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Soil erosion and erosion thresholds in an agroforestry system of coffee (*Coffea arabica*) and mixed shade trees (*Inga spp* and *Musa spp*) in Northern Nicaragua

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ABSTRACT

Soil erosion by water is one of the main environmental problems in tropical mountain regions of Central America. Agroforestry systems have been shown to reduce erosion through their canopy cover and their contribution to the litter layer. This paper analyzes the influence of the cover and height of coffee strata and mixed shade trees, the ground cover (weeds and litter), the slope gradient and various soil features and characteristics relevant to erosion in six farms that apply the agroforestry system of coffee growing (*Coffea arabica*) with mixed shade trees of *Musa spp* and *Inga spp*. We determine the corresponding erosion thresholds, i.e. the value (erodibility factor) beyond which the reduction in erosion becomes statistically significant. A purpose-designed verification method was applied to determine whether the thresholds corresponded to the effective control of erosion. The study area is located in the hills around El Cuá, in northern Nicaragua, an area with a humid tropical climate and a mean annual rainfall of 2770 mm. An analytical method, based on the use of visual indicators, was used to analyze soil erosion by water. This approach enabled us to replicate the method in a sufficiently large number of cases for the results obtained to be considered reliable and representative of the study area. These results indicate that in the agroforestry system examined, for the cultivation of coffee and mixed shade trees (*Musa spp* and *Inga spp*), an average of 10.4% of the area is affected by erosion. The erodibility factors identified were litter layer and slope gradient. The first of these factors accounted for 66% of the variability of erosion, compared with 4% in the second case. The erosion threshold value was between 60 and 65% of the litter layer; beyond this level, the reduction in erosion was statistically significant. With this threshold, the soil was relatively little affected by erosion, around 13% of the cultivated area.

1. Introduction

The replacement of forest by agriculture and livestock farming in the tropical mountains of Central America can provoke serious environmental consequences, including increased runoff and erosion (Hanson et al., 2004; Cotler and Ortega-Larrocea, 2006), soil compaction (Blanco and Nieuwenhuyse, 2011) and loss of soil fertility (McDonald et al., 2002; Tully et al., 2012). The particular environmental conditions in this region, with steep slopes, heavy rainfall and a high frequency of tropical storms and hurricanes, make erosion a major problem. Climate change is expected to cause more frequent extreme weather events (Magrin et al., 2007) and, therefore, increased erosion throughout the region.

Central America is one of the world's major coffee producing regions (Castro et al., 2005). According to the FAO (2014), the land surface area in the region dedicated to coffee cultivation increased from 0.9 million hectares in 1961 to 1.6 million hectares in 2012, representing an annual growth of 1.1% over the period. From a socioeconomic standpoint, coffee cultivation is an important source of rural employment; in 2002, it accounted for 28% of all rural employment in the region, and was especially significant in Nicaragua, with 42% (Varangis et al., 2003).

In view of these circumstances, measures and strategies are needed to prevent erosion in these coffee-producing areas. To achieve this goal, it is essential to determine the erodibility factors, on the same scale as that at which future action will be taken. Analyzes of erodibility in upland coffee plantations have highlighted the influence of environmental factors and of the agricultural system applied. In the former respect, studies have examined the influence of relief, concerning slope gradient, shape

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and length. The influence of slope gradient on erosion is beyond doubt. Regions with steep slopes are more susceptible to soil erosion due to runoff. Verbist et al. (2010) concluded that the slope gradient was one of the most important factors in the erosion produced in coffee plots, for different cropping systems (both sun coffee and shaded plantations with various types of trees). However, it has been shown that erosion is not always linearly related to slope gradient, as particular conditions in the study area may interfere, reducing or neutralising the influence of this factor (Roose and Ndayizigiye, 1997). The dynamics of erosion also depend on the shape of the slope, because if the shape varies, this may provoke changes in the overall slope (Brunner et al., 2004). In general, erodibility factors, at the land plot level, can be considered heavily dependent on the particular characteristics of the study area.

Regarding the agricultural system, studies have highlighted the importance of agroforestry systems. Sun coffee plantations have less vegetation cover (the absence of tree shade reduces the litter layer), so there is less interception of rain fall, and runoff and erosion rates are much higher than in shaded plantations (i.e., the agroforestry system) (Ataroff and Monasterio, 1997; Cannavo et al., 2011). Studies show that cover crops (Sidle et al., 2006), crop residues and the litter layer (Roose and Ndayizigiye, 1997) play a more prominent role in controlling erosion than does tree shade cover. Therefore, the ground cover plays an important role in protection against erosion (Elwell and Stocking, 1976), through the following functions: (1) it intercepts rain, neutralising its kinetic energy and splash erosion; (2) it slows runoff and reduces its carrying capacity; (3) it improves soil structure by incorporating organic matter (plant debris) and by the biological activity associated with its decomposition, thus increasing structural stability and, therefore, resistance to soil erosion.

Field methods to study erosion at the plot scale differ in precision, equipment and costs. The most precise techniques, which are usually the most expensive, do not always best match the aims of the research (Stroosnijder, 2005). Measuring erosion by means of collection tanks (Hudson, 1993) is expensive in terms of equipment and personnel, and budget restrictions tend to reduce the period and area of analysis. Moreover precise measurements obtained in one site may not be representative of the entire study area (Hudson, 1993). Accordingly, other approaches have been proposed, based on the qualitative or quantitative assessment of soil erosion using visual indicators which attenuate these drawbacks, although they are not problem free, either. The qualitative methods applied to evaluate soil erosion measure the presence/absence of these indicators and their number and size (Stocking and Murnaghan, 2001; Mutekanga et al., 2010). Quantitative methods estimate the volume of soil loss by measuring the width, depth and length of the rills and gullies (Bewket and Sterk, 2003; Okoba and Sterk, 2006), or by means of erosion pins and a microtopographic profile gauge (Sirvent et al., 1997; Desir and Marín, 2007). These methods are low cost because they do not require any infrastructure or specialized equipment, and they are simple and fast to apply because they are based on assessing erosion from visual indicators. Therefore, a large number of plots can be sampled, thus providing a sufficient volume of data to assume that the results obtained are representative of the study area.

Transferring research findings on erosion to real-world applications is a task that remains to be perfected. Most studies that have set out to analyze the dynamics of erosion and to determine soil erodibility factors in agricultural systems have done so basically from a scientific standpoint and, despite their eminently practical ambitions, have not usually managed to transmit their results to the producers in the field. In the scientific domain, specific methods should be designed and developed to facilitate the transfer of results. Such methods must be scientifically rigorous and at the same time, capable of communicating measures that are convincingly effective to producers. Only thus can results be successfully transferred, because producers are usually reluctant to introduce new measures, especially if this means changes in their work routine.

The aims of this study were: (1) to analyze the influence of slope gradient, of various soil-surface characteristics and properties, and of the form of biomass management (ground cover, aerial cover and ground clearance of coffee strata and shade trees) on soil erosion by water in an agroforestry system combining coffee cultivation and mixed shade trees of *Inga spp* and *Musa spp*; (2) to determine the thresholds of soil erosion on the basis of erodibility factors and to determine whether these thresholds correspond to the effective control of erosion, in order to facilitate the transfer of results; (3) to assess the suitability of the methods described to achieve the above objectives.

2. Materials and methods

2.1. Site characteristics

The study was conducted in 6 farms cultivating coffee in an agroforestry system with mixed shade trees species. In these farms, the predominant shade tree species were *Musa spp* (mainly *Musa acuminata* Colla, and to a lesser degree *Musa balbisiana* Colla) and *Inga spp* (*Inga oersterdiana* Benth., *Inga punctata* Willd., and secondarily *Inga paterna*) with the sporadic inclusion of other species such as *Ceiba pentandra* (L.) Gaertn, *Swietenia macrophylla* King, *Cedrela Odorata* L. and *Erythrina fusca* Loureiro. Farms areas ranged from 35 ha to 175 ha and all were located in former forest areas in the municipality of El Cuá (Nicaragua) (Fig. 1), located at 13°22′3″N, 85°40′24″W. The altitude of the study area ranged between 500 and 1200 m asl, the slope gradient was variable (mean of 40%) and the soils were classified as Chromic Cambisols (FAO-ISRIC-ISSS, 1998). It is a humid tropical region, with a mean annual rainfall of 2770 mm and high inter-annual variability (2400–3100 mm $year^{-1}$). Sampling was conducted during October and November 2011, in the rainy season, which runs from May to December, during which a cumulative rainfall of 2633 mm was recorded, equivalent to 95% of the mean annual rainfall. The mean annual air temperature ranges from 20 to 25 °C.

The town of El Cuá forms part of the buffer zone of the Bosawas Biosphere Reserve. This protection scheme requires all land use activities to be executed in accordance with the Management Plan of the Reserve, which state that coffee must be cultivated in an agroforestry setting. Coffee cultivation is the most important agricultural activity in the municipality, where the production of green coffee is between 18,000 and 32,000 t $year^{-1}$, followed by the cultivation of basic grains (maize and, especially, beans) and dual-purpose cattle (milk and meat).

2.2. Methods for soil erosion analysis

In order to study soil erosion, we analyzed: (a) the state of soil erosion, observing the surface processes affecting the soil, including all types of erosion (splash, sheet, rills and gullies), expressing the results as a percentage of the surface affected by all these processes; (b) the soil loss by erosion in rills and gullies, expressing the results as a volume (m^3 ha^{-1}).

We adapted the presence/absence test of visual indicators and their number and size (Stocking and Murnaghan, 2001; Mutekanga et al., 2010). A sampling method was used to quantitatively evaluate the surface processes that affect the soil. The visual indicators are differentiated using codes to streamline data collection during field sampling (Table 1). The index (capital