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Fusion of lidar and multispectral data to quantify salt marsh carbon stocks

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ABSTRACT

Herbaceous salt marshes are among the most productive ecosystems on earth. Unfortunately, quantification of the above-ground portion of biomass using passive optical remote sensing is constrained by the complexities of mixed spectral appearance in the water–land environment. Lidar remote sensing, on the other hand, has been extensively used to estimate forest biomass, and a few studies have reported their use in characterizing short or herbaceous plants. However, no empirical studies have demonstrated the combined use of lidar and spectral data to quantify above-ground biomass in herbaceous environments, including salt marshes. Thus, the findings of this study will contribute substantially to the understanding of potentials and limitations of using lidar and multi-spectral data for vegetation characterization and biomass estimates in salt marshes and other similar herbaceous environments. In this study, we evaluate the increased capability of a data fusion approach using small footprint discrete return lidar and multispectral data to quantify above-ground biomass and thus, carbon stocks in salt marshes. The specific objectives of our study were the following: 1) to understand the interaction between discrete-return airborne lidar and marsh vegetation; 2) to determine the appropriate grid size/s of lidar-derived datasets for characterizing marsh terrain and vegetation; 3) to investigate the applicability of a number of lidar metrics to predict salt marsh vegetation height and above-ground biomass; and 4) to evaluate the utility of integrating multispectral imagery with lidar to improve the predictability of regression models for quantifying above-ground biomass and carbon. Our results showed that salt marsh Digital Terrain Models (DTMs) derived using local minima in a grid spacing of 5 m × 5 m provided the best accuracy in terrain elevation estimates with an RMSE of less than 10 cm. Lidar-derived maximum vegetation heights (Lmax) provided the best agreement with field height measurements, but explained only 41% of the variance in vegetation height measurements (RMSE = 5.85 cm). Regardless of the metrics used, lidar-measured heights underestimated the field vegetation height, which is consistent with the findings of previous studies in short or herbaceous vegetation. The fusion of lidar with multispectral data improved model predictions of live, dead, and total biomass quantities. The improvement provided by the fusion over the use of lidar or multispectral data alone was marginal; the combination explained 47% of the variance, whereas the best models using lidar and multispectral data separately explained 37% and 28% of variances in live biomass measurements, respectively. However, the best biomass prediction models reported considerably low RMSEs and % root square errors (%RSEs). For example, %RSE for the biomass prediction model using lidar-derived maximum vegetation height (Lmax) was closer to 20%, which is the recommended error threshold for remote sensing based forest biomass prediction models that can be repeatedly applicable for estimating forest carbon stock change. Our findings also demonstrate that lidar as compared to spectral data can provide better estimates of above-ground biomass and carbon, even in the herbaceous and low-relief context of a salt marsh.

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1. Introduction

Recent climate change projections have increased scientific and public attention on carbon cycling and the sequestration of carbon by specific ecosystems. Coastal wetlands, including salt marshes, cover less than 1% of the Earth's surface (Duarte, Middelburg, & Caracao, 2005; Nellemann et al., 2009), yet comprise approximately 25% of the global soil carbon sink (Chmura, Anisfeld, Cahoon, & Lynch, 2003). Salt marshes are among the most productive ecosystems on earth (Castillo, Rubio-Casal, & Figueroa, 2010) and play an important role in global carbon cycle (Dixon & Krankina, 1995). In general, their rates of carbon sequestration are an order of magnitude higher than that of comparably-sized rainforests (Bridgham, Megonigal, Keller, Bliss, & Trettin, 2006; McLeod et al., 2011; Nellemann et al., 2009). However, these rates vary considerably, both spatially and temporarily. In their extensive review on salt marsh biomass, Castillo et al. (2010) highlight remarkable variations in salt marsh biomass accumulation rates and

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thus suggest studies that can capture this variation. Moreover, the rapid decline in the extent and health of these herbaceous wetland ecosystems (Bridgham et al., 2006) has created a need for better understanding of their carbon pools and roles in the ecosystem functioning.

Global-scale carbon studies, however, have primarily focused on dry land ecosystems that extend over large areas and have not accounted for the many small, scattered carbon-storing ecosystems such as salt marshes (Ajtay, Ketner, & Duvigneaud, 1979; Olson, Watts, & Allison, 1983). Although the estimates of the carbon in salt marshes exist, the uncertainty around these estimates remains as high as greater than 100%, mainly due to differences in the methods applied (Bridgham et al., 2006). Hence, these estimates lack comparability across time and space. Field-based techniques for estimating vegetation height, cover, biomass and carbon are labor and time intensive and are not effective at larger scales. Further, the remarkable spatial and temporal variations in salt marsh biomass accumulation rates hinder our ability to draw generalizations based on local scale, site-specific findings. In contrast, the increasing availability of remote sensing data and techniques provides rapid and non-destructive approaches for quantitative assessment of vegetation structural properties, biomass, and thus their carbon dynamics. More importantly, these approaches are applicable at regional to global scales and over different time scales, and therefore capable of capturing both spatial and temporal dynamics of these carbon stocks.

Recent developments in laser scanning altimetry (also known as lidar — light detection and ranging) have made it an important new data source for the study of 3-D structure of surfaces at sub-meter precision (Baltsavias, 1999; MacMillan, Martin, Earle, & McNabb, 2003; Rango et al., 2000). Unlike satellite-based remote sensing, lidar missions can be flown at almost any time and in most weather conditions providing spatially and temporally continuous datasets. Their laser penetration characteristics present advantages over high resolution passive optical remote sensing data, particularly for the vertical characterization of vegetation (Lefsky et al., 2002). Lidar remote sensing has been intensively researched in forestry for estimating tree heights. Findings of these studies have established correlations between field-measured and lidar-estimated tree heights that explain 64% to 99% of the variance in tree heights (Straatsma & Middelkoop, 2006). Parameters related to forest density, such as stem number (Lefsky et al., 1999; Næsset & Bjerknes, 2001), stem diameter (Drake et al., 2002; Næsset 2002), timber volume (Nilsson, 1996) or basal area (Means et al., 1999) have also been predicted ($r^2 = 0.42–0.93$) using different lidar variables. Further, these lidar-derived variables relating to vegetation structural properties have been used extensively in biomass predictions of woody vegetation (Boudreau et al., 2008; Lefsky et al., 2005; Popescu, Zhao, Neuenschwander, & Lin, 2011), including mangroves (Simard, Rivera-Monroy, Mancera-Pineda, Castañeda-Moya, & Twilley, 2008). Lefsky et al. (2002) and Lim et al. (2003) provide reviews on airborne laser scanning of forests, while Zolkos, Goetz, and Dubayah (2013) provide a meta-analysis of more than 70 papers on remote sensing of terrestrial above-ground biomass estimates with specific attention to the use of lidar in forest biomass estimates.

Compared to the extensive use of lidar in forestry, little progress has been reported in lidar applications for the characterization of relatively short herbaceous vegetation. The limited use of lidar in these environments could be attributed to two main reasons. First, dense vegetation with higher canopy closure limits laser penetration to the ground, making estimates of terrain and thus vegetation height challenging and less accurate (Chassereau, Bell, & Torres, 2011; Hopkinson et al., 2005). Second, relatively short vegetation and low variation in vegetation height and canopy characteristics demand data with high accuracy and detailed information content for achieving greater levels of relative accuracies in predicting vegetation characteristics (Rosso, Ustin, & Hastings, 2006; Wang, Menenti, Stoll, Belluco, & Marani, 2007). Regardless of these limitations, promising results have been reported for estimating terrain as well as vegetation height and cover related variables of relatively short plants using lidar. For example, ground height biases of up to 20 cm have been observed for wetland and riparian vegetation cover (Bowen & Waltermire, 2002; Töyrä et al. 2003); vegetation height estimates derived using waveform lidar data have been shown to agree well with field measurements over relatively arid grass and shrub land areas (Ritchie, Menenti, & Weltz, 1996; Weltz, Ritchie, & Fox, 1994). Some other studies have predicted heights of relatively short vegetation in croplands (Davenport et al., 2000), grass- and shrub-dominant river floodplains (Cobby, Mason, & Davenport, 2001; Hopkinson et al., 2004, 2005; Straatsma & Middelkoop, 2007), and sagebrush-dominant rangelands (Sankey & Bond, 2010; Streutker & Glenn, 2006). However, these studies do not agree on a single laser-derived statistic to predict vegetation height or cover. For example, Davenport et al. (2000) used the standard deviation within a local window as the predictor of vegetation height for agricultural crops, while Cobby et al. (2001) and Hopkinson et al. (2004) used it for aquatic grass and shrubs. Moreover, regression equations established in these studies varied greatly; Cobby et al. (2001) used a log-linear regression, which did not provide satisfactory results on the data of Hopkinson et al. (2004); the slope of the regression equation of Hopkinson et al. (2004) was three times higher than the one from Davenport et al. (2000). In a different study, Asselman (2002) suggests using the median value of lidar height distribution in a specified local window as the predictor of vegetation height for herbaceous vegetation. Hopkinson et al. (2005) followed a different approach to investigate a universal lidar canopy height indicator for different vegetation types with average heights ranging from less than 1 m to 24 m. Their findings showed that a measure of the grid-based maximum lidar height (Lmax), although potentially better than the standard deviation, varied with laser pulse density and crown morphology. Therefore, they concluded that this measure cannot be applied universally with the same expectation of accuracy. Based on these findings, it is evident that under specific environments, different vegetation types demand specific methods. More importantly in salt marsh environments, except for a few studies that have used lidar data to characterize terrain variability (Chassereau et al., 2011; Collin, Long, & Archambault, 2010; Montane & Torres, 2006; Schmid, Hadley, & Wijekoon, 2011; Yang, 2005), there is no literature demonstrating the use of lidar data for quantifying salt marsh cover, density or biomass.

On the other hand, satellite remote sensing has been extensively used in wetland research. Ozesmi and Bauer (2002) provide a comprehensive review on satellite remote sensing of wetlands. Based on their review of more than 100 papers, they state that coastal tidal marshes are the types of wetlands that have been most frequently studied using satellite remote sensing. The majority of these applications are, however, on wetland mapping and characterization (Belluco et al., 2006; Islam et al., 2008; Kulawardhana et al., 2007; Wang et al., 2007). Some other studies (Hardisky, Daiber, Roman, & Klemas, 1984; Jensen et al., 1998) relate information from spectral data to plant biomass. Similar to lidar data, these methods also suffer from several limitations. First, their signatures are highly affected by atmospheric and background conditions. Second, as the passive optical sensors utilize electromagnetic energy that is reflected or absorbed in the uppermost canopy layers, they are typically less sensitive to vegetation structure (Steininger, 2000). In contrast, lidar data, apart from their ability to directly relate to structural characteristics of the vegetation, are not sensitive to vegetation health, condition, or plant productivity (Lefsky et al., 2002). Accordingly, several other studies have applied a data fusion approach by combining lidar and multispectral signatures to predict vegetation biomass in forest environments (Nelson et al., 2009; Popescu & Wynne, 2004).

Given this background, we hypothesize that a data fusion approach that uses these two types of data will provide an increased capability for the prediction of vegetation biomass, particularly in herbaceous environments such as salt marshes. Except for a few studies that have

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