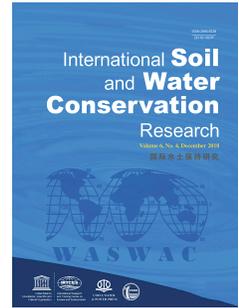# Journal Pre-proof

Spatial variations in runoff, sediment, and nutrient losses induced by toposequence and biochar application in upland maize farming

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Spatial variations in runoff, sediment, and nutrient losses induced by toposequence and biochar application in upland maize farming

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1   **Spatial variations in runoff, sediment, and nutrient losses induced by toposequence and biochar**

2   **application in upland maize farming**

3

4   **Abstract**

5   Soil erosion is a natural process that can be intensified by inappropriate land use and agricultural

6   practices. Therefore, it is essential to gain a deeper understanding of the effects of agro-ecological practices,

7   such as biochar application, on soil erosion processes in upland areas, particularly in Southeast Asia.

8   Moreover, understanding the variations in erosion characteristics across a toposequence is vital for

9   sustaining upland agriculture. The objective of this study was to investigate the effects of toposequence

10   position and biochar application on sediment loss, runoff, and nutrient losses under natural rainfall

11   conditions in Nan Province, Thailand. We installed 24 plots of 1 m² each, located at four positions within

12   the toposequence. The biochar was incorporated into the soil at 5 cm depth. Over two rainy seasons, we

13   regularly measured sediment loss, runoff, and nutrient losses on plots with and without biochar along the

14   four positions of the toposequence. Our findings indicated that the addition of biochar amendments to the

15   topsoil effectively reduced nutrient loss through runoff, particularly nitrogen. This practice also improved

16   vegetation cover, increased soil moisture, and decreased the presence of free elements such as micro-

17   aggregates, gravels, and carbon nodules (biochar) on the soil surface. During the study, we observed the re-

18   emergence of previously integrated biochar on the soil surface after eight months under natural conditions,

19   which manifested as a crust on the soil surface. Positions within the toposequence had a significant impact

20   on various soil properties, including the amount of sediment loss, runoff, and nutrient losses. Therefore,

21   considering the influence of toposequence position is essential for enhancing soil management and

22   implementing suitable agroecological practices.

23

24   **Keywords:** Agroecological practices, Soil degradation processes, Soil physicochemical characteristics,

25   Thailand, Upland areas

26

1. Introduction

Soils play a crucial role in terrestrial ecosystems by providing essential components for the achievement of major ecosystem services that support agricultural productivity and ensure food security for all (Haygarth & Ritz, 2009; De Deyn & Kooistra, 2021). However, in upland areas, the challenges posed by soil erosion and nutrient losses significantly impact ecosystem health (Pansak et al., 2008; Begum Nasir Ahmad et al., 2020; Zhidkin et al., 2023), which requires sustainable agricultural practices. Soil erosion is a natural process that can be exacerbated by steep slopes, high rain intensity, and improper land use management, resulting in the loss of fertile topsoil, decreased water quality, and reduced agricultural productivity (Lal, 2001; Valentin et al., 2005; McCool & Williams, 2008; Wang et al., 2022). Consequently, the spatial variability of soil erosion, soil nutrients, and crop yield in upland areas can be influenced by a range of factors, including soil properties, landscape position, local climate, land cover, soil type, and agricultural practices (Tesfahunegn et al., 2011; Zhang et al., 2011; Desta et al., 2021; Polykretis et al., 2023; Zhou et al., 2024). Assessing soil variation across upland agricultural fields is therefore essential for effective soil conservation, nutrient management, and precision farming (Mzuku et al., 2005). Soil properties vary along a toposequence due to processes such as detachment, transportation, water flows, and deposition of soil materials (Oo et al., 2013; Muhaimeed & Saleh, 2013; Maniyunda & Gwari, 2014; Bufebo et al., 2021). The topographic variability associated with crop production reflects the combined influence of soil properties and factors such as water balance affecting agricultural productivity (Dinaburga et al., 2010). Tsubo et al. (2006) showed different effects on water balance and productivity along the toposequence in a rainfed lowland rice ecosystem in southern Laos. Indeed, water flows played a significant role in the spatial variability of chemical properties and soil texture parameters. Consequently, exchangeable potassium (K), organic carbon (C), clay content, and yield exhibited an increasing trend from top to bottom, influenced by using intensive weed control and applying recommended fertilizer doses based on the specific toposequence position (Boling et al., 2004). These previous studies also highlighted that the degree of soil property variability depends on the spatial scale, for example, from a field to a larger regional scale.

53   For centuries, upland regions in Southeast Asia were primarily used for slash-and-burn agriculture

54   (Bruun et al., 2017; Belton & Fang, 2022). More recently, this practice has shifted toward intensive mono-

55   crop maize cultivation, driven by the transition from subsistence to commercial agriculture. The large-scale

56   conversion of forests into monoculture plantations has led to reduced biodiversity and increased soil

57   erosion, resulting in significant soil loss, runoff, and nutrient depletion. These changes raise the risk of

58   irreversible soil degradation, as well as heightened threats of flooding, lake siltation, and water

59   contamination (Tsubo et al., 2006; Turkelboom et al., 2008; Grellier et al. 2013; Lal, 2018; Fujisao et al.,

60   2020; Janeau et al., 2022). Thailand is particularly affected as predominantly devoted to maize cultivation

61   in upland areas with 720,000 hectares (64%) of plantation located in the North (Office of Agricultural

62   Economics, 2020). Pansak et al. (2024) reported that areas experiencing soil erosion over 13 t ha^{-1} yr^{-1} cover

63   125,079 km² or 24.38% of Thailand's land. Despite high erosion rates, these areas remain in use for

64   subsistence farming, while surrounding lands are intensively farmed for cash crop production.

65   Biochar is a carbon-rich material derived from biomass pyrolysis (Amalina et al., 2022). Its use as

66   a soil amendment has gained considerable attention for its potential to enhance soil fertility, boost water

67   retention, reduce bulk density and nutrient leaching, and further improve soil health (Basso et al., 2013;

68   Toková et al., 2020; Karhu et al., 2021; Yadav et al., 2023). Furthermore, biochar has been proven to

69   increase soil cation exchange capacity, neutralize acidity, and expand the surface area available in soils

70   (Hossain et al., 2020; Shetty & Prakash, 2020). As a result, biochar is regarded as a valuable tool for

71   preventing soil loss and runoff in sloping agricultural landscapes (Yu et al., 2021). Research by Li et al.

72   (2019) observed a 12.2% reduction in total runoff volume following biochar application. Lower biochar

73   concentrations (1% and 3%) were found to suppress soil loss, while higher concentrations (5% and 7%)

74   appeared to accelerate it. Similarly, Lee et al. (2018) found that combining biochar with compost was the

75   most effective method for reducing runoff, resulting in a notable decrease of approximately 17%. While

76   many studies on toposequences have examined the spatial distribution of soil properties and crop yields,

77   little research has explored how soil and water distribution interact with slope position and biochar use in

78   upland cultivation, particularly in tropical regions (Janeau et al. 2022). Moreover, the recent study by Janeau

79   et al. (2022) gave results under rainfall simulation, which does not include processes taking place under

80   natural rainfall. Understanding how biochar and topography together influence soil erosion and nutrient

81   losses under natural rainfall could offer important insights for farmers, land managers, and policymakers

82   for better soil conservation and sustainable land management practices in these areas. This knowledge

83   would help design targeted strategies to curb erosion, enhance soil fertility, and promote sustainable

84   agricultural systems.

85   This study aimed to bridge this knowledge gap by investigating the combined influences of

86   toposequence and biochar application on sediment loss, runoff, and nutrient losses under natural rainfall in

87   upland maize areas in Northern Thailand. By examining different slope positions and implementing biochar

88   application, the study seeks to elucidate the interactive effects of topography and biochar on erosion and

89   nutrient dynamics.

90

91   **2. Materials and methods**

92   **2.1 Site description**

93   A field experiment was conducted at Ban Tub Man (18°19'30.0"N 100°34'17.3"E), Na Noi District,

94   Nan Province, which is one of the 17 provinces in the Northern region of Thailand. The study area is

95   characterized by hilly topography, with elevations ranging from 444 to 525 meters above sea level. The

96   slope is characterized as moderately to steeply sloping, with gradients ranging from 10% to 44%. The study

97   area was divided into four positions (top, upper, middle, and down) with elevations of 512, 490, 480, and

98   460 meters above sea level, respectively (Figure 1). Maize fields are the major crop in this area. Farmers

99   typically cultivate maize on sloped areas, tilling the land annually before planting.

100   The climate of the study area is a tropical savannah, based on Koppen's classification, consisting

101   of three seasons: (I) rainy (July to November), (II) dry and cool (November to February), and (III) dry and

102   hot (March to June). The average annual rainfall was 1,266 mm over the last 30 years. Annual temperatures

103   ranged from a high of 32°C to a low of 15°C, with the average temperature throughout the year being 26°C

104   (Hydro-Informatics Institute, 2020).
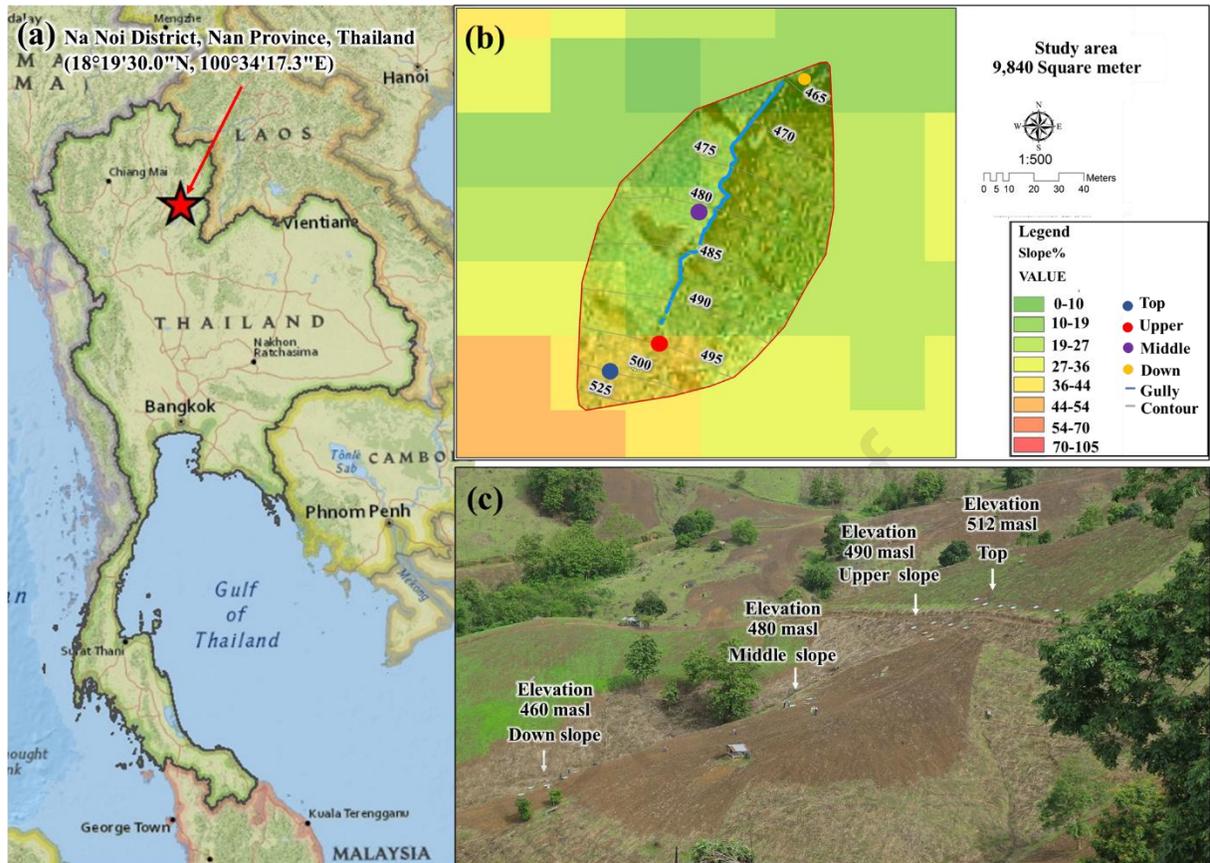
Figure 1. Location of the study site at Ban Tub Man, Na Noi District, Nan Province, Thailand (a), percentage of slope along the toposequence (b), and the distribution of the plots along the toposequence (c)

2.2 Soil properties along the toposequence

The study area is situated between 1,000 and 1,728 meters above mean sea level. The landscape can be classified as a hillslope sequence. The morphology indicates a moderately steep to steep slope gradient, which supports a runoff-dominated hydrological system and reflects a distinct toposequential pattern. The average slope gradients at the sampling positions were 49% at the top, 40% at the upper slope, 23% at the middle slope, and 14.5% at the downslope position. The curvature of the top and upper slopes appears slightly convex, suggesting areas with higher runoff potential and increased susceptibility to soil erosion. The middle slope exhibits a slightly concave profile, while the downslope position displays a nearly straight curvature. Composite soil samples from the topsoil (0-10 cm) were collected from the top, upper,

118 middle, and downslope positions before the commencement of the experiment in February 2018 (Figure 1).

119 The soil at the experimental site was classified as Alfisol (FAO, 2006) or typic Haplustalfs based on the

120 Soil Survey Staff (2022). The particle size distribution (percentages of clay, sand, and silt) for the soils at

121 different slope positions is presented in Table 1. In the topsoil (0-10 cm), the soil texture was predominantly

122 classified as clay loam at the top and downslope positions, while a silty clay loam texture was observed at

123 the upper and middle slope positions. The downslope position exhibited the highest sand content compared

124 to the top, upper, and middle slope positions, whereas the upper and middle slope positions had higher clay

125 content than both the top and downslope positions. The silt content across the top, upper, middle, and

126 downslope positions ranged from 43.01% to 48.62% (Table 1). The soil bulk density across the top, upper,

127 middle, and downslope positions was recorded at 1.10, 1.13, 1.13, and 1.22 g cm^{-3}. Additionally, the mean

128 weight diameter (MWD) of soil aggregates varied across the slope positions, ranging from 0.15 to 0.35

129 mm. The MWD was notably higher at the top position compared to the downslope position, indicating

130 greater aggregate stability in the upper part of the slope.

131 **Table 1** Soil physical properties along the toposequence at surface soil (0-10 cm)

Slope positions	Bulk density (g cm^{-3})[1/]	% Clay	%Sand	%Silt	Texture[2/]	MWD[3/] (mm)
Topsoil (0-10 cm)						
Down	1.22	28.26	28.72	43.01	Clay loam	0.15
Middle	1.13	34.69	16.70	48.62	Silty clay loam	0.24
Upper	1.13	33.72	19.84	46.44	Silty clay loam	0.23
Top	1.10	29.77	22.94	46.29	Clay loam	0.35

132

133 Note: Bulk density, clay percentage, sand percentage, silt percentage, and soil texture data are presented in

134 Janeau et al. (2022). Mean-weight diameter (MWD) was measured using the wet sieving method (Jerzy &

135 Barbara, 2003). Soil texture, using the hydrometer method (Gee & Or, 2002). Soil bulk density was

136 analyzed by the soil core method by the dry weight of soil per unit volume (g cm^{-3}) (Blake, 1965).

137   Organic carbon (%OC), total nitrogen (total N), and exchangeable potassium (Exch.K) had the

138 highest values at the top slope position (cf. Table 2). The results indicated that soil pH in the surface

139 horizons ranged from strongly acidic to moderately acidic, with values ranging from 5.75 to 6.01. Across

140 all four positions, electrical conductivity (EC) values were classified as non-saline, with mean EC values

141 ranging from 0.12 dS m^{-1} to 0.17 dS m^{-1} (Table 2).

142 **Table 2** Chemical properties of soil along the toposequence at topsoil (0-10 cm)

Slope positions	OM (%)	OC (%)	pH	EC (ds m^{-1})	Total N (%)	Avai.P (mg kg^{-1})	Exch.K (mg kg^{-1})
Topsoil (0-20 cm)							
Down	2.47	1.43	5.94	0.13	0.12	18.76	136.68
Middle	3.95	2.34	6.01	0.17	0.19	23.39	188.26
Upper	3.86	2.29	5.91	0.12	0.19	21.53	194.66
Top	4.02	2.45	5.75	0.16	0.20	21.25	205.57

143
144 Note: Soil organic carbon (OC) was analyzed using the Walkley and Black method (Walkley & Black,

145 1934). %OM (organic matter) = %OC x 1.724. Available phosphorus (Avai.P) was measured using the

146 Bray-II method (Bray & Kurtz, 1945). Exchangeable potassium (Exch.K) was extracted with ammonium

147 acetate and analyzed via atomic absorption spectrophotometry (Chapman, 1965). Electrical conductivity

148 (EC) was determined using an EC meter, with a soil-to-water ratio of 1:5 (Rhoades, 1996). Soil pH was

149 measured electrometrically in a 1:1 soil-to-water suspension using a pH meter (Peech, 1965). Total nitrogen

150 was analyzed by the Kjeldahl method (Bremner, 1996).

151 **2.3 Rainfall, soil moisture, and saturated hydraulic conductivity (Ks) measurements**

152   The intensity and quantity of rain events were measured using an automatic tipping bucket rain

153 gauge (Campbell Scientific, ARG100) connected to a data logger (Campbell CR100) located at the middle

154   of the slope. Soil moisture was measured by a Time Domain Reflectometry (TDR) sensor (HOBO sensors:

155   ECH2O™ 10HS) in each micro-erosion plots. Beerkan tests were conducted at the top, upper, middle, and

156   lower slope positions in both biochar-treated plots and control plots without biochar to quickly determine

157   infiltration rate (Braud et al. 2005). The Beerkan Estimation of soil pedoTransfer parameters (BEST)

158   algorithm enables the estimation of soil hydraulic conductivity (Lassabatere et al., 2006) following the same

159   method used by Janeau et al. (2022).

2.4 Nutrient contents in bamboo biochar

161   Bamboo was used for biochar production in traditional kilns, as it is commonly cultivated by

162   farmers in Nan province. In addition, bamboo biochar has interesting physicochemical properties, including

163   high porosity and a large specific surface area, which can enhance water and nutrient retention. It also

164   contains essential elements that contribute to soil fertility and promote plant growth, such as organic carbon

165   (5.40%), organic matter (9.24%), with nutrient contents including total nitrogen (0.46%), phosphorus

166   (0.14%), and total potassium (0.23%) (Janeau et al., 2022).

2.5 Erosion plot for collecting sediments and runoff

168   The total slope length along the 108.4-meter transect is divided as follows: the top slope position

169   extends 27 meters to the upper slope position. The upper slope position continues for 32 meters to the

170   middle slope position, and the middle slope position extends 50 meters to the down slope position.

171   Moreover, there is a small product conveyance route between the top and upper positions that did not

172   influence our measurements. Micro-erosion plots (1 m²) are used to study and quantify soil erosion by

173   measuring the amount of runoff and sediment (soil particles) that is carried away by water flowing over the

174   plot's surface, specifically focusing on the detachment process (Janeau et al. 2003).

175   To assess runoff, sediment, and nutrient losses, twenty-four micro-erosion plots (1 m x 1 m) were

176   established between 2018 and 2019 at various slope positions along the toposequence, including the top,

177   upper, middle, and downslope areas. At each slope position, six micro-erosion plots were installed: three

178   plots received biochar treatment, while three served as controls without biochar application (Figure 2).

179   Biochar was applied to the treated plots at a rate of 2 kg m^{-2} (or 20 t ha^{-1}), as shown in Figure 2.

180
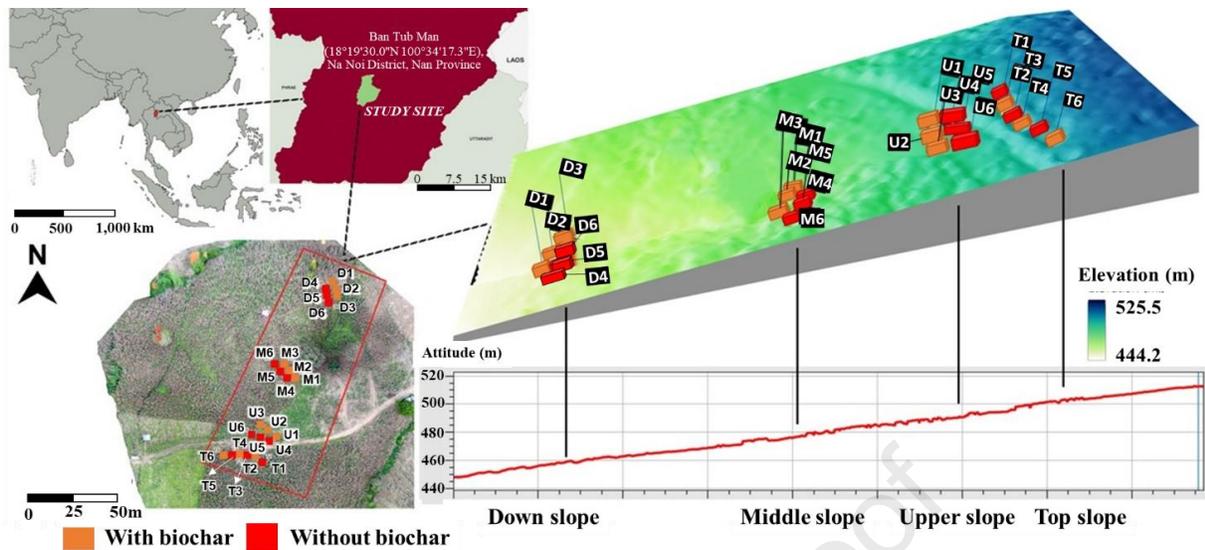
Figure 2. Micro-erosion plots with and without biochar at the top, upper, middle, and downslope

positions along the toposequence

183   The 1 m^2 erosion plots were enclosed by iron frames 20 cm high and inserted to a depth of 10 cm,

184 as described by Janeau et al. (2003), and were the same as used in Janeau et al. 2022. Iron frames are used

185 to prevent runoff from the area above. A 66-liter bucket was connected directly to a tube of the micro-

186 erosion plot via one of the 15 outlets of a divisor. Each bucket was installed below ground at the end of the

187 plots to collect runoff water and sediment (Figure 3). Runoff and soil loss samples were collected after

188 rainfall events exceeding 25 mm. After collecting a runoff sample, we poured out the remaining runoff to

189 avoid an overflowing tank. The volume of runoff water was measured using a tape measure inside the

190 buckets (small or large, depending on the water volume), and the total runoff volume was then calculated.

191 Suspended sediment fractions were collected along with the runoff water from the buckets. Approximately

192 1 L of runoff sample was taken from the buckets after stirring and filtered through the Whatman GF/F filter

193 (nominal pore size 0.7 μm). After filtration, the particles collected on the filter were dried in an oven at 105

194 ºC for 24 hours to determine the amount of sediment in the water suspension. Soil surface features and

195 vegetation cover percentage in each micro-erosion plot were measured at the same time as the sediment

196 and runoff samples.

197   Maize was planted within the erosion plots under conditions similar to those outside the

198   experimental area. Land preparation was carried out by tilling the soil before the commencement of the

199   experimental study in 2018. Maize (*Zea mays* L.), cultivar CP 888, was sown within the 1 m² erosion plots

200   along the slope using a planting stick, with a spacing of 0.25 m within rows and 0.75 m between rows

201   (Figure 3). For fertilizer management, urea (46-0-0) and compound N-P-K (16-20-0) fertilizers were

202   applied at planting at a rate of 16 g m^{-1}. The same fertilizer combination was reapplied 30 days after planting

203   at the same rate, following local farming practices. Glyphosate (48% W/V SL) was used by farmers for

204   weed control, applied at a rate of 1.88-3.11 kg ha^{-1}, approximately 15 to 20 days before planting.
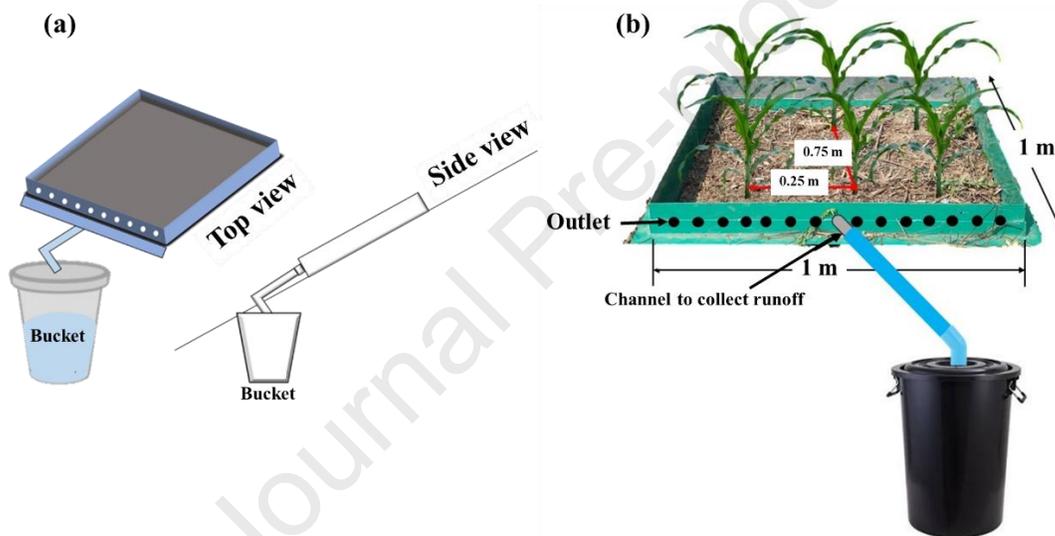
205

206   **Figure 3.** Schematic of a micro-erosion plot for collecting runoff, sediment, and nutrient losses (a), and

207   schematic of maize planting in a micro-erosion plot (b)

208

209   **2.6 Soil surface features descriptions**

210   We estimated surface conditions visually using the method of Casenave and Valentin (1992) as in

211   previous erosion studies in the tropics (Janeau et al., 2003; Neyret et al., 2020; Perron et al., 2023;

212   Podwojewski et al., 2008). We included the recognition of various types of surface features, such as

213   percentage of vegetation, free micro-aggregates, different crusts, and free or embedded elements (gravels,

214   rocks) in a crust, and we estimated the proportion of surface occupied by each parameter.

215 **2.7   Nutrient analysis of runoff**

216   Runoff samples were collected after rainfall events for nutrient analysis. They were preserved with

217 one or two drops of 4 M H_2SO_4 and then frozen. The samples were stored until laboratory analysis. Total

218 nitrogen was determined using the Macro-Kjeldahl method, while total phosphorus was analyzed using the

219 Vanadate-molybdate method. Total potassium was measured using atomic absorption spectroscopy (AAS)

220 (Rice et al., 2017).

221

222 **2.8   Statistical analyses**

223   Statistical analyses were conducted using R software version 4.3.1 (R Core Team, 2023). A

224 combination of multivariate and univariate statistical approaches was employed. First, Principal

225 Component Analysis (PCA) was performed using the FactoMineR package (Lê et al., 2008). PCA was

226 applied as an exploratory technique to reduce data dimensionality and to identify relationships among the

227 measured variables. The interpretation of PCA results was further supported by boxplots and PCA biplots.

228 A total of ten variables was used to test the study hypothesis, categorized as follows: (1) soil properties,

229 including biochar percentage, soil moisture, and saturated hydraulic conductivity (Ks); (2) soil detachment

230 metrics, such as runoff volume and total sediment yield; (3) nutrient concentrations of nitrogen, phosphorus,

231 and potassium in runoff; and (4) surface conditions, encompassing the presence of free elements, vegetation

232 cover, and crust percentage. For inferential statistical analysis, the Kruskal–Wallis test was employed to

233 assess the effects of biochar application and toposequence position on each variable. This non-parametric

234 test was selected because the data did not satisfy the assumptions of normality and homogeneity of variance

235 required for one-way ANOVA. When statistically significant differences were detected, Dunn's post hoc

236 test with a significance level of $P \leq 0.05$ was applied to determine pairwise differences among toposequence

237 levels. The Dunn test was conducted using the Fisheries Stock Assessment (FSA) package in R (Ogle et

238 al., 2023).

239 **3. Results**

3.1 Main relationships between rainfall, soil surface features, soil properties, total sediment, and runoff

Both the 2018 and 2019 results followed a similar trend, and thus, only PCA results from 2019 are presented. The first two PCA axes explained 43.8% of the dataset's variability (Figure 4a). Rainfall and runoff primarily influenced the first axis (Dim 1), while the second axis (Dim 2) was driven by silt, sand contents, and soil moisture. The first axis, reflecting rainfall and runoff volumes, was critical in differentiating between various rainfall events (Figure 4b). Indeed, runoff showed significantly lower values for several rainfall events (Table 3). A clear trend in soil texture and moisture emerged along the slope, with silt content and moisture increasing from the lower slope position (1) to the mid position (2) (Figure 4c). The downslope area (1) exhibited the highest sand content, while the middle slope (2) had the greatest silt content and soil moisture. The upper and top slope positions (3 and 4) showed less interaction with soil moisture and texture.
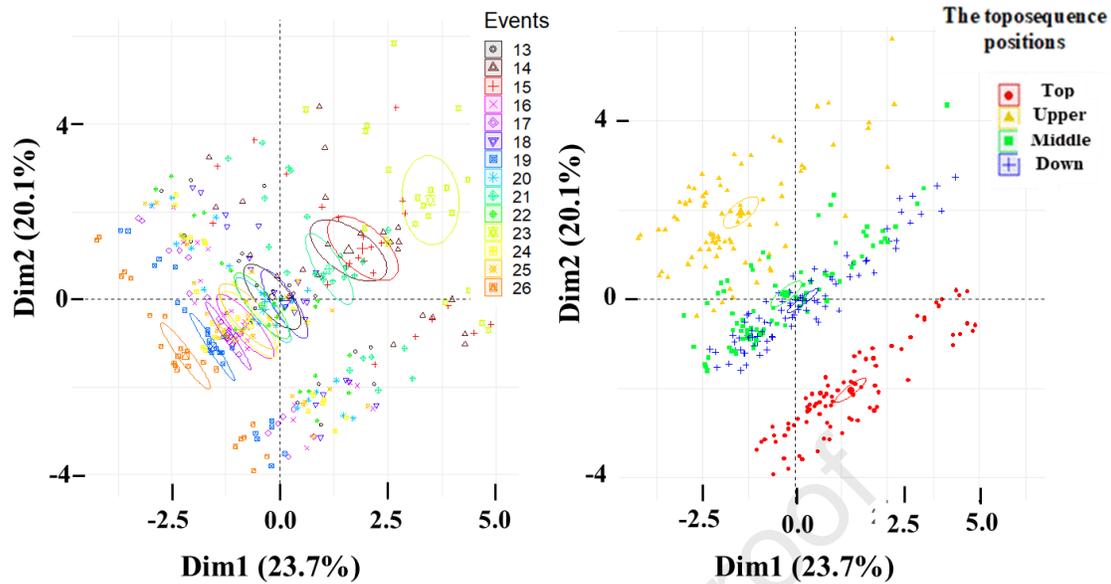
(a) Graph of variables (DIM 1 and DIM 2)
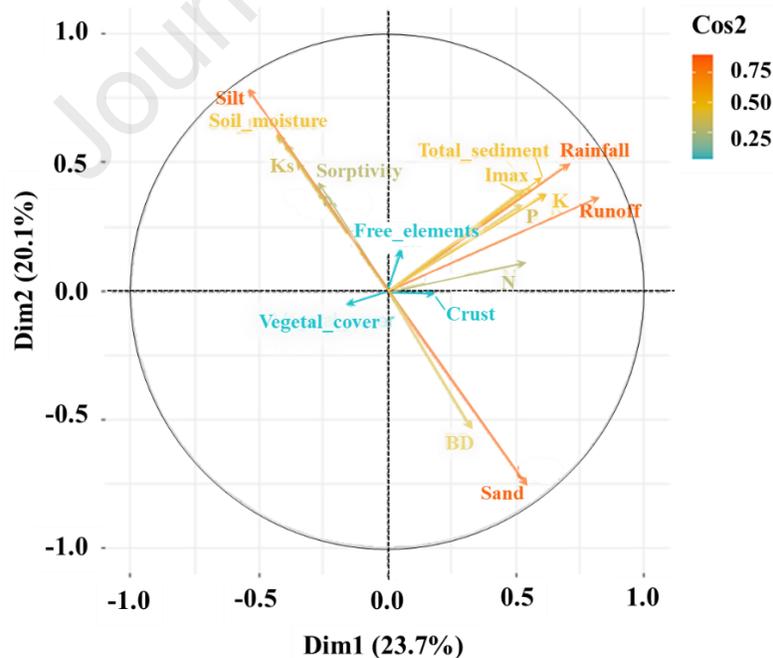
(b) Individual map   (c) Individual map

Figure 4. Principal component analyses (PCA) of the explanatory and response variables (a). Variables are represented with a cos2 colour scale indicating their weight on each axis of the PCA. Dimensions 1 and 2 explain 23.7 and 20.1% of the variance, respectively. Two individual factor maps are represented with events (b), and position along the toposequence (c) as factors on dim 1 and 2.

Table 3 Characteristics of rainfall events associated with relatively low runoff measurements.

Date of rainfall	Average Runoff (mm m^{-2})	Rainfall amount (mm)	Maximum Rainfall intensity (mm h^{-1})
June 12, 2018	16.63	85.4	60
May 30, 2019	35.06	167	156
July 25, 2019	8.25	42.0	38
August 2, 2019	29.69	71.2	38
Sept. 11, 2019	23.88	43.2	40

3.2 The effects of position along the toposequence and biochar application on runoff, total

sediments, soil moisture, and hydraulic conductivity (Ks)

In 2018, the volume of runoff ranged from 0 to 64.4 L, with a mean of 15.4±13.5 L, while total sediments ranged from 0 to 1,227.4 g L^{-1}, with a mean of 78.7±174.5 g L^{-1}. In 2019, the runoff volume ranged from 0.7 to 65.6 L, with a mean of 25±18.1 L, and total sediments ranged from 1.0 to 1,455.4 g L^{-1}, with a mean of 139.7±202.3 g L^{-1}. As 2018 and 2019 showed similar tendencies for these two parameters, we displayed the results for both years combined (cf. Figure 5a). The effect of slope position showed that runoff was significantly higher at the top slope position compared to mid and down positions ($P \leq 0.01$), and total sediments were significantly higher at the top slope position compared to all three other positions ($P \leq 0.01$) (cf. Figure 5a). Moreover, no significant difference was found in the effect of biochar on either runoff or total sediments (cf Figure. S1).

In both years, soil moisture was higher in plots treated with biochar ($P \leq 0.01$). Soil moisture was also significantly influenced by position along the toposequence ($P \leq 0.01$), with the middle and upper positions showing higher moisture levels compared to the downslope and top positions (cf. Figure 5b). In 2018, hydraulic conductivity Ks was 59% higher in biochar-treated plots ($P \leq 0.01$), whereas in 2019, it was 24% lower ($P \leq 0.05$) compared to plots without biochar (cf. Figure 5c). In 2018, the upper slope position had lower Ks than the three other positions, while in 2019, the middle slope position exhibited the highest Ks and the top position the lowest Ks.
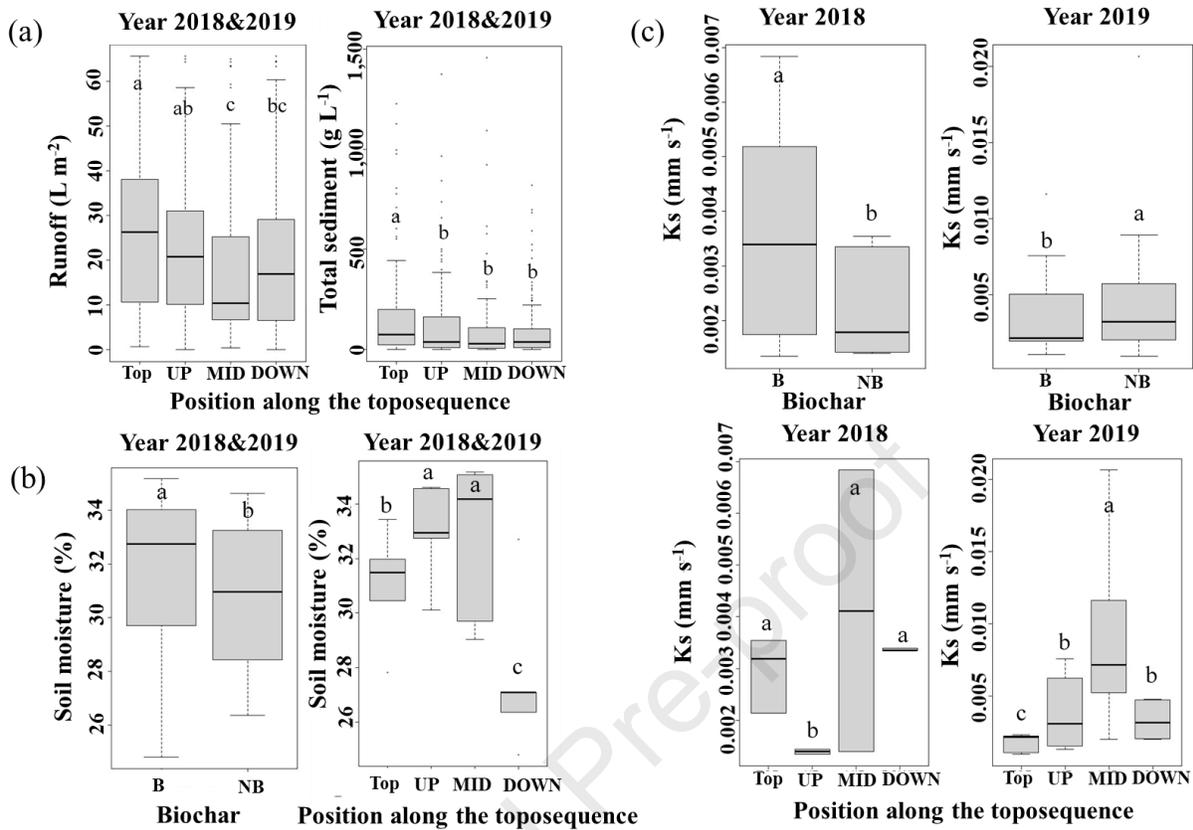
Figure 5. Boxplot of runoff and total sediment (a), soil moisture (b), and hydraulic conductivity (Ks) (c) according to biochar treatments (B = biochar; NB = no biochar) and slope positions along the toposequence (down, middle, up, top) for the years 2018 and 2019. Letters indicate significant differences at the $P \leq 0.05$ level.

3.3 The effects of position along the toposequence and biochar application on nutrient losses in runoff

In 2018, nitrogen loss via runoff exhibited no statistically significant differences attributable to biochar application. In contrast, in 2019, nitrogen loss was reduced by 34% in biochar-treated plots ($P \leq$ 0.01) (cf. Figure 6a). In 2018, nitrogen loss was higher at the top slope position compared to the downslope position. However, in 2019, the highest nitrogen loss was observed at the downslope position (cf. Figure 6a). Furthermore, nitrogen concentration in runoff was, on average, 69.4 ± 103.0 mg L^{-1} in 2018, compared to $2,096.1\pm1,692.9$ mg L^{-1} in 2019. Phosphorus loss via runoff was 74% higher in biochar-treated plots in

295 2018 ($P \leq 0.01$) (cf. Figure 6b). A similar trend was observed in 2019, although the results were not

296 statistically significant. Phosphorus loss was significantly influenced by the position along the

297 toposequence, with the highest phosphorus concentrations in runoff occurring at the top position compared

298 to the middle and downslope positions (cf. Figure 6b). Potassium concentration in runoff increased

299 significantly by 41% under biochar treatment in 2018 ($P \leq 0.05$). A similar trend was observed in 2019,

300 although the differences were not statistically significant. In 2018, potassium loss via runoff also differed

301 significantly by position along the toposequence ($P \leq 0.05$), with the highest potassium concentrations in

302 runoff observed at the top position compared to mid and down positions (cf. Figure 6c). However, in 2019,

303 no significant differences in potassium loss via runoff were observed along the toposequence.
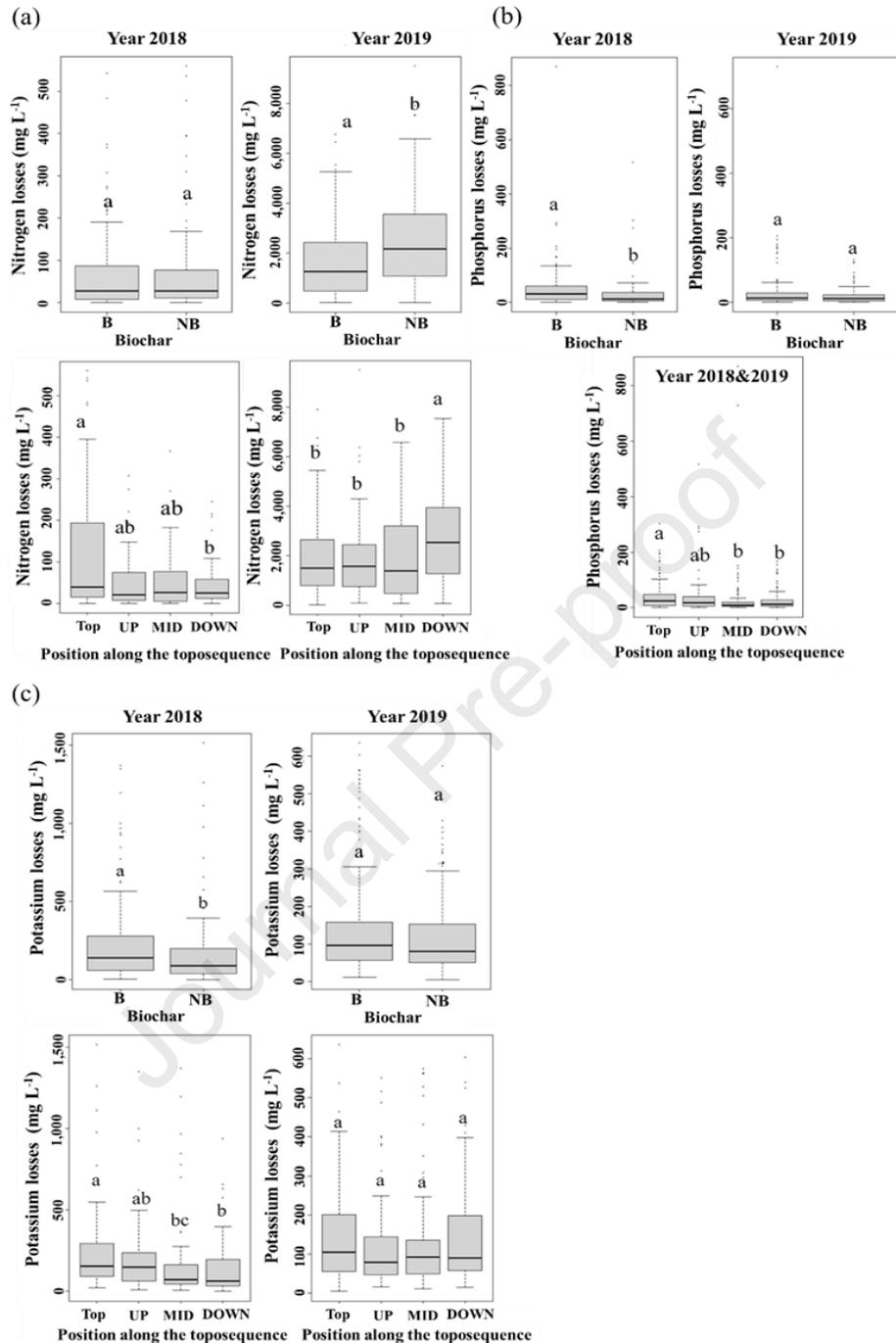
Figure 6. Boxplots of nitrogen losses (a), phosphorus losses (b), and potassium losses (c) according to biochar treatments (B = biochar; NB = no biochar) and slope positions along the toposequence (down, middle, up, top) for the years 2018 and 2019. Different letters indicate significant differences at the $P \leq 0.05$ level.

3.4 The effects of position along the toposequence and biochar application on soil surface features

In 2018, vegetal cover increased significantly by 29% with biochar application ($P \leq 0.05$), while free elements decreased substantially by 68% ($P \leq 0.01$) (cf. Figure 7a and 7b). Even if in 2019 results were not statistically significant for these two variables, the same trend was observed. We could not show that vegetal cover and free elements varied along the toposequence for both years (cf. Figure. S2). For both years, the percentage of crust decreased by 54% with biochar application ($P \leq 0.01$). Regarding the effect of slope position, the percentage of crust was significantly higher at the top position compared to the middle position (cf. Figure 7c).

Figure 7. Boxplot of vegetal cover (%) (a) and free elements (%) (b) according to biochar treatments (B = biochar; NB = no biochar)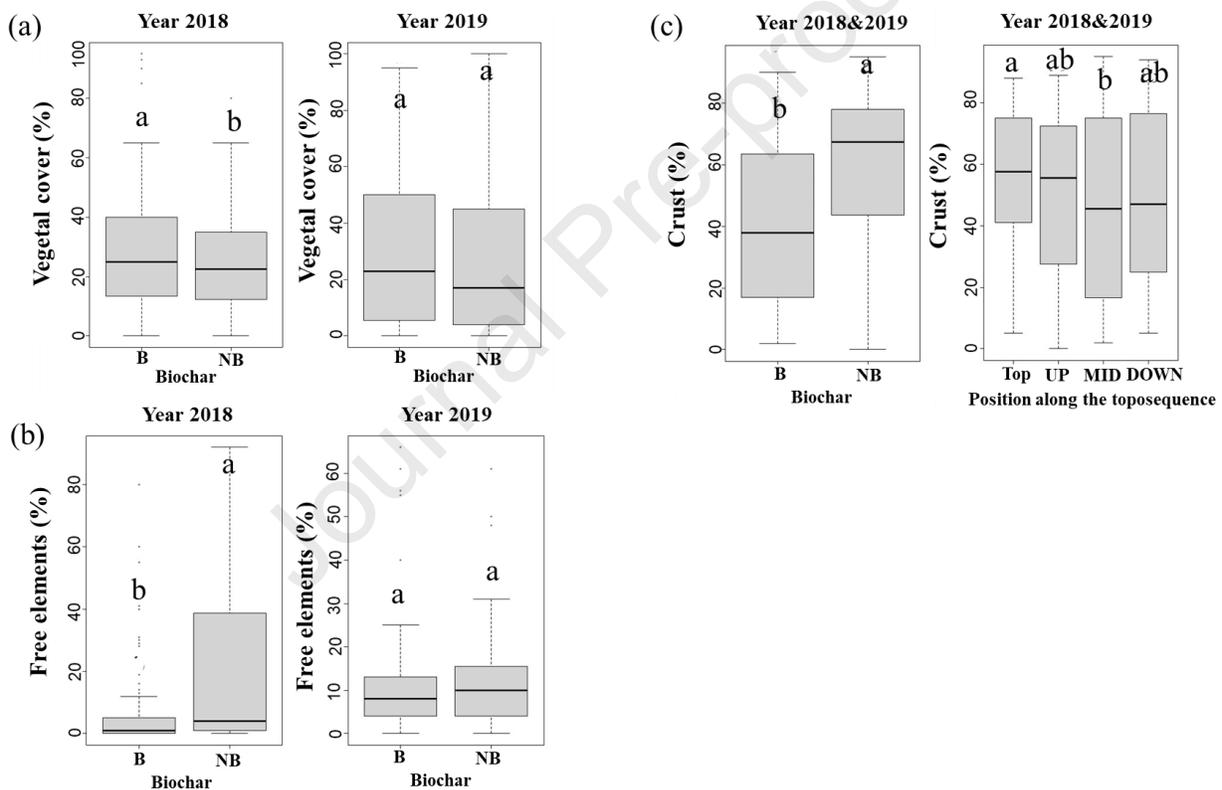 for the years 2018 and 2019. Boxplot of crust (%) (c) according to biochar treatments (B = biochar; NB = no biochar) and slope positions along the toposequence (down, middle, up, top) for the years 2018 and 2019. Letters indicate significant differences at the $P \leq 0.05$ level.

4. Discussion

4.1 Effect of biochar application on sediment loss, runoff, and nutrient losses

Our research over two years (2018–2019) under natural rainfall conditions revealed that biochar application had no measurable impact on total surface runoff or sediment loss. This outcome could be due to the fact that biochar has not been sufficiently incorporated deep into the soil. Therefore, even if several studies have shown an improvement in soil properties after biochar application (Wani et al., 2023; Pandian et al., 2024), in our case, the benefits to soil structure may not have been sufficient to reduce soil loss and runoff. Another explanation could relate to the application rate of 20 t ha^{-1} (2 kg m^{-2} per plot), that may have been insufficient to influence clay and silty clay soils in mitigating runoff and sediment loss. Consistent with our findings, Lu et al. (2024) also reported no significant decrease in soil erosion following biochar use in fine-grained soils. Doan et al. (2015) noted that biochar reduced soil loss and runoff in Acrisol soils with low organic carbon, whereas our study soil had high organic matter and organic carbon contents. Zong et al. (2016) further highlighted that biochar can reduce soil tensile strength when applied in high quantities (>50 t ha^{-1}), implying that lower application rates may have limited or negligible effects on soil strength. In contrast, Li et al. (2024) conducted a study in China and reported findings that were opposite to those of our study. Their research demonstrated that the application of biochar reduced runoff and soil loss. These contradictory results can be explained by several differences between the two studies: in the study of Li et al. (2024), biochar was made by pyrolyzing clippings of apple tree branches; soil was classified as silt loam (38.1% sand, 53.9% silt, 8.0% clay); the mean accumulated rainfall ranged between 497 and 679 mm annually, from 2017 to 2020 (almost half of the average annual precipitation of our site); finally, runoff and sample collection covered an area of 18 m², significantly larger than the 1m² plot of this study. Depending on the type of erosion, it is not always possible to compare results obtained at different scales (Wu et al. 2021). We can also find that different processes may have acted here due to the uplift movement of biochar on the soil surface.

348   The effect of biochar application on nutrient losses through runoff varied between years. In 2018,

349   there was no significant difference in nitrogen loss between the biochar-treated and control plots. However,

350   in 2019, nitrogen loss was reduced in the biochar-treated plots. This finding is supported by Liu et al.

351   (2019), who used machine learning-based regression modeling of compiled data from the literature.

352   Previous studies have also documented a significant reduction in total nitrogen loss with the application of

353   biochar (Wang et al., 2021; Yin et al., 2023). In contrast, phosphorus and potassium losses were

354   considerably higher in 2018 in biochar-treated plots compared to control plots, potentially due to the

355   movement of biochar particles in runoff, given the high phosphorus and potassium content of bamboo

356   biochar. By 2019, however, phosphorus and potassium losses showed no significant differences between

357   plots with and without biochar, suggesting a potential trend of reducing nutrient losses with continued

358   biochar use. The effectiveness of biochar in minimizing nitrogen, phosphorus, and potassium losses through

359   runoff may vary depending on the application rate (Wang et al., 2021). Additionally, the influence of

360   fertilization practices utilized by farmers each year may impact phosphorus and potassium losses, which

361   could account for the notable differences in nutrient runoff between 2018 and 2019.

362   In terms of hydrological variables, several authors have demonstrated that incorporating biochar

363   into topsoil increases soil moisture (Haider et al., 2017; Leng et al., 2021; Wei et al., 2023). This is

364   consistent with our findings, which showed increased soil moisture in both years under biochar treatment

365   incorporated at a depth of 5 cm. Additionally, we observed that biochar increased hydraulic conductivity

366   by 59% in 2018, which aligns with Yan et al. (2021), who reported that hydraulic conductivity increases

367   as the quantity of biochar increases. Moreover, biochar can enhance the germination, height, and shoot

368   biomass of species such as Robinia pseudoacacia L. (Bu et al., 2020), which may contribute to the

369   increase in vegetation cover. In our study, this mechanism likely explains the 29% increase in vegetation

370   cover observed in 2018. For some of our variables (phosphorus, potassium, vegetal cover), we found an

371   effect of biochar for 2018 and not for 2019. This can be explained by: (1) according to Janeau et al.

372   (2022) who did rainfall simulation in the same study site, there was a significant amount of soil loss, and

373   natural erosion process has resulted in the removal of the top millimeters of soil, allowing biochar (less

374   dense particles) to emerge on the soil surface. In addition to that, the presence of fine biochar particles

375   (<0.5 mm) in the soil surface could also have acted as a crust (Obia et al., 2017). After two years of

376   biochar treatment in 2019, the effect of biochar as a crust was different from the effect in 2018. (2) In

377   simulated rainfall, runoff decreased the quantity of biochar (Li et al., 2020). These two elements can

378   decrease the potential effect of biochar in 2019. We found that biochar decreased the crust for both years

379   and decreased free elements in 2018 compared to 2019. Indeed, the presence of biochar on the soil

380   surface did not allow the creation of sedimentation or erosion crust (or to a limited extent), and space

381   was occupied by biochar, which also limits free elements such as free microaggregates and gravels on

382   the soil surface. Biochar acted as a permeable crust on the soil surface but did not have any effect on

383   runoff and total sediment loss.

384

385   **4.2 Effect of position along the toposequence on sediment and nutrient losses, runoff, and hydraulic**

386   **conductivity**

387   As a reminder, the slope gradients range from 10% to 44%. The four positions (down, middle,

388   upper, and top) had elevations of 512, 498, 480, and 460 meters above sea level, respectively. The soil

389   texture was clay loam soil for the top and down positions, while silty clay loam was at the middle and upper

390   positions. We observed higher levels of total sediment loss and runoff in the top slope position, as it has

391   been found as well in the study of Farmanullah et al. (2013) in Pakistan. When trying to explain this result

392   with other soil properties at the top slope position, as did Farmanullah et al. (2013), contradictions appeared.

393   For example, we observed a higher mean weight diameter (MWD) value in the top slope position (cf. table

394   1), generally indicating better soil aggregation, meaning that soil structure should be more stable and

395   resistant to erosion. If this parameter does not adequately explain our results, additional factors are likely

396   contributing. High rainfall intensity can lead to surface sealing or crusting, especially if the aggregates are

397   disrupted at the soil surface, leading to increased sediment loss and runoff (Wu et al., 2018; Yang et al.,

398   2020). Soil texture plays a significant role in infiltration and runoff. Even with high MWD, soils with high

399   clay or silt content may exhibit low permeability, causing excess water to run off rather than infiltrate. Silty

400 clay or clay soils, despite good aggregation, tend to form surface crusts that reduce infiltration, leading to

401 higher runoff and soil loss (Li et al., 2021; Simelane et al., 2024). In this study, we observed the highest

402 percentage of surface crust formation at the top slope position. The slope of the land can significantly

403 influence runoff and soil erosion. Steeper slopes can lead to more rapid water movement, which may cause

404 greater erosion even if the soil has good aggregation (Han et al., 2018; Simelane et al., 2024).

405   Some authors have investigated the impact of topographical position within a catena on nutrient

406 losses (Van Soest et al., 2022; Zhou et al., 2024). Some studies have reported higher nitrogen losses due to

407 runoff at the top slope position compared to downslope positions (Tsui et al.,2004; Rezaei et al.,2015). This

408 finding aligns with our 2018 results, which showed significantly higher nitrogen losses from the top slope

409 position. However, in 2019, the highest nitrogen loss due to runoff was observed at the downslope position.

410 In this finding, the trend of the highest nitrogen loss in surface runoff at the downslope position in 2019

411 differs from that observed in 2018 because nitrogen loss is influenced by both runoff volume and the

412 nitrogen concentration in runoff (Gilley et al.,2012; Qian et al.,2014; Zhou et al., 2024). We found that on

413 many days, a high volume of runoff combined with a high nitrogen concentration occurred at the downslope

414 position, likely due to a lower percentage of vegetation cover compared to other positions. Consequently,

415 the total nitrogen loss in surface runoff at the downslope position was higher than at other locations in 2019.

416 For potassium loss in surface runoff, it was observed that in 2018, the top slope position experienced greater

417 losses compared to other positions. However, in 2019, the top slope and downslope positions tended to

418 have higher potassium losses than the upper and middle positions, although the differences were not

419 statistically significant. Tsui et al. (2004) presented results similar to ours concerning the higher

420 concentration of potassium in the top slope position. However, they found different results for phosphorus

421 concentration. Following our results, Magdić et al. (2022) showed an influence of the toposequence position

422 on soil moisture in a vineyard field of Croatia. However, they showed that the higher soil water content in

423 the upper slope positions was associated with higher clay content. We also add a good correlation between

424 higher soil moisture in mid and upper positions, where clay content was also higher (cf. Table 1). The

425 conclusion of Magdić et al. (2022) can also be applied to our study: soil moisture on the slope was more

426   influenced by soil texture than by the position on the slope. If hydraulic conductivity also differed according

427   to the toposequence in our study, this was in contradiction to the study of Sobieraj et al. (2002), in a tropical

428   rainforest, at least for superficial horizons. Even if hydraulic conductivity differed along the toposequence,

429   Ks still ranged between 10^{-3} to 10^{-2} mm s^{-1}, which were values representative of a permeable soil.

430

431   **5. Conclusion**

432   Biochar presents substantial potential for enhancing soil properties and minimizing nutrient losses

433   by runoff. The findings of this study in the upland maize fields of South East Asia support the hypothesis

434   that biochar amendments contribute positively to nutrient retention, particularly nitrogen, in the soil.

435   Beyond its role in nutrient retention, biochar has also been demonstrated to improve vegetation cover,

436   decrease the presence of free elements, and prevent erosion crust formation on the soil surface. The

437   experiment showed that biochar, when applied on the surface, acts similarly to a permeable soil crust by

438   offering protection against the formation of new waterproof crusts. However, to fully capitalize on its

439   benefits and avoid this unintended crust-like behavior, biochar should be integrated deeper into the soil

440   profile. Despite its favorable effects on nutrient retention, biochar did not significantly influence sediment

441   loss and runoff in this investigation. This outcome suggests that biochar application, along with other

442   agricultural practices, should be specifically adapted to distinct slope positions, as soil properties exhibit

443   spatial variability along the toposequence. The position on the slope plays a crucial role in determining

444   nutrient distribution, sediment loss, runoff patterns, and soil erosion processes. To optimize biochar's

445   ecological benefits, its application must consider the heterogeneous soil characteristics present along the

446   slope, especially soil texture. Existing research has highlighted that biochar's capacity to improve soil

447   structure and stability becomes more evident after a maturation period within the soil. Consequently,

448   ongoing monitoring of soil structure over an extended period is vital, particularly following repeated natural

449   rainfall events, to fully grasp biochar's long-term effects on soil systems. Moreover, there is a need to

450   categorize the toposequence into relatively homogeneous units, such as slope gradient percentage or soil

451   texture, to implement effective soil conservation measures. Therefore, uniform soil management practices

452   should be discouraged across the toposequence. Instead, soil management should be tailored to specific

453   locations or adapted to landscape management.

454

455   **Credit authorship contribution statement**

456

457   **Data availability**

458   The datasets used or analyzed during the current study are available from the corresponding author

459   upon reasonable request.

460

461   **Acknowledgments**

465

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Conflict of Interest Statement

☒ 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.