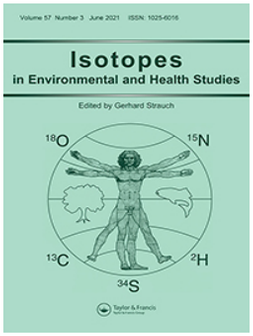

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REVIEW ARTICLE

Quantification of soil erosion using ^{7}Be in a steep watershed used for natural grazing in Brazil

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ABSTRACT

Cosmogenic ^{7}Be was used to evaluate soil loss in a mountainous micro-watershed near Belo Horizonte, Southwest Brazil. Two nearby sites were selected, a reference site in a flat area and an eroded site in a hill slope. At the reference site, soil samples were collected monthly throughout the year in order to evaluate seasonal variations of ^{7}Be inventory in soil and its relation with the precipitation regime. Additionally, rainwater was collected and the expected ^{7}Be soil content was predicted. At the reference site, the ^{7}Be inventory shows seasonal variations, in accordance with the rainy season, and its distribution in the soil profile shows an exponential decrease in depth ($h_0 = 6.9 \pm 0.6$ kg m^{-2}; $r^2 = 0.97$). At the eroded site, two soil sampling campaigns were performed in order to measure soil erosion in the watershed. The estimated net erosion was 42.2 ± 3.7 t ha^{-1}, indicating the loss of upper 5mm of soil per year. This corresponds to soil losses in the area in the range from moderate to severe erosion.

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1. Introduction

Currently, soil degradation affects about 1.9 billion hectares of agricultural lands, and increases rapidly at a rate of 5–7 million hectares per year. This degradation is due to soil erosion and riverine sedimentation processes which result in severe fertile soil losses, deterioration of navigable watercourses, and declining potential for hydropower generation. The main causes for this degradation are inadequate land management practices in agriculture and livestock farming. Among all soil degradation processes, erosion is the most common type, accounting for 84 % of the damaged areas. About three-quarters of such degraded areas are located in developing countries. This problem is of more

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concern in rugged landscapes scolded by sequencies of fully dry and intensive rain periods.

Fallout radionuclides (FRNs) are deposited from the atmosphere into the soil and provide an opportunity to gauge erosion processes using accessible and relatively simple measurement techniques. The FRNs ^{137}Cs, ^{210}Pb, and ^{7}Be are increasingly being used as tracers in soil erosion and sedimentation assessment. ^{7}Be ($t_{½}$ = 53.1 d) is a cosmogenic radionuclide formed in the stratosphere and upper troposphere by the interaction of highly energetic neutrons and other secondary cosmic radiation impinge on nitrogen, carbon and oxygen nuclei causing their fragmentation into lighter nuclei, a process named spallation. Upon formation ^{7}Be adheres to aerosols present in the atmosphere and is transported to the soil mostly by rainout. Once it reaches the soil, ^{7}Be is firmly adsorbed in high-specific surface particles, such as silicate minerals, aluminum or iron oxy-hydroxides [1,2], the complex formed thus becoming a reliable tracer of these particles. A lesser amount of ^{7}Be may be formed at soil level or even beneath by spallation in rocks. The fact that there is no other origin of ^{7}Be but the cosmogenic one is of significance for its applications in environmental process studies. ^{7}Be decays to ^{7}Li via electron capture, and a fraction of 10.4 % decays to an excited state of ^{7}Li, followed by deexcitation via emission of a 477.6 keV gamma radiation. This radiation is used to determine the ^{7}Be content of a sample by gamma spectrometry in different types of samples [1,2].

As a FRN ^{7}Be has been used to estimate soil redistribution comparing the ^{7}Be inventories (total ^{7}Be content in soil) at a site that undergoes soil redistribution to the ^{7}Be inventory at a location (designated as a reference site) where there is little or no variance in inventory due to soil redistribution [3–7]. Although the technique is easy to apply, the erosion values obtained are strongly dependent of the selected reference site. In case the ^{7}Be soil inventory measured at this site is defective, it might infer the existence of either erosion or sedimentation where neither occur. Kaste et al. [8] and Walling et al. [9] pointed out that, in order to use ^{7}Be as a tracer to evaluate soil degradation, it is necessary to know the seasonal and spatial depositional variability and quantify the relationship between precipitation and surface inventories.

Hence the objective of this work is to (a) evaluate the applicability of a simple depositional model to predict the ^{7}Be soil content and thus properly define the reference inventory for erosion quantification and (b) implement the soil transport model in the Mato Frio creek micro-watershed using this FRN for assessing the amount of soil eroded following short-term rainfall events.

2. Materials and methods

2.1. Study area

The study area (20.098935 ° S; 44.492977 ° W) is located 50 km southwest of Belo Horizonte, which is the fourth largest urban complex in Brazil (ca. 4 million inhabitants), in the central region of Minas Gerais State. The area is inside one of the headwaters of the Serra Verde river watershed which is the third main water supply system to the Belo Horizonte metropolitan region, delivering an average flow rate of 2.7 m^3 s^{-1} of treated water. Besides the strategic importance of this fluvial basin, it was chosen due

to the existence of a network of meteorological stations within the basin which produced long records of available data.

According to the Köppen–Geiger classification (Cwa), the local climate has humid subtropical characteristics: a hot mild summer, dry winters and moderate seasonality. It is warm from November to March (26 °C average temperature) and cool from April to October (16 °C average temperature). The rainy season coincides with the warm period, whereas during the cool months rain episodes are uncommon. The mean altitude at the study area is 908 m a.s.l. Most of the soil is used as pasture and is characterized by quite steep slopes of about 20 % to over 40 %. The soil is of acrisol type, with clay accumulation in the Bt horizon, leading to sand enrichment in the topsoil layer. Additionally, it exhibits an acidic character and low fertility. Such a clayey type of soil is prone to erosion and requires conservative soil management practices [10]. A much larger soil surface over and around the entire ^{7}Be study area is exclusively covered by gramineous pasture used for cattle feeding.

Two nearby sections inside the study area were selected for setting the sampling sites: Site 1 (reference site) is situated in a flat area with no evidence of soil redistribution (erosion and/or sedimentation). This site had not been previously plowed, and livestock grazing has been excluded during the sampling period. At this site soil samples were collected monthly along a whole year period (October 2015 to October 2016), with the aim of evaluating the ^{7}Be inventory, seasonal variations, as well as certifying that this site could be used as a reference site for erosion studies. Soil sampling at Site 2 (eroded site) was performed in June and October 2016, with the objective of evaluating the soil erosion process.

2.2. Rainfall

Monthly rainfall samples were collected following the standard methodology [11]. A standard rain gauge has been installed in the study area and operated from October 2015 to February 2017, collecting the accumulated rainwater at a monthly rate. Only during nine months the rainwater volume collected was sufficient to measure the ^{7}Be activity concentration by gamma spectrometry (Supplementary material). Also, a daily rainfall record was obtained from a rain gauge station located 1 km away from the study area spanning a period of 40 years, from 1977 to 2016. The recorded mean annual precipitation is 1480 mm, and the precipitation regime complies with the regional pattern, i.e. a dry season from April to October and a wet season from November to March. Figure 1 shows the monthly precipitation profile as regards the last 40 years.

2.3. Soil

The soil profile of ^{7}Be was collected monthly, slicing samples only in two vertical layers, from 0 to 2.5 cm and from 2.5 to 5 cm [12], from October 2015 to September 2016 at Site 1. This is the only site whose ^{7}Be inventory is needed to confront with the atmospheric ^{7}Be deposition by rainout. In October 2016, the vertical soil slicing sampling procedure was very cautiously performed having in mind the definition of a ^{7}Be depth profile at the site. In this last sampling campaign, the soil profile was sampled down to 5 cm deep by slicing in 1 cm thick layers. At Site 2, where soil erosion will be evaluated,

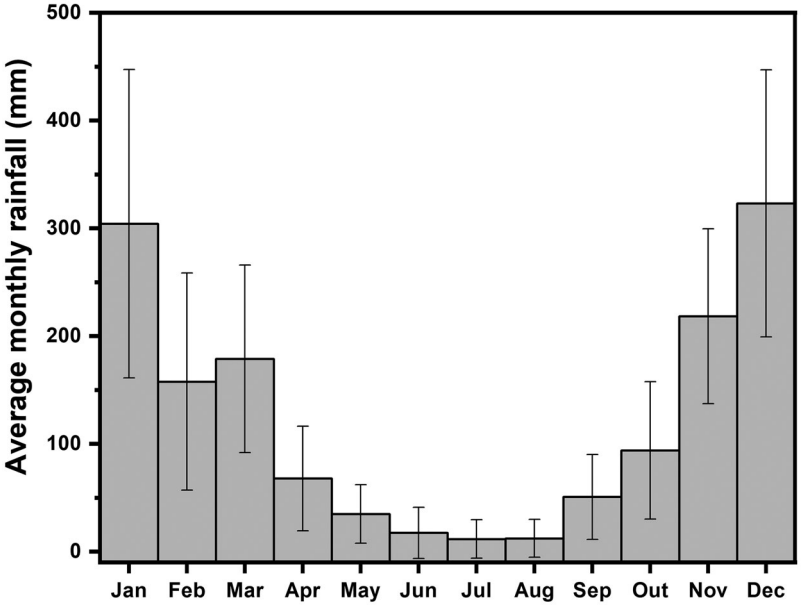

Figure 1. Mean monthly precipitation during a forty year period (1977–2016), from www.snirh.gov.br/hidroweb/FAZENDALARANJEIRASJUSANTE, Rainfall Code Station: 2044041. Error bars are the standard deviation.

a simple experimental sampling design was performed: Soil profiles were sampled over a transect along the inclined tract of land. Two sampling campaigns were performed, in June and October 2016. In June 2016 samples were collected along a 120 m long transect, summing 9 sampling points (A1 to A9) spaced 15 m between each other. In October 2016 a 165 m long transect, with 12 sampling points 15 m apart (B1 to B12) was sampled. At each sampling point, the soil samples were collected using a stainless-steel scraper plate with a 50 × 20 cm collection surface. The soil samples were dried at room temperature during 48 h, sieved through a 2 mm mesh and placed in a Marinelli beaker for gamma spectroscopy analysis.

2.4. Gamma spectrometry analysis

Soil and rainwater samples were submitted to gamma spectrometry analysis; the ^{7}Be gamma photopeak was measured at the 477.6 keV using a HPGe detector from CANBERRA, with a 1.9 keV resolution and a 50 % relative efficiency at the 1.33 MeV gamma peak of ^{60}Co. The samples, weighing around 600 g, were placed in 700 mL Marinelli beakers, and the total counting time varied between 86,000 and 180,000 s. The same procedure has been followed in other studies involving gamma spectrometry analysis in the literature [13–16]. Equation (1) has been used to calculate the ^{7}Be activity in the soil and rainwater samples (A):

$$A = \frac{N}{\varepsilon m_a t I_\gamma}, \tag{1}$$

where N is the net number of gamma (γ) radiation counts detected in a given time interval t (s), m_a is the sample mass (kg), I_γ is the absolute transition probability of the measured gamma ray, and ε is the counting efficiency. The efficiency curve has been obtained using the Genie 2000 CANBERRA Monte Carlo mathematical model software. Compounding it with the detector efficiency curve, the counting efficiency (ε) of the ^{7}Be gamma ray energy in the soil samples has been obtained; it amounts to $\varepsilon = 3.3$ %. For rainwater samples the counting efficiency was 3.4 %. All the activity measurements have been corrected for the ^{7}Be radioactive decay. The final results were expressed in terms of activity per unit mass of soil (Bq kg^{-1}) and activity per unit volume of rain (Bq L^{-1}).

The analytical protocol for the ^{7}Be determination established that the interference of the ^{228}Ac peak in ^{7}Be activity measurements by gamma spectrometry has to be evaluated [12]. The methodology used for checking the interference of ^{228}Ac ($t_{1/2} = 6.15$ h) on the ^{7}Be peak consisted in counting the same soil sample after different time periods of time at the 477.59 keV peak in order to check whether (a) the activity decay was consistent with the ^{7}Be half-life, or (b) any interference due to the ^{228}Ac photopeak (478.40 keV, 0.21 relative intensity) could be noticed. Part a was verified by checking how much the measured decay rate was close to the ^{7}Be half-life. The soil sample spectra within the 477.0–479.0 keV range were scanned to detect any anomalies at the 477.59 keV photopeak. As has been shown by Esquivel et al. [12], the spectra of the collected samples obtained after a time interval equivalent to the half-life of ^{7}Be did not show any trace of ^{228}Ac interference. Using this methodology, a half-life value of 51.3 d has been calculated, which is consistent with the value of 53.3 d of ^{7}Be half-life.

The lower limit of detection (LLD) in a given sample was determined using Equation (2), modified from Currie [17], at the 95 % confidence level:

$$LLD\left(\frac{Bq}{kg}\right) = \frac{2.71 + 4.66(\sigma)}{I_\gamma t(s)\varepsilon m_a(kg)}, \tag{2}$$

where σ is the standard deviation of the total background counts with no sample in the chamber; I_γ is the absolute transition probability for the gamma ray energy; t (s) is the background counting time; ε the counting efficiency and m_a (kg) is the sample weight. The counting time was 180,000 s and the calculated limit of detection was 0.12 Bq kg^{-1} for soil and rainwater samples.

3. Results and discussion

At Site 1 the ^{7}Be inventory reached the minimum value (52.3 ± 15.1 Bq m^{-2}) in August 2016, at the end of the dry season, and the maximum value (719.6 ± 42.7 Bq m^{-2}) was registered at the end of the rainy season, in March 2016 (Table 1). Marked oscillations in the ^{7}Be inventories have been observed at several regions in the world and were related with seasonal changes in the precipitation volumes [17], inasmuch as rain is the main mechanism conveying ^{7}Be to the soil [18–21].

The relationship between ^{7}Be wet deposition and ^{7}Be inventory in the soil along a year period was analysed in order to validate the adequacy of Site 1 as the reference site for the erosion study. Accumulated monthly rainwater samples were collected during a nine month period; their ^{7}Be activity concentrations were measured, and based on this measurement ^{7}Be from wet deposition on the soil could be estimated [22]. A conspicuous

Table 1. Monthly ^{7}Be inventories at Site 1.

Year	Months	^{7}Be inventory (Bq/m^2)
2015	October	248.0 ± 91.8
	November	310.9 ± 29.3
	December	422.6 ± 38.3
2016	February	690.0 ± 40.6
	March	719.6 ± 42.7
	April	299.3 ± 27.3
	May	111.9 ± 18.1
	June	93.9 ± 9.3
	July	71 ± 9.9
	August	52.3 ± 15.1
	September	191.0 ± 16.4
	October	78.0 ± 17.2

linear relationship between ^{7}Be from wet deposition and the amount of rainfall has been detected, with a slope 1.34 ± 0.07 Bq L^{-1} ($r^2 = 0.97$; $p < 0.0001$). Figure 2 shows the fitted parameters and the 95 % and 99 % prediction intervals [23]. Similar relationships have been reported by other authors for several regions around the word, and a major discussion can be found in Juri Ayub et al. [11]. According to Esquivel et al. [12], if it is assumed that the only ^{7}Be input to the soil are the rain episodes (dry input is negligible) with constant ^{7}Be activity concentration in rainwater and that the only ^{7}Be output is radioactive decay [11,19,21,24], then the expected value of ^{7}Be content in the soil could be estimated using the daily precipitation. The daily wet deposition of ^{7}Be (Bq m^{-2}) is shown in

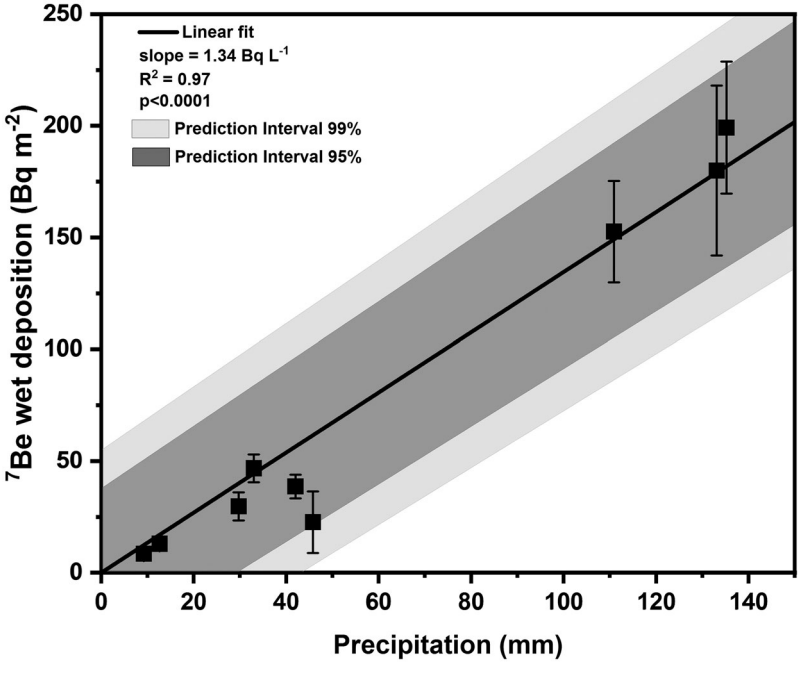

Figure 2. ^{7}Be wet deposition versus rainfall amount. Linear fit parameters and 95 % and 99 % prediction intervals are shown. Error bars allowing for both statistics of counting and amount of precipitation measurement errors.

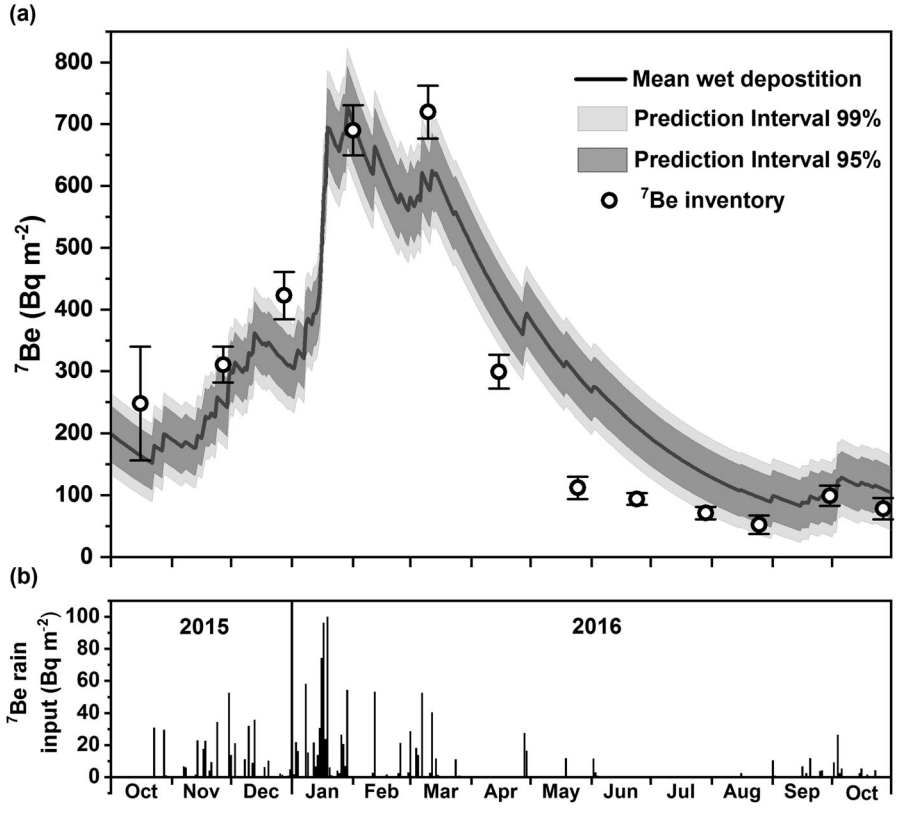

Figure 3. ^{7}Be soil content by wet deposition and ^{7}Be inventory at Site 1 (a), ^{7}Be input by rainout (b). Errors taking into account both statistics of counting and soil sampling errors.

Figure 3(b) as input pulses occurring at precipitation events. The ^{7}Be input was estimated from the amount of daily precipitation in the period from October 2015 to October 2016 and the mean ^{7}Be concentration in rain has been reported by Esquivel et al. [12]. The ^{7}Be soil content due to wet deposition was estimated from the ^{7}Be input by rain and its removal by radioactive decay. Figure 3(a) shows both the mean expected value (line) and the predicted intervals (grey zones) of ^{7}Be soil content (Bq m^{-2}). The figure reflects the expected oscillation of ^{7}Be soil content due to seasonal variations in rain events (inputs) and its loss by radioactive decay (outputs). A good match between measured ^{7}Be inventory (Table 1) and predicted ^{7}Be soil content is observed mainly in the rainy season. The figure also shows the monthly measurements of ^{7}Be inventory in soil as circles. In the second half of the dry season the ^{7}Be inventory is smaller than that predicted by the model. This could be an indication that other factors besides radioactive decay may affect the total ^{7}Be inventory. Nevertheless, this behaviour does not seem to be related with erosion, insofar as the expected ^{7}Be soil contents are rather close to the ^{7}Be inventories measured during the months in which the eroding processes are assuredly more active (rainy season). Hence, this result confirms the hypothesis that the only mechanism of ^{7}Be loss in the soil at Site 1 is radioactive decay for the main part of the year. It is then possible to state that there is no appreciable soil redistribution at Site 1 and that

this site can be used as a reference site for erosion studies applying the ^{7}Be technique. An additional evidence is provided by the vertical ^{7}Be soil profile (discussed below). Based on these results, Site 1 will be hereafter referred to as the reference site.

Using a simple model that takes into account the accumulated monthly rainfall from a six month period and the rainfall regime, Esquivel et al. [12] have shown a good correspondence between the measured ^{7}Be inventory and the predicted ^{7}Be soil content due to deposition by rain. Lohaiza et al. [25] used a relationship based upon a much longer series of rain events (68 events over 30 months. Juri Ayub et al. [11]) also obtained a good correspondence between the measured ^{7}Be inventory and the one calculated using wet deposition data. Esquivel et al. [12] and the present study once again found a good agreement between the measured ^{7}Be inventory at the reference site and expected ^{7}Be soil content given that rain is the only input source. These evidences suggest that it is not necessary to sample a large series of rain events for estimation purposes.

As mentioned above, the soil was sampled at Site 2 in June 2016, at 9 sampling points (A1 to A9) along a 120 m long transect to assess whether soil removal had occurred. In Figure 4(a) the ^{7}Be inventories at each sampling point are exhibited in absolute values and expressed as a percentage of the ^{7}Be inventory at the reference site in the same date (Table 1). Figure 4(b) shows the relative elevations of sampled points along the transect; in this figure, the basal 0 m correspond to an altitude of 910 m a.s.l. (reference site altitude). It can be seen that all points sampled at this site exhibited lesser ^{7}Be inventories

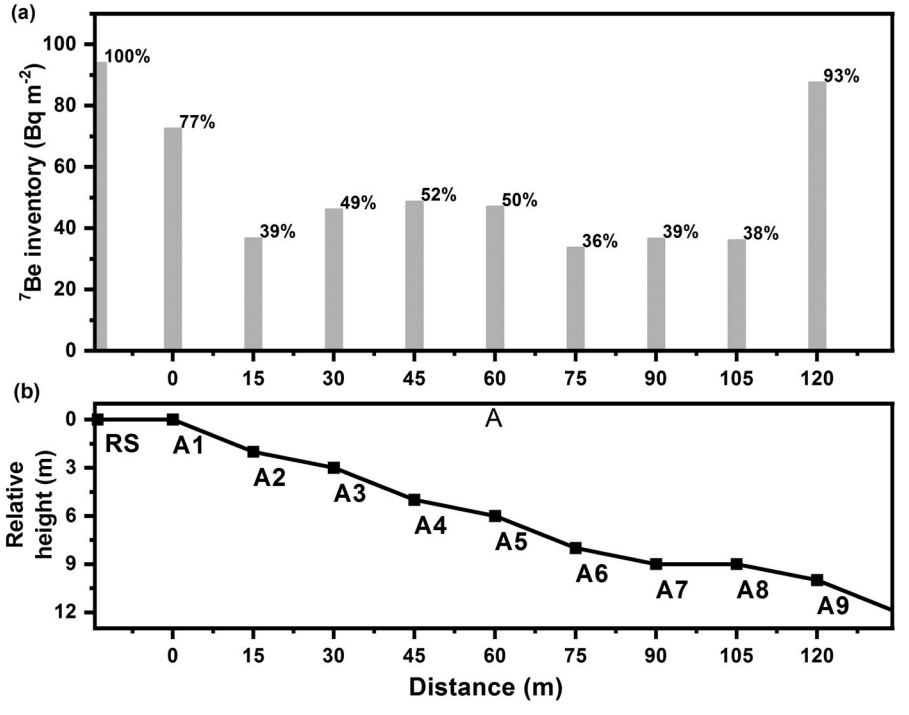

Figure 4. ^{7}Be inventories (a) along the transect (b) at Site 2, on June 2016. The position of RS point is plotted for descriptive purposes.

as compared to 93.9 ± 9.3 Bq m^{-2} recorded at the reference site. However, the lowest point in the transect (A9) has a ^{7}Be inventory value closer to the reference site inventory (93 %). This can be explained by the relative location of point P9 on the incline; at this position the slope is milder and therefore there is lesser soil loss at this place. These results indicate that soil erosion occurs in all the points along the transect. Nevertheless, since the ^{7}Be inventory at the reference site somewhat differs from the expected ^{7}Be soil content (Figure 3(a)) the June data would not be useful for evaluating soil erosion.

On that account, a new soil sampling campaign was performed in October 2016 in order to quantify the erosion at Site 2, jointly with an incremental soil sampling at the reference site (Site 1). The soil profile on the reference site was sampled at incremental depth layers 1 cm thick in order to obtain the vertical distribution of ^{7}Be in soil, and to gauge the parameters needed by the ^{7}Be technique for erosion assessment. The ^{7}Be inventory at the reference site was 78.0 ± 17.2 Bq m^{-2} in October 2016, which is lower than the value observed in October 2015 (248.0 ± 91.8 Bq m^{-2}, Table 1), but is much closer to the expected ^{7}Be soil content at this time (Figure 3(a)), taking into account the rainfall magnitude recorded in both June and October. Figure 5 shows the vertical profile of ^{7}Be in soil at the reference site in October 2016. ^{7}Be is present only in the upper soil layers (0–3 cm depth). The concentration profile of ^{7}Be in the soil shows an exponential decreasing behaviour, which is the typical distribution of ^{7}Be at sites with no soil redistribution [26]. This figure also shows the curve obtained by fitting to the measured data the model of Equation (3), in which the relaxation mass depth h_0 is the sole fitting parameter,

$$A_{ref} = A(0)e^{(-x/h_0)}, \tag{3}$$

where A_{ref} is the ^{7}Be inventory (Bq m^{-2}) at the reference site, x [kg m^{-2}] is the soil mass depth (positive downward). Soil mass depth is used to measure depth in soil and is defined as the product of the soil bulk density and the depth of soil layer. The h_0

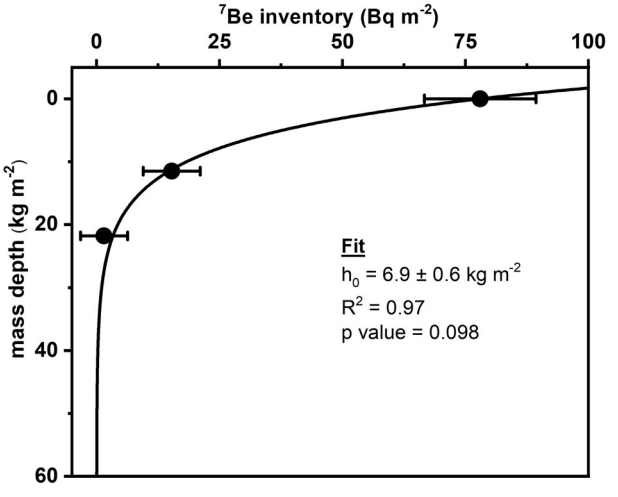

Figure 5. ^{7}Be vertical distribution at the reference site (Table 1) in October 2016. The continuous line has been fitted to Equation (3).

parameter is the massic soil depth above which 63.2 % of the local ^{7}Be inventory (Bq m^{-2}) is contained; it defines the steepness of the exponential ^{7}Be profile [5,27]. Some ranges of h_0 values obtained by other authors are reported in Table 2. The value measured in the present work at the reference site is $h_0 = 6.9 \pm 0.6$ kg m^{-2} ($r^2 = 0.97$). Similar distributions of ^{7}Be in Brazilian soils (2 cm deep) have been reported by Andrello et al. [27], and Marestoni et al. [28] have reported an h_0 value of 4.71 ± 0.22 kg m^{-2}. Esquivel et al. [12] have reported $h_0 = 43.4$ kg m^{-2} in a previous measurement at the site of the present work. These high values can be attributed to both the large ^{7}Be inventory observed at the site (248.0 ± 91.8 Bq m^{-2}) and to a deeper penetration of ^{7}Be in the soil profile. The authors describe a penetration of ^{7}Be that reaches 5 cm of soil depth and suggest that drainage structure characteristics and higher sand content in the soil might account for the deeper penetration of ^{7}Be in the studied region.

In October 2016 a somewhat longer transect than the previous one was performed at Site 2, encompassing 12 sampling points (B1 to B12), in order to investigate whether sedimentation processes also occur within the study site. This transect was located next to the June 2016 transect, thus exhibiting the same slope of 20 %. Figure 6(a) shows the ^{7}Be inventory at each sampling point, expressed both in terms of absolute values and as percentages of the ^{7}Be inventory at the reference site (78.0 ± 17.2 Bq m^{-2}). Figure 6(b) shows the relative altitude of the points sampled along the transect. The percentage value next to the bars is related to the ^{7}Be inventory at the reference site (Table 1) at the same sampling time. It can be seen that the ^{7}Be loss to the soil increased as compared with June; the ^{7}Be inventories at all sampled points are lower than the inventory at the reference site, the values at the transect are 33 % to 64 % of inventory at the reference site (Figure 6(a)). Also, at one point (B10) no measurable activity of ^{7}Be was found, indicating that severe erosion had occurred at this point. Just as in June 2016, the variations in the ^{7}Be inventory at Site 2 in October 2016 were more pronounced wherever the hill slope tends to be steeper. The higher value of ^{7}Be inventory in point A9 in June and October can be attributed to the gentler gradient at this position. These differences in ^{7}Be inventory between the reference and study site can be used to estimate the eroded/sedimented soil mass per unit area in the study sites.

According to Sepulveda et al. [5], assuming that erosion has removed a thin layer of mass depth R (kg m^{-2}) at a point, then the ^{7}Be areal activity A (Bq m^{-2}) that is left behind at the eroded point is lower than A_{ref} (inventory). Given that the soil mass eroded per unit area, R, is equal to the mass depth removed (i.e. $x = R$ in Equation (3)),

Table 2. Values of h_0 reported in the bibliography.

References	Region/Country	h_0 (kg/m^2)	
		Value	Error
[3]	Europe/England	5.4	Not reported
[6]	South America/Chile	2.14	Not reported
[28]	South America/Brazil	4.71	0.22
[5]	South America/Chile	3.4	0.1
[31]	South America/Chile	3.3 to 8.4	Not reported
[25]	South America/Argentina	1.2 to 2.9	Not reported
[4]	South America/Argentina	5.8	2.6
[29]	Asia/Iran	3.57	Not reported
[29]	Europe/Italy	2.45	Not reported
This work	South America/Brazil	6.9	0.6

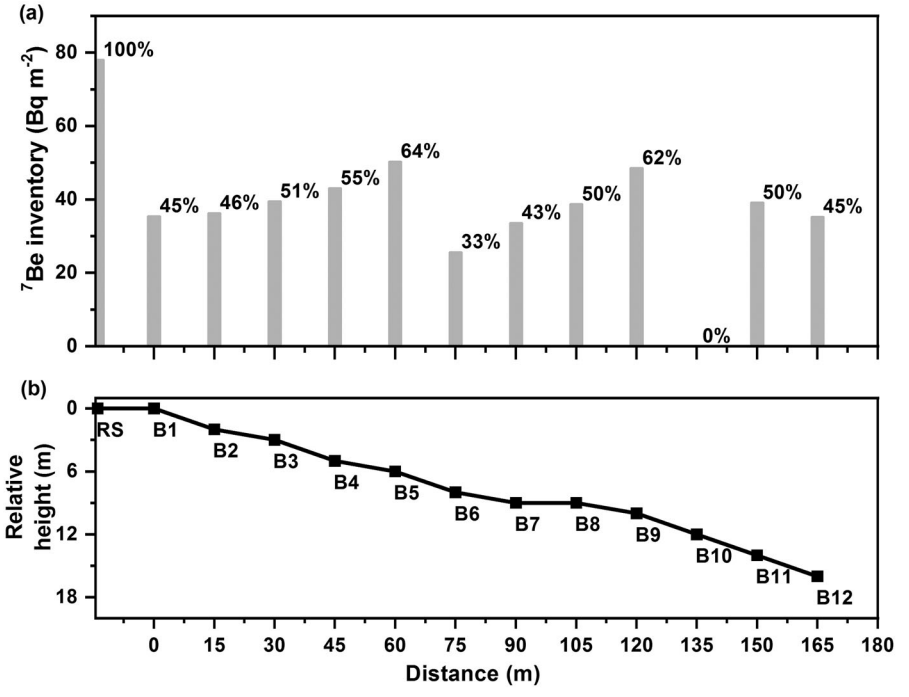

Figure 6. ^{7}Be inventories (a) along the transect (b), at Site 2, in October 2016. The position of RS point is plotted for descriptive purposes.

then the remaining ^{7}Be activity in the sampling point can be calculated as

$$A = A_{ref} \exp(-R/h_0) \tag{4}$$

Therefore, mass of soil per unit area eroded from the sampling point, R, can be calculated as

$$R = h_0 Ln \frac{A_{ref}}{A} \tag{5}$$

Applying this model, a net erosion of 42.2 ± 3.7 t ha^{-1} (4.22 ± 0.37 kg m^{-2}) was calculated for Site 2 in October 2016. Error value was calculated based on the error of the h_0 parameter, which contributes at 70 % to the total error of net erosion. This erosion value indicates that an upper soil layer 5 ± 1 mm thick was lost due to erosion. Erosion magnitude is commonly ranked into several categories, according to the value in units of t ha^{-1} of soil loss per year, as light erosion (<20 t ha^{-1}), moderate erosion (20–100 t ha^{-1}), heavy erosion (100–300 t ha^{-1}), and severe erosion (>300 t ha^{-1}). The ^{7}Be technique does not estimate the annual mean erosion; the mass of soil lost or gained which is estimated by this technique should be attributed to rainfall events that have taken place previously to the measurements [29]. Figure 7 shows the rain events that had taken place in the 100 days preceding the October 2016 soil sampling campaign. Using this record, it can be seen that 16 rainfall episodes has occurred in the period of 100 days preceding the sampling campaign. Only four of these precipitations had magnitudes above 5 mm,

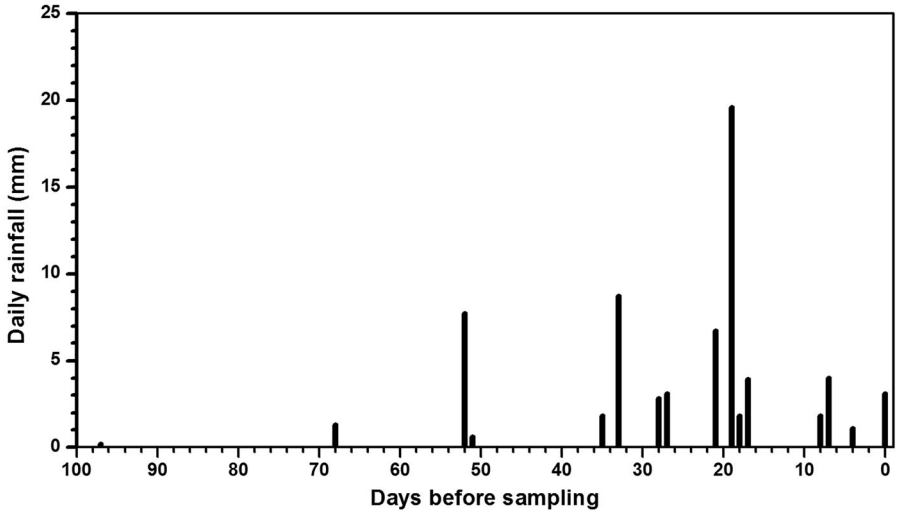

Figure 7. Daily rainfall in the 100 days preceding the October 2016 sampling time (0 time). Rainfall data obtained from www.snirh.gov.br/hidroweb/FAZENDALARANJEIRASJUSANTE, Rainfall Code Station: 2044041.

and a single one reached about 20 mm. This last precipitation, just three weeks before the sampling date, can be regarded as the main rainfall event causing the erosion at Site 2.

Several erosion rate measurements have been performed in the Minas Gerais Region of Brazil and nearby regions, using different methodologies. Unfortunately, this information generated by national organizations is available only in Portuguese. Table 3 shows erosion values reported in a selection of these measurements. The reported annual erosion rate values show that most soils in the studied regions have experienced losses within the range of light to moderate erosion. Only one record of sedimentation is reported [32].

Jardim et al. [38] using a runoff plot with no vegetal cover reported a soil mass loss of 20.76 t ha^{-1} associated to 20.9 mm rainfall (Table 3). The erosion value permits to infer erosion rates in the range of light to moderate in similar soils. The magnitude of the erosion observed in the present study using the ^{7}Be technique and a similar amount of rainfall is twice the value reported by Jardim et al. [38]. This may be explained by the higher erodibility value of Acrisol compared to Ferralsol soils [39]. The erosion value reported in the present study indicates that the area could be suffering moderate to severe erosion.

4. Conclusions

The magnitude of soil erosion was quantified using the ^{7}Be technique in a quite hilly and infertile area used for pasture. The area is characterized by steep slopes (20 % to 40 %) and as such quite susceptible to erosive processes. Erosion assessment at this place was opportune inasmuch as the area is in a watershed with relevance as a main water reservoir of Belo Horizonte city (Minas Gerais State). The correct selection of the reference site is a very important prerequisite for obtaining reliable soil erosion estimates, and considerable

Table 3. Erosion rates reported from Brazilian regions.

Region	Soil type	Mean annual rainfall (mm)	Slope (%)	Methodology	Erosion rate (t ha^{-1})	Erosion category	Reference
São Paulo	N	1381.2	N	USLE model	20.02–92.70	moderate	[30]
São Paulo	Acrisol/Arenosol/ Nitisol/Ferrasol	n	N	^{137}Cs technique	–3.14*–28.84	no erosion to moderate	[31]
Paraná	Ferralsol	a	0–15	^{137}Cs technique	13.90–15.80	light	[32]
Minas Gerais	N	523.9	4	Runoff plot	0.224–23.87	light to moderate	[33]
Minas Gerais	Ferrasol	1427–1814	0.5–5	USLE model	23.5	moderate	[34]
Minas Gerais	Ferralsol /Leptsol	n	N	Runoff plot	13.53–17.52	light	[35]
Minas Gerais	Ferralsol/Cambisol/ Fluvisol/Acrisol	n	3–15	USLE model	<10–50	light to moderate	[36]
Minas Gerais	Ferralsol/Cambisol/ Fluvisol/Acrisol	n	N	USLE model	10–22.59	light to moderate	[37]
Rio de Janeiro	Ferralsol	1159.2	30	Runoff plot	0.006–20.76**	n	[38]
Minas Gerais	Ferralsol	n	0–45	USLE model	0.05–18.64	ligth	[39]

n: not reported.
*: sedimentation.
**: values are erosion due to single rain events.

attention must be invested in its selection. At the reference site the ^{7}Be inventory was evaluated monthly during a whole year period and compared with the ^{7}Be soil content expected by wet deposition. The ^{7}Be content was calculated using a simple model whose predictions were confirmed by their similarity with *ad hoc* measured values. The results have substantiated two points concerning the ^{7}Be inventory: (1) it can be predicted from the precipitation regime provided the mean concentration of ^{7}Be in rain is known; (2) the evaluation of the ^{7}Be mean rainfall concentration does not require a large number of measurements. The use of this additional information for the confirmation of the ^{7}Be inventory at the reference site can be of relevant assistance whenever the ^{7}Be technique is applied. The ^{7}Be inventory has an exponentially decreasing concentration with the incremental soil depth and relaxation mass depth value $h_0 = 6.9 \pm 0.6$ kg m^{-2} at the reference site.

The ^{7}Be technique informed a loss of soil mass of 42.2 ± 3.7 t ha^{-1} (4.22 ± 0.37 kg m^{-2}) in the study area, indicating that a superficial soil layer of 5 ± 1 mm was lost. This erosion could be mainly attributed to the rain episode (20 mm) that took place 20 days ahead of the sampling date. Extrapolating this value to the whole year, the loss of soil mass in the region could be assumed in the range of moderate (20–100 t ha^{-1}) to severe (>300 t ha^{-1}) erosion. More extensive studies in the area are needed, because these erosion categories require prevention and restoration actions.

The application of the ^{7}Be method for soil erosion assessment has demanded two key requirements; (1) setting up a dependable reference site, and (2) measurements of ^{7}Be radioactivity in several soil samples. The first requirement is not an easy task in the majority of morphologies one meets at real application sites. The second one requires sample preparation (drying, sieving) and lengthy measurements of low ^{7}Be activity in the samples by means of sophisticated gamma spectroscopy equipment, frequently requiring *ex post* interpretations, that are not available to a large part of the research community. In the present work an endeavour is attempted to deal with such restrictions.

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Data availability

The data supporting the conclusions of this article are included within the article. Any queries regarding these data may be directed to the corresponding author.

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