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# Tree cover and carbon mapping of Argentine savannas: Scaling from field to region

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ABSTRACT

Programs which intend to maintain or enhance carbon (C) stocks in natural ecosystems are promising, but require detailed and spatially explicit C distribution models to monitor the effectiveness of management interventions. Savanna ecosystems are significant components of the global C cycle, covering about one fifth of the global land mass, but they have received less attention in C monitoring protocols. Our goal was to estimate C storage across a broad savanna ecosystem using field surveys and freely available satellite images. We first mapped tree canopies at 2.5 m resolution with a spatial subset of high resolution panchromatic images to then predict regional wall-to-wall tree percent cover using 30-m Landsat imagery and the Random Forests algorithms. We found that a model with summer and winter spectral indices from Landsat, climate and topography performed best. Using a linear relationship between C and % tree cover, we then predicted tree C stocks across the gradient of tree cover, explaining 87% of the variability. The spatially explicit validation of the tree C model with field-measured C-stocks revealed an RMSE of 8.2 tC/ha which represented ~30% of the mean C stock for areas with tree cover, comparable with studies based on more advanced remote sensing methods, such as LiDAR and RADAR. Sample spatial distribution highly affected the performance of the RF models in predicting tree cover, raising concerns regarding the predictive capabilities of the model in areas for which training data is not present. The 50,000 $km^2$ has ~41 Tg C, which could be released to the atmosphere if agricultural pressure intensifies in this semiarid savanna. In this study, we demonstrated the benefit of using high resolution imagery for regional tree cover and C analysis, increasing available training data when there is paucity of field data.



## 1. Introduction

Humans have increased the $CO_2$ atmospheric concentration over the last hundred years, introducing new forcings to the global climate (Anderson et al., 2013; Marotzke & Forster, 2015). Terrestrial vegetation plays a key role in the global carbon (C) cycle (Reichstein et al., 2013), functioning as a sink or source depending on the successional, climatic and management conditions. Natural ecosystems are highly dynamic, and are subject to the effect of natural disturbances such as fires and droughts, as well as human actions. Conversion of forests to crops, for example, removes plant biomass and alters soil conditions, releasing large amounts of C to the atmosphere annually (Don, Schumacher, & Freibauer, 2011). To quantify these C shift changes we need simple, reliable and cost effective methods to quantify and then monitor C stocks in terrestrial ecosystems. Much emphasis has been given to tropical forests which represent the most C dense areas (Baccini, Laporte, Goetz, Sun, & Dong, 2008; Saatchi et al., 2011), while less attention has been placed on savanna ecosystems. Savannas, while having smaller C stocks per unit area, cover such broad extents that they can significantly affect the global terrestrial C balance (Lucas et al., 2011). Here we present an innovative approach to quantify high resolution fractional tree cover and estimate tree C stocks in savannas by scaling up from fine scale field measurements to freely available high and moderate resolution satellite images.

Savanna ecosystems affect the global C cycle by their extensive coverage and highly dynamic nature. They cover approximately 20% of the global land surface (Lucas et al., 2011), and are predicted to expand even more in the next century if the global climate continues to change as projected (Anadon, Sala, & Maestre, 2014). Savannas are characterized by the presence of trees in a matrix of grasses, with a structure that depends on the fire, climate, animal use and human management history (Staver, Archibald, & Levin, 2011). For example, fire suppression, increases in rainfall and introduction of cattle have all been identified as main causes of woody plant encroachment in savannas of Africa, Australia and the Americas (Archer, 2010; Naito & Cairns, 2011). Native browsers, like the elephant in Africa, can also change the physiognomy of an area in only a few years of intensive use (Holdo, Holt, & Fryxell, 2009). Moreover, land use conversion to pastures and croplands has generated significant reductions in the extent of this ecosystem (Brannstrom et al., 2008; Hoffmann & Jackson, 2000). Spatially explicit C models are needed for more accurate accounting of C stocks and better

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allocation of resources targeted at the conservation of C stocks in natural ecosystems, such as payments for ecosystem services or reduced emissions from deforestation and degradation (REDD, Angelsen, Brockhaus, Sunderin, & Verchot, 2012).

Field surveys provide the most detailed accounting on C stocks from above and belowground trees, shrubs, and grasses and soil C stocks. However the time and cost of extensive field campaigns hinders its use for complete wall to wall surveying (Brosofske, Froese, Falkowski, & Banskota, 2014). Remote sensing data offer the possibility for scaling field data to regional scales via multiple approaches (Patenaude, Milne, & Dawson, 2005) at varying spatial, temporal and spectral resolutions (Kuenzer et al., 2014). Land cover classifications are useful for monitoring major change events that move an area into another land cover class, but they are not useful for the study of subtle changes in vegetation health, vigor or density such as the maturation of a forest stand over time, post fire recovery, effect of climate change, or woody plant encroachment. These subtle changes are critical for understanding C patterns and dynamics over space (Kennedy et al., 2014). Characterizing subtle canopy features such as vegetation height, cover, and productivity over large areas is urgently needed to increase the precision of current inventories, and for understanding the system itself and the factors changing it (McDowell et al., 2015).

Images from the Landsat satellite series offer the best opportunity for the study of landscape level natural resource dynamics, given (1) its long term record critical for temporal analysis and (2) its combination of spectral and spatial resolutions suitable for ecological studies (Kuenzer et al., 2014). Different methods have been used to extract subpixel information from Landsat such as machine learning algorithms to generate tree cover and C models in combination with climatic and topographic data (Asner et al., 2014; Dech, Mayhew-Hammond, James, & Pokharel, 2014). A critical element for the success of machine learning algorithms, like Random Forests, for ecological prediction is the availability of sufficient high quality data to train the model (Brosofske et al., 2014). Active sensors such as light detection and ranging (LiDAR), when available, have been successfully used for the creation of nationwide above-ground C in tropical regions (Asner et al., 2014). LiDAR provides detailed information on the canopy structure, height and density, which can then be related via allometric models to produce biomass and C estimations (McGlinchy et al., 2014). However, LiDAR data availability is still limited for regional monitoring due to the high cost associated with airborne remote sensing (Wulder, Bater, Coops, Hilker, & White, 2008). Satellite LiDAR is still experimental, offering limited spatial and temporal coverage. There is however, an increasing number of high spatial resolution images available to the general public which could be used to identify fine-scale tree cover (Kuenzer et al., 2014), and subsequently calibrate coarser-scale imagery with machine learning algorithms to efficiently monitor changes in regional estimates of tree cover and C in savannas.

High spatial resolution images allow for the detailed characterization of tree canopies. This is particularly useful in savannas where trees are widely spaced in a matrix of grasses. Commercial satellite images with sufficient spatial resolution to identify individual canopies (e.g. <5 m) are limited in their spatial and temporal coverage and are costly; their utility is limited for research and monitoring, particularly in developing countries. The China Brazil Earth Resources Satellite series (CBERS), operational since 1999 and freely available since 2008 offers high spatial resolution panchromatic images (~2.5 m) of most of South America and East Asia. Our past research has shown that tree cover in savanna ecosystems is a good predictor of tree C stocks (González-Roglich, Swenson, Jobbagy, & Jackson, 2014), providing us with the opportunity to use high spatial resolution imagery to calibrate spatially explicit models of tree cover and C stocks across the Argentine savanna ecosystem.

We modeled and mapped tree plant cover and its C content based on field surveys and a series of fine-to-coarse resolution satellite imagery. Field data were used to validate fine scale mapping of canopy cover which was then modeled over successively coarser scale satellite data. These broader scale estimates were validated and the effect of spatial aggregation was explored. The tree cover estimates were then converted to C stocks using the relationship between tree cover and C stocks we developed for the Caldenal savannas (González-Roglich et al., 2014).

## 2. Methods

We conducted field surveys that characterized canopy cover and tree C content across 35 sites. We then mapped tree cover at a fine scale (2.5-m resolution; CBERS) for 100 randomly distributed 16 km$^2$ quadrats, which we used to predict canopy and C estimates at coarser resolution for the entire region with the machine learning algorithm Random Forests. We initially tested a suite of remotely sensed variables to identify savanna tree plant cover and subsequently parsed variables to a more parsimonious and effective model. To test predictive capability at a coarser scale we scaled models with the same technique and assessed the effect of grain size on model performance. We then converted maps of tree plant cover to C based on a linear regression equation which was built using field surveys of C and canopy cover.

### *2.1. Study area*

The study area covers 50,000 km$^2$, approximately 25% of the Caldenal semiarid savannas in central Argentina (Fig. 1). The Caldenal is dominated by the Caldén tree (*Prosopis caldenia*) with an understory of perennial grasses frequently interspersed with dunes, wetlands, and lakes (Cabrera, 1994). The climate is temperate with a mean annual temperature of 15 °C; mean monthly temperature of the hottest month is 24 °C and of the coldest month is 8 °C (Cano, Fernández, & Montes, 1980). The region is flat or slightly rolling and is formed mainly of a deep mantle of loessic sediments (Soriano et al., 1991). The area is characterized by a SW–NE rainfall gradient ranging from 300 to 700 mm/yr., concentrated mostly in summer months, with year-round water deficits (Cano et al., 1980).

The area has been occupied for at least 8500 years by hunters and gatherers (Zink, 2008). With the arrival of Europeans to Buenos Aires in the 16th century, cattle appropriation, herding, and trading became primary economic activities (Zink & Salomon Tarquini, 2008). Major land cover and land use changes occurred with the arrival of new settlers at the end of the 19th century, when the Argentine government seized control of the region, and have intensified since then (Alonso, 2009). Some of these changes include replacement of natural systems with agriculture, extractive logging, introduction of non-native species, overgrazing by livestock, alteration of fire regimes (Medina, 2007; Mendez, 2007), and encroachment of native woody plants into grasslands and savannas (Baldi & Paruelo, 2008; González-Roglich, Swenson, Villarreal, Jobbagy, & Jackson, 2015).

### *2.2. Data*

#### *2.2.1. Field surveys*

Thirty-five 50 by 50 m field plots representing a gradient in tree cover from 0 to 94% were surveyed in the summer of 2013. Two belt transects (5 m by 50 m) were established in each plot 30 m apart. All trees within the belt transects were measured for later estimation of total tree biomass (above + below ground) using allometric equations. Biomass estimates were later converted to C stocks per unit area (see González-Roglich et al. (2014) for details on the field and post processing methods). In each transect, densiometer readings were taken every 10 m. Mean tree cover at the plot level was computed as the average of the 12 densiometer readings per plot (Lemmon, 1956).

#### *2.2.2. CBERS-HRC*

Very high spatial resolution panchromatic imagery can be used to generate crown metrics for forest monitoring (Mora, Wulder, & White,