USING HIGH SPATIAL RESOLUTION REMOTE SENSING, SPATIAL MODELLING AND WEB MAP SERVICES FOR SPATIAL PLANNING IN SHALLOW COASTAL WATER ENVIRONMENTS

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Abstract – Spatial planning decisions (borders of protected areas, locations of infrastructure, etc.) are often based on insufficient data as costs of *in situ* measurements (diving, video, grab sampling) are too high to cover larger areas and there is often a shortage of trained personnel. On the other hand, model simulations show that water depth and broad taxonomic groups of benthic algae (e.g. red, green and brown algae) can be mapped using remote sensing methods in optically complex coastal waters. In the present study we mapped the distribution of benthic macroalgae and invertebrates using traditional diving, a remote underwater video device and airborne (CASI) remote sensing in a brackish water habitat. Using statistical relationships between traditional and modern mapping techniques we built a GIS spatial model capable of predicting water depth, cover of algae and broad types of macroalgal habitats in optically complex coastal waters. The models were published on the internet through a standard protocol of web map services. Such spatial planning tool combining strong sides of different methods enables integrated and more efficient management of the studied coastal sea.

1. INTRODUCTION

The structure of benthic macrophyte and invertebrate habitats are known to indicate the quality of coastal water areas (Kotta et al., 2008b; Kotta and Witman, 2009). Thus, a large-scale analysis of the spatial patterns of coastal marine habitats enables adequately estimate the status of valuable coastal marine habitats, provide better evidence for environmental changes and describe processes that are behind the changes. Knowing the spatial distribution of benthic habitats is important also from coastal management point of view. For example spatial planning decisions (borders of protected areas, locations of infrastructure, etc.) require data over large areas but the decisions are often made based on insufficient data as costs of *in situ* measurements (diving, video, grab sampling) are too high. Remote sensing based mapping has been suggested as it is spatially comprehensive (Dekker et al., 2001) and has been shown to be more cost-effective than fieldwork (Mumby et al., 1999).

Our previous results (Kutser et al., 2006a; Vahtmäe et al., 2006) show that water depth and broad taxonomic groups of benthic algae (e.g. red, green and brown algae) can be mapped using remote sensing methods also in optically complex coastal waters like the Baltic Sea. On the other hand Vahtmäe and Kutser (2007) have shown that high spatial resolution is critical in many sites as the spatial heterogeneity of benthic habitats is very high in Estonian coastal waters. Therefore, it was decided to use an airborne remote sensing instrument to get data with spatial resolution similar to scale of patchiness of the benthic habitats and to have spectral resolution suitable for recognition of as many as possible benthic types.

Relying solely on remote sensing without extensive field survey may not provide sufficient detail in some cases. Therefore, remote sensing has been recommended as a complementary technology (Green et al., 2000). Our aim is to develop GIS-based tool that combines of remote sensing, *in situ* data, and spatial modelling into a spatial planning and coastal monitoring tool.

2. METHODS
2.1 Study Site and *In Situ* Measurements

The study was carried out in the Vilsandi National Park, the Western Estonian Archipelago, the Baltic Sea in August–September 2010 (Figure 1). The study area was approximately 210 km^2. Most of the area is less than 5 meters deep although water depth reaches 15 meters in some parts of the study area.

Figure 1. Location of the study site is indicated with a red box

Both *in situ* optical and biological measurements were performed in the study area. Optical measurements were carried out to characterise the sea bottom and the water column. Absorption, scattering and backscattering coefficient as well as volume scattering function spectra were measured with Wetlabs instrument set (ac-s, eco-bb3, eco-vsf3) and water samples were taken to laboratory for chlorophyll-a, CDOM and suspended matter (both organic and inorganic) concentration measurements.

Optical properties of different benthic habitats were measured with Ramses spectrophotometers in the wavelength range of 350-900 nm. Reflectance measurements were carried out above the water surface and near the bottom. To characterise the water leaving signal also without reflection of direct and diffuse light from the water surface we placed the upwelling radiance sensor just below the water surface and the downwelling irradiance sensor above the water surface.

In order to describe benthic habitats underwater video, frame, benthic dredge and grab samples were collected from 321 sites (Figure 2). The total coverage of macrophytes, coverage of visually distinguishable species (macrophytes, benthic invertebrates) and substrate (mud, clay, sand, gravel, pebbles and cobbles, boulders (diameter >20 cm), rock) were estimated from the video data using the continuous video estimation method described in Möller et al. (2009). The biological sampling was done a day before and during the CASI over flight. Ramses and underwater video were used in all IOP (inherent optical water properties) stations and underwater video was used in all Ramses stations.
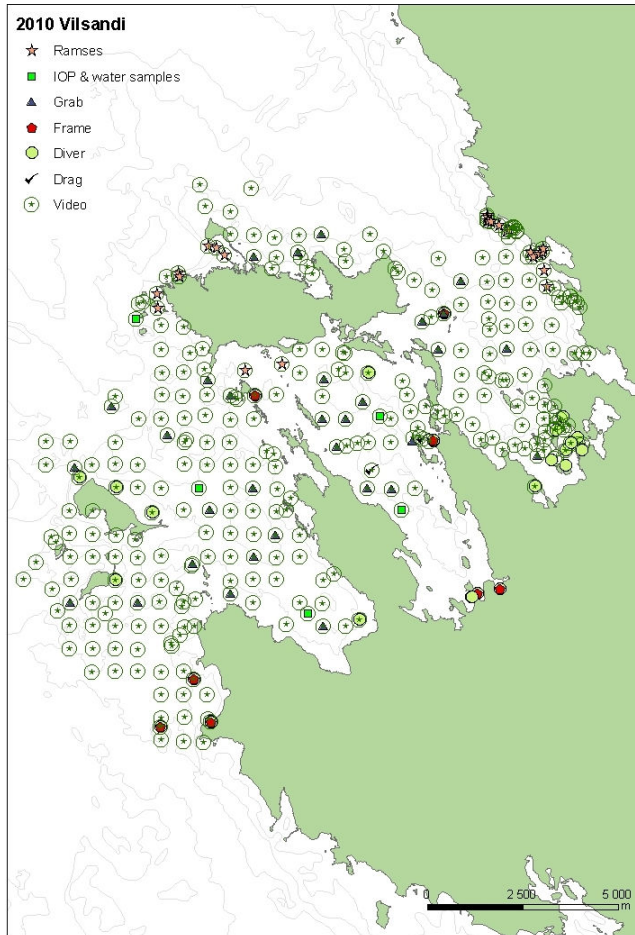

Figure 2. Locations of the sampling stations. Legend indicates the methods used.

2.2 Remote Sensing Data

The airborne imagery was collected using CASI sensor in September 1, 2010. CASI was flown with 1 m spatial resolution. Spectra were collected in the wavelength range 339-1054 nm. There were 25 spectral bands in use. Most of the spectral bands were around 5 nm except the first and last bands which were around 20 nm wide. Geo-correction of the data was performed by the Latvian Institute for Environmental Solutions i.e. the institute carrying out the CASI flights. We corrected the imagery for cross track illumination effects and mosaiced the flight lines together.

2.2 Statistical analyses and modelling

Multivariate data analyses on abiotic environment and benthic communities were performed by the statistical program PRIMER version 6.1.5 (Clarke and Gorley 2006). Similarities between each pair of samples were calculated using a zero-adjusted Bray–Curtis coefficient. The coefficient is known to outperform most other similarity measures and enables samples containing no organisms at all to be included. Non-metric multidimensional scaling analysis (MDS) on untransformed data of benthic species coverages was used to quantify the dissimilarities between study sites.

Statistical differences in benthic species coverage among the optically assessed habitat types were assessed by the ANOSIM permutation test.

In order to model the probability distribution of underwater benthic habitat types we used GLM logistic regressions using Statistica 9.1 software. The logit transformation was applied as the response variable followed a binomial error distribution. Models were validated using the measurements that belonged to the validation data sets i.e. not used in the models. Model performance was additionally tested using the area under the curve of a receiver operating characteristic plot.

3. RESULTS AND DISCUSSION

The landscape-scale diversity of benthic habitats was high in the study area spanning from unvegetated sandy bottoms to complex hard bottom macrophyte habitats. On the other hand species diversity was low as only 32 benthic macrophyte and invertebrate taxa were recorded in the study area. Such low diversity relates to the low salinity environment of the Baltic Sea (Kotta et al., 2008a).

Dominating annual seaweeds were the green alga *Cladophora glomerata* and the red alga *Ceramium tenuicorne*. The number of perennial algae was low but their biomasses were relatively high with *Fucus vesiculosus* being the prevailing habitat forming brown algal species. The study area also hosted a lush charophyte vegetation, the higher plants *Potamogeton* spp. and the drifting macroalgal mats. The bivalve *Mytilus trossulus* and the cirriped *Balanus improvisus* prevailed among benthic invertebrates.

A critical point in remote sensing habitat mapping is finding a suitable benthic classification scheme. Remote sensing can detect only optical signatures of different habitats but the benthic classification has to be reasonable also from biological or ecological point of view. Tests in coral reef environments have shown (Andréfouët et al., 2003) that using of a single classification scheme based on coral reef ecology around the world does not provide the accuracy needed as some benthic types may be inseparable based on their optical signatures. We have tested several classification schemes by analyzing our *in situ* data and spectral information (both airborne and *in situ*) available from the study site. A preliminary classification scheme was developed (Table 1) and used in classification of the CASI image. Studies on the most appropriate classification scheme for the area is still work in progress.

Benthic habitat map (Figure 3) was produced from the CASI imagery using maximum likelihood classifier, data from our *in situ* measurements and the benthic classes given in Table 1.

Table 1. Benthic classes used in processing the CASI image from Vilsandi area.

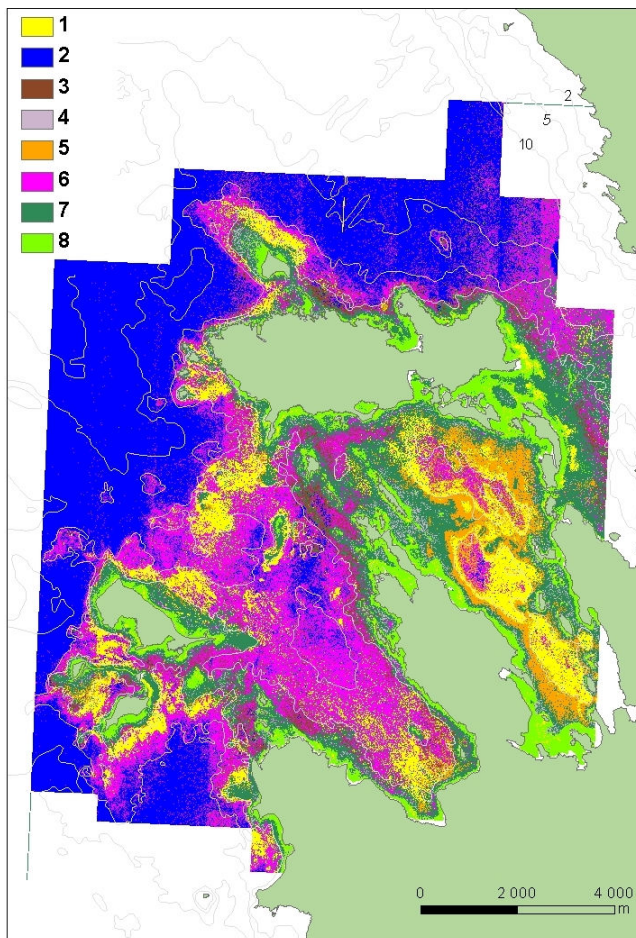| Code	Description
1	Bare sand, no vegetation
2	Areas > 5m depth, no information
3	*Fucus vesiculosus* community
4	Bare limestone , no vegetation
5	Thick charophyte community , substrate not visible
6	Thick filamentous algae, substrate not visible
7	Higher plants on sandy substrate
8	Green filamentous algae on limestone cobbles-pebbles and rock

Figure 3. Benthic habitat map of the Vilsandi National Park area produced from CASI airborne imagery using 8 benthic classes described in the Table 1.

An MDS analysis did not clearly distinguish benthic habitats; rather, there was a continuum of macroalgal cover from one species to another (Figure 4). Nevertheless, ANOSIM analysis indicated that the majority of the optically assessed habitats are clearly separated at $p < 0.05$ in terms of macrophyte and invertebrate species cover. The brown seaweed *Fucus vesiculosus* habitats and more than 5 m areas statistically distinguished from all studied habitat types. Hard bottom habitats covered with filamentous algae did not distinguish from light soft bottoms, charophyte, dense macroalgal and high plant habitats. In addition light soft bottoms and dense macroalgal communities did not distinguish from bare rock habitat.
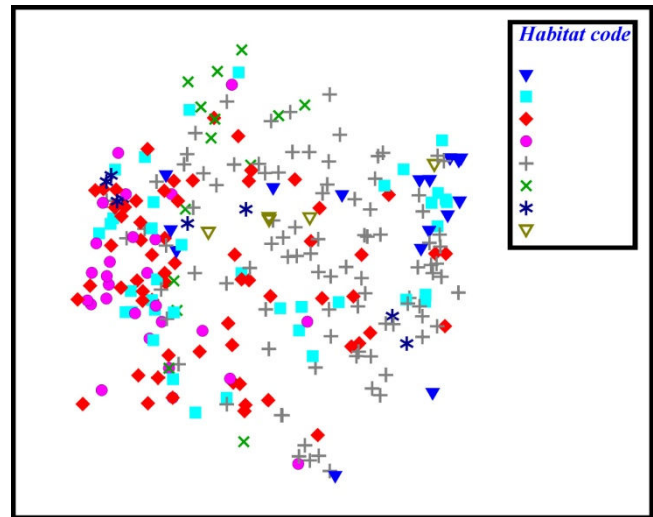

Figure 4. An MDS ordination of benthic macrophyte and invertebrate coverage. Different colors indicate the optically assessed habitat types.

A spatial modelling of a key benthic macrophyte and invertebrate species also demonstrated that there was a strong linkage of optically collected remote sensing data and the structure of benthic habitats. The used optical and statistical methods are useful and cost-efficient tools in the modelling of the distribution of higher plants, charophytes and the brown seaweed *Fucus vesiculosus*. The latter species is functionally very important as it is the only perennial habitat forming species in the in the Baltic Sea region and it is known to host a high number of benthic macrophyte and invertebrate species. In addition the *Fucus vesiculosus* habitats are important as spawning and refuge areas for fish (Kotta et al., 2008a).

Finally, the modelled layers were published in the internet through a standard protocol of web map services. We used the ESRI Arc Server platform which on the one side provides end-users multiple features and flexibility and on the other side enables the usage of large databases. In order to fasten the performance of the web map services, the published maps and queries were integrated within the Flex environment. Altogether, the published layers enable managers the possibility to reduce the overall environmental impact of multiple human uses by taking into account the spatial distribution of valuable and vulnerable benthic habitats and directing dangerous activities away from high sensitivity and low recovery sites.

Another approach in image classification is to use measured and/or modelled spectral libraries (Kutser et al., 2002, 2006b). This method allows to classify bottom type and water depth simultaneously and does not require fieldwork at the time of

image collection if the optical properties of typical bottom types are known and water properties can be estimated. We have a spectral library of typical macroalgae, higher plants, substrates (mud, sand, etc.) collected in Estonian coastal waters (Kutser et al., 2006c). The benthic reflectance spectra, inherent optical properties collected in the study site and Hydrolight 5.0 radiative transfer model allow us to simulate water reflectance spectra for all possible combinations of bottom types, water depth and its optical properties. Classifying the image with the modelled spectral library requires high quality of the image data i.e. the reflectance spectra in the atmospherically corrected image have to be correct. We collected reflectance data from boats using Ramses spectrophotometers during CASI over flight. Aforementioned allows us to say that the atmospheric correction of CASI imagery needs further improvements before the reflectance data reaches quality where the spectral library approach can be used in image classification.

REFERENCES

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

K.R. Clarke, and R.N. Gorley, Primer v6. User Manual ⁄ Tutorial. Primer-E, Plymouth: 192 pp, 2006.

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

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

J. Kotta, V. Lauringson, G. Martin, M. Simm, I. Kotta, K. Herkül, and H. Ojaveer, "Gulf of Riga and Pärnu Bay." In *Ecology of Baltic Coastal waters*, U. Schiewer (Ed.). Springer. Ecological Studies, 197, 217–243, 2008a.

J. Kotta, T. Paalme, T. Püss, K. Herkül, and I. Kotta, „Contribution of scale-dependent environmental variability on the biomass patterns of drift algae and associated invertebrates in the Gulf of Riga, northern Baltic Sea," J. Mar. Syst., 74, Supplement 1, S116-S123, 2008b.

J. Kotta, and J. Witman, „Regional-scale patterns". In: Marine Hard Bottom Communities. Wahl., M. (ed.), Ecological Studies, 206, Springer-Verlag, Berlin Heidelberg, p.p. 89-99, 2009.

T. Kutser, I. Miller, and D.L.B. Jupp, 2002, Mapping coral reef benthic habitat with a hyperspectral space borne sensor," Proceedings of Ocean Optics XVI, Santa Fe, 2002.

T. Kutser, E.Vahtmäe, and G. Martin, „Assessing suitability of multispectral satellites for mapping benthic macroalgal cover in turbid coastal waters by means of model simulations," Estuarine, Coastal and Shelf Science, vol 67, p.p. 521-529, 2006a.

T. Kutser, I. Miller, D.L.B. Jupp, "Mapping coral reef benthic substrates using hyperspectral space-borne images and spectral libraries" Estuarine Coastal and Shelf Science, vol 70, 449-460, 2006b.

T. Kutser, E. Vahtmäe, and L. Metsamaa, "Spectral library of macroalgae and benthic substrates in Estonian coastal waters," Proceedings of the Estonian Academy of Sciences. Biology.Ecology, vol 55, p.p. 329-340, 2006c.

T. Möller, J. Kotta, and G. Martin, "Effect of observation method on the perception of community structure and water quality in a brackish water ecosystem", Marine Ecology, vol. 30, p.p. 105-112, 2009.

P.J. Mumby, E.P. Green, A.J. Edwards, and C.D. Clark, „The cost-effectiveness of remote sensing for tropical coastal resources assessment and management," Journal of Environmental Management, vol 55, p.p. 157–166, 1999.

E. Vahtmäe, T. Kutser, G. Martin, and J. Kotta, „Feasibility of hyperspectral remote sensing for mapping benthic macroalgal cover in turbid coastal waters – a Baltic Sea case study," Remote Sensing of Environment, vol 101, p.p. 342-351, 2006.

E. Vahtmäe, and T. Kutser, „Mapping bottom type and water depth in shallow coastal waters with satellite and airborne remote sensing," Journal of Coastal Research, vol SI50, p.p. 185–189, 2007.