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# 有机碳流失对土壤侵蚀的响应及其驱动因素: 基于 Meta 分析

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**摘要:** 土壤侵蚀是土壤有机碳(SOC)流失的主要驱动力,在全球碳循环中发挥着重要作用. 评估侵蚀作用下SOC流失的主要驱动因素及其影响程度有助于深入理解土壤侵蚀作用下SOC的流失机制. 因此,通过Meta分析方法,基于2007~2021年间国内外期刊上发表的24个案例,研究了不同气候因素(气候类型、降雨量和降雨强度)和土壤因素(土壤类型、容重和团聚体粒径)条件下土壤侵蚀对中国SOC流失的影响. 结果表明: ①与无侵蚀扰动相比,侵蚀作用下SOC含量显著下降(整体下降16.0%),表现出明显的负响应特征; ②侵蚀背景下SOC对不同因子的负响应程度为:降雨强度(65.0%)>降雨量(24.3%)>土壤类型(21.4%)>容重(20.2%)>团聚体粒径(16.5%)>气候类型(9.1%); ③主成分分析显示,侵蚀背景下气候因素相对于土壤因素是影响SOC流失的主导因素,降雨强度则再次显示为关键影响因子. 深入分析我国土壤侵蚀作用下SOC流失特征及其影响因素,为系统理解土壤侵蚀在碳循环中的作用提供了理论参考.

**关键词:** 土壤侵蚀; 土壤有机碳(SOC); 气候因素; 土壤因素; Meta分析

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## Response of Organic Carbon Loss to Soil Erosion and Its Drivers: A Meta-analysis

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**Abstract:** Soil erosion is the main driving force of soil organic carbon (SOC) loss and plays an important role in the global carbon cycle. It is helpful to understand the mechanism of SOC loss under soil erosion by evaluating the main driving factors of SOC loss under soil erosion and their influence degree. Therefore, based on 24 cases published in domestic and foreign journals from 2007 to 2021, this study investigated the effects of soil erosion on SOC loss in China under different climatic factors (climate types, rainfall, and rainfall intensity) and soil factors (soil types, bulk density, and aggregate size) by using Meta-analysis. The results showed that: ① compared with that under no erosion disturbance, the SOC content under erosion decreased significantly (overall decreased 16.0%), showing obvious negative response characteristics. ② Under the erosion background, the negative response degree of SOC to different factors was as follows; rainfall intensity (65.0%) > mean annual rainfall (24.3%) > soil types (21.4%) > bulk density (20.2%) > aggregate size (16.5%) > climate types (9.1%). ③ Principal component analysis showed that climate was the dominant factor affecting SOC loss, and rainfall intensity was again shown to be the key factor. In this study, the characteristics and influencing factors of SOC loss under soil erosion in China were analyzed, which provided theoretical reference for the systematic understanding of the role of soil erosion in the carbon cycle.

**Key words:** soil erosion; soil organic carbon(SOC); climate factors; soil factors; Meta-analysis

土壤碳库是陆地生态系统碳库中最大的碳库,据估计,其碳储量约为大气碳库的2~3倍和植被碳库的3~4倍<sup>[1]</sup>. 土壤有机碳(soil organic carbon, SOC)作为土壤碳库的主要组成部分,其动态变化主要受到土壤侵蚀的作用<sup>[2,3]</sup>. 土壤侵蚀是一种常见的自然地理现象和土壤退化过程,包括表土的分离、分解、迁移和沉积,其通过影响土壤表层物质的再分布,进而影响SOC的动态变化<sup>[1~3]</sup>. 全球每年因土壤侵蚀造成的土壤碳发生迁移分布的量达到10~50亿t<sup>[4]</sup>. 据估算<sup>[5]</sup>,中国土壤总有机碳库接近90 Pg. 然而,作为世界上水土流失较为严重的国家之一<sup>[6]</sup>,自1970年以来我国土壤碳库损失量已高达70 Tg<sup>[7]</sup>,其中土壤侵蚀发挥了十分重要的驱动作用. 初步研究显示<sup>[6,8]</sup>,我国每年因土壤侵蚀导致的

有机碳流失量(以C计)约占到总流失量的25.7%,高达(180 ± 80) Mt·a<sup>-1</sup>. 鉴于此,探明土壤侵蚀对SOC动态过程的作用机制对于全球碳循环研究具有重要意义.

土壤侵蚀对SOC流失的作用受到许多因素的影响,如地形、土壤、植被和气候等,其中气候因素和土壤因素被证实为最强烈的因素<sup>[9,10]</sup>. 侵蚀对SOC流失的作用过程从微观上看是降雨侵蚀力与土壤抗蚀性的相对抗,一方面,降雨侵蚀力为SOC的迁移提供动力;另一方面,土壤抗蚀性阻抗降雨冲

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刷侵蚀强度,减少 SOC 流失<sup>[11]</sup>. 有研究表明,土壤侵蚀对土壤碳流失过程的影响主要受控于气候因素和土壤因素<sup>[12,13]</sup>. 有研究发现气候因素中降雨量只有达到一定程度才会发生土壤侵蚀<sup>[14]</sup>,但降雨径流会冲刷土壤颗粒导致土壤团聚体破碎释放 SOC<sup>[15,16]</sup>. 针对降雨强度对 SOC 流失的影响, Strickland 等<sup>[17]</sup>和 Ramos 等<sup>[18]</sup>认为在大降雨强度下更容易发生 SOC 流失,然而 Jacinthe 等<sup>[19]</sup>却认为在较大的降雨强度下, SOC 流失反而减少, Beguería 等<sup>[10]</sup>甚至认为降雨强度与 SOC 流失之间没有显著的关系. 土壤因素方面,有研究认为土壤类型是影响 SOC 含量的主要因素,土壤容重与 SOC 呈显著负相关<sup>[20,21]</sup>,并且发现土壤侵蚀过程中 SOC 的动态变化还与不同粒级团聚体的分布情况有关<sup>[22]</sup>, SOC 流失与团聚体粒径之间存在显著负相关关系<sup>[23,24]</sup>,这一现象的出现被认为是含有较高 SOC 的团聚体被雨滴形成的薄片流优先运移所致<sup>[25]</sup>. 然而,这些研究大多集中在土壤侵蚀对 SOC 作用的单一因素上,在大尺度上系统性探索其主要驱动因素及其影响机制尚不多见.

鉴于此,本研究利用已在中国开展的 24 项研究的数据进行 Meta 分析,系统性探索 SOC 流失对土壤侵蚀的响应. 目标包括:①揭示土壤侵蚀与 SOC 含量变化的关系;②厘清土壤侵蚀作用于 SOC 含量变化的驱动因素;③研究各驱动因素在土壤侵蚀-SOC 含量关系与作用机制中的贡献特征;④分析土壤侵蚀影响 SOC 含量变化的主导因素及其影响机制. 本研究将有助于深入理解土壤侵蚀对于陆地碳循环中的驱动过程,以期当前“碳达峰与碳中和”战略实施提供科学依据.

## 1 材料与与方法

### 1.1 文献检索

利用 Web of Science (<https://www.webofscience.com>)、中国知网 (CNKI, <https://kns.cnki.net>) 和万方 (<https://www.wanfangdata.com.cn>) 的中英文数据库,以“soil erosion”、“water erosion”、“SOC and soil erosion”、“rainfall or rain

erosion”、“土壤侵蚀”、“土壤有机碳”、“有机碳”、“降雨侵蚀”、“水蚀”和“侵蚀”等为关键词进行文献检索,筛选收集发表于 2007 ~ 2021 年的“土壤侵蚀与有机碳”相关研究论文进行 Meta 分析(图 1).

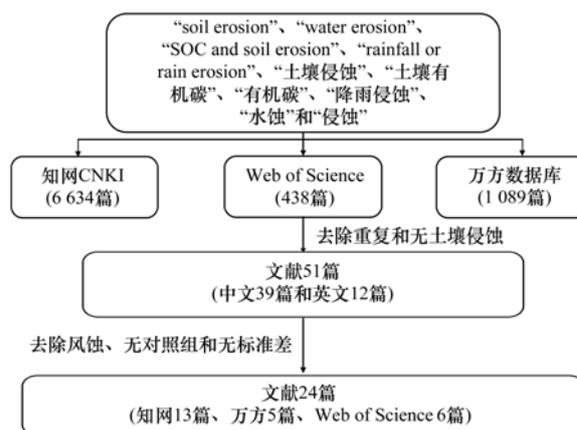


图 1 文献筛选

Fig. 1 Literature screening

为满足 Meta 分析标准,获得高质量数据集,用以下标准进行文章筛选:①研究试验为田间定位试验;②试验中必须包括对照组(无侵蚀影响)和处理组(侵蚀影响);③所提供的土壤侵蚀数据有试验的样本重复数、标准差和有机碳数据;④研究地点在中国. 根据筛选标准,最终获得 24 篇符合要求的文献以及 122 组数据.

为满足来自不同研究独立观察的统计要求,收集每一个试验的最后一次观察数据. 所选取的指标,如地点位置、pH、侵蚀类型、气候类型、土壤容重、土壤类型和年均温度的数据直接从收集文献中的文字内容和表格获取,而降雨量、降雨强度、SOC 和团聚体粒径的数据使用 GetData(版本 2.20)从筛选文献的图中提取.

### 1.2 数据分组

气候类型、降雨量、降雨强度、土壤类型、容重和团聚体粒径等因子均会影响 SOC 流失对土壤侵蚀的响应,本文对已有数据进行分组,试图研究某一特定因素如何调控土壤侵蚀对 SOC 流失的影响,具体分类见表 1.

表 1 数据分类依据

Table 1 Data classification basis

土壤因素		气候因素		
土壤类型	团聚体粒径	气候类型	年均降雨量	降雨强度
黑土	<0.053 mm	中亚热带季风性湿润气候	1 000 ~ 1 500 mm	>2 mm·min <sup>-1</sup>
紫色土	0.25 ~ 0.053 mm	中亚热带季风气候	500 ~ 1 000 mm	1.0 ~ 2 mm·min <sup>-1</sup>
黄壤	1 ~ 0.25 mm	中温带半干旱季风气候	<500 mm	<1 mm·min <sup>-1</sup>
红壤	2 ~ 1 mm	中温带半干旱气候		
	>2 mm	亚热带季风气候		
		大陆性气候		
		温带大陆性季风气候		

### 1.3 Meta 分析

使用 Hedges 等<sup>[26]</sup>、Lajeunesse<sup>[27]</sup> 和张彦军等<sup>[28]</sup> 的 Meta 分析方法来分析数据. 通过 MetaWin2.1 软件, 分别输入处理组和对照组 SOC 的均值(mean)、标准差(SD)、样本数量( $N$ )和分类变量, 计算响应比(RR). 根据响应比(RR)来反映土壤侵蚀对 SOC 的影响程度<sup>[26]</sup>.

$$RR = \frac{\ln X_t}{\ln X_c} = \ln X_t - \ln X_c \quad (1)$$

式中,  $X_t$  为土壤侵蚀条件下的 SOC 均值,  $X_c$  为无土壤侵蚀条件下的 SOC 均值,  $RR > 0$ , 表明土壤侵蚀对响应变量具有正响应, 即土壤侵蚀会增加 SOC 的流失. RR 的方差( $v$ )计算公式为:

$$v(RR) = \frac{SD_c}{N_c X_c^2} + \frac{SD_t}{N_t X_t^2} \quad (2)$$

式中,  $N_t$  和  $N_c$  分别是土壤侵蚀和无土壤侵蚀的样本数量,  $SD_c$  和  $SD_t$  分别是对照组和处理组的方差 ( $SD = SE \sqrt{N}$ )<sup>[27]</sup>.

使用 MetaWin2.1 软件计算响应比, 再用随机效应模型计算平均加权响应比  $RR_{++}$ :

$$RR_{++} = \frac{\sum_{i=1}^m \sum_{j=1}^k W_{ij} RR_{ij}}{\sum_{i=1}^m \sum_{j=1}^k W_{ij}} \quad (3)$$

加权标准误差( $S$ )的计算公式为:

$$S(RR_{++}) = \left[ \left( \sum_{i=1}^m \sum_{j=1}^k W_{ij} \right)^{-1} \right]^{1/2} \quad (4)$$

95% 置信区间(95% CI)的计算公式为:

$$95\% \text{ CI} = RR_{++} \pm 1.96S(RR_{++}) \quad (5)$$

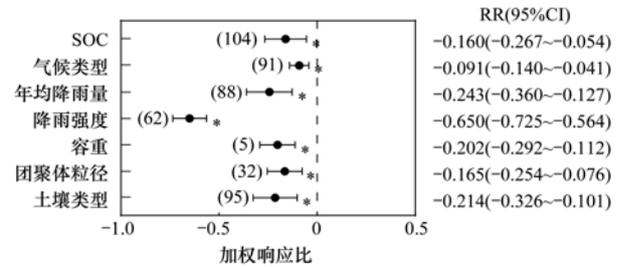
式中,  $i = 1, 2, 3, \dots, m$ ;  $j = 1, 2, 3, \dots, k$ ;  $m$  是组的数量,  $k$  为第  $i$  组中的比较数量,  $W_{ij}$  为  $RR_{++}$  的权重,  $RR_{++}$  为正值时则为正响应, 否则为负响应. 当置信区间包含 0, 土壤侵蚀对 SOC 不显著 ( $P > 0.05$ ). 当置信区间全部大于 0, 土壤侵蚀显著增加 SOC ( $P < 0.05$ ), 反之, 土壤侵蚀显著减少 SOC ( $P < 0.05$ )<sup>[28, 29]</sup>.

## 2 结果与分析

### 2.1 SOC 流失对土壤侵蚀的响应特征

土壤侵蚀造成 SOC 流失, SOC 对土壤侵蚀表现出明显的负响应特征. 从图 2 可以看出, SOC 对土壤侵蚀的响应比为  $-0.160$ , 置信区间为  $-0.267 \sim -0.054$ ,  $P < 0.05$ , 说明土壤侵蚀对 SOC 具有显著负响应, 即土壤侵蚀导致 SOC 的流失. 研究结果显示, 气候类型、降雨量、降雨强度、容重、土壤类型和团聚体粒径导致 SOC 含量显著下降 ( $P < 0.05$ ).

各因子通过影响土壤侵蚀而导致 SOC 含量下降的程度为: 降雨强度 (65.0%) > 年均降雨量 (24.3%) > 土壤类型 (21.4%) > 容重 (20.2%) > 团聚体粒径 (16.5%) > 气候类型 (9.1%).



数据以具有 95% 置信区间的加权响应比表示, 括号中的数值为样本中数据个数, \* 表示具有统计意义 ( $P < 0.05$ )

图 2 气候因素 (气候类型、年均降雨量和降雨强度) 和土壤因素 (容重、团聚体粒径和土壤类型) 的加权响应比

Fig. 2 Weighted response ratios of climatic factors (climate type, average annual rainfall, and rainfall intensity) and soil factors (bulk density, aggregate size, and soil type)

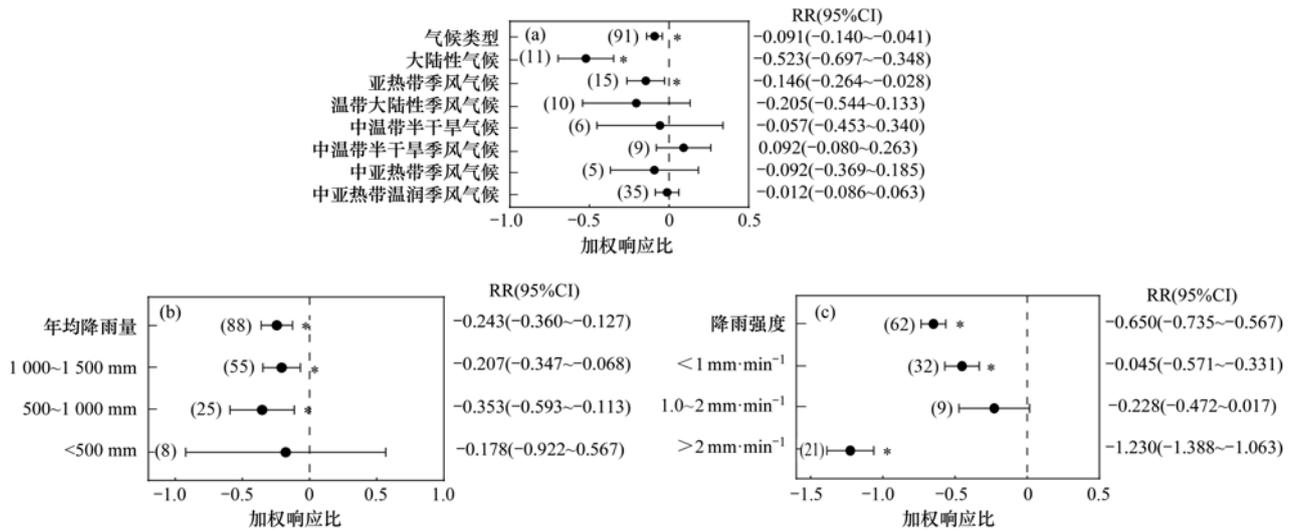
### 2.2 SOC 流失响应土壤侵蚀的驱动因素分析

气候因素是影响 SOC 流失的重要因素, 主要包括气候类型、降雨量和降雨强度等因子. 除大陆性气候和亚热带季风气候下土壤侵蚀对 SOC 流失的影响显著外 [图 3(a),  $P < 0.05$ ], SOC 的减少在其他不同气候类型下差异不显著 ( $P > 0.05$ ). 其中, 大陆性气候下 SOC 减少程度最大 (52.3%,  $P < 0.05$ ), 亚热带季风气候下 SOC 减少程度最小 (14.6%,  $P < 0.05$ ).

考虑降雨量的整体数据, 除降雨量  $< 500$  mm 条件下的侵蚀发生对 SOC 的影响不显著外 [图 3(b),  $P > 0.05$ ], 其他不同降雨量条件下 SOC 流失对土壤侵蚀的响应差异均显著 ( $P < 0.05$ ). 以未发生土壤侵蚀作为对照, 土壤侵蚀作用下的 SOC 含量减少程度在不同降雨量下呈现出  $500 \sim 1000$  mm (35.3%)  $> 1000 \sim 1500$  mm (20.7%) [图 3(b)] 的趋势, RR 值随降雨量的增加也逐渐减少.

在降雨强度整体数据中, 以未发生土壤侵蚀作为对照, 除了降雨强度为  $1.0 \sim 2$  mm·min<sup>-1</sup> 时不显著外 ( $P > 0.05$ ), 土壤侵蚀作用下不同降雨强度均显著减少 SOC 含量, 减少程度范围在 4.5% ~ 123.0% 之间 [图 3(c)]. 在降雨强度  $< 1$  mm·min<sup>-1</sup> 和  $> 2$  mm·min<sup>-1</sup> 时 SOC 含量分别减少 4.5% 和 123.0%.

土壤特性也是影响 SOC 流失的一个重要因素, 相关因子包括土壤容重、团聚体粒径和土壤类型, 图 4 分别为土壤容重、土壤团聚体粒径以及土壤类型下 SOC 受土壤侵蚀影响的加权响应比. 在土壤侵蚀条件下, SOC 含量在容重影响下呈现减少的趋势 [图 4(a),  $P < 0.05$ ], 显著下降 20.2%.



数据以具有 95% 置信区间的加权响应比表示, 括号中的数值为样本中数据个数, \* 表示具有统计意义 ( $P < 0.05$ )

图 3 加权响应比在不同气候类型、年均降雨量和降雨强度的变化特征

Fig. 3 Variation characteristics of weighted response ratio in different climate types, average annual rainfall, and rainfall intensity

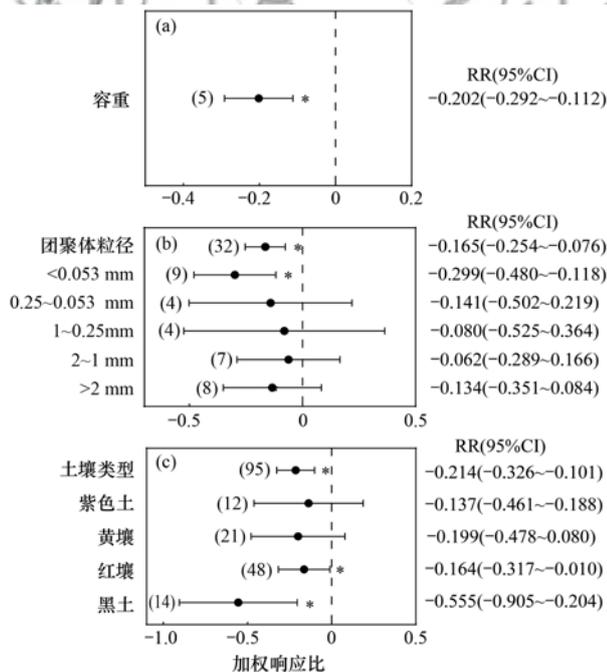
以未发生土壤侵蚀作对照组, 可以观察到土壤侵蚀对 SOC 含量减少程度因团聚体粒径的不同而发生显著差异 [图 4(b),  $RR = -0.165$ ], 但是只有团聚体粒径  $< 0.053 \text{ mm}$  时对 SOC 含量呈显著影响 ( $P < 0.05$ ). 并且, 团聚体粒径  $< 0.053 \text{ mm}$  时, SOC 减少的程度最大, 为 29.9% ( $RR = -0.299$ ,  $P < 0.05$ ).

相较于对照组, 除了紫色土和黄壤对 SOC 含量影响不显著外 ( $P > 0.05$ ), 不同土壤类型对土壤侵

蚀影响 SOC 含量变化表现为显著负响应 [图 4(c),  $P < 0.05$ ], 土壤侵蚀作用下 SOC 的减少幅度在不同土壤类型间呈现黑土 (55.5%,  $P < 0.05$ ) > 红壤 (16.4%,  $P < 0.05$ ) 的趋势.

### 2.3 SOC 流失响应比与驱动因素的相关性分析

图 5 显示, SOC 流失响应比与年平均气温 (MAT) 不相关 ( $r = -0.1075$ ,  $P = 0.3080$ ), 与 pH 显著相关 ( $r = 0.3378$ ,  $P = 0.0381$ ). 当 pH 为 4.81 时, 土壤侵蚀对 SOC 流失的作用最强, SOC 响应比



数据以具有 95% 置信区间的加权响应比表示, 括号中的数值为样本中数据个数, \* 表示具有统计意义 ( $P < 0.05$ )

图 4 SOC 在容重、不同团聚体粒径和土壤类型下对土壤侵蚀的加权响应比

Fig. 4 Weighted response ratio of SOC to soil erosion under bulk density, different aggregate size, and soil types

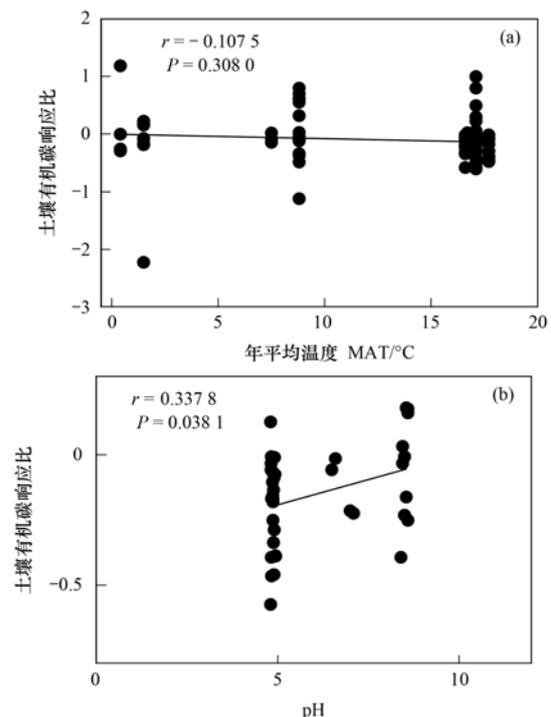


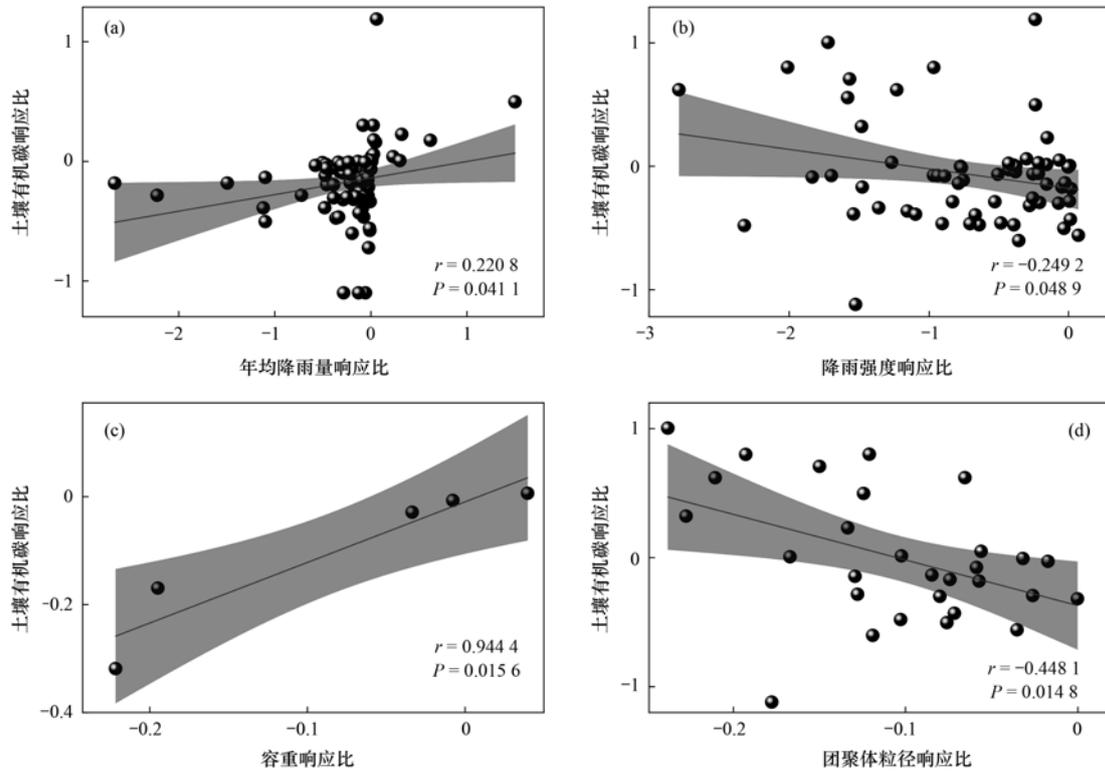
图 5 SOC 响应比 (RR) 与年平均温度 (MAT) 和 pH 的关系

Fig. 5 Correlation between SOC response ratio (RR) and mean annual temperature (MAT) and pH

随着 pH 值的减少呈上升趋势。

SOC 流失响应比与降雨量呈显著正相关关系 [图 6(a),  $r=0.2208$ ,  $P=0.0411$ ], 与降雨强度呈显著负相关关系 [图 6(b),  $r=-0.2492$ ,  $P=$

$0.0489$ ]; 此外, SOC 流失响应比与容重 [图 6(c),  $r=0.9444$ ,  $P=0.0156$ ] 呈正相关关系, 与土壤团聚体粒径 [图 6(d),  $r=-0.4481$ ,  $P=0.0148$ ] 呈显著负相关关系。



阴影部分为 95% 置信带, 红线为数据点的线性拟合

图 6 SOC 响应比 (RR) 与年平均降雨量、降雨强度、容重和团聚体粒径的 RR 关系

Fig. 6 Correlation between SOC response ratio (RR) and annual average rainfall, rainfall intensity, bulk density, and aggregate size

## 2.4 SOC 流失响应土壤侵蚀的主成分分析

SOC 流失对土壤侵蚀的响应受到多种因子的影响. 主成分分析结果显示, 前 3 个主成分累计贡献率达到 95.8%. 根据累计贡献率  $\geq 85.0\%$  的原则<sup>[30]</sup>, 这 3 个主成分可以代表 9 个性状中 95.8% 的信息。

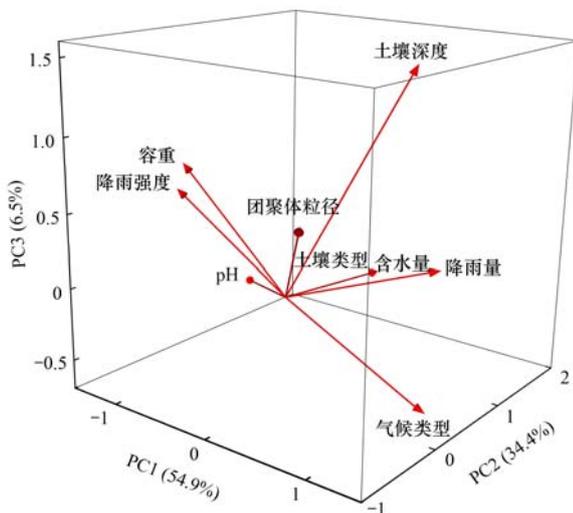


图 7 SOC 对土壤侵蚀响应的主成分分析

Fig. 7 Principal component analysis of SOC response to soil erosion

由图 7 可知, PC1 贡献率为 54.9%, 载荷较高的性状是降雨强度、气候类型、容重和降雨量, 表明这 4 个性状主要与影响土壤侵蚀的气候和土壤因素密切相关; PC2 贡献率为 34.4%, 载荷较高的性状是土壤类型、含水量和团聚体粒径; PC3 贡献率为 6.5%, 载荷较高的性状是土壤深度和 pH. 原数据变量中降雨强度、气候类型、容重、降雨量、土壤类型、含水量和土壤团聚体粒径对土壤侵蚀驱动 SOC 流失的影响程度较大, 其中, 降雨强度为关键影响因素。

## 3 讨论

### 3.1 土壤侵蚀对 SOC 流失的影响

本研究结果显示, 土壤侵蚀导致 SOC 流失, 这与以往大多数研究的结论一致<sup>[31-34]</sup>. 气候因素通过改变土壤侵蚀强度来影响土壤结构和微生物的降解能力, 进而影响 SOC 矿化流失程度<sup>[35]</sup>, 并且不同土壤团聚体组成、土壤类型和土壤结构也会影响 SOC 含量<sup>[36]</sup>. 早期研究发现<sup>[37-39]</sup>, 土壤侵蚀对有机碳的影响与土壤类型密切相关, 不同土壤类型主要通过影响

土壤抗蚀性和微生物活性来影响 SOC 含量<sup>[9,40]</sup>。土壤侵蚀条件下气候和土壤因素与 SOC 呈现显著相关关系,且在气候和土壤因素对 SOC 的响应比中,降雨强度响应比最大,气候类型响应比最小。这一结果表明,与其他因子相比,降雨强度导致 SOC 流失的影响程度更大<sup>[41,42]</sup>。因此,往后研究可以从气候因素(气候类型、降雨量、降雨强度)和土壤因素(土壤类型、容重、土壤团聚体粒径)入手,有助于深入理解土壤侵蚀与碳流失动态的影响过程。

### 3.2 SOC 流失响应土壤侵蚀的气候因素分析

本研究结果显示,土壤侵蚀背景下 SOC 流失与气候因素显著相关。首先,受土壤侵蚀直接驱动,不同气候类型条件下 SOC 含量多数显著降低,但仅大陆性气候和亚热带季风气候条件下 SOC 流失对土壤侵蚀的响应显著,这可能归因于:①大陆性气候和亚热带季风气候降雨量大且降雨频繁,容易引发水蚀;②半干旱气候分布在降雨较少的较干旱地区,缺乏土壤侵蚀发生的条件<sup>[43]</sup>。可能 SOC 含量在温暖潮湿的气候中比干燥凉爽的气候变化更大<sup>[44]</sup>。例如 Ogle 等<sup>[45]</sup>发现在热带/暖温带湿润气候的表层土壤中的有机碳含量更多。其次,降雨量和降雨强度均对 SOC 含量的降低有显著影响,SOC 流失量随降雨强度的增大而增大<sup>[46]</sup>。降雨量与降雨强度影响土壤侵蚀,两者共同作用使 SOC 流失程度达到最大<sup>[47]</sup>,例如 Bird 等<sup>[48]</sup>认为 SOC 的储量取决于气候条件,特别是降雨条件。但降雨量 < 500 mm 时没有统计意义,其原因可能在于只有达到一定程度的降雨才会导致 SOC 的显著流失<sup>[31,49]</sup>。

有学者研究气候变化与土壤侵蚀的关系认为<sup>[50,51]</sup>,降雨强度变化会导致侵蚀率变化,这一结论与本研究的一致。但本研究结果显示降雨强度  $1.0 \sim 2 \text{ mm} \cdot \text{min}^{-1}$  时对 SOC 含量不显著,这与王文欣等<sup>[52]</sup>研究发现 SOC 流失量随降雨强度加大而增大的结果不一致,导致这种结果的原因可能是不同降雨量和降雨强度改变土壤通气性、土壤质地、微生物量及活性等的强度不一,进而导致 SOC 含量变化不同<sup>[53]</sup>。例如 Jacinthe 等<sup>[19]</sup>通过研究降雨特征对侵蚀土壤碳流失的影响,发现在低强度降雨中损失的土壤碳比高强度降雨流失的多。但在高降雨强度下地表结构逐渐压实,团聚体分离破碎,孔隙堵塞,地表径流增大,表层土壤侵蚀增强<sup>[54,55]</sup>。有研究预测<sup>[56]</sup>,到 2090 年,全球土壤侵蚀将因气候变化而增加 9.0%,表明未来研究应特别关注气候因素对 SOC 流失的重要性。

### 3.3 SOC 流失响应土壤侵蚀的土壤因素分析

本研究结果显示,SOC 的响应比在黑土中明显

大于红壤,而黄壤和紫色土对 SOC 含量变化的影响不显著,与已有研究结果不一致。陈心桐等<sup>[57]</sup>发现不同土壤类型之间的 SOC 含量差异显著,其中黄壤显著大于紫色土。彭浩等<sup>[58]</sup>也通过研究土壤类型对坡面产流和降雨条件下泥沙流失的影响,发现不同土壤类型下的土壤侵蚀量呈现红壤 > 紫色土 > 黄壤的特征。这可能是由于不同土壤类型的复杂性(土壤质地和结构等),导致 SOC 含量存在较大差异<sup>[59]</sup>。例如黄壤中的固结物质含量小,土壤结构稳定性和抗侵蚀性较差,易被降雨侵蚀<sup>[60]</sup>。而红壤透水性差,导致降雨过程中地表径流大,造成土壤流失量增大<sup>[61]</sup>。也有研究发现黄壤的侵蚀强度一般高于红壤,黄壤的 SOC 侵蚀量约为黑土的 1.80 倍<sup>[62]</sup>。研究结果显示,与碱性环境相比,土壤侵蚀在酸性环境中对 SOC 流失的作用程度更大。可能是降雨的发生降低了土壤 pH,而土壤微生物在弱酸环境中活性更强,进而加快 SOC 分解速率<sup>[28,63]</sup>。

土壤容重的变化与土壤孔隙密切相关,其对土壤侵蚀强度有显著影响<sup>[64,65]</sup>。有研究显示,容重与土壤侵蚀作用下 SOC 含量变化显著相关,土壤容重与土壤抗冲能力关系密切,通过影响土壤的大孔隙数量来影响土壤渗透能力<sup>[66]</sup>。有研究发现土壤容重越大时,土壤的大孔隙数量变少,进而使得土壤渗透率减小,地表径流增加,土壤侵蚀强度增大<sup>[67]</sup>。而当土壤容重低,土层松散时,土壤的抗蚀性越强<sup>[68]</sup>。例如郑世清等<sup>[69]</sup>通过研究土壤容重与土壤侵蚀入渗关系,发现随着土壤容重的增大,土壤侵蚀量增大;沈奕彤等<sup>[70]</sup>通过分析在土壤容重影响下黑土坡面养分流失情况,也发现随着土壤容重增大,入渗率变小,地面径流增加,导致侵蚀强度显著增加。程圣东等<sup>[71]</sup>和徐燕等<sup>[72]</sup>也发现容重越大,孔隙度越小,土壤侵蚀越严重。

土壤团聚体作为土壤的结构单元,其稳定性不仅影响土壤侵蚀过程,还在较大程度上控制着 SOC 的封存与流失<sup>[73,74]</sup>。土壤侵蚀破坏团聚体结构,暴露包裹于其中的有机碳,从而加速 SOC 矿化<sup>[75]</sup>。本研究显示,与无土壤侵蚀相比较,SOC 流失量随着团聚体粒径变化表现出显著差异,特别是在团聚体粒径 < 0.053 mm 下 SOC 含量减少程度最大。这有可能是因为微团聚体易受水蚀搬动,破碎速度加快,封存于其中的 SOC 更容易流失,例如 Li 等<sup>[76]</sup>和 Fu 等<sup>[77]</sup>认为微团聚体迁移搬运过程易造成孔隙减少且形成板结,土壤下渗率减少,径流侵蚀强度增大;而大团聚体破碎速度较慢,更稳定而不易被崩解,SOC 的流失量减少<sup>[78]</sup>。但也有相反的理论,Ma 等<sup>[79]</sup>发现在高降雨强度下,大团聚体更容易发生机

械破碎; Mamedov 等<sup>[80]</sup>也发现黏粒含量较高的团聚体不易被侵蚀搬运, 因为该类团聚体粘结力大, 难以被侵蚀搬运, 机械破碎。但不可否认的是, 土壤团聚体对土壤侵蚀下 SOC 的变化影响是显著的。

#### 4 结论

(1) 土壤侵蚀导致 SOC 流失, 显著降低 SOC 含量, SOC 含量在绝大多数气候和土壤因素条件下对土壤侵蚀表现出显著的负响应特征。

(2) 不同气候因子(降雨强度、降雨量和气候类型)对 SOC 流失呈显著负响应, 其中降雨强度对侵蚀作用下 SOC 流失的影响程度最大, 表现为: 高降雨强度 ( $> 2 \text{ mm} \cdot \text{min}^{-1}$ )  $>$  低降雨强度 ( $< 1 \text{ mm} \cdot \text{min}^{-1}$ )。

(3) 土壤因素对土壤侵蚀驱动 SOC 流失具有重要影响, 所选取土壤因子中, 团聚体粒径影响程度最小, 土壤类型影响程度最大, 二者相差 1.30 倍。土壤侵蚀作用下, 不同团聚体粒径对 SOC 流失程度的影响最大是微团聚体 ( $< 0.053 \text{ mm}$ )。

(4) 侵蚀背景下, 气候因素对 SOC 流失的影响程度是土壤因素的 1.69 倍, 成为影响 SOC 流失的主导因素, 而降雨强度在众多因子中对 SOC 流失影响程度最大, 成为关键作用因子。

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