumes with CDOM-rich water can cover larger areas than usual and reach areas where the benthic macroalgal cover exists. However, the remote sensing campaigns can be organised during more favourable conditions when the river plumes are smaller.

Cyanobacteria can cause similar effects on reflectance spectra than red- and brown macroalgae as their pigment phycocyanin causes absorption feature near 630 nm. Results by Kutser et al. (2006b) show that all cyanobacteria, independently of the species, can cause this effect if the chlorophyll concentration in water exceeds 8-10 mg/m3. Cyanobacteria can also form surface scum that is spectrally similar to terrestrial vegetation

(Kutser, 2004). The scum is optically opaque and no information about benthic type or water column properties can be obtained when the surface scum occurs. Therefore, it is not reasonable to carry out remote mapping of shallow water benthic habitat during cyanobacterial blooms.

Our modelling results indicate that the green macroalgae *Cladophora glomerata* can be separated from deep water with hypothetical remote sensing instruments which SNR is better than 1000:1 in water depths down to 7 m, from sand, brown- and red macroalgae in waters down to 8 m deep. However, *Cladophora glomerata* forms monodominant belts near the shore and does not occur in belts at depth greater than 2.5 m in Estonian coastal waters. Majority of the *Cladophora* belts are found above 1 m deep water. Thus, it is relatively easy to separate *Cladophora* belts from deep water areas as remote sensing could potentially permit detecting *Cladophora* in depths that are greater than the depths where it grows in nature. This concerns areas not affected by high CDOM absorption and suspended matter loads e.g. conditions similar to our water type 3.

Fucus vesiculosus reflectance spectra can be separated from deep water reflectance at depths less than 6 m deep, from sand in waters down to 11 m deep and from *Furcellaria lumbricalis* at depths above 4 m when hyperspectral instruments with at least 1000:1 SNR are used. Six meters is also the maximum depth where the *Fucus vesiculosus* grows in belts in Estonian coastal waters as individual colonies can be found in deeper waters (Martin & Torn, 2004). Thus, mapping the extent of *Fucus vesiculosus* belts with remote sensing should not be a problem when hyperspectral instruments are used.

Unattached *Furcellaria lumbricalis* may grow at depths down to 10 m deep in Estonian coastal waters (Martin & Torn, 2004). However, the commercially harvestable community occurs at depths of 5-7 m in the West Estonian Archipelago. Optical water properties in the study area resemble the type 3 water in most of the time, except in case of storms when the amount of suspended matter may be much higher due to resuspension. Thus, most of the commercial stock of *Furcellaria lumbricalis* is in depths where it is potentially detectable by hyperspectral remote sensing sensors.

High concentrations of suspended matter would blur features in the shallow water reflectance spectra decreasing the possibility to recognise different benthic macroalgae with remote sensing. However, usually it is possible to select dates for mapping benthic macroalgal cover when the amount of re-suspended sediments in water is low.

Bloom of cyanobacteria may affect our capability of separating different shallow water bottom types with remote sensing as phycocyanin, present mainly in cyanobacteria, can cause similar effects in remote sensing reflectance as presence of brown- or red benthic macroalgae in shallow water.

Natural conditions in the Baltic Sea favour in several ways using of remote sensing in mapping of benthic algal cover. For example *Cladophora glomerata* and *Fucus vesiculosus* form almost monodominant 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. Bottom topography of the Baltic Sea is relatively flat in many regions. Water depths usually increase slowly. For example water depths may be around 1-2 meter several hundreds of meters from the shoreline. It means that from remote sensing point of view there is a need to separate different bottom types at the same depths as the depth variation is small.

The most difficult depth zone for remote sensing is 2-5 m. At those depths water column has already significant influence on measured reflectance spectra complicating recognition of different macroalgae groups. On the other hand this is the depth zone where all studied algae species may occur.

It must also be noted that reflectance of macroalgae of the same species may be variable due to physiological state or light conditions where it was growing. We have collected several specimen of each species from different regions of Estonian coastal waters (Kutser et al. 2006a). The measurement results indicate that shape of the reflectance spectra within each of the three studied species is consistent, but the reflectance values may vary. The reflectance spectra used in the present study are typical values for each species and sand. Therefore, the actual maximum depths where different substrates are separable from each other may be slightly more or slightly less than the results presented in this paper depending whether the reflectance values in a particular location are more similar or more different from each other than the "mean" spectra used by us.

Consistency in spectral shape within the species suggests that it would be preferable to use such methods in classifying remote sensing images of shallow water which are based on spectral shape rather than absolute values. For example the spectral library modelled by us can be used for classifying shallow water images using procedures like Spectral Angle Mapper (SAM). This technique, when used on calibrated reflectance data, is relatively insensitive to illumination and albedo effects since it is invariant to multiplication of signatures by a constant. In aquatic environments SAM with modelled spectral libraries has been used in classifying coral reef bottom types (Kutser & Jupp, 2002) and in quantitative mapping of cyanobacterial blooms (Kutser, 2004). Using of SAM with hyperspectral data allows mapping of water depth and bottom type simultaneously when hyperspectral data is used (Kutser & Jupp, 2002).

The spectral library created by us for studying potential of hyperspectral remote sensing instruments can be used directly for classifying remote sensing imagery in further stages of the study as the modelling results indicate that using of remote sensing is feasible for mapping shallow water benthic algal cover in such relatively turbid waters like the Baltic Sea.

5 CONCLUSIONS

Our modelling results indicate that the reflectance spectra of *Cladophora glomerata*, *Furcellaria lumbricalis*, *Fucus 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) and SNR is better than 1000:1. In that case the maximum depths where the algae occur in Estonian coastal waters are smaller than the depths where such remote sensing instruments could potentially detect the spectral differences between the studied substrates.

The modelling results indicate that the possibility of mapping benthic macroalgal cover in such CDOM dominated environment like the Baltic Sea is not much smaller than in clear waters. CDOM absorbs light in shorter wavelength region where the differences between different benthic macroalgae are relatively small and hardly detectable by remote sensing instruments anyway. The main differences between the reflectance of benthic macroalgae occur in green to red part of spectrum. Absorption of light by water molecules has the most significant contribution to the depth of penetration of light in this spectral region. Thus, the depths, where benthic macroalgae can be separated from each other by remote sensing, do not differ significantly in clear and CDOM dominated coastal waters. Exceptions here are extremely CDOM rich dark brown estuarine waters, but usually there is not much benthic algal cover in such regions due to lack of photosynthetically available radiation.

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About the **BALANCE** project:

This report is a product of the BSR INTERREG IIIB project "BALANCE".

The BALANCE project aims to provide a transnational marine management template based on zoning, which can assist stakeholders in planning and implementing effective management solutions for sustainable use and protection of our valuable marine landscapes and unique natural heritage. The template will be based on data sharing, mapping of marine landscapes and habitats, development of the blue corridor concept, information on key stakeholder interests and development of a cross-sectoral and transnational Baltic zoning approach. BALANCE thus provides a transnational solution to a transnational problem.

The BALANCE partnership is composed of the following institutions based in 10 countries: The Danish Forest and Nature Agency (Lead), The Geological Survey of Denmark and Greenland, The National Environmental Research Institute, The Danish Institute for Fisheries Research, WWF Denmark, WWF Germany, Institute of Aquatic Ecology at University of Latvia, Estonian Marine Institute at University of Tartu, Coastal Research and Planning Institute at Klaipeda University, Metsähallitus Natural Heritage Service, The Finnish Environment Institute, The Geological Survey of Finland, WWF Finland, The Swedish Environmental Protection Agency, The National Board of Fisheries – Department of Research and Development, The Geological Survey of Sweden, County Administrative Board of Stockholm, Department of Marine Ecology at Gothenburg University and WWF Sweden.

The following institutes contribute as consultants to the partnership: The Geological Survey of Norway, Norwegian Institute for Water Research, DHI Water and Environment, The Leibniz Institute of Marine Sciences, The Sea Fisheries Institute, The Finnish Game and Fisheries Research Institute, Metria Miljöanalys and The Nature Conservancy.

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