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Land use and climate change impacts on runoff and soil erosion at the hillslope scale in the Brazilian Cerrado

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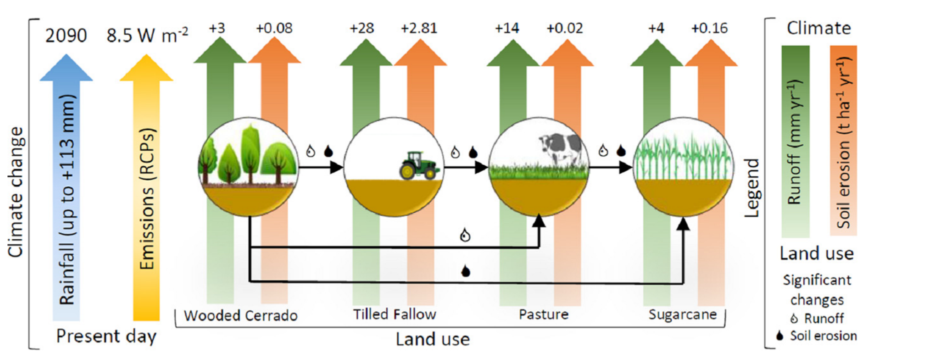
HIGHLIGHTS

- Process-based models replace empirical ones when long-term observations are scarce.
- A process-based model effectively estimates runoff and soil erosion in Brazil.
- Land use influences on runoff and soil erosion rates in a tropical soil.
- Runoff and soil erosion responses to climate change are not significant.
- Agricultural land may reach conservation levels of an undisturbed tropical woodland.

GRAPHICAL ABSTRACT



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ABSTRACT

Land use and climate change can influence runoff and soil erosion, threatening soil and water conservation in the Cerrado biome in Brazil. The adoption of a process-based model was necessary due to the lack of long-term observed data. Our goals were to calibrate the WEPP (Water Erosion Prediction Project) model for different land uses under subtropical conditions in the Cerrado biome; predict runoff and soil erosion for these different land uses; and simulate runoff and soil erosion considering climate change. We performed the model calibration using a 5-year dataset (2012–2016) of observed runoff and soil loss in four different land uses (wooded Cerrado, tilled fallow without plant cover, pasture, and sugarcane) in experimental plots. Selected soil and management parameters were optimized for each land use during the WEPP model calibration with the existing field data. The simulations were conducted using the calibrated WEPP model components with a 100-year climate dataset created with CLIGEN (weather generator) based on regional climate statistics. We obtained downscaled General Circulation Model (GCM) projections, and runoff and soil loss were predicted with WEPP using future climate scenarios for 2030, 2060, and 2090 considering different Representative Concentration Pathways (RCPs). The WEPP model had an acceptable performance for the subtropical conditions. Land use can influence runoff and soil loss rates in a significant way. Potential climate changes, which indicate the increase of rainfall intensities and depths, may increase the variability and rates of runoff and soil erosion. However, projected climate changes did not significantly affect the runoff and soil erosion for the four analyzed land uses at our location. Finally, the runoff behavior was distinct for each land use, but for soil loss we found similarities between pasture and wooded Cerrado, suggesting that the soil may attain a sustainable level when the land management follows conservation principles.

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1. Introduction

The increase of soil erosion with time is linked to the intensification of land use for agricultural purposes worldwide. There is a strong relationship between land use, soil management, soil erosion and agricultural sustainability (Vanwalleghem et al., 2017). Additionally, nutrient residence time in cropland soil is likely to decrease as the soil is disturbed (Quinton et al., 2010). The representation of the water flow patterns in the soil (under natural and disturbed conditions) is a large topic of discussions and hillslope observations are needed to improve the performance of comprehensive models (Beven and Germann, 2013).

Although potential climate changes can influence runoff and soil erosion, the prediction technologies should include rill and interrill water erosion, try to account for the role of extreme events in the simulated processes, and include different crop rotations and land use change dynamics (Li and Fang, 2016). The low resolution scale from the General Circulation Models (GCMs) can be downscaled to generate stochastic future climate scenarios for runoff and soil erosion models (Jones and Thornton, 2013; Wilby et al., 2009). Additionally, the inclusion of prediction uncertainties would improve long-term assessments in runoff and soil erosion model frameworks (Kim et al., 2016).

The Brazilian Cerrado biome is the largest savanna area in South America, comprising 2,033,601 km^2. This region is part of the country's agricultural frontier due to the intense conversion from natural vegetation to pastureland and croplands, and is becoming a biodiversity extinction hotspot (Hughes, 2017; Lapola et al., 2013). Cultivated pasturelands occupy approximately 1,120,000 km^2 in Brazil, and São Paulo is one of the Brazilian states that includes large areas of cultivated pastureland that are suitable for sugarcane production (Alkimim et al., 2015). As Brazil is the world's largest sugarcane producer and due to increasing biofuel demand, a huge extension of the Cerrado biome was converted to this crop (Loarie et al., 2011). Apparently, the substitution of pasture with sugarcane increases runoff and soil erosion due to the tillage disturbance and associated decrease in soil quality, however, more observations are needed to understand this behavior during a longer period (Youlton et al., 2016b).

An initial study to measure runoff and soil erosion in a Cerrado sensu stricto area (undisturbed tropical woodland or wooded Cerrado) indicated that <1% of the rainfall was converted into runoff and the soil loss was around 0.1 t ha^{-1} yr^{-1} (Oliveira et al., 2015). At the same site, tilled fallow conditions generated runoff that was approximately 20% of the rainfall and the soil erosion rates were >10 t ha^{-1} yr^{-1}.

In general, short period experimental studies in Brazil do not explain the long-term variability of runoff and soil erosion processes (Anache et al., 2017). In addition, climate extremes may affect agricultural sites and, consequently, their runoff and soil erosion rates (Lapola et al., 2013; Li and Fang, 2016). Thus, critical research considering hillslopes with different land use managements is needed to predict the responses of runoff and soil erosion to a changing climate.

The Curve Number (CN) method developed by the USDA-NRCS (2004) is a popular alternative to predict the overland flow in a simple way according to the rainfall depth of a given event. However, runoff estimates using the CN method in Brazil are inaccurate (Oliveira et al., 2016). In general, many erosion models do not include runoff as a factor, and empirical models, such as the Universal Soil Loss Equation (USLE) and the CN method, are not likely to be applied with no restrictions in Brazil. These problems can occur because the empirical models' input parameters are based on long-term field observations performed within the United States, under their environmental conditions, where the models provide satisfactory performances (Kinnell, 2017).

Process-based models, such as the Water Erosion Prediction Project (WEPP) (Nearing et al., 1989; Flanagan et al., 2007), can be applied to a wider range of conditions, and are powerful tools for estimating runoff and soil erosion. The WEPP model was first released publicly in 1995 by the United States Department of Agriculture – Agricultural Research Service (USDA-ARS) as a new generation of water erosion prediction technology to be used as a planning and management tool in soil and water conservation (Flanagan et al., 2001). WEPP takes into consideration water infiltration, surface runoff, plant growth, residue decomposition, flow hydraulics, tillage disturbance, residue management, soil consolidation, and erosion mechanics. The WEPP model has been shown to be efficient in estimating runoff and soil loss, and also enhances the results with the capability to predict both temporal and spatial distributions of soil erosion in a hillslope or a small watershed (Pandey et al., 2016; Tiwari et al., 2000).

The purpose of this study was to better understand how natural and agricultural land uses govern runoff and soil loss under subtropical Brazilian conditions considering future climate scenarios. We aimed to (i) calibrate and validate the WEPP model for four land uses (wooded Cerrado, fallow, pasture, and sugarcane) under subtropical conditions for a specific site inside the Cerrado biome; (ii) predict baseline runoff and soil erosion for these different land uses using stochastic climate generator inputs; and (iii) simulate runoff and soil erosion considering possible future climate change scenarios.

2. Material and methods

2.1. Study area and experimental design

The study area is located in the Arruda Botelho Institute (IAB), Itirapina, central area of the state of São Paulo, Brazil (latitude 22°11′5″ S, longitude 47°51′11″W, elevation 790 m a.m.s.l.). It was divided into two sites: site 1 had plots containing three different agricultural land uses with three replicates each (pasture, sugarcane, and tilled fallow without plant cover); and site 2 had plots under undisturbed woodland typical of the central area of Brazil (Cerrado sensu stricto also known as wooded Cerrado) in three replicates (Fig. 1). The climate in the study area is humid subtropical (Cwa, Köppen classification system). The average annual temperature and rainfall are 21.5 °C and 1486 mm yr^{-1}, respectively, with hot and rainy summers (October–March, mean temperature of 23.6 °C and 77% of annual rainfall) and dry winters (April–September, mean temperature of 19.5 °C and 23% of annual rainfall) (Alvares et al., 2014; Cabrera et al., 2016). The soil is classified as Quartzipsamments (Oliveira et al., 2016), an entisol, with a sandy texture, covering around 15% of the Cerrado biome area.

The wooded Cerrado region in Brazil is composed of tropical woodland vegetation in a continuous herbaceous layer. The trees do not form a continuous canopy, but the Cerrado has a dominant woody component of six to seven meters high and some trees reaching up to 12 m (Alberton et al., 2014). The experimental plots at site 1 were covered by three different land uses: (i) Signalgrass (*Brachiaria decumbens*) vegetation (20 continuous years) in the pastureland, used for cattle raising, with the canopy height varying between 5 and 30 cm. Cattle grazing was in a 30-day rotation of 10 animals (420 kg each) per hectare for 5 days; (ii) Sugarcane (*Saccharum officinarum*) plantation established on October 2011 was contour planted on beds with a 1.5 m spacing, with the plant canopy reaching at least 2 m in height. The soil was ploughed to a 30 cm depth, and furrows were formed with a 20 cm depth on the contour (Youlton et al., 2016b). Sugarcane was harvested every year in November; (iii) Bare soil plots were maintained in a tilled fallow condition by glyphosate application and manual tillage (Oliveira et al., 2015).

2.1.1. Runoff and soil erosion observations

Experimental plots of 5 m width and 20 m length, with a 9% uniform slope gradient were used for the field observations (Fig. 1). A metallic collector placed at the end of each plot carried runoff water and eroded sediments to a storage tank (Youlton et al., 2016a). The runoff volumes were determined using the storage tanks' water level-volume calibration curves. Runoff and sediment (well-stirred samples) were collected from the storage tanks. Overland flow and soil loss rates were measured after a group of events under the wooded Cerrado, pasture, sugarcane,