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Magnitude, spatial distribution and uncertainty of forest biomass stocks in Mexico

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ABSTRACT

Existing forest biomass stock maps show discrepancies with *in-situ* observations in Mexico. Ground data from the National Forest and Soil Inventory of Mexico (INFyS) were used to calibrate a maximum entropy (MaxEnt) algorithm to generate forest biomass (*AGB*), its associated uncertainty, and forest probability maps. The input predictor layers for the MaxEnt algorithm were extracted from the moderate resolution imaging spectrometer (MODIS) vegetation index (VI) products, ALOS PALSAR L-band dual-polarization backscatter coefficient images, and the Shuttle Radar Topography Mission (SRTM) digital elevation model. A Jackknife analysis of the model accuracy indicated that the ALOS PALSAR layers have the highest relative contribution (50.9%) to the estimation of *AGB*, followed by MODIS-VI (32.9%) and SRTM (16.2%). The forest cover mask derived from the forest probability map showed higher accuracy ($\kappa = 0.83$) than alternative masks derived from ALOS PALSAR ($\kappa = 0.72$–0.78) or MODIS vegetation continuous fields (VCF) with a 10% tree cover threshold ($\kappa = 0.66$). The use of different forest cover masks yielded differences of about 30 million ha in forest cover extent and 0.45 Gt C in total carbon stocks. The *AGB* map showed a root mean square error (RMSE) of 17.3 t C ha^{-1} and $R^2 = 0.31$ when validated at the 250 m pixel scale with inventory plots. The error and accuracy at municipality and state levels were RMSE = ±4.4 t C ha^{-1}, $R^2 = 0.75$ and RMSE = ±2.1 t C ha^{-1}, $R^2 = 0.94$ respectively. We estimate the total carbon stored in the aboveground live biomass of forests of Mexico to be 1.69 Gt C ± 1% (mean carbon density of 21.8 t C ha^{-1}), which agrees with the total carbon estimated by FAO for the FRA 2010 (1.68 Gt C). The new map, derived directly from the biomass estimates of the national inventory, proved to have similar accuracy as existing forest biomass maps of Mexico, but is more representative of the shape of the probability distribution function of *AGB* in the national forest inventory data. Our results suggest that the use of a non-parametric maximum entropy model trained with forest inventory plots, even at the sub-pixel size, can provide accurate spatial maps for national or regional REDD+ applications and MRV systems.

1. Introduction

Forests sequester carbon through photosynthesis and store it primarily as living aboveground biomass of trees (*AGB*). *AGB* is defined as the mass of living organic material for a given area, and approximately 50% of *AGB* is carbon (IPCC, 2003). Because of the slow turnover time of *AGB*, it is a key quantity when estimating terrestrial carbon stocks. In recognition of its importance, biomass has been identified as an essential climate variable (ECV) by the Global Climate Observing System (GCOS) to support the work of the United Nations Framework Convention on Climate Change (UNFCCC) and the Intergovernmental Panel on Climate Change (IPCC) in monitoring climate change.

Deforestation and forest degradation are considered to be the largest source of greenhouse gas emissions in many tropical countries (Gibbs, Brown, Niles, & Foley, 2007). Accurately monitoring and reporting the *AGB* of forests is a requirement of international policies to mitigate climate change through the reduction of greenhouse gas emissions from deforestation and forest degradation, as well as the enhancement of existing forest carbon stocks (REDD+, Reduction of Emissions form Deforestation and Forest Degradation). The implementation of REDD+ includes an element of measurement, reporting and verification (MRV) for which appropriate systems have to be developed at national, sub-national or project levels.

Mexico is actively participating in the United Nations (UN) climate mitigation programmes and is developing a national REDD+ strategy to include actions at project level and jurisdictional level accompanied by an MRV system at national level. Mexico has already developed a dense network of national forest inventory plots to support national

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forest policies through geographic and statistical information in which the first cycle started in 1961. These plots are also used in the Mexican national greenhouse gas inventory. However, the inventory plots are designed for large-scale statistics on forest carbon stocks and changes.

A transparent and efficient methodology with frequent updates is required for a national MRV system. It is recognised that a combination of remote sensing data and forest inventory data is required for this purpose, since neither data source is able to satisfy the full data requirements for MRV. Remote sensing data allows the production of spatial maps that can improve GHG monitoring at local and national scales, and provide information that can be used for land use planning and management (Gibbs et al., 2007). For example, by mapping forest biomass, deforestation and forest degradation, it is possible to provide estimates of GHG emissions and removals at local and national scales (Houghton, 2005).

In the past decade, several maps of forest structure and *AGB* have been produced at continental and national levels with resolutions from 250 m to 1 km to represent landscape-scale variations in carbon stocks (e.g. Hansen et al., 2003; Blackard et al., 2008; Lefsky, 2010; Baccini et al., 2012; Baccini, Laporte, Goetz, Sun, & Dong, 2008; Saatchi, Harris, et al., 2011b, Simard, Pinto, Fisher, & Baccini, 2011, Santoro et al., 2011; Thurner et al., 2014). In addition, regional maps at finer spatial resolutions (around 30 m) are available for specific areas (e.g. Hansen et al., 2013; Cartus et al., 2014; Avitabile, Baccini, Friedl, & Schmullius, 2012, Asner et al., 2012; Hame, Rauste, et al., 2013; Hame, Kilpi, et al., 2013). Some of these approaches are limited by the absence of well-distributed *in-situ* sample sites at the scale of the used remote sensing data (Houghton, Hall, & Goetz, 2009), and to some extent by the limited sensitivity of the selected satellite sensors to *AGB* (Patenaude, Milne, & Dawson, 2005).

Passive optical sensors can differentiate vegetation from other surfaces based on the selective absorption of electromagnetic radiation by the chlorophyll-*a* and *b* systems in plants. For the AVHRR and Landsat satellite series, several decades of data are now available from archives. The main shortcoming of these sensors is that visible light cannot penetrate clouds, and passive sensors can only operate during day-time, leading to reduced availability of cloud-free images. Due to their orbital characteristics, there is a trade-off between pixel resolution and higher revisit frequency. Medium resolution (30 m) optical sensors such as those on the Landsat satellites have a 16-day revisit time, which makes it challenging to obtain cloud-free observations over large areas. New products such as the Landsat WELD (Roy et al., 2010) are able to generate monthly, seasonal and annual top-of-atmosphere (TOA) radiance composites at 30 m resolution globally. However, even the annual composites still have gaps in very cloudy areas of the world. The few cloud-free observations acquired over those areas are subject to the time of acquisition in relation to the seasonal phenological cycle. Coarser resolution (250 m) optical sensors such as MODIS have a 24 h revisit time and therefore more opportunities to image under cloud-free conditions than Landsat. In addition, the estimation of *AGB* from optical imagery is limited by the saturation of the signal at low *AGB* (Gibbs et al., 2007).

As active sensors, synthetic aperture radar (SAR) sensors are independent of solar illumination, and can collect imagery during day and night. Microwave radiation also penetrates through haze, clouds and smoke. The radar backscatter (the amount of scattered microwave radiation received by the sensor) is related to *AGB* as the electromagnetic waves interact with scattering elements like leaves, branches and stems. The sensitivity of the SAR backscatter to *AGB* depends on the radar wavelength (Le Toan et al., 2004), with shorter wavelengths being sensitive to smaller canopy elements (X- and C-band), and longer wavelengths (L- and P-band) being sensitive to branches and stems. Longer wavelengths are theoretically more suitable for estimation of *AGB* as tree branches and stems comprise the highest fraction of *AGB* in forests. The sensitivity of L-band SAR backscatter (the longest wavelength available from spaceborne SAR at present) usually saturates between 100 t ha^{-1} and 150 t ha^{-1} (Wagner et al., 2003; Mitchard et al., 2009). Approaches that combine different types of imagery can circumvent the saturation problem and exploit the specific strengths of each sensor over large areas (e.g. Saatchi, Harris, et al., 2011b, Thurner et al., 2014).

Forest map products should not only include forest parameters such as *AGB* but also provide information about their uncertainties. Estimation of the uncertainty at the pixel scale requires a method of error propagation and needs to consider measurement error, allometric error, sampling error, and prediction error. Forest is not a well-defined semantic concept (Wadsworth et al., 2008), hence a certain degree of vagueness in the definition of forest as a land cover type is intrinsic to any forest map, whether it is explicitly described or not. Fuzzy set theory is most commonly used to tackle these issues in spatial data by providing pixel-scale information on the degree of class memberships. Given a specific definition of forest, the degree of forest class membership of each pixel provides a measure of the uncertainty whether the pixel is a forest.

It is important to differentiate between forest area and forest cover. *Forest area* is purely based on land use and includes temporally unstocked areas that are intended for use as forest, while *forest cover* only includes actual forest vegetation, independently of the land use. Forest cover can be estimated from remote sensing data, while forest area needs additional land use information. The forest definition also plays a key role. Sexton et al. (2015) demonstrated the effect of using different forest definitions to generate forest masks from remote sensing data, estimating the discrepancies in global forest extent among eight commonly used satellite products to be up to 13% of the global forest cover. Just within the tropics, the discrepancies between the satellite products lead to a variation in the magnitude of estimated carbon stocks of 45.2 Gt C with a value of approximately US$1 trillion (Sexton et al., 2015).

The Mexican Land Use and Vegetation map (LUV) developed by the Mexican National Institute for Statistics and Geography (INEGI) uses a combination of visual interpretation of optical imagery and field verification to create a land use and vegetation class vector layer at a scale of 1:250,000 (125 m spatial resolution) over the whole Mexican territory (INEGI, 2009). The dataset describes types of forest in Mexico based on several characteristics such as species composition, soils, elevation and climate (INEGI, 2014a) instead of standard biophysical parameters such as minimum canopy cover or canopy height which can be observed in remote sensing imagery. The FAO defines forest as "*Land spanning more than 0.5 hectares with trees higher than 5 meters and a canopy cover of more than 10 percent, or trees able to reach these thresholds in situ*" (FAO, 2012). However, FAO's forest definition also includes temporally unstocked areas. Forest cover maps using the FAO definition while ignoring temporally unstocked areas can be produced from optical and SAR sensors, and are often used in vegetation studies.

MODIS vegetation continuous fields (VCF) and the ALOS PALSAR Kyoto and Carbon Initiative forest/non-forest (K&C-FNF) map are examples of widely used forest cover products based on a similar FAO forest definition but generated from only optical or SAR imagery, respectively (Saatchi, Harris, et al., 2011b, Thiel, Thiel, & Schmullius, 2009, Shimada et al., 2011; Shimada et al., 2014; Hame et al., 2013). MODIS VCF provides annual, global, sub-pixel-scale data of percent tree cover (Hansen et al., 2003) at 250 m spatial resolution. This percent tree cover product is defined as the amount of skylight obstructed by tree canopies equal to or greater than 5 m in height (Hansen et al., 2003). Percent tree cover thresholds above 10%, in accordance with the FAO forest definition, are commonly used to create binary forest/non-forest maps (Saatchi, Harris, et al., 2011b). The VCF percent tree cover definition is slightly different from FAO's canopy cover definition as VCF is based on light penetration through the canopy, while FAO's canopy cover definition is based on crown vertical projection over the ground regardless of light penetration.

The ALOS PALSAR Kyoto & Carbon (K&C) Initiative is an international programme led by the Japan Aerospace Exploration Agency (JAXA)