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A multi-sensor approach for detecting the different land covers of tidal flats in the German Wadden Sea — A case study at Norderney

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ABSTRACT

The tidal flats of the Wadden Sea are a highly dynamic and largely natural ecosystem with high economic and ecological value but which are also at risk due to climate change, rising sea levels, algae blooms, invasive species and marine pollution. There is a need for the detection of emerging changes and the potential loss of the natural or semi-natural ecosystems accompanied by a decrease in water quality. Accessibility both from sea and land is very poor, which makes the monitoring and mapping of tidal flat environments from in situ measurements very difficult. In this study, a multi-sensor concept for the classification of intertidal areas in the Wadden Sea is developed. The basis for this method is a combined analysis involving RapidEye (RE) and TerraSAR-X (TSX) satellite data combined with ancillary vector data about the distribution of vegetation, shellfish beds and sediments for the accuracy assessment. The overall methodology is based on a hierarchical decision tree. First, the water coverage is separated from the tidal flats by using the normalized difference water index (NDWI). Second, the shellfish beds are estimated with the textural features of the TSX data and morphologic filters (MFs). Third, the classification of vegetation (salt marsh, sea grass/algae) is based on the modified soil-adjusted vegetation index (MSAVI), object-based features and exclusionary criteria. The remaining area is then separated into different sediment types with an algorithm that uses a thresholding technique applied to radiometric values, the MSAVI and a majority filter. The results show that we are able to identify the location and shape of salt marsh and shellfish beds (a true positive rate of 0.63 and a precision of 0.55) by using multi-sensor remote sensing data. A detailed shellfish bed classification can only be done with radar sensors, like TSX. The extraction of the sea grass areas from the multi-sensor approach is difficult. Sea grass often grows very sparsely in the study area which, with respect to the spatial resolution of RE, leads to a mixture of the spectral signatures of sediment and sea grass. The classification of the sediment types in tidal flats is a challenge compared to vegetation and shellfish beds. An overall accuracy of 64.53%, 66.85%, 68.22% and 68.2% was achieved. The results emphasize that a sediment-type classification cannot be achieved with high accuracy using spectral properties alone due to their similarity, which is predominately caused by their water content.

1. Introduction

The trilateral Wadden Sea is a large intertidal transition zone between land and sea in the south-eastern part of the North Sea, with tidal flats, barrier islands, channels, gullies and salt marshes. It is one of the last-remaining natural large-scale intertidal ecosystems, where most natural processes continue to function largely undisturbed (CWSS, 2013b). The multitude of transitions between land and sea, salt- and freshwater, are the basis for a highly adapted, partly endemic flora and fauna. The productivity of the biomass is one of the highest in the world, demonstrated by the numbers of fishes, shellfishes and birds (CWSS, 2013b). In 2009, the Dutch and German parts of the Wadden Sea were entered onto the UNESCO World Heritage List (Farke, 2011). Changes in temperature and the variety of species, harmful algae blooms and the reduction of the fish population, as well as changes in the morphology in the Wadden Sea, are examples of the effect of global climate change, changes in the environment and anthropogenic pressure (CWSS, 2013a). Furthermore, the long-lasting use by large ship transports and offshore industries have an impact on the entire ecosystem (CWSS, 2013a). The emerging change and potential loss of the natural or semi-natural ecosystem, accompanied by a decrease in water quality, caused the European Union to implement various directives: the Habitats Directive (Council Directive 92/43/EEC), the Water Framework Directive (Directive 2000/60/EC) and the Marine Strategy Framework Directive (Directive 2008/56/EC). These directives formulate objectives, such as achieving or maintaining a good environmental

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and conservation status within a given time (EU, 1992, 2000, 2008; Farke, 2011). As a consequence, the Ministry of Environment, Energy and Climate Protection and the Ministry of Science and Culture of the Federal State of Lower Saxony launched a cooperative research project called "Scientific monitoring concepts for the German Bight" (German acronym WiMo).

The ability to map intertidal sediments or surfaces through different remote sensing systems (airborne or satellite-based) has been demonstrated by various researchers over the last 30 years. Their focus has been on distinguishing between sand and mud or different grain sizes, as well as examining the influence of water or biofilm. Yates, Jones, McGrorty, and Goss-Custard (1993) used three different classification methods (maximum likelihood classification, multiple regression and a spectral mixture model) on Landsat 5 TM data to identify the spatial sediment distribution. All the methods produced high accuracies for muddy sites (MLC: 83%, MR: 93%, SMM: 94%) and lower accuracies for sandy sites (MLC: 68%, MR: 59%, SMM: 21%). Rainey, Tyler, Bryant, Gilvear, and McDonald (2000) used a series of in situ and laboratory reflectance experiments to investigate the complexity of intertidal sediments. They showed that the interstitial moisture influences the spectral contrast between sediments of contrasting grain sizes. In a subsequent study, Rainey, Tyler, Gilvear, Bryant, and McDonald (2003) took an image using the Daedalus 1268 Airborne Thematic Mapper after a drying period. They improved the image calibration significantly with a recombination of the sub-pixel end-member abundances through multivariate regression analysis for dry and wet conditions. Decho et al. (2003) found that the presence of microbial mats reduces the sediment reflectance signatures by 10–20%. Sørensen, Bartholdy, Christiansen, and Pedersen (2006) classified four different sediment classes using Landsat ETM+ and texture measures derived from orthophotos. They concluded that a single-image approach has some limitations and that the ground truth measurements have to be done at the time of the image acquisition. Van der Wal, Herman, and Wielemaker-van den Dool (2005) used synthetic aperture radar (SAR – ERS-1 and ERS-2) to relate the backscatter coefficient to field measurements of surface roughness, moisture conditions and surface texture. They found a negative correlation between the surface roughness and the mud content, which can be used in a regression model to distinguish mud from sand. In addition, they showed that a high moisture content negatively effects the correlation between the surface texture and the volumetric moisture content. Van der Wal and Herman (2007) showed that a combination of radar, visible and near-infrared (VNIR) as well as shortwave infrared (SWIR) was the best for sediment grain size monitoring. Gade, Alpers, Melsheimer, and Tanck (2008) extracted the roughness parameters of sand ripples on exposed tidal flats for a coarse sediment classification. Based on their results from 2008, Gade, Melchionna, Stelzer, and Kohlus (2014) found that multi-frequency SAR data of multiple satellites acquired at low tide provides additional information (e.g., RMS height and autocorrelation length) that can be used in monitoring systems. The RMS heights varied only slightly within the test sites, but the autocorrelation length was the largest in sandy areas which have been classified as sandy. Thomson, Fuller, Sparks, Yates, and Eastwood (1998) examined, with the use of Compact Airborne Spectrographic Imager (CASI) data, what spectral band definition is the best to distinguish between sand, mud and six different salt marsh types. They concluded that general bandsets are suitable for generating an overview map, while for distinctive surface types to be mapped the bandsets have to be adjusted to the specific spectral features. Lee, Park, Choi, Oh, and Won (2012) investigated the polarimetric SAR data of TSX to distinguish between two different kinds of salt marsh plants (annual plants and perennial plants). They concluded that winter is the best season for distinguishing between the two different species and that summer is ideal for analysing the distribution changes of annual plants in salt marshes. Lee, Parl, Choi, Ryu, and Won (2014) analysed the disappearance of a large salt marsh patch due to anthropogenic impacts on the tidal flats. In comparison to the results of Lee et al. (2012); Gao and Zhang (2006) proposed autumn as the best season to distinguish between four different salt marsh communities in China. They measured the spectral characteristics in the seasons of spring, summer and autumn using a ground FieldSpec™ Pro JR spectroradiometer. The four communities had different and rather unique spectral characteristics during the three seasons, related to the growing season, the community type and its phenology. Dolch and Reise (2010) visually interpreted a time series of aerial photographs for mapping large sandy bedforms, sea grass and mussels. They demonstrated the effect of the movement of sandy bedforms on the distribution of sea grass and mussels. Dehouck, Lafon, Baghdadi, Roubache, and Rabaute (2011) analysed TSX and optical satellite data (SPOT-5 and FORMOSAT-2) to classify sediments, sea grass and oyster beds. They found that oyster beds and salt marshes have particular SAR signatures. Choe, Kim, Hwang, Oh, and Moon (2012) analysed full polarimetric RADARSAT-2 (C-band) and ALOS PALSAR (L-band) imagery to distinguish exposed oyster reefs from mud or sand flats on the west coast of the Korean peninsula. The use of a multi-frequency polarimetric SAR system showed that the naturally distributed oyster reefs in the tidal flats could be detected. Nieuwhof, Herman, Dankers, Troost, and Van der Wal (2015) analysed dual-polarized TSX (X-band) and RADARSAT-2 (C-band) to estimate the contours, density and species of the Pacific oyster and the blue mussel. Stelzer et al. (2010) used a wide variety of optical and SAR satellite sensors to classify sand, mixed sediments, mud, vegetation and mussels in different areas of the German Wadden Sea. They showed that a combination of different sensors is favourable to improving the classification accuracy.

These studies demonstrate the difficulties involved in classifying vegetation, shellfish beds and different sediments in the tidal flats. For sediments, the distinction between general classes (e.g., dry sand or wet sand) is possible (Small et al., 2009). Problems exist with the classification of mixed sediments and mud, especially if they are influenced by water (Verpoorter, Carrère, and Combe, 2014). Besides water, the reflectance of sediments is also influenced by properties such as grain size, organic matter content, iron oxide, cyanobacteria and mineralogy, as well as satellite-based properties like sensor characteristics and illumination geometry (Decho et al., 2003; Han and Rundquist, 1996; Rainey et al., 2000; Small et al., 2009 Vaudour, Moeys, Gilliot, and Coquet, 2008). The same problems occur with the classification of vegetation and shellfish beds that are influenced by water or by macroalgae. Another challenge is the combined analysis of the ground truth measurements and the satellite data for the classification validation. Tidal areas are highly dynamic, with short-term variations over a tidal cycle or seasonal variations with respect to hydrological, biological and morphological conditions. This means that, for a combined analysis the measurement of the ground truth data and the satellite image, acquisition has to take place simultaneously during low tide (Sørensen et al., 2006). With this requirement, however, constant monitoring is not feasible. A robust algorithm is needed for long-term monitoring. The first promising results were published by Stelzer et al. (2010) and Geißler, Stelzer, Kohlus, Farke, and Gade (2011) as they incorporated satellite data into monitoring concepts.

As a consequence of these studies, we want to develop an automated/semi-automated classification algorithm which includes the preprocessing of the satellite data of two different sensors and a decision tree with a set of hierarchically structured algorithms. The preprocessing comprises a radiometric improvement and atmospheric correction for RE and a spatial resampling method for TSX. Each sensor is focused on classifying different parts of the study area. The multispectral sensor, RE, will be used to classify the water, sediments and vegetation in the tidal flats, while the shellfish beds will be classified by the radar sensor, TSX. The basis for the classification is a combined analysis of both remote sensing data coupled with ancillary vector data. These classifications use thresholding and filter techniques (e.g., majority and morphologic) for the sediment estimation, object-based features (size and location) for the vegetation estimation, and textural features (Haralick texture measure) for the shellfish bed