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Modeling of soil organic carbon loss by water erosion on a tropical watershed[1]

Modelagem da perda de carbono orgânico do solo por erosão hídrica em uma bacia hidrográfica tropical

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ABSTRACT - Water erosion under tropical climate conditions is one of the main processes that change the balance between the inputs and outputs of soil organic carbon (SOC). Water erosion modeling using the Erosion Potential Method (EPM) can be used as an alternative to assist in understand soil carbon dynamics and its interaction with the erosive process. In this context, the objective of the study was to estimate carbon losses by water erosion in a watershed with a wide land-use diversity. The modelling was performed based on the soil organic matter content (SOM) of the area, and the estimated soil losses, according EPM. To the SOM determination, soil samples were collected 50 points (0-0.2 m) distributed in the watershed. The data analysis was performed using remote sensing techniques and a Geographic Information System, which was also used to interpolate the SOM content, through the use of the ordinary kriging. The results showed that from 126.53 Mg year^{-1} of the total eroded organic carbon estimated, 111.60 Mg year^{-1} were deposited in relief depressions, while 14.93 Mg year^{-1} reached the water body system. The applied methodology represents a cost-effective and relatively fast method to estimate the soil organic carbon loss by water erosion and allows the determination of the areas that most need intervention, aiming to decrease the impact of agriculture on greenhouse gas emissions. The main advantage of this method is the little input data requirement, which increases the possibility of application in poorly studied regions.

Key words: Soil conservation. Carbon cycle. Erosion Potential Method.

RESUMO - A erosão hídrica nas condições climáticas tropicais é um dos principais processos que alteram o equilíbrio entre as entradas e saídas de carbono orgânico do solo (SOC). A modelagem da erosão hídrica usando o Método do Potencial de Erosão (EPM) pode ser usada como uma alternativa para auxiliar no entendimento da dinâmica do carbono do solo e na sua interação com o processo erosivo. Nesse contexto, o objetivo do trabalho foi estimar as perdas de carbono por erosão hídrica em uma bacia hidrográfica com alta diversidade de uso da terra. A modelagem foi realizada com base no teor de matéria orgânica do solo (SOM) na área e nas perdas de solo estimadas, de acordo com o EPM. Para a determinação do SOM, foram coletadas amostras de solo em 50 pontos (0-0.2 m) distribuídos na bacia. A análise dos dados foi realizada por meio de técnicas de sensoriamento remoto e Sistema de Informações Geográficas, que também foi utilizado para interpolar o conteúdo do SOM, por meio da técnica de krigagem ordinária. Os resultados demostraram que do total de carbono perdido (126,53 Mg ano^{-1}), 111,60 Mg ano^{-1} foram depositados em depressões do relevo, enquanto 14,93 Mg ano^{-1} atingiram os cursos hídricos. A metodologia aplicada representa um método econômico e relativamente rápido para estimar a perda de carbono orgânico do solo por erosão hídrica e permite a determinação das áreas que mais necessitam de intervenção, com o objetivo de diminuir o impacto da agricultura nas emissões de gases de efeito estufa. A principal vantagem desse método é o pequeno requisito de dados de entrada, o que aumenta a possibilidade de aplicação em regiões pouco estudadas.

Palavras-chave: Conservação do solo. Ciclo do Carbono. Método de Erosão Potencial.

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INTRODUCTION

The increased concentration of greenhouse gases in the atmosphere has drawn attention to soil organic carbon (SOC), as soils are the highest carbon reservoir of all terrestrial ecosystems (LAL, 2003). Thus, small variations in SOC stocks are very likely to have significant effects on the terrestrial carbon cycle, changing the CO_2 concentrations in the atmosphere, and influencing the greenhouse effect and global climate (ZHOU *et al*., 2019).

Water erosion under tropical climate conditions is one of the main processes that change the balance between the inputs and outputs of soil organic carbon (SOC) (LAL, 2019). This process causes soil loss, exposing the stabilized organic carbon inside the aggregates to the climatic elements and the microbial enzymes (DECHEN *et al.*, 2015). Therefore, water erosion reduces the carbon stored in the soil, which can damage food production and promote environmental degradation.

Although several studies evaluate SOC losses in agricultural systems due to the soil organic matter (SOM) mineralization (PAUSTIAN *et al*., 2016; POKHAREL; CHANG, 2019; THANGARAJAN *et al*., 2013), data about the contribution of water erosion to carbon losses are scarce, especially in tropical soils (HANCOCK *et al*., 2019; NACHIMUTHU; HULUGALLE, 2016). The few studies found in the literature may be explicated to the fact of field assessments of soil organic carbon (SOC) loss by water erosion can be costly and consume much time. Moreover, data obtained from experimental plots are unable to represent an entire watershed due to the broad topographic and edaphic variations of the area (STARR *et al*., 2000). In this context, monitoring soil carbon removed by water erosion in the hydrographic basin scale can be realized using modeling techniques (HANCOCK *et al*., 2019; PARSONS, 2019; PRASANNAKUMAR *et al*., 2012).

Starr *et al*. (2000) and Yan *et al*. (2005) obtained satisfactory results by combining the Revised Universal Soil Loss Equation (RUSLE) (RENARD *et al*., 1997) with the SOC content in the topsoil to estimate the SOC loss by water erosion and wind erosion, respectively. In addition to RUSLE, there are several models, which can be used to predict erosion and combined with information on the SOC content in the study area, could be used to estimate carbon losses. However, models application is limited to areas with little available information, which is common in many tropical regions. In these cases, an alternative approach is the use of models that require little input data, such as the Erosion Potential Method (EPM) (GAVRILOVIC, 1962).

In addition to low data requirements, EPM parameters are obtained from tabulated values, which make it inexpensive and easy to apply (EFTHIMIOU *et al*., 2016; GAVRILOVIC, 1962). Another advantage of EPM over other models is the retention coefficient (R_u), which provides an estimate of the eroded sediment fraction that reaches the water body system and the fraction deposited along the watershed area.

Modeling the SOC loss is essential to understand the dynamics of soil carbon and its interaction with water erosion process, as well as support the planning of conservation measures to avoid environmental impacts. This study aimed to estimate the SOC loss in a watershed with a wide land-use diversity. We tested the hypothesis that the EPM combined with the spatial distribution of SOC content can be used to estimate the carbon loss by water erosion with satisfactory efficiency in a tropical region of Brazil.

MATERIAL AND METHODS

Study area

The research was carried out at the Coroado Stream watershed, located at Capoerinha farm, owned by Ipanema Agrícola SA, in the Alfenas municipality, state of Minas Gerais, southeastern Brazil, at coordinates 45º55’55’’ to 45º54’14’’ W and 21º31’32’’ to 21º33’5’’ S, Datum SIRGAS 2000 (Figure 1). The delineation of the watershed was carried out with the aid of ArcGIS 10.3 software (ENVIRONMENTAL SYSTEMS RESEARCH INSTITUTE, 2015) from the level curves of the Alfenas municipality (SISTEMA ESTADUAL DE MEIO AMBIENTE E RECURSOS HÍDRICOS, 2020). The watershed belongs to the Rio Grande Basin and the climate is classified as Humid subtropical according to Köppen climate classification (Cwb) (ALVARES *et al*., 2013).

The land use and occupation map (Figure 1) was generated based on images from the Landsat-8 Operational Land Imager (OLI) satellite, bands 2, 3, and 4, at orbit 219 and point 75, obtained from the Image Generation Division (INSTITUTO NACIONAL DE PESQUISAS ESPACIAIS, 2019) using ArcGIS 10.3 software (ENVIRONMENTAL SYSTEMS RESEARCH INSTITUTE, 2015). The accuracy of the map was confirmed from field surveys.

The area is occupied by the following land use classes: coffee (36.45%), native and regenerating forests (34.85%), corn (11.71%), sugarcane (6.12%), eucalyptus (2.70%), access roads (3.27%) facilities (1.77%) and drainage (3.13%).

Erosion Potential Method (EPM)

The Erosion Potential Method (EPM) was used to estimate the annual soil loss and the rate of sediment delivered to the water bodies. The EPM takes into account factors related to climate, geology, surface, soil properties, topographic characteristics, geometric features, type and distribution of land use and the watershed erosion degree (EFTHIMIOU; LYKOUDI; KARAVITIS, 2017; GAVRILOVIC, 1962). The model was calculated by the equations described in Table 1.

Soil resistance to erosion (Y) values range from 0.20 (soils with high resistance to erosion) to 2.0 (soils with low resistance to erosion), differing according soil type (GAVRILOVIC, 1962). The soil was classified as a dystrophic Red Latosol.

Figure 1 - Map of the location and land use of the Coroado Stream Watershed, Alfenas, south of Minas Gerais, Brazil. Notes: In the sampled points were determine soil organic matter (SOM) and Bulk density (Bd)

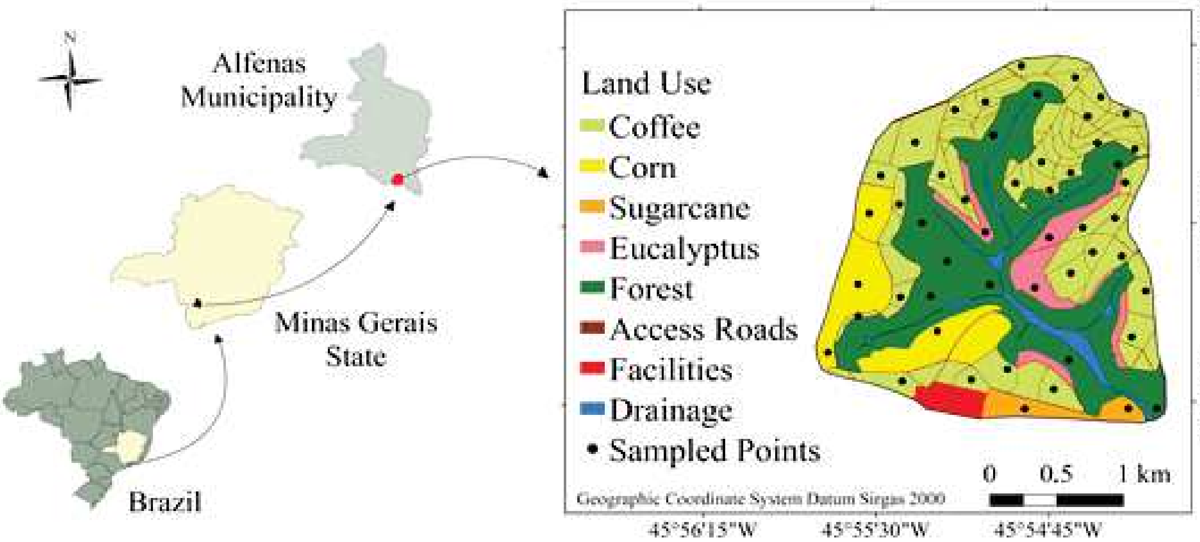


Table 1 - Equations and descriptions of the parameters used to estimate soil losses in the Erosion Potential Method

Equation	Equation
(1) $W_{yr} = T . H_{yr} . \pi .^2\sqrt{Z^3} . F . Bd$	W_{yr} = Annual erosion (Mg year^{-1}) T = Coefficient of temperature (dimen.) H_{yr} = Mean annual rainfall (mm year^{-1}) Z = Coefficient of erosion (dimen.) F = Watershed area (km^2) Bd* = Bulk density (kg dm^{-3})
(2) $G_{yr} = W_{yr} . R_u$	G_{yr} = Soil loss (Mg year^{-1}) R_u = Coefficient of retention (dimen.)
(3) $T = {}^2\sqrt{t_0/10 + 0.1}$	t_0 = Mean air temperature (°C year^{-1})
(4) $Z = y . x_a . (\varphi + {}^2\sqrt{I_{sr}})$	Y = Soil resistance to erosion (dimen.) X_a = Coefficient of soil use and management (dimen.) φ = Coefficient of visible erosion features (dimen.) I_{sr} = Mean slope (%)
(5)$R_u = (O.D)^{0.5}/0.25.(L+10)$	O = Watershed perimeter (km) D = Difference in basin elevation (m) L = Length of watershed (km)

Notes: dimen. = dimensionless. * Parameter incorporated into the original formula for conversion of m^3 year^{-1} to Mg year^{-1}. Source: Gavrilovic (1962)

The soil use and management coefficient (X_a) expresses the protection of an area against soil aggregates breakdown. Its values range from 0.05 (areas with dense vegetation) to 1.0 (areas without vegetation cover). The erosion degree is characterized by the coefficient of visible erosion features (φ), which is obtained from visual characterization. The values range from 0.1 (areas with no evident erosive processes) to 1 (areas with severe erosion processes) (GAVRILOVIC, 1962).

The parameters Y, X_a, and φ were calculated based on tabulated values adapted to Brazilian edaphoclimatic conditions by Sakuno *et al*. (2020).

The mean slope of the area (I_{sr}) was obtained based on the watershed declivity Map (Figure 2B). In order of that, a Digital Elevation Model (DEM) (Figure 2A) was elaborated using the contour lines of the Alfenas municipality (SISTEMA ESTADUAL DE MEIO AMBIENTE E RECURSOS HÍDRICOS, 2020). The altitudes range from 795 to 922 m, with an average of 861 m. Using the DEM it was possible to obtain the Declivity Map through the Slope tool from ArcGIS 10.3 (Figure 2B).

The mean annual precipitation (H_{yr}) and temperature (t_0) were extracted from a pluviometric station, operated by the National Institute of Meteorology, near the area (INSTITUTO NACIONAL DE METEOROLOGIA, 2019). Based on the t_0 values, it was calculated the temperature coefficient (T). The bulk density (Bd) was determined according to Empresa Brasileira de Pesquisa Agropecuária (Embrapa) (2017), using sampled from the soil surface layer (0-0.2 m), in 50 points into the watershed (Figure 1).

The coefficient of retention (R_u) was quantified based on physical parameters of the area previously described (O, D, L). The R_u value represents the fraction of the eroded soil that was lost from the watershed area (G_{yr}) (GAVRILOVIC, 1962).

The coefficient of erosion (Z) expresses the watershed susceptibility to erosion: values close to 0 indicate lower tendency. The input parameters of the model are expressed in Table 2.

Using the Raster Calculator tool from ArcGIS 10.3 (ENVIRONMENTAL SYSTEMS RESEARCH INSTITUTE, 2015), all the parameters were combined in the EPM equation, mapping the estimated erosion, that present the spatial distribution of the soil losses.

Validation

The soil losses estimated by the EPM were validated using data of the total solids that achieve the water bodies - daily flow -, according to Batista *et al*. (2017).

Initially, we build a water discharge curve relating to total sediments transported with water discharge (Figure 3). To construct this, we used data of total solids in the water and respective discharge from 2008 to 2018, which are monitored by a weather station operated by "Instituto Mineiro de Gestão das Águas" (IGAM) and located near the Coroado Stream exutory at coordinates 45°53'35" W and 21°39'55" S.

Moreover, the actual soil loss, given by the sediment that leaves the watershed per year, was calculated based on the water discharge curve and the dataset of the daily flow rate in 2019, obtained from the "Agência Nacional de Águas". The results were then compared to the estimates of generated sediment acquire from EPM.

Figure 2 - Digital Elevation Model (A) and declivity Map (B) of the Coroado Stream Watershed, Alfenas, south of Minas Gerais, Brazil

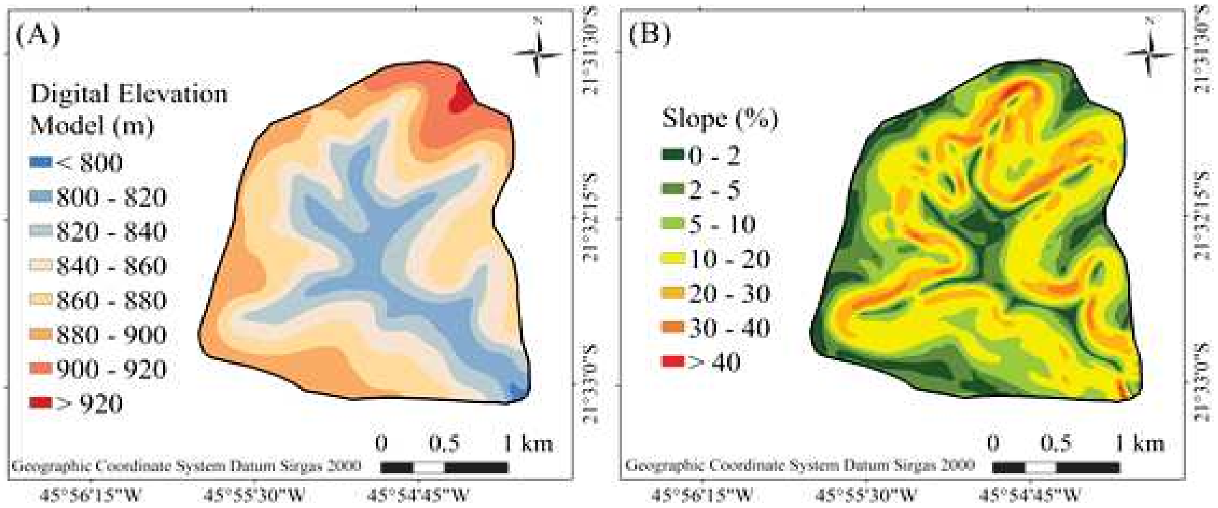
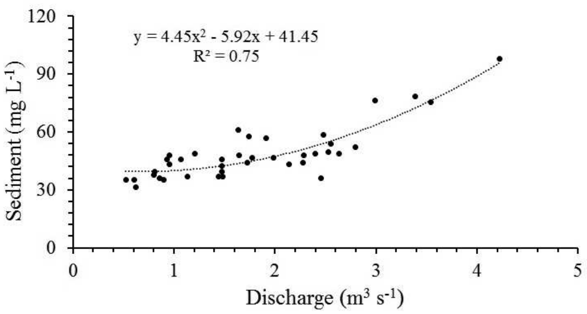


Table 2 - Values of the input parameters to the soil loss estimate performed by Erosion Potential Method in the Coroado Stream Watershed, Alfenas Municipality, south of Minas Gerais State, Brazil

Parameter	Value	Parameter	Value
Y (dimen.)	0.80	T (dimen.)	1.52
X_a (dimen.)	0.43	Ds (kg dm^{-3})	1.22
φ (dimen.)	0.40	F (km^2)	5.59
I_{sr} (%)	13.54	O (km)	9.28
Z (dimen.)	0.29	D (km)	0.06
t_0 (°C)	22.00	L (km)	3.32
H_{yr} (mm)	1500.00	R_u (%)	11.80

Notes: Y = Average of soil resistance to erosion; X_a = Average coefficient of soil use and management; φ = Average coefficient of visible erosion features; I_{sr} = mean slope; Z = Average coefficient of erosion; t_0 = Mean air temperature; F = watershed area; O = perimeter; D = average elevation difference; L = length of the area, which was measured from the main watercourse; R_u = retention coefficient and; dim. = dimensionless

Figure 3 - Water discharge curve (sediment transported × water discharge), of the Coroado Stream Watershed, Alfenas, south of Minas Gerais, Brazil



Soil organic carbon loss estimation

The carbon soil loss by water erosion was estimated using Equation 6, based on methodologies proposed by Starr *et al*. (2000) and Yan *et al*. (2005), combined with the parameters of the EPM.

$C_{erosion} = W_{yr} \,.\, SOM \,.\, 0{,}58$ Equation 6

Where $C_{erosion}$ = eroded SOC (Mg $year^{-1}$); W_{yr} = annual erosion (Mg $year^{-1}$); SOM = soil organic matter content (%) and 0.58 = van Bemmelen constant, used for the conversion of SOM to SOC (0.58 kg C kg SOM^{-1}).

The retention coefficient (R_u) estimate the rate of eroded carbon that was deposited at lower relief positions and the fraction lost by the subbasin area.

$C_{loss} = C_{erosion} \,.\, R_u$ Equation 7

Where C_{loss} = SOC loss (Mg $year^{-1}$); $C_{erosion}$ = eroded SOC (Mg ano^{-1}) and R_u = retention coefficient.

To determine soil organic matter (SOM) content, soil from the surface layer (0-0.2 m) was sampled, in 50 points distributed in the watershed according to the land use (Figure 1), and then the SOM was determined according to Embrapa (2017). We choose to carry out to estimate only at the 0-0.20 m soil depth, once water erosion is a surface phenomenon, and the superficial layer concentrates the highest carbon content. The spatial distribution of SOM was interpolated by the ordinary kriging method, using the Geostatistical Wizard tool from ArcGIS 10.3 (ENVIRONMENTAL SYSTEMS RESEARCH INSTITUTE, 2015), according to Chen *et al*. (2019). The exponential model was fitted with a coefficient of determination (R^2) of 0.97 and a residue sum of squares (SQR) of 0.000023.

The maps of estimated erosion and SOM contents were crossed in the raster calculator tool of ArcGIS 10.3 (ENVIRONMENTAL SYSTEMS RESEARCH INSTITUTE, 2015) to generate the SOC loss map.

RESULT AND DISCUSSION

Soil Loss

The calculated coefficient of the intensity of erosion (Z = 0.29) indicates that the watershed mainly presents lower erosion susceptibility areas. The good vegetation cover (X_a = 0.43) provided by conservationist practices adopted in the coffee cultivation zones and the presence of native and reforested forests contributed to this result. Besides that, the local Latossolos are resistant to erosion (Y = 0.08), contributing to the overall low susceptibility of the watershed, once X_a and Y are the most sensitive parameters to the variations of Z (DRAGIČEVIĆ; KARLEUŠA; OŽANIĆ, 2017).

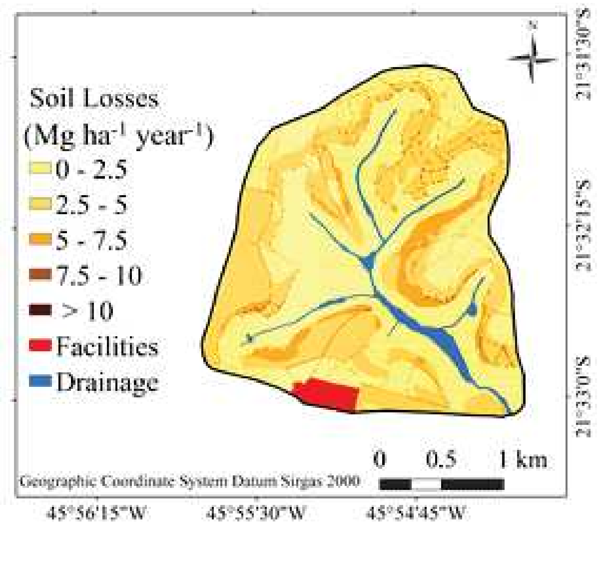
The total soil loss (W_{yr}) estimated was 11,132.63 Mg $year^{-1}$. Considering the retention coefficient (R_u = 11.80%), it was estimated the total sediment delivery rate, that is, the amount of soil that actually reaches the water bodies, which corresponds to the area actual soil loss (G_{yr}), was estimated in 1,175.00 Mg year^{-1}.

The average G_{yr} estimated by EPM was 2.10 Mg ha^{-1} year^{-1}, with a maximum value of 12.72 Mg ha^{-1} year^{-1}. The soil loss calculated using the flow versus sediment ratio and the daily runoff dataset was 2.52 Mg ha^{-1} year^{-1}. Thus, the EPM showed an error of 16.67%, underestimating the soil losses at 0.42 Mg ha^{-1} year^{-1}. According to Pandey, Chowdary and Mal (2007), errors of less than 20% is acceptable. Thus, the EPM model presented acceptable efficiency and reliability it is possible to validate the erosion simulation, process based on the application of EPM for the Coroado Stream Watershed conditions. Efthimiou *et al*. (2016), applied EPM in a watershed in Greece and reported underestimation of results regarding field-observed sediment generation, with an error of 38%.

Around 90% of the watershed presented soil loss under 5 Mg ha^{-1} year^{-1}, which is considered low (PANDEY; CHOWDARY; MAL, 2007; PRASANNAKUMAR *et al*., 2012), and only 1.60% of the area present losses higher than 7.5 Mg ha^{-1} year^{-1}. Areas with steeper slope and bare soil had the highest soil erosion rates (Figure 4).

The areas with bare soil (access roads) exhibited the highest soil losses (average of 8.91 Mg ha^{-1} year^{-1}), while the forest displayed the lowest rates (average 0.07 Mg ha^{-1} year^{-1}), which highlight the role of vegetal density to provide soil protection against the raindrop impact and runoff detachment. Coffee crop was the agricultural-crop with the lowest soil loss rate (average of 2.47 Mg ha^{-1} year^{-1}), likely due to the adoption of conservation practices such as vegetation management between rows, containment basins in the steeper slope and catchment areas. However, the soil loss rate for eucalyptus (5.03 Mg ha^{-1} year^{-1}), also a permanent crop, was higher than the temporary crops, due to the absence of conservationist management practices, such as planting following the contour lines, and also the temporary crops being mainly located in the steepest sites. The sugarcane and corn areas presented soil loss of 3.35 Mg ha^{-1} year^{-1} and 4.15 Mg ha^{-1} year^{-1}, respectively. Facilities and drainage were not considered in the calculation, once they do not participate in sediment generation.

Figure 4 - Spatial distribution of soil losses in the Coroado Stream Watershed, Alfenas, south of Minas Gerais, Brazil



Carbon Loss

The SOM contents ranged from 2.10 to 3.00% with the highest values observed in the areas with lower altitudes and the northeast portion of the watershed. The spatial distribution is represented in Figure 5A.

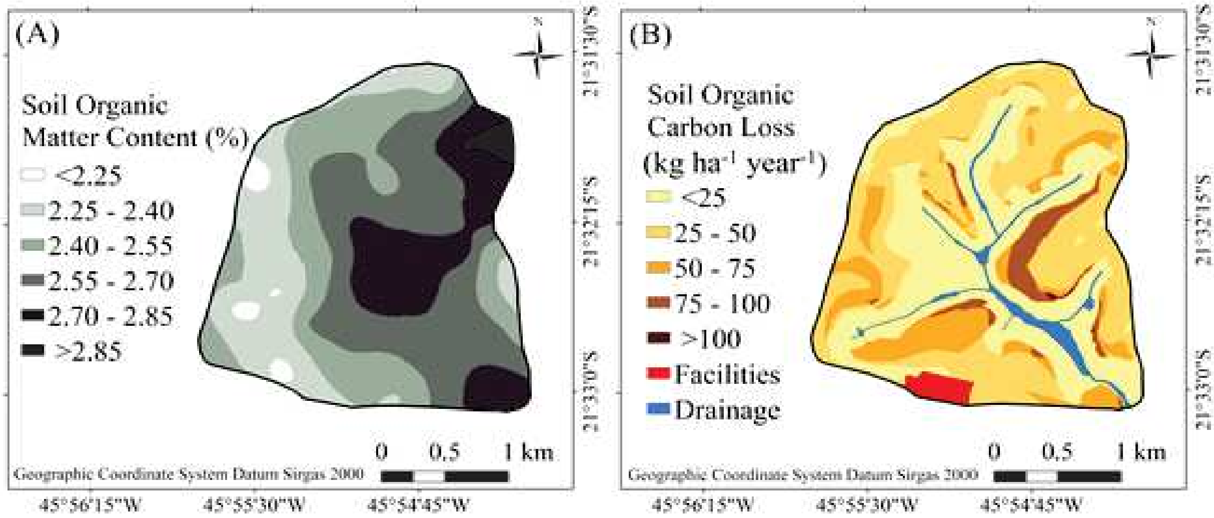
The spatial distribution of SOM showed higher carbon contents in the low relief areas, which may be related to the SOC deposition. However, it is complex to determine the final destination of the eroded carbon since it depends on several factors, including the type and stage of erosion and the fractions removed (LAL, 2019).

The total eroded carbon ($C_{erosion}$) estimated was 126.53 Mg year^{-1}. According to the retention coefficient (R_u), 88.20% of the $C_{erosion}$ was deposited and redistributed on the area relief (111.60 Mg year^{-1}). Thus, the estimated carbon content that reaches the water bodies (C_{loss}) was 14.93 Mg year^{-1} (11.80%), with rates ranging from 0.16 kg ha^{-1} year^{-1} to 109.50 kg ha^{-1} year^{-1}, with an average of 26.67 kg ha^{-1} year^{-1} (Figure 5B). The lower rates were found in forest areas (1.73 kg ha^{-1} year^{-1}), followed by coffee (36.29 kg ha^{-1} year^{-1}), sugarcane (50.41 kg ha^{-1} year^{-1}), corn (57.96 kg ha^{-1} year^{-1}), and eucalyptus (76.75 kg ha^{-1} year^{-1}). The access roads was not considered in carbon losses calculation due to imprecision in determining soil organic matter content in such location.

The values estimated are close to those found by Roose and Bartches (2006), which compared data from numerous experiments concerning the contribution of water erosion to carbon losses in different climatic, relief, soil type, and management conditions. These authors found values from 1 to 50 kg C ha^{-1} year^{-1} in soils protected by plant remains and 50-500 kg C ha^{-1} year^{-1} in harvested fields.

In the entire watershed, the controlling of the water erosion is essential to keep or even increase soil carbon sequestration. Even low rates of carbon loss by water erosion, in the long term, restrict carbon sequestration and damage the soil quality as a whole (HUA *et al*., 2016). The carbon loss by water erosion could be mitigated by the adoption of better management practices, such the maintenance of crop residues on the soil surface, cultivation of eucalyptus along the contour lines and vegetation management between rows. No-tillage should be introduced in temporary crops,

Figure 5 - Spatial distribution of the Soil Organic Matter Content (A) and Soil Organic Carbon Loss (B) in the Coroado Stream Watershed, Alfenas, southern Minas Gerais, Brazil



as this practice provides greater accumulation of SOC and improves the physical indicators of the soil, such as water infiltration (SALES *et al.*, 2016).

The estimation of the carbon losses caused by water erosion in large areas using EPM and geostatistical techniques allows us to evaluate the sustainability of a productive system and to determine the areas that most need intervention, concerning to decrease the impact of agriculture on greenhouse gas emissions.

CONCLUSION

1. The results support the hypothesis that the applied methodology represents a cost-effective and relatively fast method to estimate the soil organic carbon loss by water erosion and to identify priority areas that need intervention. The main advantage is the little input data requirement, which increases the possibility of application in poorly studied regions;
2. Soil loss estimates could provide valuable information for the creation of strategies to cope with the effects of water erosion on soil carbon loss and the construction of measures to mitigate the agricultural contribution to the greenhouse gases emissions.

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