Catena 140 (2016) 31–42

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

Effects of climate, land cover and topography on soil erosion risk in a semiarid basin of the Andes

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ARTICLE INFO

Article history:
Received 23 June 2015
Received in revised form 7 January 2016
Accepted 11 January 2016
Available online 22 January 2016

Keywords:
Climate
Dryland
C-factor
Landform
Soil erosion risk
Ecuadorian Andes

ABSTRACT

Understanding soil erosion processes in the Ecuadorian Andes with a tropical wet-dry climate and a variable topography, is fundamental for research on agriculture sustainable, environmental management, as well as for a stable water supply for the local populations. This work proposes method to estimate soil erosion risk in the semiarid Catamayo basin with limited data. The results show that the rainfall distribution and the erosivity along with the rugged topography, followed by the land cover (*C*-factor), are the most important factors to estimate soil erosion risk. The soil erodibility is the most important factor in the dry season for agricultural areas and where the ground cover is sparse. Soil erosion risk is higher in the centre and southwest than in the northeast of Catamayo basin. In protected areas with evergreen vegetation, the soil erosion risk is very low, even with steep slopes and high annual rainfall amounts. The methodology developed allows understanding of the soil erosion processes and the factors that lead to the spatio-temporal variability of soil erosion risk, and as a consequence improves the potential to achieve sustainability of this ecosystem through proposed conservation measures.

1. Introduction

The soil is a non-renewable resource (Zhao et al., 2013) that controls the biological, hydrological and geochemical cycles in the Earth System and provides the human societies with goods, services and resources (Berendse et al., 2015). There is a need to improve the land use practices to obtain a sustainable management and reduce soil erosion risk. Therefore, it is indispensable to understand how climate, topography and land cover affect the soil erosion processes and the mechanism involved (Gabarrón-Galeote et al., 2013; Lieskovský and Kenderessy, 2014). Soil is principally degraded by water erosion threatening its sustainability and causing high losses of fertile soil, which is especially pronounced in areas that are subject to inappropriate agricultural management, land abandonment, intense road construction or wild fires (Cerdà et al., 2010; Palacio et al., 2014; Panagos et al., 2014).

Soil erosion by water is also the major environmental problem for agriculture in Ecuador (Ochoa-Cueva et al., 2015), especially in the southern and southwestern parts of the province of Loja, bordering Peru. The zone has unique environmental conditions, including rugged topography, which leads to strong changes in climate within short distances, amplifying soil erosion risk (Pineda et al., 2013). The El Niño Southern Oscillation (ENSO) phenomenon plays an important role in this area, because the high rainfall intensities during ENSO events cause higher soil erosion (Tote et al., 2011).

Furthermore, land use change in this area enhances soil erosion vulnerability (Castro et al., 2013). The expansion of agriculture has put pressure on natural ecosystems not only in this region, but also in the whole country. In Ecuador, the area cultivated with maize has increased about 20% since the 1990s (FAO, 2010a). Also, investments were expanded to US$ 20.3 million during the period 2007–2009 (MAGAP, 2011), due to local and global demand of maize to produce ethanol and livestock feed. The primary natural forest was mainly converted to secondary forest or replaced by irrigated crops and dry agriculture. This change to the natural ground cover continues mainly through slash and burn activities (Bahr et al., 2013; Espinosa et al., 2012; Winckell et al., 1997a).

Ecuador has the lowest percentage of natural forest of all countries in South America (FAO, 2010b). In the study area, the ecosystem most threatened by deforestation is the Tropical Dry Forest. Deforestation has economic significance for firewood collection, construction and even for charcoal. Because of the high demand for timber, farmers prefer to exploit their lands for quick profits instead of long-term use of the forest (Castro et al., 2013).

Morgan (2005) shows an additional complication for these environments, which is caused by the need for water conservation and its

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http://dx.doi.org/10.1016/j.catena.2016.01.011
0341-8162/

ecological sensitivity. The change of the natural cover to pasture or crops, produces a rapid decline in organic matter content of the soil leading to a depletion and desertification risk.

In this context, our study area is the Catamayo basin in southern Ecuador, which is representative of the susceptibility of the region to land degradation because of the various climatic, topographic and land cover characteristics that lead to high soil erosion risk. However, understanding soil erosion process in this region is hampered by the scarcity of data on erosivity, erodibility and the traditional form of managing the soil resource (Ochoa et al., 2014; Romero et al., 2007; Tote et al., 2011), which is similar to many parts of the world (Cerdà, 1998, 2000; Chavez, 2006; Ruiz-Sinoga and Romero, 2010).

There are various empirical soil erosion models, such as the Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1997), Soil Loss Estimation Model for Southern Africa (SLEMSA) (Stocking, 1981), and the European Soil Erosion Model (EuroSEM) (Morgan et al., 1998); which facilitate the calculation of soil erosion risk at different locations. However, to apply these models outside their area of origin and validation, local climatic and soil data is required as an additional input. For this reason, there is increasing interest to develop methodologies adapted to local conditions, identifying areas and quantifying soil erosion risk to propose sustainable management practices (Nigel and Rughooputh, 2010a; Zhao et al., 2013). The use of stochastic models to estimate rainfall erosivity for areas with limited data (i.e. generate synthetic data series from simple statistical characteristics of existing data) can be a useful tool to generate sequences of the necessary input data for empirical models (Morgan, 2005). Geographic Information Systems (GIS) can display the digital input data on cartographic maps and help to calculate, understand and explain the soil erosion risk for the required areas on the Earth's surface.

This work attempts to provide the necessary seasonal details for estimation of soil erosion risk at regional scales, providing a methodology for policy-makers and managers to validate and approve their taken decisions. The study, executed in the semiarid Catamayo basin, seeks to advance the understanding of soil erosion risk under strong anthropogenic pressure in the Ecuadorian Andes, examining (i) the influence of altitude and topography on the climatic factors of rainfall and air temperature; (ii) soil erosion risk during the dry and the wet season; and (iii) the most important factors controlling soil erosion vulnerability in this semiarid basin.

2. Study area

The Catamayo watershed is located between 3°39′S and 4°31′S (latitude), 79°05′W and 80°11′W (longitude) in the south of Ecuador, province of Loja, close to the border with Peru (Fig. 1). The Catamayo River has a length of 120 km, whose watershed covers an area of 4184 km^2. This river is one of main tributaries of the Ecuadorian–Peruvian hydrographic system (17000 km^2), called the Catamayo–Chira Basin, which drains into the Pacific Ocean (Tote et al., 2011). The Catamayo River supplies potable water for the people in southern Ecuador and northern Peru and also for the irrigation systems inside the basin. The average annual water flow is 35 m^3/s, which significantly decreases during the dry season (22 m^3/s; Oñate-Valdivieso and Bosque, 2010).

In comparison to the northern Andes of Ecuador, which are characterized by two distinct mountain ridges (Eastern and Western Cordillera), the Southern Highlands do not show this strict separation of the cordilleras. The Eastern Cordillera reaches altitudes up to 3900 m a.s.l. near the Peruvian border, whereas the Western Cordillera only rises up to 2500 m a.s.l. (Winckell et al., 1997b). The lower altitudes of the Western Cordillera facilitate the interaction with the Ecuadorian coast. The Catamayo Basin has a strong altitudinal gradient, reaching from 240 m a.s.l. in the southwest to 3760 m a.s.l. in the northeast (Fig. 1a).

The study area is characterized by an alternation between valleys and ridges within short distances, which leads to different climate conditions due to the fast changing topography (complex terrain; Fig. 1b). The air temperature mainly depends on the altitude (Richter et al., 2009), whereas the rainfall depends on wind speed and direction, which is modified by the topographic conditions, forming barriers and pathways for humidity transport (Fries et al., 2014). The rainy season is during austral summer (December to May), when the tropical easterlies are frequently interrupted by low westerlies, carrying moisture from the Pacific Ocean up to the study catchment (Pineda et al., 2013). In the dry season (June to November) the tropical easterlies prevail, bringing dry and sunny weather to the study area, because the higher Eastern Cordillera forms a barrier, blocking the humidity transport from the Amazon Basin.

The tropical dry forest grows in the vicinity of the Ecuadorian coast, due to the annual precipitation distribution (dry period >6 months), evincing one of the most conspicuous features of this forest type: seasonal loss of the tree leaves (Maass and Burgos, 2011). Due to the influence of the south Pacific Anticyclone during most of the year, the vegetation is characterized by semiarid species (spare brushy vegetation), especially at the valley bottom and at the western part of the study area, where altitudes are lower and air temperature higher. Around 60% of the Province of Loja is covered by deciduous and semideciduous dry forests (Aguirre and Kvist, 2005). The maize production with conventional tillage is the dominant crop during the wet season (Castro et al., 2013), whereas sugarcane grows in secondary valleys (e.g. Malacatos, Vilcabamba) during the whole year using irrigation systems. Due to the general wind direction from the east (Amazon Basin - tropical easterlies) the annual precipitation is highest at the upper eastern mountain ridge, where air temperature is lower and tropical humid forest and the páramo are formed (Richter et al., 2009).

3. Material and methods

Three landforms or zones were established in the basin using the ArcGIS 9.2 software and its classification tool called Natural Breaks. This tool identifies break points by picking the class breaks those best group similar values and maximizes the differences between classes. Our watershed was classified using as input data altitude and slope derived from a digital elevation model (DEM), as well as an air temperature map (Fig. 4) with a resolution of 100 m × 100 m.

The first zone corresponds to the lower area called Dry-Farming and Irrigation Zone (DFIZ) from 240 to 1400 m a.s.l., with a mean annual temperature over 21 °C. This zone generally shows slight slopes varying from 0 to 16%. The middle area, called Dry-Farming Southern Highlands (DFSH) reaches from 1400 to 2200 m a.s.l. and has a mean annual temperature between 15.5 and 21 °C. The topography is characterized by steeper slopes from 16 to 30%. The areas above 2200 m a.s.l. are mainly located in the eastern part of the basin, called Wet-Land Southern Highlands (WLSH), which are characterized by extreme slopes between 30 and 58% and a mean annual air temperature below 15.5 °C. Fig. 1a, shows the three classified zones.

These three zones are consistent with the major morphopedological sets of the Southern Highlands of Ecuador proposed by Winckell et al. (1997b); the wet rocks masses in WLSH, the slopes of transition in DFSH and depressed areas with severe drought in DFIZ.

3.1. Rainfall erosivity

The climatic data for the study was provided by a network of 24 rain gauges operated by the Ecuadorian Weather Service (INAMHI), and 2 automatic meteorological stations from Thiess — Clima (Germany), situated at the eastern edge of the watershed (TIRSTA and PARSTA, see Table 1). For this study, data from 1990 to 2013 was used and quality controlled by INAMHI. Compared to other Ecuadorian basins the rain gauge density is higher 1.7 per 174 km^2 (Ochoa et al., 2014) in the Catamayo catchment and only few missing or erroneous data were found.