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Estimation of wetland vegetation height and leaf area index using airborne laser scanning data

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ABSTRACT

Wetland vegetation is a core component of wetland ecosystems. Wetland vegetation structural parameters, such as height and leaf area index (LAI) are important variables required by earth-system and ecosystem models. Therefore, rapid, accurate, objective and quantitative estimations of wetland vegetation structural parameters are essential. The airborne laser scanning (also called LiDAR) is an active remote sensing technology and can provide accurate vertical vegetation structural parameters, but its accuracy is limited by short, dense vegetation canopies that are typical of wetland environments. The objective of this research is to explore the potential of estimating height and LAI for short wetland vegetation using airborne discrete-return LiDAR data.

The accuracies of raw laser points and LiDAR-derived digital elevation models (DEM) data were assessed using field GPS measured ground elevations. The results demonstrated very high accuracy of 0.09 m in raw laser points and the root mean squared error (RMSE) of the LiDAR-derived DEM was 0.15 m.

Vegetation canopy height was estimated from LiDAR data using a canopy height model (CHM) and regression analysis between field-measured vegetation heights and the standard deviation (σ) of detrended LiDAR heights. The results showed that the actual height of short wetland vegetation could not be accurately estimated using the raster CHM vegetation height. However, a strong relationship was observed between the σ and the field-measured height of short wetland vegetation and the highest correlation occurred ($R^2 = 0.85$, RMSE = 0.14 m) when sample radius was 1.50 m. The accuracy assessment of the best-constructed vegetation height prediction model was conducted using 25 samples that were not used in the regression analysis and the results indicated that the model was reliable and accurate ($R^2 = 0.84$, RMSE = 0.14 m).

Wetland vegetation LAI was estimated using laser penetration index (LPI) and LiDAR-predicted vegetation height. The results showed that the vegetation height-based predictive model ($R^2 = 0.79$) was more accurate than the LPI-based model (the highest R^2 was 0.70). Moreover, the LAI predictive model based on vegetation height was validated using the leave-one-out cross-validation method and the results showed that the LAI predictive model had a good generalization capability. Overall, the results from this study indicate that LiDAR has a great potential to estimate plant height and LAI for short wetland vegetation.

1. Introduction

Wetlands are among the most productive ecosystems in the world, however, there are various definitions of wetlands and none are widely accepted (Desta et al., 2012). Wetlands have been described as “the kidneys of the landscape” and “ecological supermarkets” (Desta et al., 2012; Mitsch and Gosselink, 2007). Various studies have indicated that wetlands are the richest ecosystems next to tropical rainforests found on this planet earth (Desta et al., 2012). Wetlands provide a critical suite of regulating, provisioning, supporting and cultural ecosystem services, for example to stabilize streams, intercept and attenuate diffuse

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pollutants, enhance biodiversity and nutrient cycling, sequester carbon, and provide aesthetic, spiritual, and recreational benefits for human culture (Ausseil et al., 2007; Tanner et al., 2013).

Wetland vegetation is an important component of wetland ecosystems, which plays a vital role in the ecological functions of wetland environments (Adam et al., 2010; Silva et al., 2008). Quantitative understanding of the spatial distribution and characteristics of wetland vegetation is critical for sustainable ecosystem management and preserving biological diversity (Mutanga et al., 2012). Vegetation structural parameters (such as height, vegetation cover fraction, leaf area index and biomass) are important variables required by earth-system and ecosystem models (Popescu et al., 2011). The accuracy of these models' outputs depends on accurate inputs of the key model parameters (Chasmer et al., 2008). Therefore, rapid, accurate, objective and quantitative estimations of wetland vegetation attributes are essential (Nie and Li, 2011). Direct field measurements can obtain the most accurate structural parameters of wetland vegetation and are considered to be the most reliable methods. However, this method is labor intensive and time consuming and expensive and often unfeasible for remote locations, and is thus, only practical in relatively small areas (Adam et al., 2010; Jonckheere, 2004; Wang et al., 2005).

Remote sensing techniques, on the other hand, can rapidly, repetitively and economically acquire data on the study area. The use of remotely sensed images allows multi-temporal studies and provides comprehensive information for detection of change over time (Silva et al., 2008). Remotely sensed data show the most promise for estimating structural parameters of wetland vegetation at large spatial scales (Adam et al., 2010). There are many studies on structural parameters of wetland vegetation using remote sensing techniques (Mutanga et al., 2012; Proisy et al., 2007; Schile et al., 2013). However, most of the previous studies have focused mainly on passive optical or radar remote sensing (e.g., He et al., 2013; Kovacs et al., 2005). Conventional sensors have significant limitations for ecological applications, and the sensitivity and accuracy of these devices have repeatedly been shown to decrease with increasing aboveground biomass and leaf area index (LAI) (Lefsky et al., 2002). The problem of asymptotic saturation is common with conventional sensors, particularly true for short, dense vegetation with high canopy cover or LAI, such as grassland, agricultural and wetland vegetation (Adam et al., 2010; Mutanga and Skidmore, 2004). This will severely affect accuracy of short vegetation biomass and LAI estimations (Chen et al., 2009). Frequently, vegetation structural parameters are estimated from the empirical relationships between field measurements and vegetation indices (VIs) derived from remotely sensed data (e.g., He et al., 2013; Kovacs et al., 2005; Zheng et al., 2007). The commonly used VIs are the normalized difference vegetation index (NDVI), the simple ratio (SR) and the enhanced vegetation index (EVI) (Jensen et al., 2008). Many researchers have observed that optically-derived VIs tend to an asymptote or saturation when LAI values are greater than 3.0 (i.e., in densely vegetated cover areas) (Adam et al., 2010; Mutanga et al., 2012; Peduzzi et al., 2012). Particularly for wetland vegetation, their structural parameters are more difficult to estimate accurately using optical remotely sensed data, because the performance of near to mid-infrared bands are attenuated by the occurrences of underlying water and wet soil (Adam et al., 2010). Furthermore, optical remote sensing does not take into account the three-dimensional structural characteristics of vegetation canopy and is only appropriate for examining the variation of features on horizontally distributed basis (Peduzzi et al., 2012). Although interferometric synthetic aperture radar (InSAR) can provide some three-dimensional vegetation structural information, it is generally of insufficient spatial resolution to adequately measure stand-level variations in vertically distributed canopy features (Dupuy et al., 2013; Lee et al., 2009; Slatton et al., 2001).

Laser scanning systems (also called light detection and ranging, LiDAR) on the other hand can provide both high spatial resolution and canopy penetration with a high vertical accuracy in a three-dimensional laser point cloud format (Cook et al., 2009; Lee et al., 2009). LiDAR is an active remote sensing technology, and LiDAR platforms are classified into three categories, i.e., ground-based, airborne, spaceborne. Airborne LiDAR utilizes an aeroplane or helicopter mounted laser scanner with an integrated global positioning system (GPS) and inertial navigation system (INS), also referred to inertial measurement units (IMU) for collecting three-dimensional data points (Lim et al., 2003; Richardson et al., 2009). The high vertical and horizontal precision and accuracy of LiDAR make it suitable for mapping land surfaces with great detail (Rosso et al., 2006). Therefore, LiDAR techniques provide opportunities to generate high-quality DEM even in sub-canopy topography and wetland environments (Lefsky et al., 2002; Rose et al., 2013). Laser penetration characteristics can be effectively used to produce three-dimensional characterizations of vegetation ecosystems (Rosso et al., 2006). Furthermore, the three-dimensional distribution of vegetation canopies derived from LiDAR systems can provide highly accurate estimates of vegetation height, cover fraction, and canopy structure (Glenn et al., 2011; Lindberg et al., 2012). In addition, LiDAR has been shown to accurately estimate LAI and aboveground biomass even in those high-biomass ecosystems where passive optical and active radar sensors typically fail to do so (Dolan et al., 2011; Korhonen et al., 2011; Zhao et al., 2011).

Some studies have been conducted on wetland ecosystems using LiDAR data, such as acquiring and accurately assessing wetland DEM (Montané and Torres, 2006; Ward et al., 2013); identifying suitable sites for wetland constructions (Tomer et al., 2013); mapping wetland vegetation (Yang and Artigas, 2010; Zlinszky et al., 2012); studying saltmarsh characterization (Morris et al., 2005); measuring wetland vegetation height (Genç et al., 2004; Hopkinson et al., 2004), and modeling species habitat (Chust et al., 2008; Collin et al., 2010). LiDAR has the potential to improve the detail and reliability of forested wetland maps and the ability to monitor hydrological processes in wetlands (Lang and McCarty, 2009). Previous studies have indicated the potential of LiDAR data to map wetland vegetation (Zimble et al., 2003) and also showed that LiDAR data can significantly improve the estimation accuracy of wetland vegetation structural parameters (Chust et al., 2008; Klemas, 2013). Some studies have been performed on wetland vegetation using LiDAR data, however, most of the previous studies have focused mainly on forest wetlands and mangrove wetlands (Farid et al., 2008; Michez et al., 2013). Although airborne LiDAR has been used to measure wetland vegetation height, the use of this technology for estimating LAI in these environments is unproven.

The overall goal of this study is to estimate height and LAI of short wetland vegetation using airborne discrete-return LiDAR data. To fulfill this goal, three main objectives were pursued: (1) assess the accuracy of raw laser point elevations and the DEM generated from LiDAR using field-measured GPS elevations; (2) estimate height and LAI of the short wetland vegetation; and (3) validate the accuracies of LiDAR-estimated vegetation height and LAI in the study area. There are two major challenges in this study. First challenge is to correctly separate ground returns from vegetation points. Another is to accurately estimate vegetation height to improve LAI estimation of short wetland vegetation. However, it is not a simple task to determine which returns are really ground returns (Brovelli et al., 2004), especially in wetland areas with low elevation relief, and much of the wetland is covered by dense vegetation that can conceal underlying terrain features (Rosso et al., 2006).