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The seasonal carbon and water balances of the Cerrado environment of Brazil: Past, present, and future influences of land cover and land use

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A B S T R A C T

The Brazilian savanna (known as Cerrado) is an upland biome made up of various vegetation types from herbaceous to arboreal. In this paper, MODIS remote sensing vegetation greenness from the Enhanced Vegetation Index (EVI) and evapotranspiration (ET) data for the 2000–2012 period were analyzed to understand the differences in the net primary productivity (NPP-proxy), carbon, and the evaporative flux of the major Cerrado natural and anthropic landscapes. The understanding of the carbon and evaporative fluxes of the main natural and anthropic vegetation types is of fundamental importance in studies regarding the impacts of land cover and land use changes in the regional and global climate. The seasonal dynamics of EVI and ET of the main natural and anthropic vegetation types of the Cerrado biome were analyzed using a total of 35 satellite-based samples distributed over representative Cerrado landscapes. Carbon and water fluxes were estimated for different scenarios, such as, a hypothetical unconverted Cerrado, 2002 and 2050 scenarios based on values derived from literature and on the PROBIO land cover and land use map for the Cerrado. The total growing season biomass for 2002 in the Cerrado region was estimated to be 28 gigatons of carbon and the evapotranspiration was 1336 gigatons of water. The mean estimated growing season evapotranspiration and biomass for 2002 was 576 Gt of water and 12 Gt of carbon for pasture and croplands compared to 760 Gt of water and 15 Gt of carbon for the Cerrado natural vegetation. In a modeled future scenario for the year 2050, the ET flux from natural Cerrado vegetation was 394 Gt less than in 2002 and 991 Gt less than in an unconverted scenario, with only natural vegetation, while the carbon was 8 Gt less than in 2002 and 21 Gt less than in this hypothetical pre-conversion Cerrado. On the other hand, the sum of the pasture and cropland ET flux increased by 405 Gt in 2050 relative to 2002 and the carbon by 11 Gt of carbon. Given the increasing global demand for agricultural products and the insufficient protected areas in the Cerrado (with a significant area of remaining native vegetation in privately owned lands that may be legally deforested), our analyses suggest that potential future changes to the water and carbon balances are likely to be highly significant in the severely threatened Cerrado biome. On the other hand, our results also suggest that the recovery of degraded pastures can have a positive impact on climate, due to the higher rates of carbon sequestration and water transfer to the atmosphere.

1. Introduction

The Brazilian savanna (known as Cerrado in Brazil) is an upland biome located in the central part of Brazil, covering about 25% of the country's land area (i.e. ~2 million km^2) (Eiten, 1972). The rapid deforestation occurring in the Cerrado, with a mean deforestation rate of 1.6% (Silva et al., 2009; Rocha et al., 2011), is potentially important for the energy, water, and carbon cycles, as the replacement of natural vegetation by pastures and cropland affects the land surface - atmosphere feedbacks. The soils of the Cerrado are mainly deep with low fertility, high iron and aluminum content, and excellent internal drainage (Buol, 2009). The average annual temperature varies from 20–26 °C, and total rainfall and evapotranspiration are 1481 mm and 895 mm, respectively (Marcuzzo et al., 2012; Eiten, 1972). The climate has two defined seasons, a wet season from October to April and a dry season from May to September (Camargo, 1963). The vegetation of the Cerrado has many different structural forms (height, density,

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and layers), varying from herbaceous, grassy, and shrubby vegetation to woodland (Goodland, 1971). The Cerrado trees and shrubs generally have thick bark, twisted branches and trunks, glabrous or soft and hairy leaves, relatively low leaf density, and crown wider for its height than forest trees (Eiten, 1972). The ground layer is more or less xeromorphic with grasses and sedges with hard siliceous leaves. Most of the Cerrado species are perennial with some annual species in the northeastern region.

The combination of different structural forms determines the various Cerrado vegetation types, and these can be divided into five main types: campo limpo (Cerrado grassland), campo sujo (Cerrado shrubland), campo Cerrado (low tree and shrub Cerrado), Cerrado (Cerrado *stricto sensu*) and Cerradao (Cerrado woodland). The most abundant vegetation type is the Cerrado *stricto sensu* (22%), and the least abundant are the Cerrado woodland (5%) and Cerrado grassland (4%) (Sano et al., 2010). The forested vegetation types in the Cerrado biome differ from the Cerrado woodland, in their structural components, such as higher height and larger canopy size, and compositional components, like the occurrence of different tree species (Eiten, 1972). These forests, when located away from river courses, are called seasonal forests (floresta estacional). The forested vegetation types are also classified based on the fraction of leaf loss during the dry season, as evergreen (less than 20%), semi-deciduous (20 to 50% leaf loss), or deciduous (more than 50%) (Pereira et al., 2011). About 50% of the natural Cerrado vegetation has been converted to pasture and agriculture, and less than 3% are within protected areas (Couto et al., 2010; Garcia et al., 2011).

The occupation of the Cerrado biome started in the 18th century with cattle ranching activities over natural pastures and small subsistence farming (Silva et al., 2013). In the 70s, the Brazilian government conducted studies that showed the agricultural potential of the Cerrado and the required technical implementations in order to increase its productivity (Silva et al., 2013). Since the 1970s, the herbaceous and woody vegetation, formerly used as natural pastures and sources of food for cattle, have been replaced by exotic cultivated pastures of African origin in the genre *Brachiaria* (more than 80% of the cultivated pastures in the central part of Brazil), *Panicum,* and *Andropogon* (Brossard and Barcellos, 2005). Cultivated pastures occupied 29% of the Cerrado biome in 2002, with 40% of that concentrated in the southern portion of the biome, particularly in eastern Mato Grosso do Sul and western Goiás (Sano et al., 2000; Sano et al., 2010). The Cerrado biome supports 40% of the Brazilian cattle herd, over 50 million hectares of cultivated pastures, and contributes to about 55% of the national meat production (Vendrame et al., 2010; Brossard and Barcellos, 2005).

The transformation of the naturally poor and acid soils of the Cerrado biome into productive soils in the 1970s by the introduction of correctives and fertilizers, and improved infrastructure, also allowed for a boom in the expansion of soy, corn, and bean crops (Cunha et al., 1994; Jepson, 2005; Klink and Machado, 2005). Such technological advances and increased land profitability were instrumental for transforming the Cerrado into the most prominent agricultural frontier of the country (Rezende, 2002). Together, the commodity crops occupy about 10% of the total Cerrado area. With the global demand for food rapidly increasing, future expansion of crops into degraded pastures and intensification of cattle ranching (through the use of partial confinement and fodder) are likely to occur (Mueller, 2003; Klink and Machado, 2005; Brandão et al., 2006)

Compared to forests, pasturelands and croplands have lower above-ground and below-ground biomass, higher albedo, decreased evapotranspiration, lower canopy interception of rainfall and less atmospheric turbulence (Aragão et al. 2007; D'Almeida 2007; Bonan, 2008; Coe et al., 2009, 2013; Loarie et al., 2011; Lathuilliére et al., 2012; Spracklen et al., 2012). In fact, during the 1850–2000 period, land use change accounted for the release of about 156 PgC globally (60% from the tropics) (Houghton, 2003), while the net carbon flux from land use and land cover change alone accounted for approximately 13% of the carbon emissions from 1990 to 2010 (Houghton, 2012). This substantial increase in atmospheric carbon hinders the absorption of carbon by the oceans, changing the carbon-cycle feedbacks, which accelerates climate change.

Thus, land use transitions from natural vegetation to pastures and crops decrease carbon stocks, increase greenhouse gas emissions (Soares-Filho et al., 2014), reduce evapotranspiration (Costa and Pires 2009; Lathuilliere et al. 2012), and increase sensible heat flux (Ferreira et al., 2011; Giambelluca et al., 2009), all of which have significant environmental implications. Bustamante et al. (2012) showed that GHG emissions from cattle ranching in the Cerrado biome (229–231 Mt CO2 eq) accounted for approximately 20–30% of all GHG emissions from cattle ranching in Brazil (813–1,090 Mt CO2 eq). The decrease in ET associated with land use change leads to a soil moisture increase, with excess water being exported via increased runoff and river discharge (Costa et al. 2003; Coe et al. 2011; Hayhoe et al. 2011), which can, ultimately, reduce regional rainfall (Costa and Pires 2009).

Regarding the Cerrado landscapes, some studies have investigated the impact of land use change on soil carbon stocks (Batte-Bayer et al., 2010; Silva et al., 2004; Pinto et al.; 2014; Braz et al.,2013; Pimentel et al., 2012), as well as on GHG emissions from land use and land cover changes (Fearnside et al., 2009; Bustamante et al., 2012; Cerri et al., 2009), and on the carbon and water fluxes of the different Cerrado vegetation types (Rocha et al.; 2002; Paiva and Faria, 2007; Miranda et al., 1997; Santos et al., 2003). A literature review by Miranda et al. (2014) showed that the biomass of the Cerrado vegetation types varies from a mean value of 24 $Mg\,ha^{-1}$ for the Cerrado grassland, 58 $Mg\,ha^{-1}$ for the Cerrado shrubland, and 98 $Mg\,ha^{-1}$ for the Cerrado forestlands (Miranda et al., 2014). Rocha et al. (2009) estimated the water and heat fluxes for a gradient of natural vegetation from the Amazon forest to the Cerrado savanna biomes, indicating evapotranspiration rates during the dry season of 2.5 mm d^{-1} in the forest and 1.0 mm d^{-1} in the Cerrado. Using MODIS products (Moderate Resolution Imaging Spectroradiometer), Loarie et al. (2011) found that the conversion of native Cerrado to pasture or non-sugar cane crops resulted, on average, in a 0.6 mm d^{-1} decrease in evapotranspiration, showing that the Cerrado natural vegetation plays a key role in maintaining the water balance.

Our study estimates both ET and carbon fluxes based on a regional scale, taking into consideration both the different Cerrado vegetation types, as well as the changes in ET and carbon fluxes from the conversion of these natural vegetation types to anthropic vegetation types (pastures and crops). Differently from previous studies, focused on small, restricted areas, this is the first study that estimates carbon and water fluxes for the entire Cerrado biome, based on freely available and ready to use satellite products and on simple and replicable approaches. Specifically, we used monthly MODIS data on vegetation greenness from the Enhanced Vegetation Index (EVI) and evapotranspiration (ET) from 2000 to 2012, to quantify the differences in the net primary productivity (NPP-proxy) and water vapor flux (ET) of the major Cerrado natural and anthropic landscapes. Additionally, we investigated the historical changes to biomass and water vapor flux that have resulted from deforestation in the Cerrado and the potential changes that may occur in the future if deforestation continues at its current rates.