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Runoff and soil erosion plot-scale studies under natural rainfall: A meta-analysis of the Brazilian experience

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ABSTRACT

Research to measure soil erosion rates in the United States from natural rainfall runoff plots began in the early 1900′s. In Brazil, the first experimental study at the plot-scale was conducted in the 1940′s; however, the monitoring process and the creation of new experimental field plots have not continued through the years in either country, and are relatively rare in other parts of the world. To better understand runoff and soil erosion rates in Brazil, we review the plot-scale studies that have been conducted across the country. We also evaluated trends, challenges, and perspectives of plot-scale studies in Brazil. Runoff and soil loss records under natural rainfall were compiled from peer-reviewed journals, books, M.Sc. theses, and Ph.D. dissertations, and we organized a database containing the following information: geographic coordinates, region, rainfall, runoff, soil erosion, length of record (plot-years), land cover, tillage system, slope length, and slope gradient. We found mean values of observed annual soil loss ranging from 0.1 t ha y^{-1} (grassland and pasture in the southern region) to as great as 136.0 t ha y^{-1} (tilled fallow plots, without plant cover, in the northeastern region). Our findings indicated that the southern and southeastern regions of Brazil have the greatest number of runoff and soil loss monitoring sites and length of records (plot-years), corresponding to 67% and 88% of the totals, respectively. In addition, the number of plot-years of data collected has decreased 86% in the last 15 years. However, the number of published documents has increased 10 times in the same period. Around 50% of the experimental studies have 2 years or less of monitored data. In order to reduce the variability of the observed data, develop models, and support decisions, it is important to increase the monitoring period of the experimental sites. Moreover, efforts should continue to allow field observations in all regions of Brazil where data is scarce, in particular paying special attention to the central-western region, where crop production is the main land-use, and along the largest Brazilian agricultural expansion frontier (northern region).

Contents

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1. Introduction

Soil is a key component of the earth's system, controlling hydrological, erosional, geochemical, biological, and ecological cycles, in addition to being a key source of goods, services, and resources for humankind (Keesstra et al., 2016; Brevik et al., 2015; Decock et al., 2015; Smith et al., 2015). However, accelerated soil erosion rates threaten many societies due to their negative impact on soil production and the damages caused to the environment (Tsozué et al., 2015; Nyssen et al., 2015; Tesfaye et al., 2015; Adimassu et al., 2014).

To supply the worldwide demand for food, fiber, and fuel, agricultural cropland and pasture areas have been increasing, mainly in tropical developing countries such as Brazil (Gibbs et al., 2010). However, this expansion of new cropland and pasture areas has the potential to change hydrological and soil erosion processes (Merten and Minella, 2013; Wohl et al., 2012).

To better understand soil erosion processes, efforts have been made to determine soil erosion rates using runoff plots in many countries over the last century (García-Ruiz et al., 2015; Guo et al., 2015). Data from global compilations show that soil loss rates resulting from conventional agricultural systems are much greater than those from land under native vegetation. Local and regional variations in natural settings, cultural traditions, and socioeconomic conditions play a major role in the dynamics and the rates of soil erosion (Dotterweich, 2013). For instance, in order for land to be sustainable as an agricultural site, erosion rates must approximate natural soil production rates (Montgomery, 2007).

Experimental studies on hydrological and soil erosion processes are crucial to improve agricultural and livestock production efficiency while promoting sustainable development. Therefore, it is important to organize historical records to better understand and provide new perspectives and solutions to minimize soil erosion (Dotterweich, 2013). Research on soil erosion is often performed on bounded plots, from which both runoff and soil loss are monitored after each rain event (Mwango et al., 2016; Strohmeier et al., 2016; Zhao et al., 2016; Nanko et al., 2015; Sadeghi et al., 2015; Morgan, 2009; Toy et al., 2002). The United States is a successful example of soil erosion monitoring, where around 50 experimental field stations (Gilley and Flanagan, 2007) were operated for more than 20 years, leading to the development of the Universal Soil Loss Equation (USLE) and its variants (Renard et al., 1997; Wischmeier and Smith, 1978).

In Brazil, agricultural expansion has exponentially increased water erosion (Oliveira et al., 2015a, 2015b). This reinforces the importance of field measurements on soil loss, which began in Brazil in the 1940′s in the States of Minas Gerais and São Paulo using bounded plots (Bertoni, 1949). In addition, the longest and most recognized dataset (more than 40 years) was published by Bertoni and Lombardi-Neto (2012), who operated field experiments in the State of São Paulo (southeastern Brazil) to provide reference soil loss rates for the main crops found in the country (Castro and Queiroz Neto, 2009; Merten and Minella, 2013). Furthermore, recent studies show that changes in land use in Brazil are increasing land degradation and, as a consequence, soil erosion (Moraes Sá et al., 2015; Oliveira et al., 2015a, 2015b).

However, the monitoring process and the creation of new experimental field plots have not continued through the years in Brazil. On the other hand, to improve soil and water conservation techniques in Brazil, it is necessary to initiate new field studies on runoff and soil erosion (Oliveira et al., 2015b, 2015c). There are currently few quantitative studies underway regarding those issues for different land covers, soil types, tillage systems, and slope gradients. Furthermore, there is no national inventory for these measurements, which might be used in order to organize and publish data to support decisions concerning policies and actions to control accelerated erosion.

Although runoff and soil erosion experimental data obtained under natural rainfall can be found in Brazil, these records are dispersed, and some of them are not published in peer-reviewed journals. Thus, the goals of this meta-analysis study were to compile runoff and soil loss records from experimental plots monitored in Brazil, and to assess the variability of runoff and soil erosion rates among Brazilian regions, land covers, tillage systems, and slope gradients. We also evaluated trends, challenges, and perspectives of plot-scale studies across the country.

2. Material and methods

2.1. Regional setting

Pasture and agricultural land comprise around 32% (275 million ha) of the total area of Brazil (851 million ha). Currently, approximately 59% (497 million ha) of the country is covered by native vegetation (FAO, 2016). Brazil is regarded as an important producer of foodstuffs both for its own domestic needs and for the world market, and has recently established a national bio-fuels program in order to diversify its energy framework (Merten and Minella, 2013). Therefore, there are several indications that cropland expansion will continue, most importantly into undisturbed Cerrado vegetation (Lapola et al., 2013; Loarie et al., 2011; Oliveira et al., 2015b, 2015c). Nevertheless, Brazil is ranked third in the world in the adoption of conservation agriculture practices (more than 25 million ha), which comprise (i) minimum soil disturbance: no-tillage and direct seeding; (ii) organic soil cover; and (iii) crop rotations and associations (Friedrich et al., 2012).

2.2. Experimental plots under natural rainfall data collection

To compile runoff and soil loss under natural rainfall records from scientific journal articles, conference papers, books, M.Sc. theses, and Ph.D. dissertations (including the grey literature) we reviewed the ISI Web of Science, Scopus, SciELO, and Google Scholar databases. The studies were organized into a database where useful data and information for our analyses were registered. The final database was comprised of 401 data entries that are available in the supplementary information.

The geographic coordinates, municipality, plot dimensions (length and width), slope gradient, land cover, tillage system, monitoring period, rainfall, runoff, and soil loss records are related in a worksheet. The plot data had to meet the following requirements to be considered in the database: experimental plot data under natural rainfall; continuous monitoring data; and clear information about the experimental site, such as: geographic coordinates, plot description, land cover, and monitoring period. Table 1 shows all selected papers used in the present study.

2.3. Data analysis

We organized a database containing the following information: land cover (fallow, eucalypt, cropland, forest, pasture, grassland, orchard, and shrubland); consistent units for slope gradient (percent rise), slope length (meters), rainfall (mm y^{-1}), runoff (mm y^{-1}), and soil loss (t ha^{-1} y^{-1}); and monitoring period for each plot treatment. Furthermore, to allow comparison between land covers, we computed