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A systematic method for 3D mapping of mangrove forests based on Shuttle Radar Topography Mission elevation data, ICEsat/GLAS waveforms and field data: Application to Ciénaga Grande de Santa Marta, Colombia

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Abstract

Mangrove forests are found within the intertropical zone and are one of the most biodiverse and productive wetlands on Earth. We focus on the Ciénaga Grande de Santa Marta (CGSM) in Colombia, the largest coastal lagoon–delta ecosystem in the Caribbean area with an extension of 1280 km^2, where one of the largest mangrove rehabilitation projects in Latin America is currently underway. Extensive man-made hydrological modifications in the region caused hypersaline soil (>90 g kg^{-1}) conditions since the 1960s triggering a large dieback of mangrove wetlands (~247 km^2). In this paper, we describe a new systematic methodology to measure mangrove height and aboveground biomass by remote sensing. The method is based on SRTM (Shuttle Radar Topography Mission) elevation data, ICEsat/GLAS waveforms (Ice, Cloud, and Land Elevation Satellite/Geoscience Laser Altimeter System) and field data. Since the locations of the ICEsat and field datasets do not coincide, they are used independently to calibrate SRTM elevation and produce a map of mangrove canopy height. We compared height estimation methods based on waveform centroids and the canopy height profile (CHP). Linear relationships between ICEsat height estimates and SRTM elevation were derived. We found the centroid of the canopy waveform contribution (CWC) to be the best height estimator. The field data was used to estimate a SRTM canopy height bias (−1.3 m) and estimation error (rms = 1.9 m). The relationship was applied to the SRTM elevation data to produce a mangrove canopy height map. Finally, we used field data and published allometric equations to derive an empirical relationship between canopy height and biomass. This relationship was used to scale the mangrove height map and estimate aboveground biomass distribution for the entire CGSM. The mean mangrove canopy height in CGSM is 7.7 m and most of the biomass is concentrated in forests around 9 m in height. Our biomass maps will enable estimation of regeneration rates of mangrove forests under hydrological rehabilitation at large spatial scales over the next decades. They will also be used to assess how highly disturbed mangrove forests respond to increasing sea level rise under current global climate change scenarios.

Keywords: Radar; SRTM; Lidar; ICEsat; GLAS; Mangroves; Mangrove; Wetlands; Forest; Height; Waveforms

1. Introduction

Mangroves are found between latitudes 31° north and 38° south, particularly along the tropical and subtropical coasts of Australia, Asia, Africa and the Americas. The mangrove forest is one of the most productive ecosystems on Earth with a mean production of 2.5 g C m^{-2} per day (Jennerjahn & Ittekkot, 2002). The combination of shallow waters, high levels of nutrients, and high primary productivity makes these areas ideal for supporting intricate food webs in several types of environmental settings (Twilley & Rivera-Monroy, 2005). Mangrove wetlands generate ample goods and services to society such as providing critical habitat for bird, fish and other wildlife, playing key roles in biogeochemical hydrologic cycles, regulating water quality, reducing shoreline erosion, offering

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flood protection (as result of tropical storms, hurricanes, and tsunamis (Kathiresan & Rajendran, 2006)), moderating climate, and supporting numerous economic activities such as hunting, fishing, and recreation (Ewel et al., 1998).

Because mangroves couple biogeochemical processes between land and sea, landscape degradation in these coastal zones magnifies regional impacts. A recent United Nations Environment Programme report (UNEP, 2006) estimates that their economical value varies geographically between \$200 k and \$900 k per km^2 per year. The primary drivers of mangrove conversion are related to human impacts: urban expansion, shrimp farming, water management practices, charcoal cut as well as natural hazards such as sea level rise, hurricanes, severe storms and tsunamis. Among the major impacts of mangrove loss are decline in biodiversity, degradation of clean water supplies, siltation of coral reefs and acidification of coastal soils, erosion, loss of shoreline stability, release of more carbon into the atmosphere, and reduction (or disappearance) of important commercial fish stocks (Sanchez-Ramirez & Rueda, 1999; Rueda & Defeo, 2001). It is estimated that the loss of original mangrove forests is as high as 35% and may reach 60% by 2030 (Valiela et al., 2001; UNEP, 2006; Alongi, 2002). These are, however, gross estimates and do not rely on accurate landscape analyses, which can only be improved through remote sensing landscape scale assessment.

Both radar and optical remote sensing have been used extensively to map mangroves with varying degrees of success (e.g. Kovacs et al., 2005; Laba et al., 1997, Ramsey et al., 1996; Rasolofoharinoro et al., 1998; Wang et al., 2004; Held et al., 2003; Simard et al., 2000; Mougin et al., 1999). Recently, structural (tree height) and functional (biomass) attributes of mangroves have been estimated using radar interferometry (Simard et al., 2006). In February of 2000, Space Shuttle Endeavour collected nearly global coverage of Earth's topography using radar interferometry (SRTM, Shuttle Radar Topography Mission). And because of limited penetration of microwaves within vegetation, the SRTM topographic maps contain information related to vegetation height (Kellndorfer et al., 2004). Mangrove forests are located within the intertidal zone (i.e. at sea level), which particularly simplifies the canopy height estimation technique since the ground topography is as flat as the tidal range. SRTM data are distributed with a 90 m spatial resolution around the Earth, reduced from the original 30 m through averaging and subsampling. In a previous paper, Simard et al. (2006) used an airborne lidar (i.e. light detection and ranging) to calibrate SRTM elevation. Lidar measures the time of return of a light pulse reflected off a target and thus measures the relative distance. Recent results using space-borne lidar showed that these data could also be used to estimate vegetation height and correlate it with biomass (Lefsky et al., 2005; Drake et al., 2002a,b). GLAS (ICEsat Geoscience Laser Altimeter System) is the first space-borne lidar instrument for global observations of Earth (Schutz et al., 2005) which has been collecting data since early 2003 and is the benchmark Earth Observing System mission for measuring ice sheet mass balance, cloud and aerosol heights, as well as land topography and vegetation characteristics. Carabajal and Harding (2006) showed that the GLAS waveform (laser return as a function of time) centroid is highly correlated to the SRTM phase center elevation over densely vegetated regions.

In this paper, we present a methodology based on SRTM elevation, ICEsat/GLAS, and field data to map mangrove forest height and aboveground biomass. We focus on the Cienaga Grande de Santa Marta (CGSM), Colombia, a large wetland complex where one of the largest mangrove rehabilitation projects in Latin America is currently underway (Botero & Salzwedel, 1999; Rivera-Monroy et al., 2004; Rivera-Monroy et al., 2006). Large man-made hydrological modifications in the region caused hypersaline soil conditions (>90 g kg^{-1}) since the 1960s triggering a large dieback of mangrove wetlands (~247 km^2). Thus, remote sensing tools are needed to evaluate if current freshwater diversions initiated in 1995 will be successful in restoring mangrove wetlands at the landscape scale. Our objective is to build a baseline map to quantitatively estimate the extent, height and biomass of the mangrove forests in CGSM. We describe how to use ICEsat/GLAS data to systematically calibrate SRTM elevation data, potentially providing a robust method to extend 3D mapping of mangrove forests to other parts of the World. In addition, we collected field data on structural attributes along four mangrove transects in CGSM to calibrate SRTM and to derive a site-specific relationship between mean canopy height and aboveground biomass. The GLAS and field data do not overlap since we were unable to obtain accurate geolocation for our sampling points because of weak GPS signal under the dense canopy. We relied on distance and orientation using a measuring tape and a compass to locate the sampling points on the SRTM maps. The height–biomass relationship enables mapping of biomass in CGSM by extrapolating with the calibrated SRTM canopy height estimates. Biomass estimates in this ecoregion are badly needed to evaluate the impact of mangrove mortality on nutrient cycling (i.e. carbon, nitrogen, phosphorus) and to understand how the loss of above- and belowground biomass affect the role of mangroves as carbon sinks.

2. Data and methods

2.1. Site description

Located on the Caribbean coast (10° 37′ to 11° 07′N and 74° 15′ to 74° 51′W), the Ciénaga Grande de Santa Marta (CGSM) forms the exterior delta of the Magdalena River, the fifth largest river in South America with an annual average water discharge of 7000 m^3 s^{-1} (Restrepo & Kjerfve, 2000; Rivera-Monroy et al., 2004) (Fig. 1). The wetland complex was designated as a Wetland of International Importance under the Ramsar Convention by the Government of Colombia on the 18th of June 1998 (Ramsar site no. 951). It was also designated as a UNESCO Biosphere Reserve in 2000. The CGSM is the largest lagoon–delta complex in Colombia (1280 km^2). To the north, the ecosystem is separated from the Caribbean Sea by the barrier island Isla de Salamanca, which has an inlet (Boca de la Barra) approximately 100 m wide and 10 m deep on its eastern end that connects the largest lagoon directly to the sea. To the