Remote Sensing of Environment 186 (2016) 616–625

Contents lists available at ScienceDirect

Remote Sensing of Environment

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

Statistical correction of lidar-derived digital elevation models with multispectral airborne imagery in tidal marshes

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ARTICLE INFO

Article history:
Received 6 January 2016
Received in revised form 1 September 2016
Accepted 16 September 2016
Available online xxxx

Keywords:
RTK-GPS surveys
Accuracy
LEAN
Normalized Difference Vegetation Index (NDVI)
Sea-level rise

ABSTRACT

Airborne light detection and ranging (lidar) is a valuable tool for collecting large amounts of elevation data across large areas; however, the limited ability to penetrate dense vegetation with lidar hinders its usefulness for measuring tidal marsh platforms. Methods to correct lidar elevation data are available, but a reliable method that requires limited field work and maintains spatial resolution is lacking. We present a novel method, the Lidar Elevation Adjustment with NDVI (LEAN), to correct lidar digital elevation models (DEMs) with vegetation indices from readily available multispectral airborne imagery (NAIP) and RTK-GPS surveys. Using 17 study sites along the Pacific coast of the U.S., we achieved an average root mean squared error (RMSE) of 0.072 m, with a 40–75% improvement in accuracy from the lidar bare earth DEM. Results from our method compared favorably with results from three other methods (minimum-bin gridding, mean error correction, and vegetation correction factors), and a power analysis applying our extensive RTK-GPS dataset showed that on average 118 points were necessary to calibrate a site-specific correction model for tidal marshes along the Pacific coast. By using available imagery and with minimal field surveys, we showed that lidar-derived DEMs can be adjusted for greater accuracy while maintaining high (1 m) resolution.

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1. Introduction

The structure and function of tidal marshes are strongly driven by physical gradients including elevation and tidal range. Elevation, relative to mean sea level, is responsible for variation in abiotic features like accretion rates (Butzeck et al., 2014), soil characteristics (Cahoon and Reed, 1995), pore water salinity, and oxygen availability (Hackney et al., 1996). Tidal marsh plants and animals have numerous adaptations for surviving these gradients in physical conditions (Pennings et al., 1992; Silvestri et al., 2005); however, the elevation range in which species can persist is often narrow (<1 m). In addition, small changes in marsh elevation can lead to large increases in inundation time under normal tidal cycles. Consequently, accurate characterization of elevation is critical for understanding tidal marsh ecogeomorphology, and tidal marsh structure and function are especially sensitive to changes in relative elevation due to sea level rise (Kirwan and Temmerman, 2009; Kolker et al., 2009).

Growing concern about the effects of climate change and sea-level rise on tidal marsh sustainability has increased interest in creating accurate digital elevation models (DEMs) of tidal marshes to better inform modeling and planning efforts. Airborne light detection and ranging (lidar) is a common tool used to generate DEMs and is becoming more readily available to coastal managers and scientists. High point return densities (1–10 points/m) and relative ease of data collection across large areas have made lidar a popular option for measuring bare earth elevation and vegetation height (Hodgson and Bresnahan, 2004; Kane et al., 2010). In areas with low vegetative cover (e.g., open terrain or concrete), the vertical accuracy of airborne lidar is between 15 and 25 cm root mean squared error (RMSE, Eq. (2); Hodgson and Bresnahan, 2004; Mitasova et al., 2009), with normally distributed errors (mean error approaching zero). However, the inability of the laser pulse to penetrate the dense vegetation canopy of most tidal marshes limits the accuracy of lidar-derived DEMs (Montané and Torres, 2006; Rosso et al., 2005; Sadro et al., 2007; Schmid et al., 2011; Hladik and Alber, 2012). For example, one study found that just 3% of lidar points were reflected off the marsh surface (Sadro et al., 2007), and another found that error in tidal marshes was greater than in adjacent upland habitats (Schmid et al., 2011), creating a positive bias in mean elevation of 10–40 cm (Sadro et al., 2007; Foxgrover et al., 2011; Hladik and Alber, 2012). Even lidar collected during periods of seasonally low biomass in tidal marshes can exhibit significant (>20 cm) vertical errors (Schmid et

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http://dx.doi.org/10.1016/j.rse.2016.09.020
0034-4257/Published by Elsevier Inc.

al., 2011). Correcting vertical errors is necessary for accurate predictions of flooding risk, marsh elevation change under sea-level rise, or any application where inundation is of primary concern.

Several methods have been used to correct lidar error in tidal marshes, including vegetation correction factors (Hladik and Alber, 2012), minimum-bin gridding (Schmid et al., 2011), an aboveground biomass model (Medeiros et al., 2015), and statistical correction of full waveform lidar (Parrish et al., 2014); however, each of these methods have limitations that may hinder broad adoption. Vegetation correction factors require extensive vegetation surveys or expert knowledge of a marsh coupled with high accuracy GPS surveys to correlate lidar error with plant communities (Hladik and Alber, 2012; overall RMSE = 0.1 m). Hyperspectral data can be useful in species and community classification in wetlands (Rosso et al., 2005; Sadro et al., 2007; Adam et al., 2010) and has been used to address lidar error (Hladik et al., 2013), but those data are not widely available and expensive to acquire. In addition, plant height and cover can vary substantially across elevation and salinity gradients, potentially requiring multiple corrections for a single species or community. Minimum-bin gridding (MBG) uses the minimum lidar return value within a predefined grid pixel to set the value for the DEM; as pixel size increases lidar error generally decreases as more low values are included; however, horizontal resolution of the DEM decreases and because so few lidar returns hit the marsh platform, a positive bias remains (Schmid et al., 2011; RMSE = 0.17 m). Medeiros et al. (2015) used a combination of remote sensing datasets (ASTER imagery and interferometric synthetic aperture radar, InSAR) in a Florida tidal marsh to model aboveground biomass density and then correct lidar error. They achieved a 38% reduction in RMSE at 5-m horizontal resolution (0.65 to 0.40 RMSE). In addition to Real-Time Kinematic (RTK) GPS surveys, the biomass model requires labor-intensive vegetation sampling that may necessitate destructive sampling if allometric equations for biomass are not available. Relying on two statistical models, each with a measure of uncertainty, may also limit the accuracy of the adjusted DEM. Vertical correction of full waveform lidar using waveform features is promising (Parrish et al., 2014), however, broad collection of waveform lidar is still relatively rare and it requires extensive processing skills; we focus our analysis on DEMs derived from discrete return lidar.

Our objective was to develop a correction model for lidar-derived DEMs using readily available, high resolution (1 m), multispectral (red, green, blue, near-infrared) airborne imagery from the US Department of Agriculture (USDA) National Agriculture Imagery Program (NAIP). Derived products from the NAIP imagery, such as the Normalized Difference Vegetation Index (NDVI), correlate well with the spatial variation in vegetation biomass and structure (Gamon et al., 1995; Myneni et al., 1995; Filella et al., 2004; Pettorelli et al., 2005), and we tested the ability of NDVI to calibrate a statistical model of lidar error when used in conjunction with baseline elevation datasets (e.g., RTK-GPS surveys). We developed a statistical model of lidar error for 17 tidal marsh sites along the Pacific coast. We applied the models and compared them to RTK-GPS field data to assess DEM accuracy, and we compared the performance of our model against other commonly applied correction techniques. Finally, we determined the minimum density of RTK-GPS data points necessary to achieve a DEM with maximum accuracy and tested the sensitivity of the statistical model to use NAIP images from years different than when the lidar data were collected.

2. Methods

2.1. Study area

Our study included 17 tidal marsh sites located in eleven estuaries where both lidar data and NAIP imagery were available (Fig. 1, Table 1). Sites were chosen to be representative of historic marsh conditions and many were on U.S. Fish and Wildlife Service National Wildlife Refuges (NWRs). While each study site had unique ecological and geomorphic characteristics, for broad comparisons they were grouped into three regions. Pacific Northwest (PNW) sites included: Grays Harbor NWR (hereafter Grays Harbor); Tarlet Slough in Willapa Bay NWR (Willapa); Millport Slough in Siletz Bay NWR (Siletz); Bull Island within the South Slough National Estuarine Research Reserve in Coos Bay (Bull Island); and the Bandon marsh unit in Bandon NWR in the Coquille Estuary (Bandon). San Francisco Bay (SFB) sites included: Black John marsh (Black John) and Petaluma marsh (Petaluma) on the west shore of the Petaluma River at the northwest corner of San Pablo Bay; Coon Island and Fagan along the Napa River; San Pablo NWR (San Pablo) along the north shore of San Pablo Bay; China Camp State Park along the south shore of San Pablo Bay (China Camp); and the Corte Madera Marsh Ecological Reserve (Corte Madera) on the west shore of Central San Francisco Bay. Southern California (SCA) sites included: Morro Bay State Park (Morro); Naval Air Station Point Mugu (Mugu); Seal Beach NWR (Seal Beach); Upper Newport Bay Nature Preserve (Newport); and Tijuana Slough NWR (Tijuana). Tides are mixed-semi diurnal and tidal range increases with latitude, from 1.75 m at Tijuana in the south, to 2.79 m at Grays Harbor in the north (tidesandcurrents.noaa.gov).

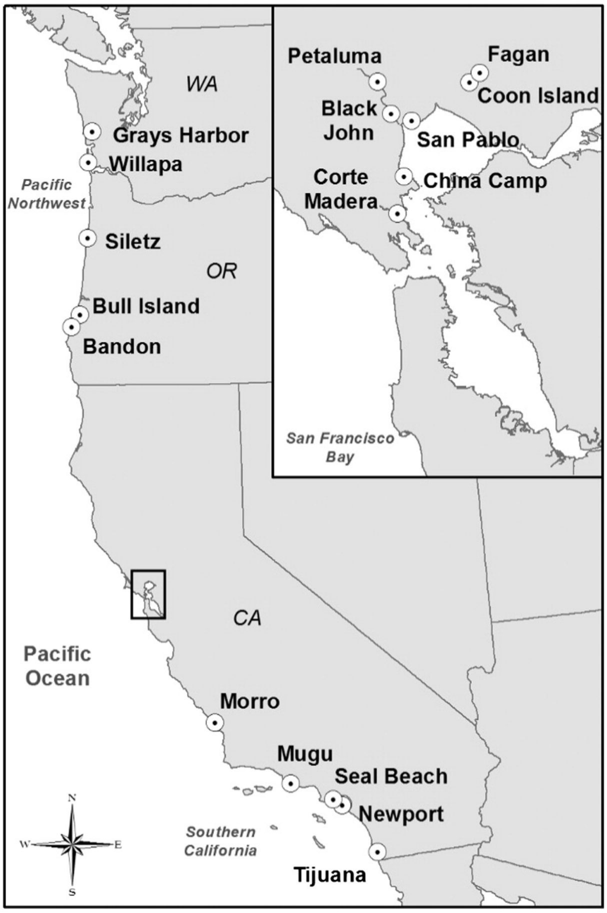

Fig. 1. Location of 17 tidal marsh study sites along the Pacific coast of the United States. Study sites represented a range of dominant tidal marsh vegetation, climate, and tidal ranges to test the applicability of model corrections across different vegetation types.

Plant community composition and species richness varies substantially in marshes along the Pacific coast (Table 1). The PNW sites are comparatively species rich with a mix of salt, brackish, and fresh water sedges, grasses and rushes (Thorne et al., 2015). In SFB, the higher salinity sites (San Pablo, China Camp, Corte Madera, Black John and Petaluma) are dominated by *Salicornia pacifica* (mean height 20 cm), that creates dense mats at mid-high elevations, with *Schoenoplectus spp.* (mean height 86 cm) and *Spartina foliosa* and invasive *Spartina alterniflora* hybrids (mean height 91 cm) in lower elevations and