Catena 228 (2023) 107182

Contents lists available at ScienceDirect

Catena

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

A scenario modelling approach to assess management impacts on soil erosion in coffee systems in Central America

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ARTICLE INFO

Keywords:
Soil erosion
Coffee agroecosystems
Costa Rica
Guatemala
RUSLE
GIS

ABSTRACT

Soil erosion is one of the major causes of soil degradation worldwide, because it causes the depletion of soil organic carbon, nutrients, and water holding capacity. In Central America, coffee production is vulnerable to soil erosion since it often occupies steep slopes with high annual precipitation. To assess management options to control erosion, soil and vegetation field data were collected from 90 Costa Rican and 96 Guatemalan coffee plantations, mainly shaded, distributed in six coffee production areas. Soil erosion was modelled using the RUSLE (Revised Universal Soil Loss Equation), integrating soil and vegetation cover field data, with remote sensing data. Management scenarios were developed to assess the role of two principal coffee management strategies in mitigating soil erosion: increasing vegetation cover, and soil conservation practices. Average estimated erosion rates of 17 and 7 Mg ha^{-1} yr^{-1} were predicted for plantations of Costa Rica and Guatemala, respectively, with erosion from coffee plantations representing between 23% and 40% of the estimated erosion of the watershed within which they were situated. If all plantations achieved vegetation cover equivalent to the best 25% of plantations, the estimated erosion would be reduced by 7% in Costa Rica and 8% in Guatemala. If all plantations implemented soil conservation practices, estimated erosion would be reduced by 11% in Costa Rica and 35% in Guatemala. With the two combined management strategies a reduction of estimated erosion of 17% and 40% was predicted in Costa Rica and Guatemala, respectively. The reduction in erosion from soil conservation or better vegetative cover varied among regions within countries depending on current management, local climate, and topography. These results show the importance of coffee system and soil management practices in moderating erosion from highland coffee production, and how RUSLE analyses can identify priority practices in different regions supporting more effective policies to reduce soil erosion.

1. Introduction

Soil erosion is one of the major causes of soil degradation worldwide. Soil erosion causes carbon and nutrient depletion, it deteriorates soil structure and nutrient cycling, and depletes the soil quality and the soil water holding capacity (Lal, 2003, 1997; Pimentel and Kounang, 1998). Overall soil erosion is a key factor in affecting food security worldwide (Lal, 2009; Pimentel, 2006; Wuepper et al., 2020). At a global scale, water erosion is responsible for 56% of the human-induced soil degradation (Oldeman, 1992), and 85% of the erosion in the agricultural area (Doetterl et al., 2012). Moreover, approximately 30 years ago, the Global Assessment of Soil Degradation (GLASOD) (Oldeman, 1992) estimated that 74% of soil degradation in Central America was caused by water erosion. Soil erosion represents a crucial issue in Central American countries which rely on the agricultural sector for their exports as well as for the population that rely on the agricultural sector for their livelihood and income. Soil erosion caused a loss of 7.7% of the agricultural gross national product in Costa Rica in the 1970–1989 period as reported by CADETI (2004). This loss accounted only for the nutrient and soil fertility depletion caused by the soil erosion; therefore, it did not consider other side-effects of soil erosion, such as water pollution, or economic losses due to sediments deposition in the dams for production

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https://doi.org/10.1016/j.catena.2023.107182
Received 20 December 2021; Received in revised form 11 March 2023; Accepted 19 April 2023
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of hydro-electric energy (Brandt and Swenning, 1999; Schleiss et al., 2016). In fact, due to soil erosion and sediment deposition, it was estimated a loss of 13% of the annual production of the hydroelectric dam of Cachí in Costa Rica because of a reduction on storage capacity of the reservoir (Centro Científico Tropical and Instituto de Recursos Mundiales, 1991), with many flushing events taken to remove sediment (Jansson and Erlingsson, 2000; Jiménez et al., 2005; Morris and Fan, 1998). Furthermore, soil runoff and sedimentation have other downstream effects such as depletion of freshwater quality, impacts on freshwater ecosystems, as well as detrimental impacts on coral reef (Carilli et al., 2009; Touma et al., 2020; Wenger et al., 2015).

Due to water erosion, 18% of the Costa Rican soil has been severely eroded, and 24% of the country's soil was moderately eroded in the early 1980s (Hartshorn et al., 1982). Sancho (1991) measured erosion rates from 2 to 42 Mg ha^{-1} in Costa Rican coffee plantations through field experiments. Fernández-Moya et al. (2014) reported a range of soil loss between 6.7 and 35.1 Mg ha^{-1} on experimental plots inside teak plantations with different management practices in Costa Rica, and by further analyses of other studies on soil erosion on teak plantations, concluded that the major factor in affecting erosion was the type of management. Presence of undisturbed litter layer and understory vegetation was found an important condition to reduce soil erosion (Fernández-Moya et al., 2014). Furthermore, in an area highly prone to erosion in Costa Rica, half of the farmers studied stated that to maintain good yields they needed to apply higher amounts of fertiliser, due to the loss of soil productivity caused by soil erosion (Melo Abreu, 1994). In coffee areas of six different Nicaraguan regions, a soil erosion rate of 53–114 Mg ha^{-1} yr^{-1} was reported by Alfsen et al. (1996) based on soil erosion classification maps. Alfsen et al. (1996) considered that the reduction in productivity due to soil erosion indirectly led to an increase in food prices and labour wages, reduction demand for labour, and subsequently induced changes in migration patterns.

Coffee agroforestry systems (also called shaded coffee) are considered to conserve more biodiversity, deliver more ecosystem services, and sequester more carbon, as compared to intensive coffee systems and coffee monocultures (De Leijster et al., 2021; Goodall et al., 2014; Jha et al., 2014; Perfecto et al., 1996). Coffee agroforestry systems with approximately 300 trees ha^{-1} can also promote higher water infiltration and better soil protection from water erosion and runoff as compared to coffee monocultures (Cannavo et al., 2011). This is through a combination of greater canopy cover, soil cover through the formation of a thicker litter layer, and likely through the generation of macropores from old root channels (Cannavo et al., 2011; Ghestem et al., 2011; Verbist et al., 2010). Furthermore, shade tree products (fruits, fodder, timber) provide also a valuable source of income that can reach up to a third of the total revenue of a coffee plantation (Rice, 2008). Lower erosion rates and water runoff were reported in coffee agroforestry systems as compared to coffee monoculture, with a reduction of water runoff by a range of 4–8 % (Cannavo et al., 2011; Hoyos, 2005). Moreover, a study in Venezuelan coffee plantations found that soil erosion was higher in full sun plantation (5.1 Mg ha^{-1} yr^{-1} on average) as compared to shaded coffee plantation (1.2 Mg ha^{-1} yr^{-1} on average) especially in the first years of a new established plantation. However, a 7 year full sun plantation showed low soil erosion rates (1.8 Mg ha^{-1} yr^{-1}), similar to the rate registered under fully shaded systems (0.7–1.8 Mg ha^{-1} yr^{-1}) (Ataroff and Monasterio, 1997). This could be explained due to other factors, apart from shade trees in reducing and controlling soil erosion, such as soil cover with litter, crop residues or cover crops, living hedges, grass strips, and understory biomass, as well as differences in soil disturbance (Anh et al., 2014; Blanco Sepúlveda and Aguilar Carrillo, 2015; Craswell et al., 1998; Roose and Ndayizigiye, 1997). In agroforestry systems the litter layer has higher influence on reducing the area affected by erosion compared to the shade trees; the litter cover protects the soil surface from direct impact of the rainfall, as well as it increases water infiltration rates (Blanco Sepúlveda and Aguilar Carrillo, 2015; Roose and Ndayizigiye, 1997). Area covered by mulch or herbaceous vegetation in coffee plantations were found to produce 13% and 1.2% of the water runoff, respectively, compared to bare soil. Furthermore, presence of mulch or herbaceous vegetation reduced soil erosion rate by 90% and 99%, respectively, compared to bare soil (Ramos-Scharrón and Figueroa-Sánchez, 2017). In another study about runoff and erosion in coffee farms in Puerto Rico, it was found that mulch reduces water runoff by approximately 98% on average compared to area covered by herbaceous vegetation or bare soil (Ramos-Scharrón and Thomaz, 2016). Another important and crucial factor in reducing erosion risk is the implementation and establishment of soil conservation practices especially on steep slopes; type, structure, maintenance level of the soil conservation practices (such as terraces, contour-hedgerows, bunds) play an important role in mitigating or exacerbating erosion (Sidle et al., 2006; Subhatu et al., 2017). Comparisons of erosion rates between different production systems are influenced both by their management (such as degree of intensification, mechanisation or presence of shade or agroforestry trees) but also by variations in the site conditions, such as topography, climate, soil type, geomorphology. In this study, by intensification we mean the inputs (fertilisers and pesticides) and labour level, and the reduction of shade tree density or cover (Haggar et al., 2021). In this study, we estimate by modelling the erosion from coffee plantations in a selection of coffee producing watersheds in Guatemala and Costa Rica, and their contribution to current erosion. Furthermore, the study aims to provide estimates of the potential for erosion reduction at the plantation and watershed level if best practice of maintenance of soil cover, and soil conservation practices were uniformly implemented. This would be a first quantification of the impact of good soil management on erosion risk at watershed level in tropical montane regions.

Our study was conducted in coffee plantations of different regions of Costa Rica and Guatemala, where coffee is cultivated with different methods. Costa Rica is characterised by a more intensive productive system, with high coffee yield and intensively pruned shade trees, especially in areas like the Tarrazú region (López and Picado, 2012; Montero et al., 2021), while Guatemala is characterised by a more traditional coffee agroforestry systems in the whole country but with variations in use of agrochemicals (ANACAFÉ, 2011; Rice, 1999). However, within each country, different levels of intensification are found even within regions. Therefore, there is the need to understand the influence of different management strategies on erosion across a range of environmental conditions, and the potential to reduce erosion levels with improved production system design and management. In this study, we estimated soil erosion from different coffee systems using the RUSLE (Revised Universal Soil Loss Equation) (Renard et al., 1997; Wischmeier and Smith, 1978). USLE and the derived RUSLE are the most used modelling approaches used worldwide today (Borrelli et al., 2021), as they can be integrated with GIS and remote sensing data, allowing to scale-up the estimations to produce spatial predictions. We coupled and integrated the RUSLE equation approach with GIS tools and remote sensing data in order to estimate the soil erosion rates in the study areas. This study aimed to assess how different management strategies concerning shade levels, soil cover, and soil conservation practices affect estimated soil erosion rates within coffee plantations, and how changes in management might exacerbate or reduce soil erosion. In turn, we estimated the potential of changes in coffee management practices to reduce soil erosion at a watershed scale.

2. Study area and datasets

2.1. Study area

The study area is located in three of the main coffee production regions in Costa Rica and Guatemala (six regions in total). The regions were chosen to cover different agroclimatic conditions in terms of total annual rainfall, length of dry season, and range of elevations (Table 1). The coffee plantations were also chosen to cover a variety of agro-

Table 1
Characterisation of the areas of interest in Costa Rica and Guatemala. Values are reported as means, with range in parenthesis.

	Costa Rica			Guatemala		
	Turrialba	Valle Occidental	Tarrazú	West	Mid	East
Elevation (m)	1281 (333–3302)	1100 (178–2180)	1636 (97–3161)	1460 (167–4161)	1853 (632–3529)	1809 (450–3962)
Annual precipitation (mm)	3109 (2077–4540)	2597 (2065–3799)	2423 (1884–3241)	2926 (1469–3956)	2250 (1472–4111)	1957 (1282–3917)
Dry months*	1 (0–4)	4 (0–5)	4 (2–5)	5 (3–6)	6 (4–6)	6 (4–6)
Slope (degrees)	14 (0–70)	13 (0–61)	21 (0–67)	19 (0–70)	15 (0–71)	17 (0–71)
Soil type	Ultisol and Andisol	Andisol, Ultisol, Inceptisol	Ultisol	Andisols	Andisols	Andisols

* Number of months with < 100 mm of rainfall.

environmental management, including differing fertilisation levels, shade tree covers and densities, sustainability practices, and coffee productivities (Haggar et al., 2021). A total of 186 coffee plantations were included in the study, 90 for Costa Rica and 96 for Guatemala. The majority of plantations (122) were selected from a database used in a previous study which compared agronomic and socioeconomic aspects from certified and uncertified farms (Soto et al., 2011). The remaining coffee plantations were selected in collaboration with Manos Campesinas and National Coffee Association (ANACAFÉ) in Guatemala, and the Institute of Coffee (ICAFE) in Costa Rica (Haggar et al., 2021). In Costa Rica, the plantations are situated in three regions: Turrialba-Orosi (27 plantations; abbreviated to Turrialba), Valle Occidental (31), and Tarrazú (32). Turrialba-Orosi has a tropical rainforest climate with high rainfall and short dry season, while the other two regions have a more prolonged dry season and slightly lower total rainfall. The soils all have volcanic influence; some are Andisols, others have weathered to Ultisols, or are Inceptisols eroded from volcanic material. In Guatemala, the plantations are located in three main regions identified as West (that included the departments of Quetzaltenango, Retalhuleu, and San Marcos; 28), Mid (department of Sololá; 30), and East (departments of

Fig. 1. Canopy cover strategies in the plantations of the study area from high (a), to moderate (b), and low (c) shade. Plantations were characterised also by different soil cover, from bare soil (d), to cover from litter and few herbaceous plants (e), and complete cover from herbaceous plants (f).

Guatemala, Sacatepéquez, and Chimaltenango; 38). These three regions lie along a rainfall gradient with high rainfall in the west and low in the east with a 3–5 month dry season. Furthermore, they lie along the Pacific volcanic chain of Guatemala characterised by steep slopes, of volcanic ash derived soils of varying age, but all are Andisols. Across the two countries different levels of shade tree density and cover (from high shade to full sun plantation) can be found. Furthermore, soil cover management can also vary from farms with bare soil and other with intermediate or high cover from litter, mulch, and herbaceous understorey vegetation (see Fig. 1). The main soil conservation practices employed in the coffee plantations of the two countries are micro terraces, terraces, live dead barriers, water infiltration trenches, planting in contour lines.

In Costa Rica, 11 watersheds (with a minimum of 3 plantation per watershed), covering an area of 1,290 km^2, were selected for detailed analysis (509 km^2 in Tarrazú, 311 km^2 in Turrialba, and 470 km^2 in Valle Occidental) (Fig. 2a). The coffee area inside the selected watersheds amounted to 429 km^2 (204 km^2 in Valle Occidental, 59 km^2 in Turrialba, and 166 km^2 in Tarrazú). In Guatemala, 10 watersheds (with at least 3 plantations) occupying an area of 1,364 km^2 (447 km^2 in the West region, 358 km^2 in the Mid region, and 559 km^2 in the East region) were selected (Fig. 2b). The coffee area inside the considered watersheds covered an area of 385 km^2 (154 km^2 in the West region, 60 km^2 in the Mid region, and 171 km^2 in the East region). Each agroclimatic region was represented by 2-4 watersheds.

2.2. Data collection and preparation

For this study, the erosion rate was estimated using the RUSLE. RUSLE factors and source data (data used for the calculation of each RUSLE factor) and main preparation needed for their estimation are reported in Table 2.

In the remainder of Section 2 the data collection (from field survey and local and global datasets) and preparation is explained. Co-kriging interpolation was done using covariates mainly obtained from Landsat 8 and Sentinel-2. Section 3 reports the methods used to calculate each individual RUSLE factor and the erosion rate. The estimated erosion was calculated at a spatial resolution of 100 m. To infer changes of erosion rates some management scenarios were development as explained in Section 3.2.

Table 2
RUSLE factors and then source data used to calculate them.

RUSLE factor	Source data	Data preparation
R factor (rainfall erosivity)	Daily and hourly precipitations	Daily precipitation averaged to monthly precipitation and interpolated using co-kriging
K factor (soil erodibility)	Soil organic carbon (SOC) and texture field data	Calculation of organic matter from SOC, and interpolation using co-kriging
LS factor (slope length and steepness)	Digital Elevation Model	–
C factor (cover and management)	Canopy (shade tree) and soil (litter and herbaceous vegetation) cover field data	Interpolation using co-kriging
P factor (support practice)	Soil conservation practices from field survey	–

2.2.1. Field survey data

Field data was taken to determine soil characteristics, soil and vegetation cover, and soil conservation practices. On each farm, sampling was conducted from September 2019 to January 2020 in the coffee plantation field with the most typical management on that farm. Three subplots were established at least 30 m apart from each other (in case the coffee plantation was too small only two or one subplot were assessed). Inside each subplot, 2 soil samples (in between rows and within the rows of the coffee plants), at two depth intervals (0–13 cm and 13–26 cm), were collected. These soil samples from the same depth were combined and used to obtain data on soil texture (% of sand, silt, and clay) and soil organic carbon content (%) at plantation level. A total of 182 composite samples per depth were analysed (90 for Costa Rica and 92 for Guatemala). Soil organic carbon (SOC) was determined using an elemental analyser which determines the total carbon using the thermal conductivity of the combusted sample (ThermoFinnigan, 2001). The organic matter (OM) percentage was subsequently calculated by multiplying the SOC (%) by 1.724 (Van Bemmelen, 1890). The particle size was determined using the hydrometer method which calculates the proportion of clay, silt and sand based on their setting rates in a water and sodium hexametaphosphate solution (Bouyoucos, 1951). Canopy cover of shade trees was assessed analysing hemispherical photographs taken with a camera (Canon 80D) fitted with a fish-eye lens (Sigma 4.5 mm) and a self-levelling mount, at the centre of each subplot. The photographs were taken at two heights: i) above the coffee plants to

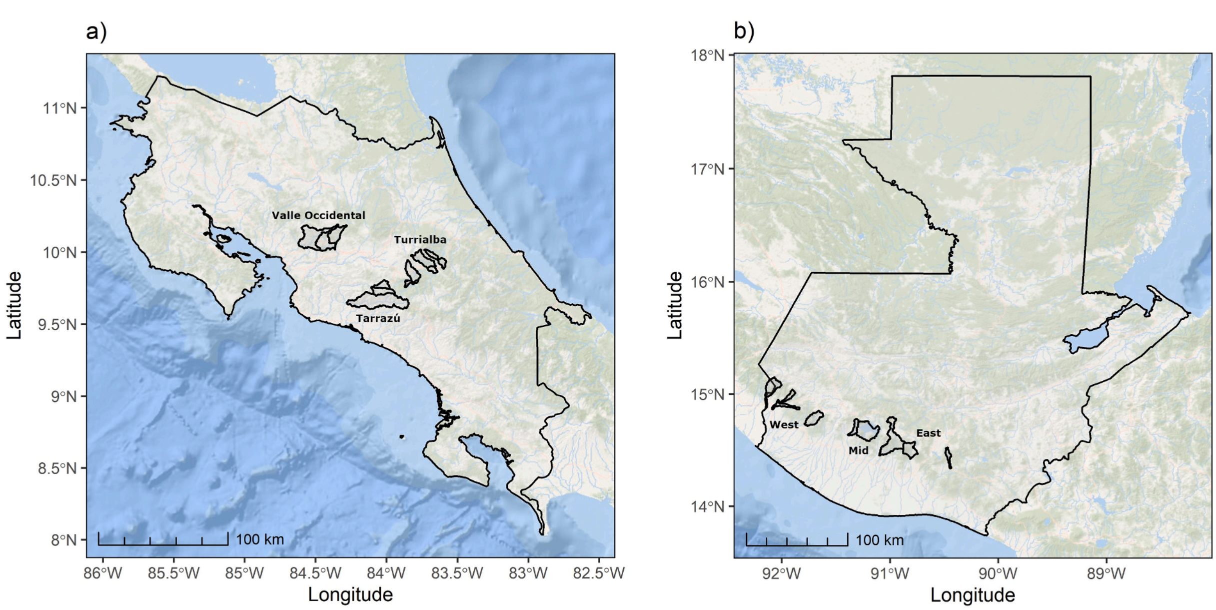

Fig. 2. Selected watersheds in the three regions in Costa Rica (Fig. 2a) and Guatemala (Fig. 2b).

measure the cover given by the shade tree canopy (2–4 m above the ground), and ii) below the coffee plants pointing upwards in two positions (in between rows and within the rows) to measure the cover given by the coffee plants. The images obtained were selected and then analysed as described in Haggar et al. (2021) to derive the leaf area index (LAI) and the canopy cover (% of not visible sky). The LAI of the coffee plants was obtained by averaging the two values obtained in between row and within row position, then subtracting the LAI of the tree canopy. When possible, the photographs were taken with overcast sky conditions (Haggar et al. 2021). The hemispherical photographs were analysed using the HemiView software version 2.1 (Rich et al., 1999) as described in Haggar et al. (2021). Furthermore, along a transect of 100 m (from the borders to the centre of the coffee plantation) at every metre the soil cover was noted (the categories used were: bare soil, plants or living roots, litter, rocks/stones). This method was adapted from the point intercept method used to assess the plant cover at soil level in Haggar et al. (2017) and derived from Guharay et al. (2000). Finally, the presence of soil conservation practices was noted indicating the presence or absence of different types of practices as: micro terraces, terraces, live or dead barriers, water infiltration trenches, planting in contour lines, or others.

2.2.2. Secondary data and software used

For Costa Rica, daily and hourly precipitation data from 2009 until 2019 were obtained from the Instituto Metereológico Nacional (10 climatic stations) and from Icafe (10 stations) for a total of 20 climatic stations. For Guatemala, we collected daily and hourly precipitation data for 2008–2020 from 32 climatic stations. Data from 9 climatic stations were obtained from Insivumeh (Instituto Nacional de Sismología, Vulcanologia, Meteorologia e Hidrología), while ANACAFÉ provided data from 23 additional climatic stations. For both countries, the climatic stations were distributed in the proximity of the areas of interest (see Supplementary material). Daily or hourly data were aggregated to obtain average monthly data. Months with more than 11 days of missing data were deleted. The average monthly data were calculated by averaging the monthly precipitation of the years considered. The average annual precipitation was subsequently obtained by summing the average monthly precipitation. For calculating the LS factor of the RUSLE, a 30 m resolution Digital Elevation Model (DEM) was obtained from the SRTM (Shuttle Radar Topography Mission) and downloaded from the USGS Earth Explorer data portal (https://earthexplorer.usgs.gov/). The elevation data was used to compute the slope, the flow accumulation, and to derive the spatial distribution of the watersheds. The watersheds were obtained using the multiple flow direction (MFD) method (Ehlschlaeger, 1989; Holmgren, 1994; Quinn et al., 1991). In Costa Rica the selected watersheds were 3 in Tarrazú, 5 in Turrialba, and 3 in Valle Occidental, while in Guatemala 3 watersheds were located in the East region, 2 in the Mid region, and 5 in the West region. Land cover data were used to derive the coffee area distribution inside the selected watersheds. The most recent available land cover maps for both countries were utilised. For Costa Rica we used a land use map of 2005 derived from the Costa Rican 2014 ATLAS, while for Guatemala we used a land use map of 2012 developed by the Guatemalan government and several research institutions (Grupo Interinstitucional de Monitoreo de Bosques y Uso de la Tierra, 2014). Remote sensing data used to obtain covariates maps for the interpolation of RUSLE factors (C factor and K factor), and other secondary data (monthly average precipitation) were derived from Landsat 8 (Collection 1, Level 1) and Sentinel-2 (Level-2A). The bands of different scenes were downloaded from the USGS Earth Explorer data portal. Furthermore, several maps (e.g. Normalised Difference Vegetation Index - NDVI, Enhanced Vegetation Index - EVI, Normalised Difference Water Index – NDWI) were produced from Sentinel-2 and Landsat 8 using the web-based code editor of Google Earth Engine (Gorelick et al., 2017). See the Supplementary material for further details about how the covariates were obtained, calculated, and used.

For this study, we used GRASS GIS open-source software (GRASS Development Team, 2020), and R CRAN (R Core Team, 2020) open source software: in particular we used the following packages: "raster" (Hijmans, 2015) and "rgrass7" (Bivand, 2015) for the spatial statistical analysis, "rasterVis" (Perpiñán-Lamigueiro and Hijmans, 2013) and "ggplot2" (Wickham, 2016) for spatial visualisation and graphs development.

3. Methods

3.1. Soil erosion calculation

RUSLE was used to estimate soil erosion (Wischmeier and Smith, 1965; Ballabio et al., 2017; Panagos et al., 2015a, 2015b; Renard et al., 1991, 1997) (Eq. (1)):

$$A = R \cdot K \cdot LS \cdot C \cdot P \tag{1}$$

where: A = average annual soil erosion (Mg ha^{-1} yr^{-1}); R = rainfall erosivity factor (MJ mm $ha^{-1}h^{-1}$ yr^{-1}); K = soil erodibility factor (Mg h ha MJ^{-1} $mm^{-1}ha^{-1}$); LS = slope length and steepness factor; C = cover and management factor; P = support practice factor.

3.1.1. R factor

The rainfall erosivity factor (R factor) represents the runoff associated with the rain, and predicts the effect that rainfall has on soil erosion (Wischmeier and Smith, 1978). For Costa Rica, the R factor (MJ mm ha^{-1} h^{-1} yr^{-1}) was calculated using the Eq. (2) developed for Costa Rica by Calvo-Alvarado et al. (2014):

$$R = 2383.523 - 1.808 \cdot alt + 7.769 \cdot P_{Jan} + 8.5 \cdot P_{Apr} - 9.093 \cdot P_{Nov} + 19.406 \cdot MFI \tag{2}$$

where: R = Rainfall erosivity factor (MJ mm ha^{-1} h^{-1} yr^{-1}); alt = elevation (m), P_{Jan}; P_{Apr}; P_{Nov} = monthly precipitation of January, April, and November (mm); MFI = Modified Fournier Index calculated as in Arnoldus (1977) (Eq. (3)):

$$MFI = \sum_{i=1}^{n} \frac{{p_i}^2}{P} \tag{3}$$

where: MFI = Modified Fournier Index (mm); n = 12, p_i = monthly precipitation (mm); P = annual precipitation (mm). The MFI has been used to calculate the rainfall erosivity by many studies (Fenta et al., 2017; Oliveira et al., 2013), since it constitutes a good approximation of the R factor (Arnoldus, 1977; Ferro et al., 1999).

For Guatemala a different equation (Eq (4)), that had previously been used in several Central American countries, including Guatemala (Burke and Sugg, 2006; Krishnaswamy et al., 2001; Mikhailova et al., 1997), was used:

$$R = 3786.6 + 1.5679P - 1.9809alt \tag{4}$$

where: R = Rainfall erosivity factor (MJ mm ha^{-1} h^{-1} yr^{-1}); P = annual precipitation (mm); alt = altitude (m).

The two different equations used to derive the R factor were chosen to better infer the climatic differences of the two countries, making sure the values obtained for the two countries were comparable and similar to the values estimated by other studies (Calvo-Alvarado et al., 2014; Mikhailova et al., 1997; Vahrson, 1990). Co-kriging method (Cressie, 1993) was used to obtain the spatial distribution of the monthly average precipitation. Several covariates (mainly calculated from remote sensing data; NDVI, NDWI, Landsat 8 and Sentinel-2 bands, elevation, and coordinates) were used for the interpolation. An interpolation grid of 100 m resolution was used. For interpolation purposes we used the "georob" package (Papritz, 2020). Further details on the covariates and on the results of the interpolation are reported in the Supplementary material.

3.1.2. K factor

The erodibility factor represents the influence of the soil properties (such as texture, organic matter content, permeability, water infiltration capacity) on the soil erosion (Wischmeier and Smith, 1965).

The equation used to calculated the K factor in this study was developed by Torri et al. (2002, 1997) and considers data on soil texture and organic matter content (Eq. (5)).

$$K = 0.0293\cdot\left(0.65 - D_g + 0.24D_g^2\right)\cdot exp\left\{-0.0021\frac{OM}{C} - 0.00037\left(\frac{OM}{C}\right)^2 - 4.02C + 1.72C^2\right\} \tag{5}$$

where: K = soil erodibility factor (Mg h ha MJ^{-1} mm^{-1} ha^{-1}); OM = percentage of organic matter; C = fraction of clay content; Dg = logarithm of the geometric mean of the distribution of particle-size (Borselli et al., 2009; Shirazi et al., 1988), where CL, SL, SA = percentage of clay, silt, and sand.

$$D_g = \frac{-3.5CL - 2.0SL - 0.5SA}{100} \tag{6}$$

The organic matter (OM) percentage was obtained by multiplying the soil organic carbon (%) by 1.724 (Van Bemmelen, 1890). This conversion factor has been largely used in past literature (Bai et al., 2018; Stockmann et al., 2013). After calculating the K factor at plantation level (using the data from the analysis of the soil samples averaged per plantation), a co-kriging interpolation method (Cressie, 1993) employing several covariates (Soil Moisture Index, Soil Colour Index, average annual precipitations, soil type map), was used to obtain the spatial distribution of the K factor for the areas considered (see Supplementary material).

3.1.3. LS factor

The slope length and steepness factor (LS factor) depicts the effect and influence of topography on soil erosion risk. To calculate the LS factor the equation developed by Moore and Wilson (1992) was used (Eq. (7).

$$LS = (m+1)\left(\frac{U}{22.1}\right)^m\left(\frac{\sin\beta}{0.0896}\right)^n \tag{7}$$

where: LS = length slope and steepness factor (unitless); U = upslope area per unit width (measure of water flow length (m) obtained using the “r.flow” command in GRASS GIS and multiplied by the grid resolution, in our case 30 m); β is the slope angle in degrees; m = 0.4 and n = 1.3 as suggested by Neteler and Mitasova (2004).

3.1.4. C factor

The cover and management factor (C factor) estimates the influence of the management practices on soil erosion rates. It mainly depicts the effect of plants and soil cover on erosion (the lower the factor, the higher the capacity of the vegetation to reduce the erosion risk). Data from two field methods (hemispherical photos and transect soil cover) were used in the calculation of the C factor. A three-steps approach was used to obtain the spatial distribution of the C factor: i) development of composite index using different indicators and different weights to consider the soil cover (percentage of coverage by plants or litter obtained in the field survey), understory and canopy cover (at plantation level) obtained from the analysis of the hemispherical photographs; ii) transformation of the composite index by assigning a value range calculated using an equation, for tropical regions, that estimates the C factor using the NDVI values (Almagro et al., 2019; Durigon et al., 2014); and iii) interpolation of the obtained composite index using co-kriging methods to derive a spatial distribution from plantation level values. Below the individual steps are explained in detail.

We developed a composite index using data on soil cover (% for soil covered by herbaceous plants and litter) and on leaf area index (LAI) of the coffee plants and the shade trees (canopy). The different indicators (percentage of soil cover by litter, percentage of soil cover by herbaceous plants, LAI of coffee bushes, LAI of shade trees) were individually normalized from 0 to 1 using the following formula as in Herzog et al. (2006):

$$I_{norm} = \frac{(I - I_{min})}{(I_{max} - I_{min})} \tag{8}$$

where I_{norm} = normalised indicators (0–1); I = indicator’s actual value (% soil cover by litter, % of soil cover by herbaceous plants, LAI of coffee bushes, LAI of shade trees); I_{min} = lower value of the indicator in the whole population; I_{max} = higher value of the indicator in the whole population.

Then, the composite index was calculated by summing the 4 different indicators (percentage of soil cover by litter, percentage of soil cover by herbaceous plants, LAI of coffee bushes, LAI of shade trees) to which different weights were assigned (Table 3). The weights assigned to the different indicators were supported by previous studies that assessed the importance of shade trees, understory vegetation, grass strips, or litter cover in affecting erosion risk in agroforestry systems or coffee monoculture as well as forested systems (Anh et al., 2014; Blanco Sepúlveda and Aguilar Carrillo, 2015; Bruijnzeel, 2004; Craswell et al., 1998; Li et al., 2015; Roose and Ndayizigiye, 1997; Wischmeier and Smith, 1978).

The composite index was then normalised (from 0 to 1) and inverted by subtracting it to 1 (reverse index), to obtain the index in the right orientation for the C factor (because the higher the C factor, the lower the capacity to reduce the soil erosion). Then, Eq. (9) was used to estimate the range of C factor across all the plantations based on NDVI. The Eq. (9) was developed for tropical areas by Durigon et al. (2014) and modified by Almagro et al. (2019). Subsequently, the range of C factor obtained for the plantations (using Eq. (9)) was assigned to the plantations ranked using the reverse composite index. The reverse composite index was used to rank the plantations, from the one with higher soil and canopy cover to the one with lower cover, to include the vegetation structure of the plantations into the C factor.

$$C = 0.1\cdot\left(\frac{-NDVI + 1}{2}\right) \tag{9}$$

Finally, the spatial distribution of the C factor, calculated as described in the aforementioned steps, was obtained through an interpolation approach using co-kriging with several covariates (NDVI, NDWI, Soil Moisture Index, EVI, and some bands from Sentinel-2 and Landsat 8) mainly derived from remote sensing (Cressie, 1993). Further details on NDVI calculation and on the co-kriging modelling can be found in Supplementary material.

3.1.5. P factor

The support practice factor (P factor) reflects the effect and impact of soil conservation practices on the annual soil erosion risk. As with the C factor, the lower the P factor, the higher the efficiency of the conservation practice to reduce soil erosion. The value assigned to each soil conservation practice and combination of practices was justified by similar values found in the literature (Angima et al., 2003; Gebremichael et al., 2005; Maetens et al., 2012; Mati and Veihe, 2001). At plantation level, we used the information of the field survey to assign a P factor value for each farm. The practices considered were: terraces, micro

Table 3
Weights of the different indicators used to calculate the composite index.

Plants cover	Litter cover	Coffee plants (understory) LAI	Tree LAI
0.35	0.25	0.3	0.1

terraces, live or dead barriers, water infiltration trenches and planting in contour lines. Depending on the practices used and on the combination of practices, the P factor in the coffee plantations ranged from 0.3 (if three practices including terraces were present) to 1 in Costa Rica, and from 0.15 (if all five practices were present in the plantation) to 1 in Guatemala, in accordance with P factor values found in the literature (Angima et al., 2003; Gebremichael et al., 2005; Maetens et al., 2012; Mati and Veihe, 2001). If no information were available a P factor of 1 was used. At watershed level we used a P factor of 1, which assumes no practices, due to the lack of information about the use of conservation support practices in the different land cover classes. Further details on the P factor can be found in Supplementary material.

3.2. Management scenarios

In order to identify the effects of possible management strategies to reduce soil erosion, different scenarios at watershed or plantation level were developed (Table 4). We considered only C factor and P factor in order to explore changes in soil erosion rates due to changes in coffee plantations' management. The scenarios were developed based on the percentile population distribution of the plantations for the C and P factors. For improved management the C or P factor value of the 25th percentile (best managed) of plantations was applied to all other plantations. On the contrary, to reflect a reduction in conservation practices and vegetation cover the value factor at the 75th percentile (worst managed) was applied to all plantations. Different combinations of increase or decrease in C factor (vegetation cover) and P factor (soil conservation practices) were used to identify changes in erosion estimates and identify recommendations at the regional level.

The C factor was changed for the area under coffee of the watershed and at plantation level, and the P factor only for estimations at plantation level. For the scenarios with the 25th percentile the C factor was changed only if the value was higher than the 25th percentile value. If the value was lower, we kept that value. The same method was applied at plantation level for the P factor in the scenarios with P factor at the 25th percentile. For the scenarios with the 75th percentile of C factor or P factor we changed the C factor or the P factor value only if it was lower than the 75th percentile. For the scenarios at plantation level these changes affected 75% of the farms, while the area percentage changed due to C factor value variation per region in the first two scenario (applied at watershed level) is reported in the Supplementary material.

Table 4
Scenario descriptions considering the changes in C factor and P factor made at watershed and/or at plantation level.

Scenario ID*	Description	C factor	P factor
25C-NP	Higher soil and canopy cover, no changes on conservation practices	25th percentile	No changes
75C-NP	Lower soil and canopy cover, no changes on conservation practices	75th percentile	No changes
NC-25P	No changes on soil and canopy cover, higher conservation practices	No changes	25th percentile
25C-25P	Higher soil and canopy cover, higher conservation practices	25th percentile	25th percentile
75C-25P	Lower soil and canopy cover, higher conservation practices	75th percentile	25th percentile
NC-75P	No change on soil and canopy cover, no conservation practices	No changes	75th percentile
75C-75P	Lower soil and canopy cover, no conservation practices	75th percentile	75th percentile
25C-75P	Higher soil and canopy cover, no conservation practices	25th percentile	75th percentile

* The codes in the column "Scenario ID" are the acronyms used to identify the different scenarios in the next paragraphs (25 and 75 mean 25th and 75th percentile, N means no change (as compared to the baseline situation), C and P mean C factor and P factor).

3.3. Data analysis

The maps of the different variables, obtained through GIS calculation (i.e.: LS factor, slope, etc.), were resampled at 100 m using a nearest neighbour resampling algorithm, before estimating erosion rates using the RUSLE model. For the interpolation of the different variables (monthly precipitations, C factor, K factor) we used a prediction grid of 100 m × 100 m. Therefore, we estimated a spatial distribution of the yearly erosion at 100 m of resolution. The estimated erosion per plantation were extracted using the coordinates for the centre of the plantation. Use of conservation practices were integrated by multiplying the erosion estimates by the P factor calculated in each plantation. Furthermore, zonal statistics were obtained for the watershed and the coffee area inside the watersheds considered. For the zonal statistics at watershed level, the stream and river network was masked. Estimated erosion rates of the coffee plantations were also aggregated at region level to identify possible differences between regions.

Linear multiple regression models were used to identify the importance of the different RUSLE factors in explaining the variance obtained at the plantation level. Linear model ANOVA, using the regions as class variable and the erosion estimate as response variable, was run to identify possible differences among regions. Moreover, we ran the two-way ANOVA of the baseline C factor and P factor at plantation level with the regions as class factor to identify possible differences on vegetation cover and conservation practices implementation among regions. The Tukey method was used to evaluate the mean differences after rejection of null ANOVA hypothesis. The post hoc p-values of the Tukey test were reported in case of significant difference among regions. In order to differentiate the shade and soil cover management strategies and to assess the differences in management practices, a two-way ANOVA model was employed dividing the plantations by quantiles of the C factor values as a class variable with the coffee vegetation characteristics as response variables (e.g.: shade trees LAI, coffee plant LAI, % of soil covered by plants or litter). This analysis was simply used to determine the contribution of these variables to the C factor quantiles, not as a statistical analysis of significance per se, since we are aware that the C factor was constructed from the shade and soil cover, therefore clearly affecting the significance outcomes. The graphs of the linear multiple regression models, the linear regression between the RUSLE factors and the estimated erosion, as well as the spatial distribution of the RUSLE factors are shown in the Supplementary material.

4. Results

4.1. Estimated erosion in the coffee plantations

4.1.1. Costa Rica

The estimated erosion rates in the Costa Rican plantations without accounting for the P factor, therefore assuming no soil conservation practices, ranged from 0 to 76.3 Mg ha^{-1} yr^{-1} with a mean of 20.8 Mg ha^{-1} yr^{-1}, and a median of 15.8 Mg ha^{-1} yr^{-1} (SD = 18.4 Mg ha^{-1} yr^{-1}). When P factor was integrated the mean estimated erosion rate decreased to 17.1 Mg ha^{-1} yr^{-1}, while the median decreased to 12.6 Mg ha^{-1} yr^{-1} (SD = 16.2 Mg ha^{-1} yr^{-1}) (in the Supplementary material, the two sets of erosion rates (without or with the integration of the P factor) are summarised by regions; Table S.4).

There were significant differences between regions in estimated erosion rate (p-value = 0.04) at the plantation level without the P factor, with Tarrazú having a higher rate by 44% than Valle Occidental (Tukey post hoc p-value < 0.05). However, if the estimated erosion rates with the P factor were considered (p-value = 0.02) there was significantly higher erosion rates by 52% in Turrialba than Valle Occidental (Tukey post hoc p-value = 0.02).

A multiple linear regression model of the estimated erosion rate without the P factor against the LS factor, R factor, K factor, C factor was used to determine the amount of variance explained by each variable (factors) ($R^2 = 0.94$, p-value $< 2.2 \times 10^{-16}$). When the erosion calculated with the P factor is considered, the R^2 of the linear regression model decreased to 0.87 (p-value $< 2.2 \times 10^{-16}$) (Table 5). In both models, all the factors had a high significance in the model (p-values $<$ 0.001), with topographical aspects (LS factor) explaining the majority of the difference.

4.1.2. Guatemala

The Guatemalan plantations were characterised by an estimated erosion rate that ranged from 0 to 113.2 Mg ha^{-1} yr^{-1} with a mean of 9.6 and a median of 4.1 Mg ha^{-1} yr^{-1} (SD = 16.2 Mg ha^{-1} yr^{-1}), without inclusion of the P factor. If the P factor was considered the estimated erosion rates ranged from 0 to 67.9 Mg ha^{-1} yr^{-1}, with a mean of 7.0 and a median of 2.7 Mg ha^{-1} yr^{-1} (SD = 12.2 Mg ha^{-1} yr^{-1}) (see Table S.5 in the Supplementary material for estimated erosion rates by region). There was a significant difference in estimated erosion rate between regions (p-value = 0.005) with significantly higher rate by 69% and 55% for the West region compared to the East (p-value = 0.004) and Mid regions, respectively (p-value = 0.07). The multiple linear regression model of the estimated erosion rate at the plantation level against the LS factor, R factor, K factor, C factor (and P factor) was used to determine the amount of variance explained by each factor (Table 5). The model showed highly significant correlation but lower than for Costa Rica ($R^2 = 0.56$, p-value $< 7.2 \times 10^{-16}$, and $R^2 = 0.63$, p-value = $< 2.2 \times 10^{-16}$ with or without the P factor, respectively). The LS, R, and K factors were highly significant and explained the majority of variance in decrescent order, the C factor was not significant, while moderate significance was found for the P factor when included (p-value = 0.03).

4.2. Estimated erosion rates in the watersheds

The estimated erosion rates were aggregated at the watershed level. At this level the rivers were masked to obtain reasonable estimated erosion rates. In the Costa Rican watersheds, an overall erosion rate of 26.7 Mg ha^{-1} yr^{-1} (median: 17.3 Mg ha^{-1} yr^{-1}, range: 12–40 Mg ha^{-1} yr^{-1}) was estimated. The estimated erosion rate of the coffee area within the watersheds was 24.2 Mg ha^{-1} yr^{-1} (median: 18.5 Mg ha^{-1} yr^{-1}, range: 12–38 Mg ha^{-1} yr^{-1}). The coffee area accounted for an average of 29%, 23% and 36% of the total erosion of the watershed considered in Tarrazú, Turrialba, and Valle Occidental, respectively (Table 6). Fig. 3 shows the spatial distribution of the estimated erosion rates in Costa Rican selected watersheds as well as the plantations' distribution.

In Guatemala, in the selected watersheds, average estimated erosion rate was 10.8 Mg ha^{-1} yr^{-1} (median: 3.4 Mg ha^{-1} yr^{-1}, range: 1–32 Mg ha^{-1} yr^{-1}). The estimated erosion rate of the coffee area within the watersheds was 13.6 Mg ha^{-1} yr^{-1} (median: 4.7 Mg ha^{-1} yr^{-1}, range: 1–46 Mg ha^{-1} yr^{-1}). The coffee area accounted for an average of 37%, 30%, and 37% of the total erosion in the watersheds for the East, Mid, and West regions, respectively (Table 6). Fig. 4 shows the spatial distribution of the estimated erosion rates in Guatemalan selected watersheds as well as the plantations' distribution.

Table 5
Variance explained by each variable of the multiple linear regression model of the estimated erosion rates at plantation level.

Variable	Explained variance	
	Erosion without P	Erosion with P
Costa Rica		
LS factor	86.6%	67.2%
R factor	3.0%	3.6%
K factor	3.5%	3.5%
C factor	1.2%	2.6%
P factor	–	11.0%
Guatemala		
LS factor	41.7%	31.8%
R factor	13.0%	14.5%
K factor	9.0%	9.4%
C factor	0.4%	0.6%
P factor	–	2.2%

4.3. Management scenarios modelling

4.3.1. Management factors characterisation

In Costa Rica, the two-way ANOVA found significant differences in the C factor and the P factor between the plantations of the three regions; the average P factor and C factor were significantly different (higher) in the plantations of Turrialba compared to the plantations of the other two regions (Table 7). In Guatemala, we found that the C factor was significantly lower in the West region and significantly higher in the East region. No significant differences were found in the P factor among the three regions. Overall, at plantation level, in Guatemala, higher values of C factor (less canopy and soil cover) and lower values of P factor (higher implementation of conservation practices) were found as compared to Costa Rican plantations (Table 7).

4.3.2. Cover management strategies (C factor) assessment

In order to identify erosion management strategies, the characteristics for different C levels were disaggregated, and further analyses were done. In Costa Rica, significant differences across the 1st and the 4th quartiles of the C factor, were found for shade cover, LAI coffee, litter, and number of tree species, but not herbaceous plant cover, and for the LAI of the shade trees, where the 4th quartile differed from the 2nd quartile but not from the 1st quartile (Table 8). For Guatemala, the quartiles of the C factor showed significant differences for canopy LAI, litter, and herbaceous plant cover. No significant differences were found in the LAI of the coffee plants between the groups of plantations (Table 8).

4.3.3. Estimated erosion under different management scenarios

To assess the role of shade and soil cover (represented by the C factor) and soil conservation practices (represented by the P factor), RUSLE was estimated for the different C and P scenarios (see Table 4) at watershed (only C factor) and plantation level (both P an C factors). In Costa Rica, application of the 25th percentile of C factor (high soil and canopy cover) (25C-NP) in the coffee area on average reduced the estimated erosion by 3.1% across the selected watersheds, or by 9.6% across the coffee area inside the selected watersheds. If in the whole area under coffee the 75th percentile value of C factor (low soil and canopy cover) of the plantations was used (75C-NP), an average increase of estimated erosion of 1.3% or 4.1% was found across the selected watersheds or the coffee area inside watersheds, respectively. The decrease in estimated erosion (in scenario 25C-NP) was higher in the Turrialba region (Fig. 5a). Furthermore, in Turrialba, in the scenario with less shade and soil cover (75C-NP), there was a slight increase in erosion (1%). This result indicated that plantations in the Turrialba region on average have a high C factor (i.e. lower soil and canopy cover) than the other regions). In Guatemala, application of the 25th percentile of C factor (25C-NP), reduced the estimated erosion by 4.5% in the selected watersheds or 11.9 % in the coffee area inside the watersheds. With the application of the 75th percentile of C factor (75C-NP), the estimated erosion increased on average by 5.6% across the selected watersheds, or by 14.9% across the coffee area inside the watersheds. The high increase of estimated erosion in the coffee area of the West region (Guatemala) in the scenarios with lower shade and soil cover (75C-NP) indicated that the coffee area in that region is characterised by a high soil and canopy cover (Fig. 5b). At plantation level the effects on estimated erosion for scenarios 25C-NP and 75C-NP were similar to the results obtained at watershed level in Costa Rica and Guatemala, respectively (Fig. 6).

Across all regions in Costa Rica and Guatemala, the scenarios with the 25th percentile of P factor (increase of soil and water conservation management; 25P) considerably reduced potential soil erosion. The

Table 6
Zonal statistics of the estimated erosion rates (A) for watersheds (WS) and coffee area inside the watersheds of each region.

Region		N WS	N plantation	WS area (km^2)	Coffee area inside WS (%)	A (Mg ha^{-1} yr^{-1}) in WS	A (Mg ha^{-1} yr^{-1}) in coffee area inside the WS	A (%) in coffee area inside the WS
Costa Rica								
	Tarrazú	3	30	470	33	32	32	29
	Turrialba	5	22	311	19	19	22	23
	Valle Occidental	3	30	509	43	22	19	36
Guatemala								
	East	3	32	559	31	7	8	37
	Mid	2	27	358	17	10	17	30
	West	5	20	447	34	17	18	37

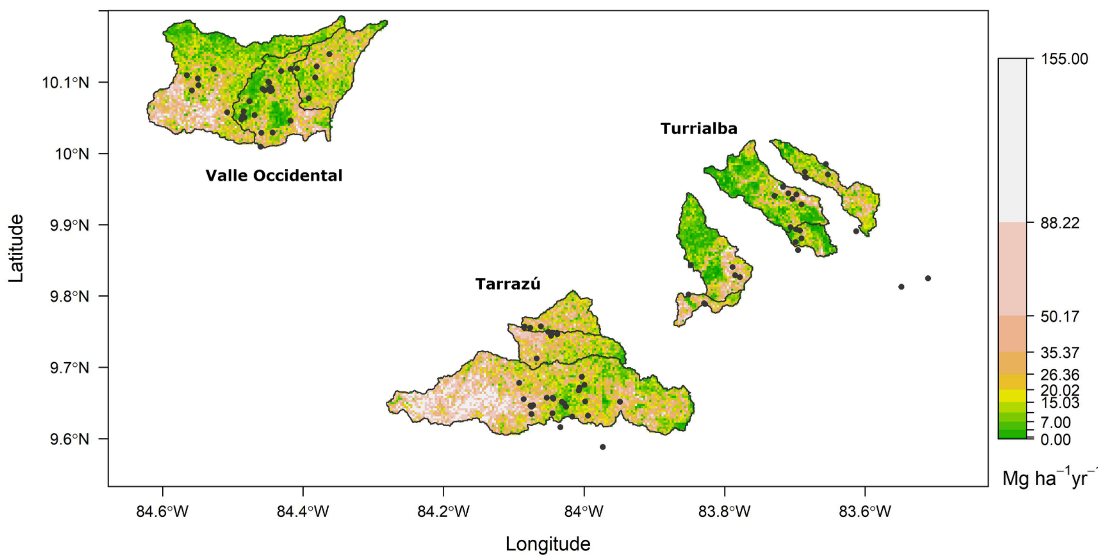

Fig. 3. Spatial distribution of estimated erosion rates in the selected watersheds of Costa Rica. The polygons represent the selected watersheds, whereas the points identify the plantations.

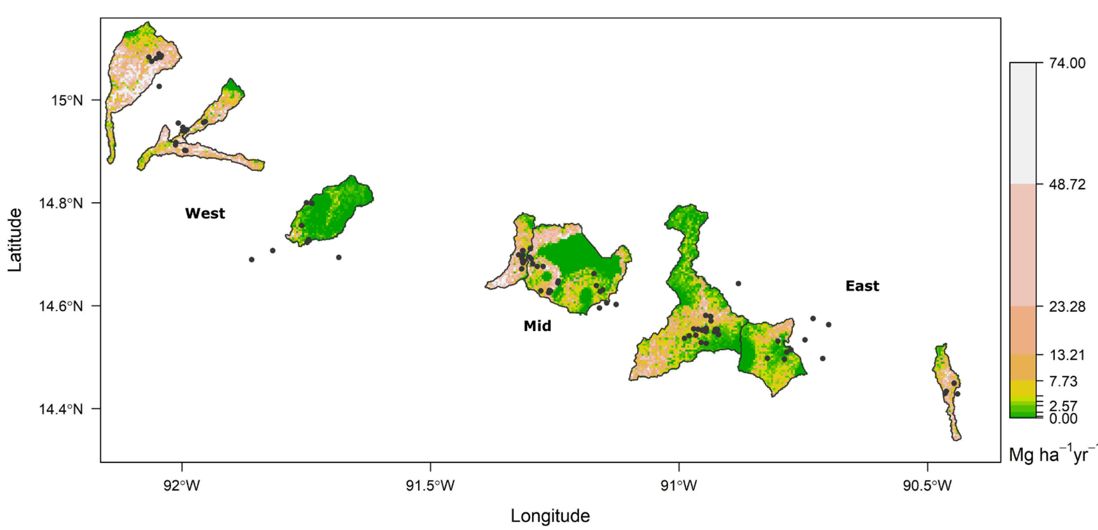

Fig. 4. Spatial distribution of estimated erosion rates in the selected watersheds of Guatemala. The polygons represent the selected watersheds, whereas the points identify the plantations.

decline was i) slightly greater when combined with increased shade and soil cover (25C), or ii) reduced with decrease of shade and soil cover (75C). On the contrary, almost all the 75P scenarios had considerably higher estimated erosion except for the 25C combined scenarios in Turrialba for Costa Rica and the East region for Guatemala, where the 25C effect was sufficient to outweigh the 75P effect and lead to a marginal decrease in estimated erosion (Fig. 6). This indicates that in these regions of low vegetation cover and little use of soil conservation

Table 7
Averages and ranges in parenthesis of P factor and C factor per region. The different letters within the columns identify significant differences between regions within the same country. Absence of letters identify the lack of significance in the ANOVA model.

Country	Region	C factor*	P factor**
Costa Rica	Tarrazú	0.0166 a (0.0115–0.0214)	0.795 a (0.30–1)
	Valle Occidental	0.0160 a (0.0136–0.0192)	0.821 a (0.55–1)
	Turrialba	0.0179 b (0.0130–0.0209)	0.941 b (0.60–1)
Guatemala	East	0.0285 b (0.0207–0.0411)	0.768 (0.30–1)
	Mid	0.0258 ab (0.0187–0.0379)	0.648 (0.30–1)
	West	0.0233 a (0.0174–0.0292)	0.730 (0.15–1)

* P-value = 0.00016 for Costa Rica and = 0.0003 for Guatemala. ** P-value = 0.002 for Costa Rica and = 0.15 for Guatemala.

practices there is a good potential of reducing erosion by increasing the vegetation cover. This was probably due to high baseline values of C factor (lower vegetation cover) and P factor (lower establishment of soil conservation practices). Generally, in Costa Rica the decrease in estimated erosion was greater for the Turrialba region than in the Valle Occidental region. In Guatemala, a similar decrease in estimated erosion was found in the Mid and West regions, with larger reductions in the East region.

5. Discussion

5.1. Model limitations and assumptions

In this study, we estimated the soil erosion rates of three of the major coffee areas in Costa Rica and Guatemala. We also assessed the potential to reduce the erosion rates and identified possible strategies to achieve this. The RUSLE equation was employed to derive the annual estimated erosion rate, while changes in two of the RUSLE factors (C and P factor) were implemented to assess changes of estimated erosion rates under different management scenarios. The RUSLE primarily models sheet and rill erosion from rainsplash and sheet flow, overlooks sediment redeposition and sediment yield (Borrelli et al., 2021; Warren et al., 2005), and does not well represent erosion from gullying, streambank, or landslides (Renard et al., 1991) that can also occur in coffee plantations (Ramos-Scharrón et al., 2022b, 2021; Ramos-Scharrón and Figueroa-Sánchez, 2017; Ramos-Scharrón and Thomaz, 2016). On the contrary, another study found that sheet and interrill erosion is the predominant erosive process, whereas erosion in gullies has not been frequently observed in coffee plantations with similar topographical conditions (Blanco Sepúlveda and Aguilar Carrillo, 2015). However, in spite of the aforementioned limitations, RUSLE is easy to interpret, it requires relative few data, and the data needed are usually globally available. Different sources of data can be used, and the different factors can be calculated using different equations based on data availability. Therefore, RUSLE equation represents for our study a "simple", flexible, and adaptable model to obtain estimations of yearly erosion risk, assumed the limitations are accounted for and understood.

Concerning our study, the spatial variability of some RUSLE factors (K factor, and C factor) was predicted and inferred only using data obtained from samples collected in coffee plantations (mainly agroforestry systems and some few cases of full sun plantations). For this reason, our estimate of erosion was focused on the coffee area, with estimates across all land uses in the watershed only used to gauge the relative importance of the erosion from coffee growing areas. Furthermore, in this study, for the calculation of the rainfall erosivity (R factor), we could not consider the role of rainfall kinetic energy and intensity due to lack of fine time resolution data. Our estimates of R factor (rainfall erosivity) were realistic if compared to estimates reported by previous studies in Central America (Calvo-Alvarado et al., 2014; Krishnaswamy et al., 2001; Mikhailova et al., 1997; Vahrson, 1990). Another study found that a large proportion of soil loss was due to few intense and heavy rainfall events throughout the year (Hoyos, 2005). Although the lack of fine time resolution rainfall data might have affected the absolute estimations, our study did not attempt to assess erosion under different climatic scenarios. Relative estimates of erosion do suffice with the main objectives of this study, which were to estimate the contribution of erosion from coffee plantations to watershed level rates, and understand how different management strategies could help to reduce soil erosion. The comparison between the estimates obtained in the two countries should be taken with caution as different equations were used to calculate the R factor. Furthermore, low and no significance in explaining the estimated erosion was found for the C factor in Costa Rica and Guatemala, respectively. This could have implications for RUSLE application in Central America, where topographical factors (LS factor) have higher significance. However, in our study, changes in the C factor did have significant effect on reducing or increasing estimated erosion with different magnitudes in different regions. Therefore, this study can give

Table 8
Management characteristic per plantations grouped by C factor quartiles. Means within a column within the country with a different letter are significantly different (p-value < 0.05). Letters are not present if the linear model was not significant (p-value greater than 0.05).

Costa Rica							
Group*	N plantation	Canopy cover (0–1) (p-value = 0.001)	LAI trees (p-value = 0.005)	LAI coffee (p-value < 0.001)	Litter (0–1) (p-value < 0.001)	Plants (0–1) (p-value = 0.235)	N tree species (p-value = 0.03)
1st quartile	23	0.61 b	0.842 ab	3.34 c	0.705 c	0.223	5.30 b
2nd quartile	22	0.55 b	1.045 b	2.84 c	0.670 bc	0.203	4.29 ab
3rd quartile	23	0.52 ab	0.827 ab	2.16 b	0.586 ab	0.174	3.00 ab
4th quartile	22	0.39 a	0.469 a	1.54 a	0.537 a	0.138	2.45 a

Guatemala							
Group	N plantation	Canopy cover (0–1) (p-value = 0.002)	LAI trees (p-value = 0.03)	LAI coffee (p-value = 0.14)	Litter (0-1) (p-value = 0.004)	Plants (0-1) (p-value < 0.001)	N tree species (p-value = 0.098)
1st quartile	24	0.66 b	1.172 ab	2.08	0.436 ab	0.504 c	4.17
2nd quartile	24	0.60 ab	1.036 ab	2.11	0.565 b	0.2745 b	5.25
3rd quartile	23	0.66 b	1.321 b	2.31	0.480 ab	0.203 ab	7.84
4th quartile	25	0.48 a	0.741 a	1.67	0.266 a	0.051 a	3.75

* "Group" identifies the plantations grouped by value of C factor (1st quartile: plantations until the 1st C factor quartile; 2nd quartile: plantations between 1st and 2nd quartile; 3rd quartile: plantations between 2nd and 3rd quartile; and 4th quartile: plantations above 3rd quartile).

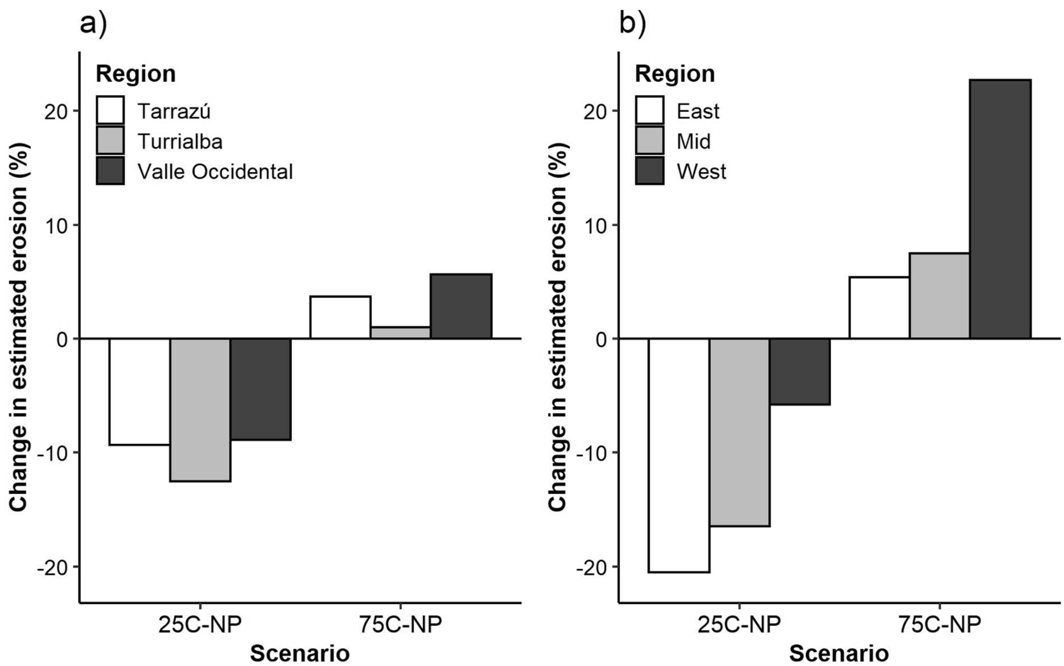

Fig. 5. Percentage change in estimated erosion compared to the baseline situation under scenarios with high (25C) and low (75C) canopy and soil cover applied across the whole coffee area in regions of Costa Rica (Fig. 5a) and Guatemala (Fig. 5b). No use of soil conservation practices (NP) is assumed.

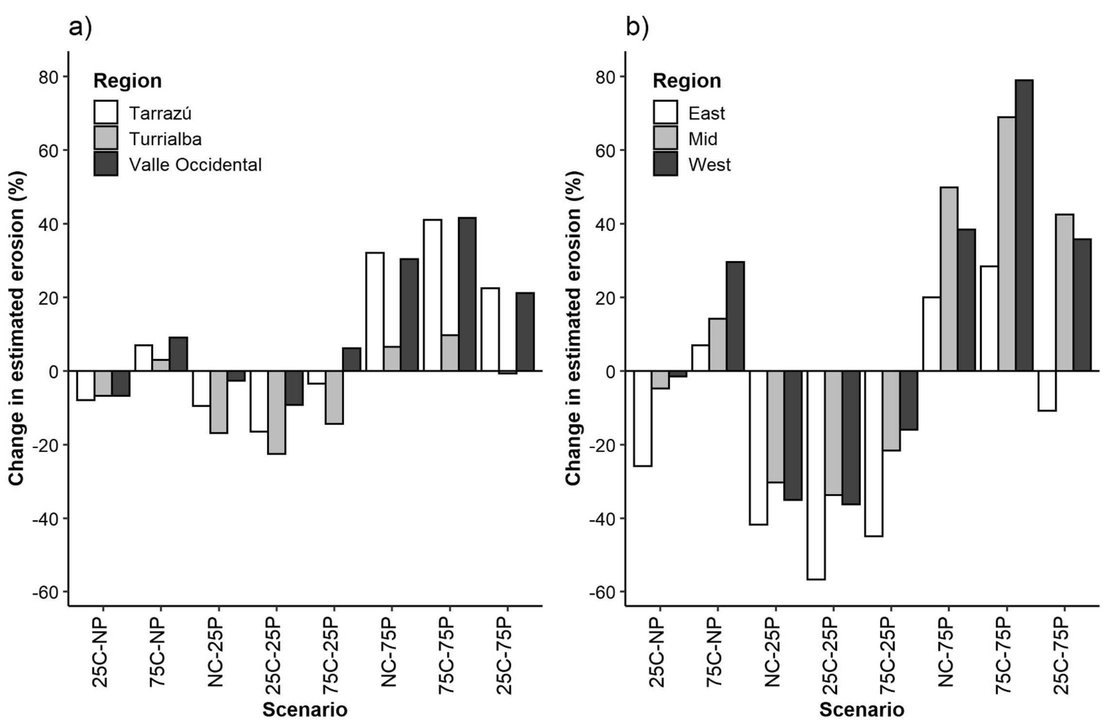

Fig. 6. Percentage change in estimated erosion compared to baseline situation under different scenarios of high (75C or 75P) and low (25C or 25P) C and P factors (see Table 3 for explanation of codes) applied across all coffee plantations in regions of Costa Rica (Fig. 6b) and Guatemala (Fig. 6b). No changes from the baseline situation are indicated as NC or NP, for the C and P factors respectively.

a good indication of the potential impacts of different management scenarios on the soil erosion at different spatial levels (watersheds, regional, or plantation level).

5.2. Soil erosion estimates in coffee systems

Overall, the higher erosion estimates in Costa Rica as compared to erosion estimates in Guatemala were mainly due to higher LS factor (concerning both length and steepness factor) and K factor values, despite lower values of C factor. Both in Costa Rica and Guatemala, the variance obtained at plantation level was mainly explained by the slope length and steepness (LS) factor. Accordingly, the increase in use of conservation practices such as terraces are effective in reducing erosion as they reduce the length of slope. The multiple regression analysis showed that the second most important factor in explaining the variance in estimated erosion rates was the rainfall erosivity (R) factor. In Costa Rica, the R factor was significantly lower in the Tarrazú plantations, while it was significantly higher in the West plantations in Guatemala. Furthermore, in Guatemala, the multivariate analysis showed that also the K factor (soil texture and organic matter parameters) was a significant factor in explaining the variance of the estimated erosion rate obtained at plantation level. The more sandy soil texture and higher organic matter in Guatemala compared to Costa Rica likely contributed to the lower soil erosion estimations.

Generally, and especially in Costa Rica, our study found higher estimates of erosion compared to other studies in similar Central American environmental conditions. In Costa Rica, almost one fifth of the plantations were characterised by an estimated erosion rate higher than 30 Mg per hectare per year. However, the mean and median estimates at plantation level in our study were in agreement with soil erosion rates calculated by previous studies such as those of Sancho (1991) who estimated erosion rates from 2 to 42 Mg ha^{-1} per year depending on weeding strategies in Costa Rican coffee plantations (reported by Veihe et al. (2001)). However, lower soil losses were estimated by Villatoro-Sánchez et al. (2015) who measured a maximum total soil loss of 1.69 ± 0.78 Mg ha^{-1} y^{-1} in experimental plots inside of a coffee plantation in Costa Rica. Higher estimates of soil loss (6.7–35.1 Mg ha^{-1}) were however found from field experiments in teak plantations with different management strategies (Fernández-Moya et al., 2014). While in coffee farms in Puerto Rico, erosion estimates of 11–18 Mg ha^{-1} yr^{-1} and 15–27 Mg ha^{-1} yr^{-1} were found, but the main source of erosion and sediment production (from 22 to 95% of the total plantation erosion) were the roads, and road cuts (Ramos-Scharrón et al., 2022a; Ramos-Scharrón and Figueroa-Sánchez, 2017; Ramos-Scharrón and Thomaz, 2016). Field measured soil losses in coffee plantation in the range of 0.18 and 3.2 Mg ha^{-1} yr^{-1} were found by Vahrson and Palacios (1993) in coffee plantations, while, in the same plantations, Vahrson and Cervantes (1991) estimated erosion rates of 49–55 Mg ha^{-1} yr^{-1} using the USLE equation. Thus, there is a substantial difference in erosion estimated from field measurements compared to those modelled through the RUSLE equation. Accordingly, we agree with other authors that suggested that USLE and RUSLE based estimates should be considered as relative values (de Asis and Omasa, 2007; Kim et al., 2005; Vahrson, 1990), for example to compare relative erosion estimates between different areas or areas with different management strategies. On the contrary, caution is needed when considering the absolute values obtained through modelling processes (de Asis and Omasa, 2007). Indeed, it has been stated that USLE-type models might overestimate soil erosion in tropical regions especially in steep areas (Vahrson, 1990; Vahrson and Cervantes, 1991), and this is also shown by our study if our estimates are compared to empirical field-based erosion estimates in similar growing coffee areas. Therefore, when using erosion modelling approaches, relative comparisons between areas or, such as in our case, among management scenarios, should be prioritised rather than focusing on absolute values (Millward and Mersey, 1999).

5.3. Changes of erosion in different management scenarios

The estimation of the erosion rate in different scenarios was useful to identify the management strategies to reduce erosion and select priority areas or regions for interventions. If all plantations reduced their soil and canopy cover as well as the conservation practices (scenario 75C-75P), the estimated erosion rate could increase by an average of 29% (with a maximum of 42% in Valle Occidental) and 65% (with a maximum of 79% in the West region) in Costa Rica and Guatemala, respectively. While with good soil and canopy cover and conservation practices (scenario 25C-25P) the estimated erosion rate could decrease by an average of 17% (with a maximum of 23% in Turrialba) and 40% (with a maximum of 57% in the East region) in Costa Rica and Guatemala, respectively. While 17% decrease does not seem a high percentage, a consistent and gradual reduction of erosion (especially sheet erosion) would positively affect soil fertility, and soil water holding capacity at a long-term perspective (Bronick and Lal, 2005).

5.3.1. The role of the vegetation cover in changes of erosion estimates

In Turrialba (Costa Rica) and the East region (Guatemala), there was higher potential to reduce erosion through increasing the shade and soil cover with herbaceous vegetation and litter, as compared to the other regions. Conversely, a decrease in shade tree cover and vegetation cover of the soil would lead to high increase of estimated erosion rates in the other regions. In fact, even with fewer soil conservation practices in the plantations, a higher shade and soil cover could foster a reduction of soil erosion, as was shown by the scenario with higher shade and soil cover and no implementation of conservation practices (25C-75P), in Turrialba in Costa Rica and in the East region in Guatemala. This result suggested that, despite greater weight of the P factor in the erosion estimates, the C factor could still have an important influence on the erosion estimates in the scenario analysis.

Costa Rican results agree with other studies which measured soil losses through empirical field data, on the importance of the understory vegetation and soil cover (through litter, cover crops, mulch, herbaceous plants, crop residue) in reducing the risk of erosion (Anh et al., 2014; Ataroff and Monasterio, 1997; Roose and Ndayizigiye, 1997; Verbist et al., 2010). Development of a litter layer was indicated as the main reason for a 45% reduction of soil loss in coffee monoculture plantations of more than 6 years (as compared to plantations of 1 to 5 years) by Verbist et al. (2010). In Puerto Rico, presence of mulch and herbaceous vegetation in coffee farms reduced the soil erosion to 1–10% of the erosion in farms with bare soil (Ramos-Scharrón and Figueroa-Sánchez, 2017). Also in the Guatemalan plantations, the importance of the soil cover was highlighted by the importance of the percentage of herbaceous plants in reducing the C factor. It has also been found that the thickness of the litter layer, from natural leaf fall but also pruning from coffee bushes and shade trees, plays an important role in reducing the impact of raindrops on the soil surface (Ataroff and Monasterio, 1997), thereby affecting the overall erosion risk (Ramos-Scharrón and Figueroa-Sánchez, 2017). In our study these effects were integrated into the C factor.

Higher density of coffee plants (higher LAI), as well as higher shade tree density, might foster better soil retention and reduce soil erosion (Anh et al., 2014; Fernández-Moya et al., 2014). Shaded coffee systems also increase the water infiltration rates as compared to full sun coffee monoculture (Cannavo et al., 2011; Meylan et al., 2017), thereby reducing water runoff by an average of 36% of the total rainfall (Cannavo et al., 2011). Higher shade and soil cover foster a better water holding capacity of the soil (Lin and Richards, 2007). The importance of shade trees in reducing water induced soil erosion has been found in several studies (Cannavo et al., 2011; Meylan et al., 2013; Verbist et al., 2010). In Venezuela, erosion can be reduced by approximately 67% in coffee plantations under shade as compared to full sun plantation (Ataroff and Monasterio, 1997). Furthermore, a modelling study of erosion in a Puerto Rican watershed found that replacing all full sun coffee plantation with shaded coffee plantation would reduce the sediment yield of the watershed by 9% (Yuan et al., 2016), which is consistent with the results of our study.

5.3.2. The role of the conservation practices in changes of erosion estimates

Implementation of soil conservation practices was also key to reduce estimated erosion, in both Costa Rica and Guatemala. In areas where shade and soil cover strategies are already in place and well established (West region in Guatemala, and Valle Occidental in Costa Rica), another possible way to reduce and mitigate soil erosion risk would be the implementation of soil conservation practices. The establishment of conservation practices (such as trenches, live or dead barriers, micro terraces, and especially terraces) should be prioritised in the coffee plantations inside the Turrialba region, where their utilisation was lower as compared to Valle Occidental and Tarrazú plantations. Concerning the use of conservation practices (P factor), plantations in the 25th percentile in Costa Rica (P factor of 0.8) were represented by implementation of a single practice (from among planting in contour lines, water infiltration trenches, live or dead barriers, or micro terraces). The 25th percentile of P factor in Guatemala was 0.5, which represented the implementation of multiple conservation practices more effective in reducing the length and steepness of the slope (e.g. terraces together with live and dead barriers or planting in contour lines, and micro terraces together with live or dead barriers and planting in contour lines). Moreover, in both countries the 75th percentile of the P factor was 1, meaning that in the scenarios with 75P no conservation practices where applied. Implementation of conservation practices seems key in Central America, areas that are affected by and exposed to increasing frequency of extreme rainfall events and rainfall intensity (Aguilar et al., 2005; Fernández-Moya et al., 2014). Terraces, if properly managed and monitored, are key practices not only to reduce the degree and length of the slope but also to increase soil capacity to retain soil water and enhance organic matter content (Chen et al., 2021, 2020; Deng et al., 2021; Wen et al., 2021). The adoption of conservation practices is a complex process that involves several factors, such as farmers' risk perception (on climate changes, soil erosion hazards), farmers' age, education and experience, presence of conservation programs, agricultural land size, land tenure security, economic return, trade-offs between mitigation of soil erosion risk and conservation practices costs (Harvey et al., 2017; Vignola et al., 2010). Adoption of soil conservation practices is promoted through the technical assistance offered by the coffee institutes in both countries (ICAFE in Costa Rica, and ANACAFÉ in Guatemala). In Costa Rica there are national regulations on soil conservation (https://www.pgrweb.go.cr/scij/Busqueda/Normativa/Normas/nrm_texto_completo). These are mandatory for specific development projects and promoted by government agencies but application by farmers is voluntary. Within the coffee sector, application of most if not all sustainability standards include soil conservation criteria, although the farms gain points for their implementation they are not mandatory (Haggar et al., 2017). As in most processes of sustainable development there are potential trade-offs between environmental sustainability, coffee production and economic growth generation. Nevertheless, adopting soil conservation practices as well as good soil and canopy cover management seems to be crucial especially considering the potential increase of soil erosion due to climate change. Under the current patterns of climate change (Aguilar et al., 2005; Easterling et al., 2000; Groisman et al., 2005; Trenberth, 2011), models are predicting an increase in soil erosion rates especially when changes in rainfall intensity are considered (Nearing et al., 2005; Pruski and Nearing, 2002).

6. Conclusions

The integration of GIS techniques and remote sensing data in the erosion modelling of different management scenarios was key to obtain spatial estimates of annual erosion that can be used as decision-making support. Coffee plantations contributed to about 30% of estimated soil erosion in the watersheds studied. While estimated erosion levels are mainly determined by the topographical aspects (slope length and steepness factor), they can be substantially reduced through the use of canopy and soil cover as well as soil conservation practices. Improving canopy and soil cover of all coffee plantations to that implemented by the best 25% of farmers reduced soil erosion by 10% in the coffee area of the Costa Rican watersheds and 12% in Guatemalan watersheds. Application of soil conservation practices as done by the best 25% of farmers would reduce on-plantation erosion by 11% in Costa Rica and 35% in Guatemala. There were also regional differences depending on local coffee management and environmental conditions. In the coffee area of Turrialba in Costa Rica, and the East region in Guatemala with low canopy and soil cover estimated erosion would be decreased most with an increased vegetation cover in order to better protect the soil. On the contrary, the coffee area of the West region in Guatemala, which was already characterised by high vegetation cover (low C factor) and had high annual rainfall, would benefit most from increased application of soil conservation practices. To conclude, the erosion modelling approach used in this study was a valid means to estimate relative erosion rates at different spatial levels (regional, watershed, coffee area, or plantation level) and under different management scenarios, and identify appropriate actions for different regions. Similar approaches could be of use in other agroforestry systems to identify priority areas and strategies for interventions aiming in reducing soil erosion.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

This research was funded by the UK Research and Innovation Biotechnology and Biological Sciences Research Council (UKRI/BBSRC), from the Global Challenges Research Fund (GCRF) under the Agrisystems research to enhance rural livelihoods in developing countries programme (Grant number: BB/S01490X/1). We acknowledge the Institute for Coffee in Costa Rica (ICAFE), and the National Coffee Association of Guatemala (ANACAFÉ) for their support in contacting the farmers and making the field work possible. We also thank the coffee farmers for their precious time during the initial part of this research, and the field teams of CATIE in Costa Rica and CEAB in Guatemala for carrying out the extensive field work. The soil laboratories of CATIE, CEAB, and ANACAFÉ analysed the soil samples. Finally, we would like to thank two anonymous reviewers for their valuable comments and insights that helped improving the initial version of the manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.catena.2023.107182.

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