Estuarine, Coastal and Shelf Science 171 (2016) 11–22

Contents lists available at ScienceDirect

Estuarine, Coastal and Shelf Science

journal homepage: www.elsevier.com/locate/ecss

Improved seagrass mapping using linear spectral unmixing of aerial photographs

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ARTICLE INFO

Article history:
Received 22 May 2015
Received in revised form
30 November 2015
Accepted 11 January 2016
Available online 13 January 2016

Keywords:
Seagrass spatial configuration
Seagrass classification
Linear spectral unmixing
Visual photointerpretation
Remote sensing
Digital aerial photography
North Carolina

ABSTRACT

Mapping of seagrass is challenging, particularly in areas where seagrass cover ranges from extensive, continuous meadows to aggregations of patchy mounds often no more than a meter across. Manual delineation of seagrass habitat polygons through visual photointerpretation of high resolution aerial imagery remains the most widely adopted approach for mapping seagrass extent but polygons often include unvegetated gaps. Although mapped polygon data exist for many estuaries, these are likely insufficient to accurately characterize spatial pattern or estimate area actually occupied by seagrass. We evaluated whether a linear spectral unmixing (LSU) classifier applied to manually-delineated seagrass polygons clipped from digital aerial images could improve mapping of seagrass in North Carolina. Representative seagrass endmembers were chosen directly from images and used to unmix image-clipped polygons, resulting in fraction planes (maps) of the proportion of seagrass present in each image pixel.

Thresholding was used to generate seagrass maps for each pixel proportion from 0 (no thresholding, all pixel proportions included) to 1 (only pixels having 100% seagrass) in 0.1 increments. The optimal pixel proportion for identifying seagrass was assessed using Euclidean distance calculated from Receiver Operating Characteristic (ROC) curves and overall thematic accuracy calculated from confusion matrices. We assessed overall classifier performance using Kappa statistics and Area Under the (ROC) Curve (AUC). We compared seagrass area calculated from each threshold map to the total area of the corresponding manually-delineated polygon. LSU effectively classified seagrass and performed better than a random classification as indicated by high values for both Kappa statistics (0.72–98) and AUC (0.80–0.99). The LSU classifier effectively distinguished between seagrass and bare substrate resulting in fine-scale seagrass maps with overall thematic accuracies that exceeded our expected accuracy target of 85% (range: 86.3–99.0%) and were comparable to those reported from previous seagrass mapping studies utilizing aerial image spectral data. The pixel proportion producing seagrass maps with highest accuracy varied among sites (range: 0 to 0.5). The optimal pixel proportion determined from Euclidean distance varied among sites (range: 0.2 to 0.6) and differed from those having highest accuracy. Importantly, the classifier identified small patches of seagrass, resulting in seagrass area estimates that were 2–94% lower than the area of the corresponding habitat polygon. We conclude that where seagrass polygon data exist, LSU can be used together with photointerpretation to generate spatially resolved maps suitable for analysis of seagrass spatial configuration and provide improved estimates of actual seagrass acreage.

1. Introduction

Seagrasses are widely recognized as sensitive indicators of overall estuarine health (i.e., high water quality), due in large part to light requirements that are higher than other estuarine primary producers (Dennison et al., 1993). Seagrass seascapes vary

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http://dx.doi.org/10.1016/j.ecss.2016.01.021
0272-7714/Published by Elsevier Ltd.

substantially in extent and pattern and persist given a delicate balance between processes of disturbance and recovery (den Hartog, 1971; Fonseca et al., 1983). Seagrass seascapes display high spatial pattern heterogeneity, the result of localized hydrodynamic stress gradients (i.e., wind-wave exposure, tidal currents), and exhibit pattern-specific responses to acute disturbances like tropical cyclones (Fonseca and Bell, 1998; Fonseca et al., 2000; Gera et al., 2013; Pu et al., 2014). Large, contiguous seagrass meadows can develop in the absence of disturbance and in locations where current velocity, wave action, or biological disturbance (bioturbation) are relatively low. In contrast, numerous small seagrass patches characterize locations where storms are more frequent, or current velocity, wave action, and perhaps bioturbation are relatively high. In addition, seagrasses 'migrate' across the seascape in response to sedimentary processes including erosion and sediment accretion, leading to temporal pattern dynamics (Patriquin, 1975; Ferguson et al., 1993; Marba and Duarte, 1995; Ferguson and Korfmacher, 1997; Robbins and Bell, 2000; Fonseca et al., 2008). These patterns likely develop as a dynamic equilibrium (den Hartog, 1971; Patriquin, 1975; Fonseca et al., 1983; Fonseca and Bell, 1998; Koch et al., 2006; Walker et al., 2006).

The extent and pattern of seagrass seascapes influence both biological and physical functions of the broader seagrass ecosystem. Seagrass patch configuration and extent variably affect the distributions of a diverse assemblage of fauna (Turner et al., 1999; Boström et al., 2006, 2011), many with important commercial value (Thayer et al., 1984; Jackson et al., 2001; Heck et al., 2003). Patchy seagrass seascapes are vulnerable to seasonal bioturbation activities by sting rays that target the edges of intermediate-sized patches, exposing roots and rhizomes and leaving patches more susceptible to erosion (Townsend and Fonseca, 1998; Peterson et al., 2001). Seagrass patch spacing influences sediment resuspension, deposition, and erosion (Folkard, 2005) with implications for coastal stability and water quality. Seascapes characterized by patchy seagrass cover are more susceptible to loss of additional cover during extreme wind events (Fonseca et al., 2000; Gera et al., 2013). Seagrass coverage and pattern are relevant metrics for planning restoration projects (Fonseca et al., 1998). Moreover, given the link between disturbance and seagrass spatial heterogeneity (den Hartog, 1971; Patriquin, 1975; Fonseca et al., 1983; Fonseca and Bell, 1998; Koch et al., 2006; Walker et al., 2006), changes in the spatial configuration of a seagrass seascape may affect ecosystem resilience (*sensu* Holling's 'ecological resilience', 1973, 1996) and could serve as an indicator of system transition (Kéfi et al., 2014).

The spatially heterogeneous nature of most estuarine seagrass seascapes presents a challenge for accurately mapping this highly productive coastal resource. Visual interpretation of aerial photography remains the most widely adopted approach for mapping seagrass extent, including along the mid-Atlantic seaboard of the United States (Carroway and Priddy, 1983; Ferguson et al., 1993; Moore et al., 2000; Finkbeiner et al., 2001; Lathrop et al., 2006; Costello and Kenworthy, 2011). Visual interpretation involves hand-digitization of seagrass habitat boundaries while adhering to a minimum mapping unit (MMU), i.e. some smallest feature (e.g., an individual seagrass patch) or aggregate of features (e.g., scattered seagrass patches on sand) that provides a balance between generating maps with sufficient detail to meet the requirements of the end user and the time and cost to make the maps (Finkbeiner et al., 2001; Rohmann and Monaco, 2005). The high spatial resolution (sub-meter) of aerial images offers a distinct advantage over more widely available multi-spectral sensors, in terms of the visibility of fine-scale seagrass features. However, when seagrass patches are mapped as bounded aggregate features, substantial unvegetated substrate is found both between large, continuous seagrass beds and among smaller patches. As a result, a recognized limitation of this method is the inability to estimate the actual area of seagrass occupation in patchy habitats or to analyze fine-scale seagrass spatial pattern (Finkbeiner et al., 2001).

Another advantage of high resolution aerial images over those generated by some multi-spectral sensors is the reduction, but not elimination, of errors in classification accuracy due to mixed pixels (when features of interest are smaller than image spatial resolution; Woodcock and Strahler, 1987). Mixed pixels impede accurate habitat mapping because entire pixels are often assigned a single, unambiguous class membership (Smith et al., 1985; Pech et al., 1986; Settle and Drake, 1993; Fisher, 1997). Although mixed pixels continue to occur at boundaries between features regardless of feature size or sensor resolution (Schowengerdt, 2006), the issue can be alleviated by either using the finest resolution imagery available or employing spectral unmixing classifiers (Boyd and Foody, 2011). Spectral unmixing has been used to classify coral reefs from multi- and hyperspectral imagery (Hedley and Mumby, 2003; Mobley et al., 2005; Goodman and Ustin, 2007; Torres-Madronero et al., 2009; Hamylton, 2011). Applications to seagrass are few yielding mixed results for both hyper- and multi-spectral images (Meyer, 2008; Torres-Madronero et al., 2009).

Application of traditional image processing techniques to aerial images is challenging because individual image frames are often edge-matched for mosaicking to provide regional coverage, thus altering spectral data and precluding the development of consistent spectral signatures. We reviewed the range of digital image processing techniques used to classify seagrass from aerial images (Supplemental Data 1). The selection of a particular technique was location-dependent based on bathymetry, water clarity, seagrass spatial pattern, and neighboring habitats, and also limited by software accessibility and technical expertise. But overall, semi-automated and automated techniques increase overall accuracy compared to manual delineation alone (Supplemental Data 1).

The primary objective of this research was to evaluate the effectiveness of combining visual photointerpretation of high resolution digital aerial images (0.3 × 0.3 m) with a semi-automated linear spectral unmixing (LSU) classifier to improve mapping detailed seagrass spatial pattern in the shallow waters of the Albemarle-Pamlico Sound Estuary System in North Carolina. Specifically, we (1) determined whether a LSU classifier performed better than a random classification for all seagrass pixel proportions, (2) performed an accuracy assessment on seagrass fraction planes (maps) generated from LSU for all seagrass pixel proportions, (3) determined the optimal pixel proportion for labeling seagrass presence via LSU, and (4) evaluated whether the LSU classifier led to improved fine-scale seagrass maps by identifying small, individual seagrass patches and excluding bare substrate.

2. Methods

2.1. Study site description

The Albemarle-Pamlico Sound Estuary System is a coastal lagoon bordered on the east and south by a chain of barrier islands (Outer Banks). Broad shallows (<2 m deep at mean low water) are punctuated by deeper basins and channels. Seagrass beds along this portion of the North Carolina coast cover an area of ~554 km^2 behind the extensive barrier island system (APNEP, 2012). The beds are dominated by a mixture of the temperate seagrass *Zostera marina* (eelgrass) and the subtropical seagrass *Halodule wrightii* (shoal grass), with occasional *Ruppia maritima* (widgeon grass) in quiescent areas. Coastal North Carolina represents the only known overlapping acreage of *Z. marina* and *H. wrightii* in the world (Thayer et al., 1984).