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Soil changes under different land-uses in the Cerrado of Mato Grosso, Brazil

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ABSTRACT

This study aimed to (1) examine the effects of land-use change on the soils of natural Cerrado transformed to common croplands (soybean/cotton/maize rotation and sugarcane) and pasture and (2) indicate how agricultural production affects water quality across a meso-scale catchment. Land conversion caused significant reduction in infiltration rates near the soil surface (0–40 cm depth) of pasture (−96%) and croplands (−90% to −93%). Soil aggregate stability was significantly lower in croplands than in Cerrado and pasture. Topsoil pH and nutrient concentrations were high in croplands and pasture. Soybean crops had extremely high extractable P concentrations (80 $mg \cdot kg^{-1}$; 9 times greater than the natural background), whereas pasture N levels declined. Nutrient accumulation of N and P did not occur at deeper horizons for any land-use type. Snapshot water sampling showed strong seasonality in water quality parameters. Higher temperature, oxi-reduction potential (ORP), NO_2^-, and very low oxygen concentrations (<5 $mg \cdot l^{-1}$) and saturation (<60%) were recorded during the rainy season. In contrast, remarkably high (up to 0.8 $mg \cdot l^{-1}$) PO_4^{3-} concentrations were measured during summer. Water quality parameters were affected by agricultural activities at all sampled sub-catchments across the meso-scale catchment, regardless of stream characteristics (stream order, percentage of riparian vegetation, sub-catchment size); thus, no spatial trends were observed. Direct NO_3^- leaching appeared to play a minor role; however, water quality is affected by agricultural non-point sources, due to topsoil fertiliser inputs affecting the entire catchment, from small low order streams to the larger rivers of the modified catchment. In conclusion, land-use conversion has degraded soil physical properties, leaving cropland soils more susceptible to surface erosion with potential lateral nutrient transport to the stream network.

1. Introduction

There is major concern about how the deforestation of large parts of natural savannah woodlands for mechanised agriculture has altered the terrestrial ecosystem, affecting water and soil resources (D'Almeida et al., 2007; Lapola et al., 2014; McGrath et al., 2001). Since the 1980s, the most rapid deforestation in South America has occurred in the Cerrado biome (La Rovere et al., 2011). This biome has lost half of the 2 million square kilometre extent for agricultural land use and is considered the most threatened biome in Brazil (Marris, 2005; Sano et al., 2010). The deforestation rate in the Cerrado was double than that in the Amazon Basin between 2008 and 2010 (Lambin et al., 2013). The federal state of Mato Grosso is heavily affected by landscape scale conversion, and has the highest deforestation rates in Brazil for conversion to pastures and cash crops (Sano et al., 2010). In the last two decades, extensive pastures have been increasingly transformed for more intensified land use, such as soybean, maize, and cotton single- and double-cropping practices, in addition to sugarcane (Redo et al., 2012). Consequently, the Cerrado is among the world's top regions for cash crop production. Since the revision of 2012 Forest Code (Government of Brazil, 2012 Law No. 12.727), it is even easier to convert native vegetation outside the Legal Amazon (encompassing 9 states; Marris, 2005; Sparovek et al., 2012). Thus, future land-use projections predict further land-use intensification (Lapola et al., 2014) with serious concerns that most of the Cerrado's natural vegetation will be lost by the year 2030 (Machado et al., 2004).

The acceleration of agricultural activities has generated economic wealth in the region, but has also generated environmental problems related to soil degradation and the contamination of water resources (Batlle-Bayer et al., 2010; Martinelli et al., 2010; Schiesari and Grillitsch, 2011; Schiesari et al., 2013). Cerrado soils are very poor in nutrient because this area is dominated by dystrophic deeply weathered soils characterised by a pseudo-sand structure (Goedert, 1983; Lopes et al., 2004). Thus, to produce high biomass yields, enormous lime application and fertilisation are needed (Carvalho et al., 2009; Yamada, 2005). Several studies have demonstrated the effects of increasing agriculture

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in the Cerrado, but most have focused on specific aspects of land-use change (e.g. pesticide transport: Laabs et al. (2000); soil fertility change: Lilienfein et al. (2003); change in soil organic carbon content: Corbeels et al. (2006); and tillage effects on soil biological activity: Green et al. (2007)). Other studies have assessed natural Cerrado soils (Goedert, 1983; Lopes and Cox, 1977) or focussed on how to increase soil productivity, rather than investigating the negative impacts of land modification (de Sousa and Rein, 2011; Fageria et al., accepted for publication).

Several studies in the tropics have indicated that land-use and vegetation cover influence the physical properties of soils (e.g. Hassler et al., 2011; McGrath et al., 2001; Scheffler et al., 2011; Zimmermann et al., 2006). Soil hydraulic properties, bulk density, compaction, and soil aggregate stability control water and nutrient flow; thus, these parameters represent sensitive parameters for quantifying the effect of deforestation and land-use change. Soil aggregate stability is a key indicator of soil quality and rangeland health, indicating soil erosion processes and changes in water quality (Herrick et al., 2001). Thus, identifying changes in soil properties may help towards understanding the effects of land-use change on stream water chemistry, which is mainly regulated by soil properties (Biggs et al., 2004). The establishment of pastures in the Amazon has caused nutrient loss to the soils, due to increased overland water flow patterns in the last four decades (Biggs et al., 2006). However, it remains unclear to what extent soils are influenced by the surplus of agrochemicals in the Cerrado and how water quality is affected by altered hydrologic flow paths in this originally nutrient-limited ecosystem. The increasing agricultural land extent tends to be related to declining water quality (reviewed by Allan, 2004); yet, only a few studies have assessed the impact of mechanised agriculture on water quality and how nutrient cycling has altered in the Cerrado (e.g. Fonseca et al., 2014; Gücker et al., 2009; Silva et al., 2007, 2011). Numerous small streams connect the terrestrial environment to rivers and, subsequently, to the sensitive Pantanal wetlands; thus, it is essential to understand the biogeochemical processes in headwaters (Fonseca et al., 2014). Most water quality data of the Agencia Nacional de Águas (ANA) are only available for the largest watersheds of Brazil, with a relatively low temporal resolution and irregular sampling intervals (ANA, 2009). Consequently, the scale effects of land-use change on solute loads in streams across meso-scale catchments are unclear (Germer et al., 2010).

Thus, this study aimed to assess how changes in land use of natural Cerrado transformed to agricultural production over the last 20–30 years have affected soil physical, hydrological, and biogeochemical soil properties at the hillslope scale and, subsequently, water quality at the meso-scale. Specifically, we aimed to examine (1) the effects of changes in land-use from natural Cerrado to planted pasture, soybean–cotton rotation, and sugarcane on a range of parameters (soil aggregate stability, infiltrability, saturated hydraulic conductivity, pH, and soil nutrients [NPK]) and (2) provide insight how agricultural production affects water quality, by examining the seasonal patterns in water quality parameters across a heavily modified catchment.

We hypothesise that an increase in soil nutrient concentrations, due to the extensive fertilisation of agricultural land, is correlated with increased nutrient concentration in streams across altered meso-scale catchments, especially in the rainy season.

2. Material and methods

2.1. Study site description

The study area is located within the Cerrado biome in Mato Grosso State, Brazil. The Tenente Amaral Catchment is a typical meso-scale catchment that has been subject significant land-use change from natural Cerrado to pasture and cropland over the last 20–30 years. It is situated ca. 120 km southeast of the capital Cuiabá in Mato Grosso (Fig. 1) on the southern edge of the Brazilian Planalto, which is part of the Brazilian Shield (Marques et al., 2004). The catchment waters drain into the São Lourenço River, which is a major tributary of the Pantanal floodplain.

The catchment covers ca. 865 km^2, with the elevation ranging from 225 to 800 m above sea level (a.s.l.). The climate type is classified as Aw according to the Köppen classification, with a distinct dry season between May and September. Mean annual precipitation is 1500 mm, of which about 80% falls as heavy rain from October to April. Characteristic topographical soil sequences determine the distribution of Latosols (after the Brazilian soil classification; Ferralsols, according to the FAO classification; or Red Oxisol according to USDA taxonomy). The plateaus of the central part of the catchment are more deeply weathered, and are dominated by heavier Red and/or Red-Yellow Latosols than the surrounding valley slopes (Vasconcelos, 1998).

About 70% of the catchment area is used for sugarcane and soybean production in rotation with maize and cotton. Several sub-watersheds (covering about 18% of the catchment) are used for cattle grazing (Rio Brilhante and parts of the Rio Verde tributaries; Fig. 1). The small remaining part of the lower catchment is under nature conservancy.

Double-cropping without irrigation is mainly used within the Tenente Amaral. Previously, no or minimal tillage was used, with soybean–maize rotation being directly planted for more than 15 years (Wantzen and Mol, 2013). Furthermore, cover crops were widely used during the dry season and small elevated contour banks were often installed on pastures and soybean fields. However, when cotton prices peaked in 2011, crop rotation practices shifted from soybean–maize to soybean–cotton, accompanied by the increased use of conventional tillage, which has resulted in the levelling of existing contour banks. At sugarcane sites, deep ploughing is conducted before the replanting every 4–5 years. The pastures are planted with *Brachiaria*, *Andropogon*, and *Panicum* sp., and are regularly fertilised.

Farmers apply fertilisers, lime, and between 10 and 13 pesticides of about 2 $kg\cdot ha^{-1}$ depending on the crop (personal communication from the farmers, Table 1). Sugarcane is also fertilised with P and K rich filter cake residues and vinasse (*vinhaça*, a by-product of sugarcane distillation).

2.2. Soil sampling

2.2.1. Sampling design

Soil was sampled from January to March 2011, during the rainy season. To compare the impact of dominant land-use types, four representative single hectare plots (100 m × 100 m) were selected: natural Cerrado, planted pasture (with a grazing intensity of one cattle per hectare), soybean–cotton rotation, and sugarcane. Five to 11 sampling points per plot were used.

All plots were located on soils that developed from sandy-clayey tertiary laterites on the wide plains with low slopes (of maximal 2–3%). The parent materials are a saprolitic layer of Paleozoic quartz arenites. All plots had similar slopes so as to compare differences in soil physical and chemical properties as a function of land use only. The soils were homogenously weathered and showed little horizonation, with stonelines appearing at 1.5 m soil depth. The plot soils were classified as Dark Red dystrophic Latosols (*Latosolos vermelho escuro distrofico*) according to the Brazilian soil classification (Rhodic Ferralsols according to the FAO classification), with low chroma colours for the Bw horizon (Table 2).

The following soil measurements were carried out on each land-use type (Fig. 2): ponded infiltration and Ksat measurements at 17 and 11 locations, respectively, with a minimum distance of 25 m between each location. Measurements were made at three depths (14, 20, 40 cm), because we expected land-use change to have less effect at deeper layers (Hunke et al., accepted for publication). Soil was sampled using cores at five points every 25 m at three depths up to 1 m, to analyse soil nutrients (NPK), pH, and texture. At these five points, 45 soil aggregate stability tests were performed on the soil surface and at a depth of two centimetres. During the sampling period, gross precipitation was recorded continuously by a tipping-bucket rain gauge with a resolution of 0.2 mm (HOBO event logger) to determine rainfall intensity for comparison with the soil permeability of the different land uses.