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Continuous field mapping of Mediterranean wetlands using sub-pixel spectral signatures and multi-temporal Landsat data

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ABSTRACT

Wetlands rank among the most diverse ecosystems on earth and function as important ecosystem service providers. Pressures on wetland ecosystems caused by human activities, such as land use transformations or agricultural intensification, lead to strong wetland degradation. Satellite-based wetland mapping still bears the most uncertainties compared to other land cover types mapping. Image classification techniques have to better adapt to specific wetland characteristics, such as spatial heterogeneity, seasonal dynamics and fuzzy transitions between different land cover classes. For this purpose, a pixel-based method for wetland delineation based on multi-temporal Landsat data in West Turkey was developed and analyzed. In addition to common vegetation indices and texture measures, the usefulness of seasonal indices was tested. Multi-temporal Landsat imagery was combined with high resolution satellite data to extract sub-pixel information of coastal and inland wetland classes based on a random forest regression algorithm. The classification achieved an overall accuracy of 79.02%. In addition to the hard wetland classification the mapping framework provides a map of fractional cover information of different wetland classes including information about fuzzy spatial transitions of highly heterogeneous distribution patterns of wetland habitats and related intra-annual seasonal dynamics. Mapping spatio-temporal wetland dynamics at continuous field scales increases the applicability of Landsat-derived maps for local-scale ecosystem monitoring and environmental management on habitat level.

1. Introduction

Subtropical wetlands provide important habitats for many endangered species and perform important ecosystem services including ground-water recharge, water filtering, flood and erosion control and sediment and carbon accumulation (Mitsch and Gosselink, 1993; Finlayson et al., 2005; UNEP, 2010). More than 78% of Ramsar listed sites are linked to agricultural activities. Rebelo et al. (2009) are highlighting the importance of wetlands for food security. 80–90% are located in forest and savanna biomes hosting the majority of the world's population.

Wetlands are closely linked to the regional climate (Fan and Miguez-Macho, 2011), therefore protection of these ecosystems is of high benefit to the health of local biota. Progressing wetland degradation is caused by disturbances and pressures, such as agricultural intensification, urban growth or increasing tourism infrastructure.

Cost effective and accurate wetland mapping is needed to provide regular monitoring for wetland management and wetland protection. Frequent wetland mapping is important for the understanding of wetland functions and monitoring their response to natural variability and anthropogenic actions (Baker et al., 2006). In fact, there are explicit spatial information needs for wetland management, in particular for fostering and supporting the reporting requirements for the Ramsar convention on wetlands (MacKay et al., 2009). Space agencies and the remote sensing science community have contributed to a few international projects on wetland monitoring, such as JAXA's Kyoto & Carbon Initiative (Global Mangrove Watch) by investigating L-band ALOS PALSAR for wetland mapping (Rosenqvist et al., 2007), and ESA's data user GlobWetland (I and II) initiative using the 35 year Landsat archive for providing land use and land cover (change) products and assessment tools to the wetland management user community (Jones et al., 2009; Weise et al., 2010).

Remote sensing and GIS techniques are building crucial tools for wetland inventory tracking and update. Next to SAR-based methods (Rosenqvist et al., 2007; Bartsch et al., 2012; Reschke et al., 2012), the use of multispectral and hyperspectral satellite data generates valuable output on wetland classification and delineation, as many studies have shown (Adam et al., 2010; Ozesmi

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and Bauer, 2002; Davranche et al., 2009; Wright and Gallant, 2007; Na et al., 2010; Liaw and Wiener, 2002; Pal, 2005; Watts and Lawrence, 2008; Hüttich et al., 2011). Landsat data is broadly used for this purpose, but for mapping highly heterogeneous wetland systems, it is sometimes considered to be insufficient in terms of spatial resolution. Further, wetlands are considered to be difficult to map on solely multi-spectral basis due to the spectral similarity between different wetland classes and between wetland and upland as well as their context-dependant spatial and spectral characteristics (Stehman et al., 2003). Seasonal time series can be used to improve spectral discrimination of different vegetation types, and hence wetland types, in a single growing season (Ghioca-Robrecht et al., 2008). Hüttich (2011) and Ozesmi and Bauer (2002) emphasized the high suitability of time series for wetland mapping because of their capability to discriminate between vegetation types by their specific growth stages and to detect and integrate water regimes with periodic changes. Wetland mapping activities, e.g., in the Camarque, France, showed the high potential of classification trees (Wright and Gallant, 2007; Davranche et al., 2009). Classification trees adapt data from different scales and make no assumptions on distribution of the data (Breiman, 1996). High accuracies of wetland maps generated by using Machine Learning Algorithms were demonstrated in various studies (Na et al., 2010; Liaw and Wiener, 2002; Pal, 2005; Watts and Lawrence, 2008). Random forests (Breiman, 2001) aggregate decision trees in ensemble classifiers thus resulting in improved classification accuracies by combining the benefits of decision tree classification and bagging. Disadvantages of single classification trees such as their instability concerning outliers and training data changes are minimized by the ensemble setting.

According to the mainly used land cover classification schemes (e.g. International Geosphere-Biosphere Programme and Land Cover Classification System), wetlands can be defined as lands with a permanent (or non-permanent) mixture of water and herbaceous or woody vegetation, where the vegetation can be present in either salt, brackish, or freshwater (Herold et al., 2009). Single wetland types are poorly represented by coarse pixels. The mixed species composition of wetlands often leads to comparatively low mapping accuracies and class confusions with croplands and shrublands, as the global land cover validation results are now showing (Herold et al., 2008).

Wetland ecosystems are characterized by a high fragmentation level, spatial heterogeneity, and diversity of the vegetation type distribution. Assessing wetland distribution with the use of Landsat-like sensors often leads to the challenging task of dealing with mixed pixels of different wetland surface reflectance types. Moreover, wetlands are characterized by a high degree of spatio-temporal 'fuzziness' as they combine seasonal dynamics of vegetation activity and inundation magnitudes, and fuzzy transitions between different types of wetlands and other land cover types. Beside the fact that wetland classes are still underrepresented in regional to global scale products in terms of accuracy assessment and mapping uncertainty assessment, the high range of spatio-temporal dynamics of wetlands have to be taken into account when developing satellite based mapping techniques. Future mapping approaches will have to be better adapted to specific wetland characteristics in both, the classification process and their representation in the resulting wetland maps.

Fuzzy logic offers an alternative to hard classifications based by evaluating the membership of a specific class to each pixel. Fuzzy membership is based on fuzzy set theory by assuming that membership to a given category will range from 100% membership to non-membership (Gopal and Woodcock, 1994). These class fractions can accurately be derived from using sub-pixel classification that can provide the additional benefit of resolution upgrade to overcome sensors' limitations as suggested by Verhoeye and De Wulf (2002, 2007) and Foody and Cox (1994). Sub-pixel classification approaches used in several studies resulted in an improved cartographic representation of transitional zones and heterogeneous landscapes in general (Zilioli et al., 1994; Frohn et al., 2012; Wei et al., 2008; Zhang, 2009).

In this paper a supervised Random forests (Rf) regression technique is used on Landsat time series of 2002/03 to estimate per-pixel continuous field information for selected wetland types related to the Ramsar nomenclature in a Mediterranean delta system in West Turkey. We collected training data using very high resolution satellite and field data. Random forests regression techniques were used to generate wetland type likeliness maps indicating the probability of the occurrence of a specific wetland type. These were merged into an overall wetland likeliness map based on membership threshold rules. Thinking beyond the classic concept of discrete land cover classes, the application of fractional cover information of different wetland types will enhance their integration in operational wetland management processes, since spatial transitions can be displayed in a map showing continuous field information.

The aim of the paper is to:

- assess the utility of wetland mapping based on sub-pixel classifications of wetland types using a Random forests regression technique,
- analyze the applicability and relevance of multi-temporal Landsat acquisitions for the mapping of coastal Mediterranean wetlands by assessing the variable importance of spectral and temporal features and indices,
- demonstrate the advantage of flexible continuous field map products by introducing wetland type likeliness maps.

2. Data and methods

2.1. Study area

Our study focused on the Aegean coast in the southwest of Turkey covering the provinces of Izmir, Aydin and Mugla (Fig. 1). The landscape is dominated by agricultural fields, forests and semi-natural areas. Different Mediterranean wetland types are located in plains, attached to inland water bodies or in coastal deltas, such as the Great Menderes Delta National Park, characterized by seasonally inundated mudflats with halophytes, salt marshes and reed beds. In addition to the Great Menderes Delta, the wetland sites Tahtali Dam, Small Menderes Delta, Lake Bafa and Güllük Bay are surveyed. Typical regional marshes are characterized by *Tamarix spec*. vegetation on periodically flooded ground. Freshwater impact from irrigation channels or natural founts results in increased occurrence of specific reed species. Wetland disturbance from grazing cattle generates a non-typical mixture of wetland and non-wetland vegetation species due to nutrient input or damage of seedlings and upper soil layers. The climate of the Aegean coast is characterized by warm dry summers and cool wet winters (Fig. 1). Pressures on local wetlands are mainly generated by agricultural intensification and increasing tourism infrastructure.

2.2. Satellite data and pre-processing

Wetland mapping was conducted using Landsat Enhanced Thematic Mapper Plus (ETM+) data of 2002/03 which is available free of charge from the United States Geological Survey (*USGS*). Three terrain-corrected and cloud-free scenes of different time steps covering one seasonal cycle of a wet and a dry season were downloaded (18 March 2002, 28 October 2002 and 16 January 2003). The pre-processing of multi-temporal Landsat imagery includes an