Hyperspectral remote sensing and analysis of intertidal zones: A contribution to monitor coastal biodiversity

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Abstract

This report deals with the use of hyperspectral remote sensing methods in rocky intertidal areas. These methods were evaluated in a pilot study analyzing hyperspectral imagery from the rocky intertidal of Helgoland. The paper discusses the potential of hyperspectral image analysis for monitoring elements of coastal diversity apparent in this area and discusses the potential and limitations of the method. This is especially relevant for application-oriented monitoring of protected areas and for coastal zone management. The discussed issues also contribute to monitoring works within European programs such as the Water Framework Directive or the Natura 2000 network. The results show that a classification based on a spectral library allows a mapping of the dominant intertidal macrophyte vegetation and general intertidal structures. Limitations remain for separation of mixed vegetation types which cannot be identified without ancillary data sources. One major potential for future use of these methods is their efficiency for high-resolution geospatial data acquisition. The integration of remote sensing techniques in GIS-based automated monitoring systems will help to combine different levels of resolution as well as different data sources needed to detect significant changes in structural and compositional coastal biodiversity. The success of this approach also depends on the selection of the best suitable imaging sensor and an appropriate analysis approach which fits the specific needs in the areas of investigation.

1 Introduction

The detection of changes in the natural environment is of special interest since increasing global environmental problems are affecting and threatening our basic living conditions. Before these ongoing processes can be understood, they have to be identified and observed – which is a major task of monitoring systems. The harmonization of environmental policies in the European Union (EU) (e. g. shown in the Natura 2000 network or the EU Water Framework Directive) and the changing perception of environmental risks during recent years raised the need for monitoring programs on a broad range of environmental issues which finally led to a European-wide monitoring initiative GMES (Global Monitoring for Environment and Security[1]) (EU, 2006, 2007; FRENCH, 2004).

In this context, coastal zones have also become part of politically initiated monitoring programs since they are recognized as a key ecosystem in preservation efforts of biodiversity. Within this ecosystem, the intertidal areas are an important transitional zone between the marine and terrestrial realms and an important area of ecological research. Growing coastal development increases the need for such data to improve coastal zone management (CZM).

Data acquisition for monitoring purposes is a special challenge in the coastal zones, as access time is limited by daily tidal fluctuations. Monitoring systems are often cost and time consuming, so new approaches are needed to make this more effective. Remote sensing based monitoring is increasingly used not only in research but also in applied fields. In part, this is because remote sensing is regarded as a cost-effective monitoring method for efficient long-term surveillance of larger or party inaccessible areas. Independent of the cost-aspect, it is a valuable contribution to gain more knowledge on the processes of changing ecosystems in the context of global change and also supports biodiversity conversation (BLASCHKE, 2002; CLARKE, 1986; REISE, 1989).

For terrestrial portions of the coast, methods of long-term monitoring are well developed (e. g. CRACKNELL, 1999; FRENCH, 2004; WEIERS, 1999). In the open ocean, ship-based sampling and acoustic remote sensing are used for habitat management and constantly enhanced by major technical advances (BARNES ET AL., 2003; KOSTYLEV ET AL., 2001). The intertidal zone stands midway, inaccessible by ship and ecologically distinct from terrestrial environments. Remote sensing is an appropriate way to gather basic information of wide areas in the intertidal zones.

Hyperspectral sensors are able to measure the reflection of the landscape as an image built from many narrow spectral bands similar to laboratory- or field-spectrometers. The result is a continuous spectral pattern for each pixel of a hyperspectral image – composed of dozens to hundreds of spectral bands. It is not simply the high number of bands which characterizes the specifications of a hyperspectral sensor. Equally significant are the narrow and close spacing of the spectral bands. These advanced sensors have a high potential to measure unique spectral responses of different ecological conditions (RICHARDS and JIA, 1999; VAN DER MEER and DE JONG, 2003).

The presented pilot study was conducted by the Alfred-Wegener-Institute for Polar and Marine Research (AWI / Bremerhaven, Germany) at the island of Helgoland (North Sea, Germany) in order to evaluate the potential of hyperspectral remote sensing methods to aid research on the ecology of intertidal areas and their constant monitoring. The main objective was the evaluation of suitable methods in hyperspectral image analysis with a focus on the special ecological condition in the rocky intertidal area of Helgoland. Further tasks

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[1] http://www.gmes.info

included the utilization of these methods in a scientific context as well as from the general perspective of CZM.

2 Methodological approach

2.1 Study area

The study area on the island of Helgoland is located in the northern and northeastern rocky intertidal areas of the main island (Figure 1). The rocky substrates of the intertidal zone result from the special geologic development of the island which is – in terms of ecological conditions – unique in the German North Sea. The rocky intertidal here is characterized by a stable red sandstone abrasion platform which is covered by a variety of brown, red and green seaweeds that compose unique biotopes within the German North Sea (BARTSCH and TITTLEY, 2004; PODJACKI ET AL., 2003).

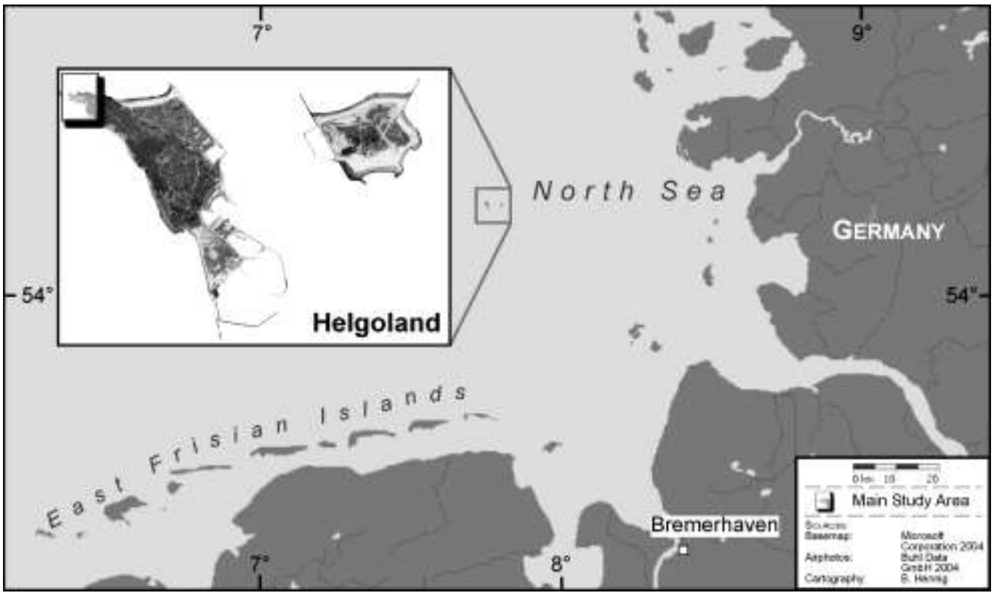

Fig. 1: Overview of the study area on the island of Helgoland, Germany

2.2 Data

With the goal to assess as many details of biodiversity as possible in the intertidal study area, a high spectral resolution remote sensing sensor is just as critical as a high spatial resolution instrument to detect the fine grain structure of the intertidal biotopes. Each of these criteria was met with ROSIS[2] (Reflective Optics System Imaging Spectrometer), an airborne sensor developed by the German Aerospace Centre (Deutsches Zentrum für Luft- und Raumfahrt - DLR[3]), which (unlike spaceborne sensors) also allowed image acquisition times to be synchronized with low spring tides.

ROSIS operates with a pushbroom scanner technique which allows it to record all spectral responses of a pixel at the same time. The sensor covers 512 pixels in a row while a maximum of 115 spectral bands from 430 nm in the visible light to 860 nm in the near infrared are covered. (Thiemann et al., 2001; van der Piepen, 1995). In the present campaign a spatial resolution of 0.84 m per pixel was reached. The recorded data were delivered radiometrically and geometrically corrected. During preprocessing, a total of 14 so-called bad bands were eliminated leaving 101 spectral channels for the further analysis steps (see Thiemann and Bartsch, 2005 for technical details of the flight campaign). The flight campaign was accompanied by a groundtruth survey, recording representative biological spots with the aid of a global positioning system (GPS).

2.3 Analysis

The main part of the feasibility study was focused on hyperspectral image analysis, with the challenge of finding a suitable approach to analyze these complex coastal data. A 3D cube depiction of a section line in the northern intertidal gives a first impression of the high spectral variance especially in the near infrared region of the reflected light (Figure 2), indicating that these wavelengths are of special interest during data analysis.

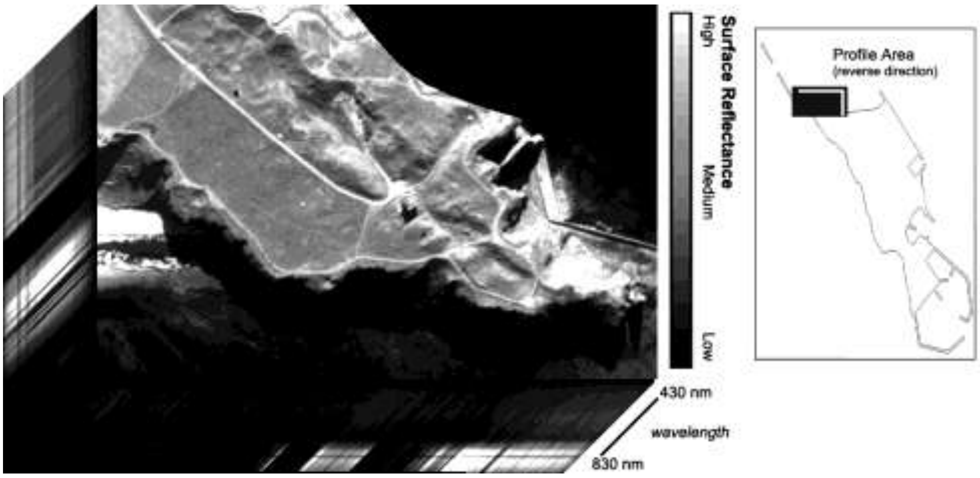

Fig. 2: 3D image cube along a transect in the northern intertidal

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[2] http://www.op.dlr.de/ne-oe/fo/rosis/home.html

[3] http://www.dlr.de/

Due to the lack of comparable studies especially on remote sensing of fine grain biotope structures which include sub-meter patches, a new analytical approach was needed. A semi-empirical method integrating groundtruth information to prioritize further investigation was employed (Figure 3). For the data analysis the software ENVI (Environment for Visualizing Images - Version 4.0) by Research Systems (now ITT Visual Information Solutions[4]) was used. Due to the lower spectral response and a more gradual transition from the intertidal, the water-covered areas were included in the image analysis.

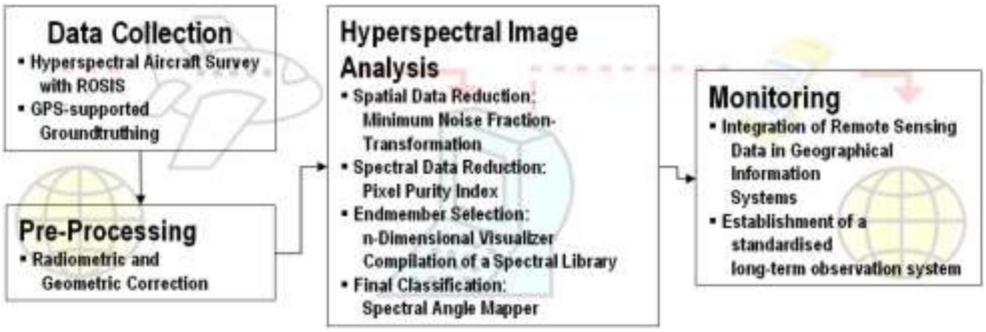

Fig. 3: Main steps in building a remote sensing-based monitoring system

The first analysis step was based on a statistical approach calculating spatial and spectral data reduction to detect suitable spectral endmembers. Spatial data reduction was performed with a principal component analysis using ENVI's minimum noise fraction (MNF) transformation. The reduced data were further examined calculating the so-called pixel purity index (PPI) to detect those pixels which are spectrally most significant. These pure pixels were examined in the n-Dimensional Visualizer. By means of a manual inspection of these purest pixels in the image, reasonable endmember matching features based on groundtruthing were derived. These endmembers were used to set up a spectral library which was the basis for the main analysis. The image classification was performed using the spectral angle mapper (SAM) which takes the spectral similarity of pixels into account. This approach has been evaluated in detail for the diverse biotope structure of the Helgoland intertidal, where the most heterogeneous biotope structures were found and an extended set of groundtruth data was available.

In addition, a concept of using between-band differences and ratios following the concept of the normalized difference vegetation index (NDVI) was applied to the data to verify the general vegetation-dominated biotopes (CAMPBELL, 2006; GOWARD, 1991; VAN DER MEER and DE JONG, 2003).

Another classification approach, transforming hyperspectral to simulated multispectral data (with six bands distributed over the visible light wavelength and two covering the near infrared), was tested to rate the advantage of the hyperspectral dataset.

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[4] http://www.ittvis.com/

3 Results

The analysis of the data permitted the extraction of 20 spectral classes which were used to perform the final SAM classification. The comparison of the data with the ecological background information and groundtruth data helped to summarize the classes and to match them with information on ecological features.

The spectral classes of the Helgoland classification corresponded well to the main vegetation types and discriminated the structures dominated by either red, green or brown seaweeds as well as faunal habitats (e.g. poorly vegetated mussel beds). Differentiation of individual species had limited success and some mixed vegetation types were not confidentially classified. Further spectral classes separated water and sandy areas. Figure 4 shows an extract of the feature class mapping in the northern intertidal of Helgoland. Among the mapped features are feature classes for areas dominated by either red, green or brown algae and sparsely vegetated areas dominated by mussels and limpets. In Figure 4, the original classes which included patches with e.g. different dense composition of similar dominant species have been combined to major component classes. These show a more homogeneous picture and clarify the general distribution of the major components within this area.

Nevertheless, a patchiness resulting from high structural complexity is still evident in this generalized classification result. BLASCHKE (2000) and BLASCHKE and STROBL (2001) refer to this problem as the *salt-and-pepper* effect caused by approaches treating each pixel in the same way. Furthermore, so called *edge effects* at the borderlines of larger biotope sites are a conspicuous symptom in the classified Helgoland data. Presumably, this is caused by a diffuse spectral response from changing geomorphological structures.

The results of the simulated multispectral data analysis showed that the complex fine grain biotope structure of the Helgoland intertidal could not be classified with an accuracy achieved in the original hyperspectral ROSIS data analysis.

An accuracy assessment was performed to estimate the quality of the classification results. This was done following the approach described by CONGALTON and GREEN (1999). It combines the classification and groundtruth data in an error matrix. To implement the classification data in the matrix, the derived spectral classes were labeled with the best corresponding ecological information (Table 1). The overall accuracy averaged 75.9 %.

Transitional zones cannot be judged by an accuracy assessment approach which only uses the categories ‘right’ or ‘wrong’ for each control pixel. It will be a task for basic methodological research to evaluate new accuracy assessment approaches for a better assessment of spatially high resolution remote sensing data. These methods should take into account the balance between the spatial scale (study area size, pixel size, point precision) and the thematic scale (number of thematic classes, hybrid classes, transition zones, errors in terms of spectral similarity between several features).

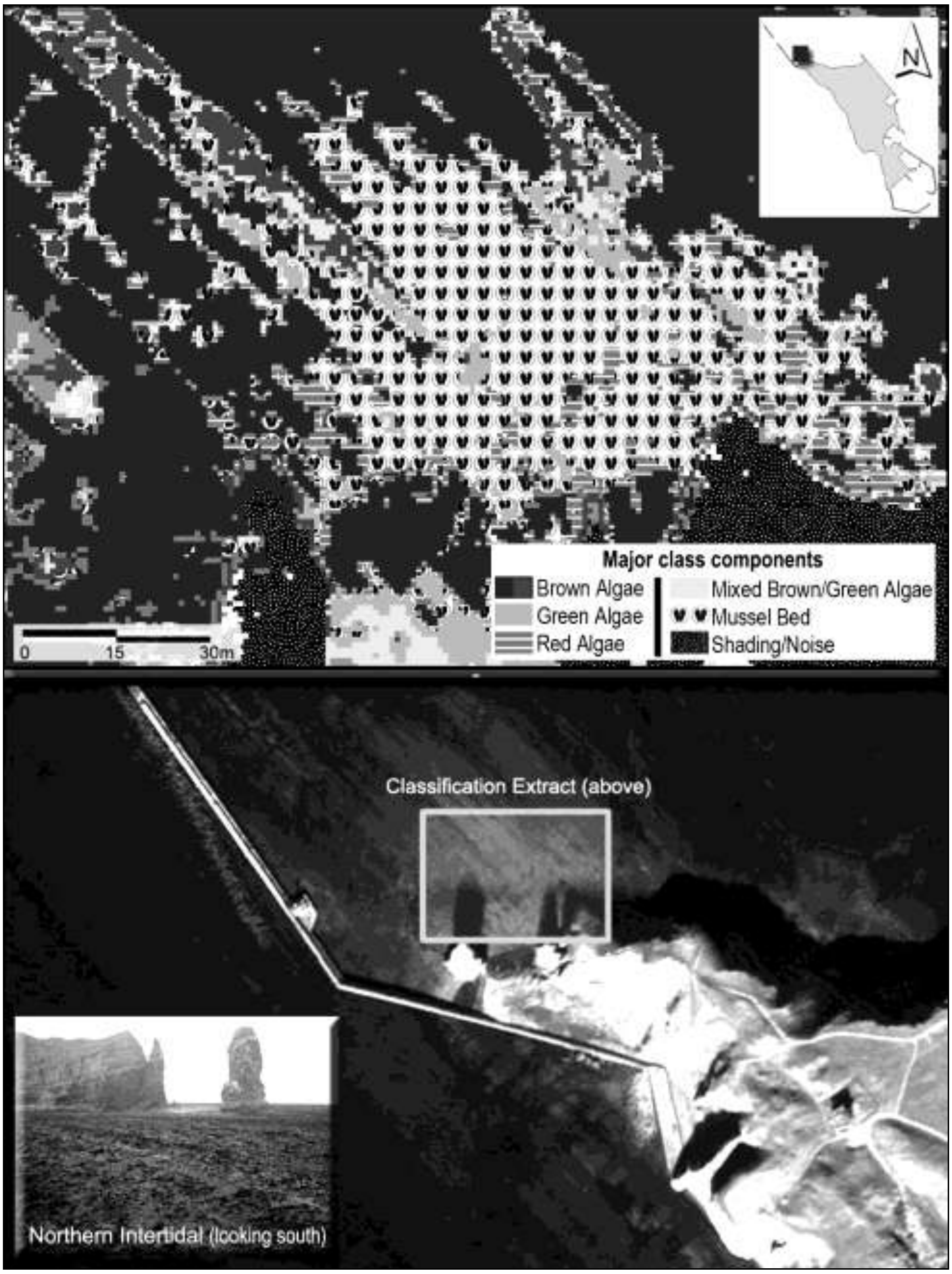

Fig. 4: Extract of the Helgoland classification results (above) in the northern intertidal (photo inset) and the corresponding area in a ROSIS depiction (below)

Tab. 1: Error matrix of the classification results showing the main feature classes

		Reference Data										
		No Vegetation	Brown Algae	Dense Brown Algae.	Red Algae	Green Algae	Kelp	Vegetated Channels	Mussel bed	Barnacles	**Total**	**User´s Accuracy %**
Classified Data	No Vegetation	9						6			15	60
	Brown Algae		19		9			4			32	59,4
	Dense Brown Algae			38	4						42	90,5
	Red Algae				24			2			26	92,3
	Green Algae					18					18	100
	Kelp					3	17	8			28	60,7
	Vegetated Channels					1	3	20			24	83,3
	Mussel bed								27	9	36	75
	Barnacles	3							12	30	45	66,7
	Total	12	19	38	37	22	20	40	39	39	266	76,4
	Producer's accuracy %	75	100	100	64,9	81,8	85	50	69,2	76,9	78,1	75,9

The complex geomorphological and related biological structure of the rocky intertidal at Helgoland contributes inconsistency to classification results. The fine-grain complexity also causes the described negative effects of pixel-based classification techniques (salt-and-pepper, edge effects). These effects cannot be prevented since the algorithm tolerates one-pixel large classes even in high resolution areas. To set thresholds for larger groups of pixels in the classification is not suitable. This would influence the results considerably if the small scale of the biotopes (which can be as small as the spatial resolution of one pixel) is taken into account. In addition, no biotope is so homogeneous that it consists of pixels with exactly the same spectral responses.

The subsequent interpretation of these differences as well as the consideration of additional information (e. g. small scale elevation data) to calibrate the classification results can be quite valuable to locate and better understand these marginal zones and to develop image analysis techniques to reduce these unwanted effects.

Beyond these needs for further methodological research, different aspects are of interest from a more application-oriented point of view. The results suggest that the general approach is also a suitable way of analyzing hyperspectral data of intertidal coastal zones to obtain ecological information for larger areas in an efficient manner. It has also been shown that background knowledge of the study area is needed to increase the precision of classification results. Nevertheless, detection of different species of the same genus (e. g. different *Fucus* species) was not possible in this approach, indicating that remote sensing cannot replace basic field work. If however remote sensing data are taken back to the field, e. g. by integrating remote sensing data, classification results and further biotope information in portable, D-GPS linked mobile GIS environments, future field work can greatly benefit from the methodological headway using these techniques.

Thus, the integration of remotely sensed data in geographical information systems can be the basis for a powerful and meaningful tool to improve the future use of remotely sensed data. The danger of building just another data layer in a GIS, as described by EHLERS (2002), is of course high. Therefore, an integrated and hybrid processing approach – sensitive to the specific subject of interest – must be evaluated when transferring classification results to the GIS. The correct conversion of the raster-to-vector data without losing basic information is only the first step. Further integration of existing data should also be considered whenever possible, not just to better visualize but also to use further data as ancillary sources to specify classifications with regard to their specific environment (Figure 5). In the introduced case study, this would include e. g. the automated integration of elevation data in image classification techniques to better separate edge effects from changes in the real spectral response of the vegetation.

However, such a high level of detail is not always needed to benefit from the depicted methods. Observations of sediment structures as they are typical e.g. for the areas of the mud-flat Wadden Sea along Germanys North coast are time-consuming, and some areas are poorly accessible due to the muddy substrate, so the methods developed here are potentially useful for a comprehensive monitoring program of such areas (HENNIG, 2005).

For further operational use of the spectral data, current field studies of different coastal surroundings should be used to combine this background information with remote sensing data. These results could be used to build and calibrate a spectral library for future operational use in different settings and more independent from a specific sensor. With such an approach, the remote sensing surveys become a powerful tool in geospatial data acquisition – and thus more than a cartographic approach to map the location of geomorphological, hydrographical and ecological structures. Compared to the traditional use of true color or b/w orthophotos, this approach to use additional spectral information allows a more objective as well as an automated extraction of knowledge that is behind the spectral information.

The advantages of hyperspectral data become obvious in the analysis of complex biotope structures such as in the rocky intertidal of Helgoland. Nevertheless it should be kept in mind to take into consideration that not always a higher spectral resolution is needed for the extraction of useful ecological information, so that depending on the investigated surroundings less expensive – e.g. multispectral satellite data – can also bring up adequate results also in coastal and intertidal environments (HENNIG, 2005).

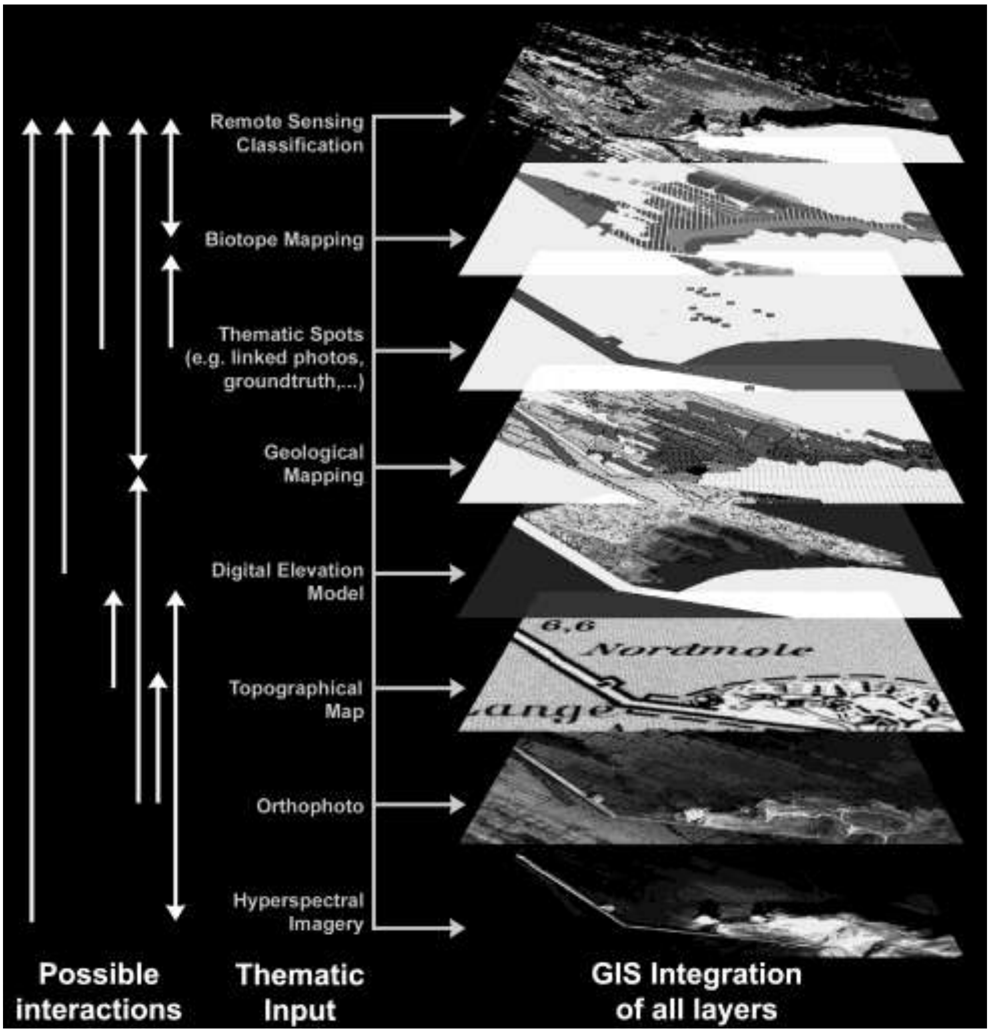

Fig. 5: Possible interactions of thematic layers in geographical information systems

4 Perspectives

The results suggest that the use of hyperspectral remote sensing applications in coastal ecosystems can be rated as a suitable method for semi-automated issues of change detection rather than for assessing complex biological and ecological tasks. Therefore, the results contribute well to several aspects of monitoring tasks especially in inaccessible environments.

As the area of the case study as well as significant parts of the German Wadden Sea are nature protection areas, they are also subject to intensive ecological research (e. g. BARTSCH and TITTLEY, 2004; REISE, 1989; SCHMIDT ET AL., 2003). Thus, one major task is the identification of suitable datasets for their potential integration in GIS-remote sensing based environmental monitoring programs.

As stated by REISE (1989: p. 262), "*the protection of the Wadden Sea is doomed to failure without sustained ecological research with a comprehensive monitoring strategy.*" As a corollary of this statement, the ongoing and future long-term ecosystem research should be evaluated and improved. This can be initiated with improved remote sensing approaches, using selected areas on a local scale where fundamental ecological data exist on historical development as well as on the present state. These data provide a basis to combine remote sensing approaches in GIS databases and develop a powerful environmental monitoring system.

As this study shows, the use of remote sensing data marks an important step to integrate the spatial dimension in monitoring large areas as well as inaccessible surroundings and to detect the "*hot spots of change*" (WEIERS, 1999: 85). The selection of the best suitable sensor is an important decision at the starting point of the remote sensing integration that goes beyond financial considerations. Without the appropriate sensor for the parameters which need to be monitored with the help of remote sensing, the results will be compromised. The highest resolution – spatial and spectral – is not always the best and can lead to specific problems such as misinterpreted pixels. The results suggest that the appropriate sensor should rather be decided as the case arises and depending on the targets that ought to be derived from the image analysis. In a second step, the evaluation and integration of a standardized analysis procedure is an important component of ecological monitoring systems. The evaluation of standards for certain environments like the one presented here will help to develop much needed measures to monitor ecological conditions.

With the growing range and continuous upgrade of multi- and hyperspectral sensors, the availability of data is no longer limited to financially strong institutions so that the implementation of long-term assessed hyperspectral data is a feasible perspective for application-oriented monitoring tasks. Besides, the spatial and spectral resolution of spaceborne sensors (e. g. Hyperion[5] or the proposed EnMAP[6] sensor) is improving continuously, and so is data availability. These developments have the potential to generate an increasing number of scientific as well as commercial users, evaluating improved methods to extract reliable information from these data and to contribute to the availability of a wide range of data for monitoring systems. This marks a major advance in the task to conserve biodiversity as well as to recognize ecological changes that result from or have impact on human activities.

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[5] http://eo1.usgs.gov/hyperion.php

[6] http://www.gfz-potsdam.de/pb1/pg5/research/methods/sensor/enmap_main_uk.html

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