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Marsh Dieback, loss, and recovery mapped with satellite optical, airborne polarimetric radar, and field data

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ABSTRACT

Landsat Thematic Mapper and Satellite Pour l'Observation de la Terre (SPOT) satellite based optical sensors, NASA Uninhabited Aerial Vehicle synthetic aperture radar (UAVSAR) polarimetric SAR (PolSAR), and field data captured the occurrence and the recovery of an undetected dieback that occurred between the summers of 2010, 2011, and 2012 in the *Spartina alterniflora* marshes of coastal Louisiana. Field measurements recorded the dramatic biomass decrease from 2010 to 2011 and a biomass recovery in 2012 dominated by a decrease of live biomass, and the loss of marsh as part of the dieback event. Based on an established relationship, the near-infrared/red vegetation index (VI) and site-specific measurements delineated a contiguous expanse of marsh dieback encompassing 6649.9 ha of 18,292.3 ha of *S. alterniflora* marshes within the study region. PolSAR data were transformed to variables used in biophysical mapping, and of this variable suite, the cross-polarization HV (horizontal send and vertical receive) backscatter was the best single indicator of marsh dieback and recovery. HV backscatter exhibited substantial and significant changes over the dieback and recovery period, tracked measured biomass changes, and significantly correlated with the live/dead biomass ratio. Within the context of regional trends, both HV and VI indicators started higher in pre-dieback marshes and exhibited substantially and statistically higher variability from year to year than that exhibited in the non-dieback marshes. That distinct difference allowed the capturing of the *S. alterniflora* marsh dieback and recovery; however, these changes were incorporated in a regional trend exhibiting similar but more subtle biomass composition changes.

1. Introduction

1.1. History of marsh diebacks and studies

Salt marshes are essential for terrestrial to ocean energy and nutrient exchanges, storm buffering, maintenance of water quality, and as habitat and nursery for a myriad of wildlife and fish (Cullinan, LaBella, & Schott, 2004; Elmer et al., 2013; Zhang, Ustin, Reimankova, & Sanderson, 1997). Although they perform a critical dynamic role and have intrinsic ecological importance, salt marshes face detrimental pressures from natural and human-induced forces (Belluco et al., 2006; Cullinan et al., 2004; Elmer et al., 2013; Mendelssohn & McKee, 1988; Zhang et al., 1997). Researchers have applied remote sensing monitoring techniques to provide timely and synoptic status and trend information that addresses the spatial heterogeneity and seasonal changes of salt marshes, (Belluco et al., 2006; Cullinan et al., 2004; Elmer et al., 2013; Mendelssohn & McKee, 1988; Wickland, 1991; Zhang et al., 1997). Because biomass production is the primary indicator of salt marsh health, remote sensing activities have focused on changes in biomass composition (e.g., Ramsey & Rangoonwala, 2005; 2006; 2010; Zhang et al., 1997). This paper describes remote sensing applied to the detection and monitoring of *Spartina alterniflora* salt marsh biomass composition changes that revealed the occurrence and recovery of a recently observed phenomenon termed marsh dieback (Elmer et al., 2013; Ramsey & Rangoonwala, 2005; 2006; 2010).

Since the 1960s, *S. alterniflora* (smooth cordgrass) salt marshes that dominate regularly flooded salt marshes of the Atlantic and Gulf coasts of the United States have been documented to experience scattered and irregularly timed periods of browning (chlorotic) leading in most cases to dead marsh and at times marsh loss (Bacon & Jacobs, 2013; Elmer, LaMondia, & Caruso, 2012; Kearney & Riter, 2011; McFarlin, 2012; McKee, Mendelssohn, & Materne, 2004; Mendelssohn & McKee, 1988; Ogburn & Alber, 2006). The driving factors shown to contribute to the dieback include water logging, drought, reduced flushing, herbivory, pathogens, and others (Bacon & Jacobs, 2013; Kearney & Riter, 2011; McFarlin, 2012; McKee et al., 2004; Mendelssohn & McKee, 1988); however, the causes of dieback are likely varied and in most cases remain uncertain (Ogburn & Alber, 2006).

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One of the largest (>100,000 ha) and intensely studied and referenced marsh diebacks occurred in coastal Louisiana between 2000 and 2001 and progressed for up to eight months after discovery (e.g., Bacon & Jacobs, 2013; McKee et al., 2004). Even though the 2000–2001 Louisiana marsh dieback event was large and well-documented, satellite optical remote sensing detected and mapped a marsh dieback in 2008 that dwarfed that event (Ramsey, Werle, Suzuoki, Rangoonwala, & Lu, 2012). In the 2008 dieback, 111,000 ha of fresh and 411,100 ha of salt marshes exhibited moderate to severe marsh dieback within three weeks of Hurricanes Gustav and Ike storm surges impacting the Louisiana coastal region. Also in contrast to all other dieback occurrences, satellite radar remote sensing mapping showed that the dieback was the direct consequence of elevated salinity hurricane storm surges (Ramsey et al., 2012).

1.2. Optical and radar mapping of marsh dieback

The satellite remote sensing detection and mapping of the 2008 dieback event were based on spectral methods developed as part of the 2000 Louisiana dieback study (Ramsey & Rangoonwala, 2005; 2006; 2010). Chance observations leading to early detection of the 2000 dieback provided the opportunity to apply remote sensing techniques to detect the occurrence of marsh dieback and to determine the stage of dieback progression. Pigment concentrations were analyzed at the plant-leaf scale along four transects covering the transition from dead to healthy *S. alterniflora* to determine spectral changes indicative of dieback onset and progression (Ramsey & Rangoonwala, 2005). Those plant-leaf transect results were then extrapolated to the plant-canopy scale in order to simulate aircraft and satellite spatial and spectral resolutions (Ramsey & Rangoonwala, 2006).

Our field studies confirmed the loss of the leaf chlorophyll pigment with marsh dieback noted by McKee et al. (2004) and related the pigment losses to leaf reflectance increases in visible reflectance magnitude, specifically in the blue (400–500 nm), green (500–600 nm) and red (600–700 nm) wavelength bands (Ramsey & Rangoonwala, 2005). The same study showed that although leaf water (spectral determination after Peñuelas & Filella, 1998) and near-infrared (NIR, 700 to 1300 nm) leaf reflectance magnitude decreased with dieback progression, the relationships were weak and only clearly evident at a single late stage marsh dieback site (coefficient of determination, R^2, of 0.35 [leaf water] and 0.72 [NIR], $p < 0.05$) (Ramsey & Rangoonwala, 2005). In order to more fully account for site to site differences in dieback progression, particularly the later stage exhibiting progressive NIR changes, and provide a more reliable satellite remote sensing biophysical measure, vegetation indexes (VI) calculated as the NIR/Green and NIR/Red ratios were applied (Ramsey & Rangoonwala, 2005; 2006). In this study we relied solely on the NIR/Red ratio as the marsh dieback indicator. Although the NIR/Green ratio performed slightly better in earlier stage diebacks, both NIR/Green and NIR/Red were good indicators of dieback progression, and NIR/Red performed better at later stage diebacks at the plant-leaf scale (Ramsey & Rangoonwala, 2005).

The dieback progression explained 0.68 and 0.79 (R^2, $p < 0.10$) and 0.82 and 0.85 (R^2, $p < 0.05$) of the VI leaf-based reflectance variance at the younger and later stage diebacks, respectively (Ramsey & Rangoonwala, 2005). A follow-on study extended the plant-leaf dieback results to the site-specific plant-canopy spectral changes and found that aircraft and satellite remote sensing data could distinguish (1) healthy marsh, (2) live marsh impacted by dieback, and (3) dead marsh, and provide some discrimination of dieback progression (Ramsey & Rangoonwala, 2006). In addition, VI based on the NIR/Red band ratio reproduced hyperspectral plant-canopy indicators of marsh dieback at a 0.88 R^2 (mean square error = 0.21) level (Ramsey & Rangoonwala, 2010). A final mapping of the 2000–2001 dieback event based on six Landsat Thematic Mapper (TM) images collected before and after the dieback onset affirmed the necessity of atmospheric correction and conversion of the remote sensing data to surface reflectance. Further, the TM dieback mapping emphasized that the most convincing evidence of dieback impact or nonimpact is reflected in the temporal pattern of the vegetation index (Ramsey & Rangoonwala, 2010).

In remote sensing of vegetation, even if a pixel contains only a single plant species (with similar leaf spectral properties), natural variability in the background (i.e., substrate, water) and canopy structure, (e.g., the plant orientation and density) along with leaf reflectance are combined into the remote sensing reflectance (e.g., Huete & Jackson, 1988; Jensen & Lorenzen, 1988; Peñuelas & Filella, 1998). The background and structure contributions to the canopy reflectance, which likely have a varied relationship and importance to dieback occurrence or progression, complicate linking of the leaf reflectance to canopy reflectance (Ramsey & Rangoonwala, 2006). Thus, in order to more directly link leaf optical indicators of dieback progression to canopy reflectance, we need to determine indicators that account for or minimize canopy structure and background influences in the canopy reflectance spectra.

While accounting for structure influences in the optical data is challenging, synthetic aperture radar (SAR) mapping is largely directly relatable to the 3-dimensional distribution of water contained within the marsh leaves and stalks and underlying sediment (Dobson, Ulaby, & Pierce, 1995; Ramsey, 1998; Ramsey, 2005). SAR's sensitivity to the 3-D water distribution as represented in the backscatter is illustrated in a mapping application closely related to the marsh dieback and recovery. In that study, the near vertical stalk and leaf orientations increasingly exhibited in the early stages of marsh burn recovery became a denser and taller mix of horizontal and vertical orientations (relative to ground) as the recovery progressed (Ramsey et al., 1999). These changes in preferential orientation and increased density with increasing time-since-burn were tracked with polarimetric SAR (PolSAR) L-band data collected from a P3 Orion aircraft operated by the Naval Warfare Office (Ramsey et al., 1999). Initially, relatively higher VV (vertical send and receive) backscatter reflected the dominantly vertical regrowth. As growth progressed, VV backscatter decreased relative to increased HH (horizontal send and receive) backscatter, and cross polarization, HV and VH, backscatter representing the depolarized horizontal and vertical send radiation (Ramsey, Rangoonwala, Baarnes, & Spell, 2009a; Ramsey et al., 1999). Time-since-burn explained 73% ($p < 0.01$) of the VV/VH power depolarization ratio representing nine marsh burn sites, and the highest single polarization R^2 of 0.83 ($p < 0.01$) was associated with VH backscatter (decibels) (Ramsey, Rangoonwala, Baarnes, & Spell, 2009a; Ramsey et al., 1999). VH was used as an indicator of canopy biomass variance.

Particularly relevant to this study, the single date PolSAR scene predicted the time to complete marsh canopy recovery to be around 1000 (±59) days (Ramsey, Rangoonwala, Baarnes, & Spell, 2009a; Ramsey et al., 1999). In contrast, a single date optical image estimated only 400 to 500 days until complete canopy recovery (Ramsey, Rangoonwala, Baarnes, & Spell, 2009a). It took temporal analyses of nine TM images collected over five years to correctly predict marsh canopy recovery to be around 1000 (±88) days (Ramsey, Sapkota, Baarnes, & Nelson, 2002). A comparison of canopy reflectance and canopy structural measurements collected over three years at one of these marsh sites explains the advantage of SAR over optical monitoring in this case. While the canopy had recovered its stock of live biomass as represented by the optical reflectance spectra and lack of subsequent change after one year of regrowth, the canopy structure differed substantially from a fully mature canopy even after 1.5 years of regrowth (Ramsey, Rangoonwala, Baarnes, & Spell, 2009a). PolSAR's heightened sensitivity to canopy structure as compared to optical imaging should provide additional indicators of marsh dieback that enhance the detection of dieback onset and monitoring of dieback progression, with the additional advantage of radar's all-weather and day-night operability.