Remote Sensing of Environment 216 (2018) 201–211

Contents lists available at ScienceDirect

Remote Sensing of Environment

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

Mapping continuous fields of tree and shrub cover across the Gran Chaco using Landsat 8 and Sentinel-1 data

Matthias Baumann[a,*], Christian Levers[a], Leandro Macchi[a,b], Hendrik Bluhm[a], Björn Waske[c], Nestor Ignacio Gasparri[b,d], Tobias Kuemmerle[a,d]

[a] Geography Department, Humboldt-Universität zu Berlin, Unter den Linden 6, 10099 Berlin, Germany
[b] CONICET, Instituto de Ecología Regional (IER), Universidad Nacional de Tucumán, CC:34, CP 4107 Yerba Buena, Tucumán, Argentina
[c] Institute of Geographical Sciences, Freie Universität Berlin, Malteserstr. 74 - 100, Berlin 12249, Germany
[d] Integrative Research Institute on Transformations of Human-Environment Systems (IRI THESys), Humboldt-Universität zu Berlin, Unter den Linden 6, 10099 Berlin, Germany

ARTICLE INFO

Keywords:
Gradient Boosting Regression
Savannas
Tropical dry forests
Canopy structure
Forest degradation
Essential Biodiversity Variables (EBVs)
Vegetation Continuous Fields (VCFs)
Sensor fusion

ABSTRACT

Tropical dry forests and savannas provide important ecosystem services and harbor high biodiversity, yet are globally under pressure from land-use change. Mapping changes in the condition of dry forests and savannas is therefore critical. This can be challenging given that these ecosystems are characterized by continuous gradients of tree and shrub cover, resulting in considerable structural complexity. We developed a novel approach to map, separately, continuous fields of tree cover and shrub cover across the South American Gran Chaco (1,100,000 km^2), making full use of the Landsat-8 optical and Sentinel-1 synthetic aperture radar (SAR) image archives. We gathered a large training dataset digitized from very-high resolution imagery and used a gradient-boosting framework to model continuous fields of tree cover and shrub cover at 30-m resolution. Our regression models had high to moderate predictive power (85.5% for tree cover, and 68.5% for shrub cover) and resulted in reliable tree and shrub cover maps (mean squared error of 4.4% and 6.4% for tree- and shrub cover respectively). Models jointly using optical and SAR imagery performed substantially better than models using single-sensor imagery, and model predictors differed strongly in some regions, especially in areas of dense vegetation cover. Mapping tree and shrub cover separately allowed identifying distinct vegetation formations, with shrub-dominated systems mainly in the very dry Chaco, woodlands with large trees mainly in the dry Chaco, and tree-dominated savannas in the wet Chaco. Our tree and shrub cover layers also revealed considerable edge effects in terms of woody cover away from agricultural fields (edge effects extending about 2 km), smallholder ranches (about 1.2 km), and roads and railways (about 1.4 and 0.9 km, respectively). Our analyses highlight both the substantial footprint of land-use on remaining natural vegetation in the Chaco, and the potential of multi-sensoral approaches to monitor forest degradation. More broadly, our approach shows that mapping canopy structure and distinct layers of woody vegetation in dry forest and savannas is possible across large areas, and highlights the value of the growing Landsat and Sentinel archives for doing so.

1. Introduction

Tropical dry forests and savannas cover about 20% of the Earth's surface, account for about 30% of the primary production of all terrestrial vegetation (Grace et al., 2006), harbor high biodiversity (Mayle et al., 2007), and provide many important ecosystem services (Abreu et al., 2017; Lehmann, 2010; Murphy et al., 2016; Parr et al., 2014). However, dry forests and savannas are under increasing pressure from agricultural expansion and intensification (Espirito-Santos et al., 2016; Kaya et al., 2018; Klink and Machado, 2005), leading to major carbon emissions (Chen et al., 2018; González-Roglich and Swenson, 2016; Lucas et al., 2011), and biodiversity losses (Ratter et al., 1997). Monitoring the condition of dry forest and savannas is therefore important.

This is challenging given the nature of these ecosystems, characterized by continuous gradients of woody and grass cover (House et al., 2003; Sankaran et al., 2008). These ecosystems can contain a wide variety of canopy types, including woodlands dominated by smaller trees and shrubs (House et al., 2003), woodlands with interspersed larger trees, and savannas dominated by grassland and scattered palm trees (Bucher, 1982), or shrublands (Archer et al., 1995;

* Corresponding author.
E-mail address: matthias.baumann@hu-berlin.de (M. Baumann).

https://doi.org/10.1016/j.rse.2018.06.044
Received 26 March 2018; Received in revised form 22 June 2018; Accepted 27 June 2018

Asner et al., 2003; Roques et al., 2001). This complexity in vegetation types arises from heterogeneous soils, climate conditions and, importantly, land use (Morgan et al., 2007; Polley et al., 1997). For example, fire suppression in savannas often results in increasing shrub cover and declining grassy vegetation (Archibald et al., 2005; Moreira, 2000). Similarly, logging and firewood collection lead to a loss of large trees (Gillespie et al., 2000), and grazing by cattle or goats might reduce or increase shrub cover (Stern et al., 2002). Monitoring gradients of woody vegetation, and stratifying woody cover into tree and shrub components, is therefore important for better understanding dry forest and savanna structure, composition, and functioning.

Remote sensing is a key technology to do so, and regression-based approaches to derive continuous fields of woody vegetation (Hansen et al., 2003; Hayes et al., 2008; Pengra et al., 2015) are particularly promising. Approaches to map fractions of woody cover were originally introduced to overcome limitations due to relative coarse resolution of sensors such as the Advanced Very High Resolution Radiometer (AVHRR) (Defries et al., 2000; Hansen and DeFries, 2004; Hansen et al., 2003) or the Moderate Resolution Image Spectroradiometer (MODIS) (Hansen et al., 2006; Hansen et al., 2003). While this has increased our understanding of the global distribution of woody cover substantially, broad-scale products are typically too coarse to provide reliable estimates for dry forests and savannas. With the opening of the Landsat archives (Wulder et al., 2012) mapping continuous fields of woody cover across local (Gessner et al., 2013; Johansen and Phinn, 2006), regional (Higginbottom et al., 2018; Schwieder et al., 2016), and continental extents (Hansen et al., 2011; Hansen et al., 2013) has become possible, representing a step change in our understanding of woody cover gradients. Yet, current broad-scale products still have low accuracy in dry forests and savannas (Brandt et al., 2016; Hansen et al., 2013; Sexton et al., 2013; Tian et al., 2016).

Existing approaches also typically do not allow separating between tree and shrub cover which would be important to assess dry forest and savanna complexity. Tree and shrub cover maps are potentially highly useful for land-use and conservation planning in savannas and dry forests, given that these systems are lost rapidly in many places, yet remain often unmapped (de Carvalho and Mustin, 2017). Mapping tree and shrub cover separately would also allow assessing the role of land use in shaping natural vegetation, moving beyond assessing full conversion only towards better capturing processes of woodland degradation. For example, grazing impacts are often highest close to a farm but decrease with larger distances (Macchi and Grau, 2012), and extractive activities such as logging are often highest close to infrastructure such as roads or railways (Chomitz and Gray, 1995). The spatial footprint of such land-use processes, however, is often unknown.

A promising avenue for stratifying woody cover into tree and shrub constituents is to combine Landsat imagery with synthetic aperture radar (SAR) imagery, as these data are highly complementary (Joshi et al., 2016). For example, optical data are powerful for mapping large trees, particularly when the phenology of vegetation is considered (Melaas et al., 2016), but have limited capabilities in identifying scattered woody vegetation. Contrary, SAR signals respond well to the density and size of scattering elements and are therefore potentially powerful to map sparser woody vegetation (Durigan and Ratter, 2006; Mitchard et al., 2011; Ryan et al., 2012; Santos et al., 2002). A number of studies have attempted to map savannas and dry forests by combining these data, for example in the Cerrado (Carreiras et al., 2017), in the South Africa-Mozambique border region (Naidoo et al., 2016), or in Bolivia (Reiche et al., 2018). Yet, these studies either mapped small regions only, classified savannas and dry forests into broad categories, or did not distinguish between trees and shrubs. A new generation of sensors now provides potentials for an improved mapping of dry forest and savanna vegetation. Landsat 8, operational since 2013, provides global coverage of high-resolution optical data at unprecedented radiometric resolution (Irons et al., 2012; Roy et al., 2014). Likewise, the Sentinel-1 sensors (since 2014) provide consistent C-band SAR data at high temporal and spatial resolution. Combining these data should provide tremendous potential for dry forest and savanna mapping, but to our knowledge, no study has attempted to do so across larger areas.

We focused on the Gran Chaco, a 1.1 million km^2 dry forest region in South America characterized by strong gradients in woody vegetation cover. The Gran Chaco contains dense and tall dry forests, palm savannas, open grasslands, and shrublands (Bucher, 1982), and is also a global hotspot of land-use change, with many land-use practices affecting the extent and composition of woody vegetation in the landscape (Grau et al., 2008; le Polain de Waroux et al., 2017). Yet, spatial patterns of woody cover and composition remain unclear, or are only available for smaller study regions (Cabido et al., 2018). Our overarching goal was thus to develop a methodology to use Landsat-8 and Sentinel-1 data to characterize woody vegetation across the Chaco. Specifically, our objectives were:

1. to map continuous fields of tree and shrub cover across the entire Chaco,
2. to assess whether the joint use of Landsat-8 and Sentinel-1 data improves the mapping of these woody cover components,
3. to map major vegetation types of dry forests and savannas across the Chaco, and
4. to assess the relationship of tree and shrub cover and a suite of environmental and socio-economic variables.

2. Methods

2.1. Study area

Our study area encompassed the entire Gran Chaco in South, stretching across Argentina, Bolivia and Paraguay, as well as into Brazil (Fig. 1, inlet). The Chaco is characterized by a marked dry season from May to September, with mean monthly temperatures of up to 29 °C, and a rainfall gradient between 1200 mm and 450 mm in the center, which results in substantially vegetation heterogeneity across the Chaco. In the west, medium-tall xerophyllous forests are dominant, with trees about 12 m high and sometimes reaching 18 m (Bucher, 1982). The eastern Chaco represents the wettest part, with widespread wetlands. The dominant vegetation types are wet savannas consisting of a mosaic of dense or open woodland patches, intermixed with grasslands. The woodland patches are occupied by subtropical semi-deciduous forests, with some trees reaching 25–30 m (Bucher, 1982), and gallery forest, mainly along the Paraguay and Parana rivers. Two semi-deciduous (*schinopsis balansae* and *astronium balansae*) and one evergreen species (*aspidosperma quebracho blanco*) are dominant here. The central Chaco is an ecotone between the eastern and the western Chaco, and dominated by xerophyllous subtropical forests with quebrachos (*Schinopsis quebrachos colorados*, *S. lorentzii*, and *Aspidosperma quebracho*), but also with grasslands and savannas dominated by wire grasses (*Elionorus muticus*) (Bucher, 1982; Cabrera, 1976). The driest section is the very dry Chaco in the south. Here, large trees are almost absent and grassland-shrub savannas (mostly *spartina argentinensis* and *Elionurus muticus*) with scattered low trees (mainly *proposes algarrobilla*) dominate (Bucher, 1982).

The Chaco is also a global hotspot of deforestation (Baumann et al., 2017b; Graesser et al., 2015; Kuemmerle et al., 2017), with various land-use actors affecting tree- and shrub-cover differently. Industrialized agribusinesses are now common in the Chaco, producing cattle and soybean (Baumann et al., 2016; Piquer-Rodríguez et al., 2018). In the case of cropping, no woody vegetation (i.e., no trees and shrubs) remains on the fields, and massive pesticide applications and run-away agricultural fires affect the surrounding woody vegetation. Pastures are traditionally also cleared completely of all trees and shrubs, but long-term grazing results in shrub encroachment. In recent years, so-called silvipastures are increasingly common, as the Argentine Ley de Proteccion Ambiental de Bosques Nativos (2007) requires