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Cultivating the dry forests of South America: Diversity of land users and imprints on ecosystem functioning

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ABSTRACT

In the South American dry forest of the Dry Chaco and Chiquitania, the area under cultivation rose from 10% to 19% over the last 10 years, and little biophysical, economical, or political constrains seem to prevent further expansion. Although typically associated to a homogeneous agribusiness system, agriculture and its expansion in this territory involve a diverse array of land users. Here we (i) identified and mapped the most conspicuous groups of land users based on existing scientific literature and technical reports, and (ii) described their associated landscape pattern and (iii) vegetation functioning based on different remote sensing tools applied to a set of 218 sample points. We recognized 14 groups of land users of local or foreign origin, composed by individuals or corporative organizations, and dedicated either to pasture or crop production, or its combination. These groups displayed a wide variation in the scale of their operations as suggested by a 60-fold difference in paddock sizes. Twelve years of MODIS-NDVI data showed small and non-significant differences in the magnitude of primary productivity (1.2-fold difference) but strong contrasts in its seasonality and long-term variability, including shifts in the rates of vegetation greening and browning (up to 4-fold differences), growing period length (193 to 278 days y^{-1}), number of cultivation seasons per year (1–1.75), and inter-annual coefficient of variation (up to 0.13). Agriculture under capitalized groups was characterized by very large paddocks, less stable productivity patterns, and more divergent seasonality. Instead, all smallholders showed more stable productivities both seasonally and inter-annually. Deforestation and cultivation in these dry regions does not have a single imprint on landscapes configuration and primary production dynamics, but one that shifts depending on the human and productive context under which they take place.

1. Introduction

Dry subtropical regions face a rapid expansion of agriculture over the still dominant areas of natural and seminatural vegetation (Miles et al., 2006; Portillo-Quintero and Sánchez-Azofeifa, 2010; Baldi and Jobbágy, 2012). Among the driving factors of these changes are the increasing overseas demand of food and fuel, the enhanced connectivity of formerly remote areas, more stable economies, and the release of local population from poverty and violence (Unruh, 1997; Redo et al., 2011). Agricultural land in these regions is managed by a broad array of users ranging from small-scale subsistence to large-scale commodity production, depending on the balance between population density, connectivity to global markets, and affluence/technology conditions (Grau et al., 2005b; Cotula et al., 2009; Lobell et al., 2010; Baldi and Jobbágy, 2012). Thus, the results of such transitions in terms of landscape pattern (rate of agricultural subdivision, paddocks shape), and of vegetation functioning (magnitude and temporal variability of primary productivity) may depend greatly on the human context under which changes occurs and not only on the biophysical conditions of the territory (Ellis and Ramankutty, 2008; Baldi et al., 2013).

In South America, the Dry Chaco and Chiquitania ecoregions do not escape from this general trend of expanding cultivation (Grau et al., 2005b; Killeen et al., 2007; Guyra Paraguay, 2013). Although they still encompass one of the largest extents of subtropical dry forests in the world, their transformation become

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noteworthy at a regional scale since the beginning of the 1990's (van Dam, 2003; Adámoli et al., 2011; Leguizamón, 2014). This occurred both through the expansion of the few early (i.e. 1950s) agricultural foci and emerging new areas, where no large biophysical limitations seem to constrain their establishment (Ewel, 1999; Pacheco, 2006; Houspanossian et al., 2014). The historical availability of federal lands, an ethnically and economically diverse population, governmental immigration campaigns, and a recent openness to the global market of agricultural goods, led to an exceptionally heterogeneous scenario of agricultural land users (Glatzle, 2004; Vázquez, 2006; Killeen et al., 2008; Redo, 2013). Under this complexity, local- to country-scale research showed a noticeable imprint on landscape composition and its dynamic (Killeen et al., 2008; Casco Verna, 2011).

In this territory, a developing body of studies is showing the effect of deforestation and subsequent cultivation on primary productivity patterns, carbon pools and emissions, groundwater hydrology, and climate regulation (Nitsch, 1995; Gasparri et al., 2008; Jobbágy et al., 2008; Santoni et al., 2010; Amdan et al., 2013; Houspanossian et al., 2013). In particular, cultivation introduces an amplification of the seasonal and inter-annual variability of productivity, apparently without changing its average magnitude (Volante et al., 2012; Baldi et al., 2013). However, little is known about the regional spatial and temporal heterogeneity of primary productivity patterns, and even less about its relationship with the diverse land management approaches performed by farmers and ranchers (Guerschman et al., 2003).

Our guiding questions are: Who are the agricultural land users in the Dry Chaco and Chiquitania territory? Users have a particular imprint on landscape patterns and vegetation functioning? Is there an interaction between this variable human context and aridity restrictions? To address these questions we (i) identify agricultural land users and characterize a series of social, operational, and productive traits from existing scientific literature and technical reports. Then we quantify (ii) the imprint of these groups on landscape patterns (i.e. paddock size and shape) using Google Earth high resolution imagery and (iii) their vegetation functioning (i.e. magnitude, and seasonal and long-term variability of primary productivity) using high temporal resolution MODIS spectral data. Finally, we (iv) assess the effect of climatic water availability on vegetation functioning patterns. While characterizing contrasts across the entire region, we make emphasis on the comparisons between neighbouring groups of land users (sharing presumably a same physical environment).

2. Methods

2.1. Study area

We focused our analyses on the dry portion of the Dry Chaco and Chiquitania territory (Fig. 1, left panel), encompassing an area of 775,000 km^2 in Northern Argentina (40%), Southeastern Bolivia (38%), and Western Paraguay (22%) according to Olson et al. (2001) limits. The territory is characterized by an extremely flat relief, and by fertile and deep soils of quaternary origin (aeolian and fluvial). Rainfall follows a monsoonal pattern, ranging from 450 mm $year^{-1}$ – in the north-center – up to 1200 mm $year^{-1}$ – in the outer limits – and average temperatures from 20 to 25 °C from south to north, according to the "Ten Minute Climatology database" (New et al., 2002). These two factors determine a general water deficit (especially from May to October). The ratio of mean annual precipitation-to-potential evapotranspiration (PPT:PET) ranges from 0.3 to 0.7.

Originally composed of dry forests and savannas, natural vegetation has been subject to different uses including logging, charcoal extraction, and grazing, which led to changes in structure and composition (Morello et al., 2005; Adámoli et al., 2011; Gasparri and Baldi, 2013; Rueda et al., 2013). Currently a dominant, continuous, cover of woody vegetation characterize the area (Baldi et al., 2013), with agricultural areas reaching in March 2013 19% of the study area (21, 13, and 25% in Argentina, Bolivia and Paraguay; respectively) (Killeen et al., 2008; UMSEF, 2008; REDIEX, 2009; Vallejos et al., submitted; Volante et al., 2012; Guyra Paraguay, 2013). In Argentina and Bolivia agriculture is mainly devoted to the production of cereals, oil, and industrial crops (e.g. soy, wheat, cotton, and sunflower) or exotic pastures (e.g. *Cenchrus ciliaris*, *Panicum* spp.). This last use is dominant in Paraguay, were exotic (i.e. *Leucaena leucocephala*) and native shrubs (e.g. *Prosopis* spp.) are additional components of pastures (van Dam, 2003; Glatzle, 2004).

2.2. Agricultural land users

In order to identify the different land users within the agricultural territory of Dry Chaco and Chiquitania (Fig. 1, left panel), we explored a set of 22 technical reports, papers, thesis, and websites dealing with local to regional agricultural production and expansion. Each of these sources of information described for widely accepted groups (e.g. ranching corporations), social (ethnic origin, settlement history, ownership), operational (source of capital, use of inputs, mechanization), and productive traits (crops vs. pastures, fate of products) – following Kostrowicki (1992). From the described dominant traits, and with the aid of local expertise and from our own knowledge, we generated a single scheme of groups by avoiding overlaps and inconsistencies. Due to the strength of political factors driving land use in the region (Vázquez, 2007; Redo et al., 2011; Leguizamón, 2014), we further distinguished groups by country. Though we acknowledge that some unmanaged variability within groups may exist, quantitative information at a paddock level is not currently available for the entire region.

2.3. Sampling scheme

Spatiality explicit location of the different agricultural land users groups was available in 12 of the 22 bibliographic information sources. The spatial accuracy and the extent of this information varied from sketches (e.g. Vázquez, 2007) to detailed maps (e.g. DGEEC, 2004), and from very small (e.g. Arístide, 2009) to large areas (e.g. Killeen et al., 2008). This information encompassed the entire Bolivian territory, almost two-thirds of Paraguay, and scattered areas throughout Argentina. Within these areas allocated to different agricultural land users, we determined a variable number of sample points for each group in order to characterize landscape patterns and vegetation functioning. The number of sample points depended on the known extent of each group, and on the accomplishment of points of the following criteria: (i) be composed of >95% of crops or pastures within a 250 m-radius area (the remaining area being woody corridors or isolated trees), (ii) >3 km away from any other sample point (with the exception of Argentinean Mennonites due to their reduced territorial extent), and (iii) subject to cultivation since 2000 or earlier. We set a maximum of 25 points per group, discarding extra sites through a random selection process, resulting in the 218 selected samples. The first two conditions were evaluated by a visual inspection of very high (≤1 m, Quickbird) to high (2.5–10 m, Spot) spatial resolution images from Google Earth (http://www.google.com/earth/index.html). The third condition was evaluated by a visual inspection of imagery circa 2000 from the "GeoCover" Orthorectified Landsat ETM+ Mosaics project (MDA Federal, 2004), and several existing land cover/land use classifications (Huang et al., 2009; Consorcio L. Berger – ICASA, 2010; Casco Verna, 2011; Vallejos et al., submitted; Volante et al., 2012). Agricultural paddocks were easily recognizable from the uncultivated surrounds by