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典型黑土区坡耕地表层土壤活性有机碳变化特征

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摘要:以典型黑土区3种地貌类型区(漫川漫岗区、丘陵漫岗区、平原低地区)坡耕地不同坡位表层土壤为研究对象,通过测定土壤总有机碳、高活性有机碳、中活性有机碳和低活性有机碳等指标,分析黑土区坡耕地不同坡位表层土壤活性有机碳的变化特征,探究不同地貌类型区坡耕地土壤活性有机碳变化特征的差异。结果表明,坡耕地各坡位表层土壤总有机碳含量变化范围为26.57~38.61 g/kg,土壤活性有机碳含量变化范围为1.85~5.67 g/kg。3种地貌类型区坡耕地不同坡位土壤总有机碳和活性有机碳含量变化特征不同。漫川漫岗区总有机碳、中活性有机碳和低活性有机碳含量变化特征均表现为坡上和坡中显著大于坡下、坡上和坡中无显著差异;高活性有机碳含量变化特征则以坡中最高坡下最低,且不同坡位之间高活性有机碳含量差异显著。丘陵漫岗区不同坡位土壤总有机碳和低活性有机碳含量差异显著,并表现为坡下显著大于坡上、坡上显著大于坡中;高活性有机碳和中活性有机碳含量的变化则呈现坡上和坡下显著大于坡中、坡上和坡下无显著差异。平原低地区总有机碳及3种活性有机碳组分的含量在各坡位间的差异均为未达显著水平。不同地貌间典型黑土区坡耕地表层土壤活性有机碳分布规律有所差异,漫川漫岗区和丘陵漫岗区坡耕地土壤有机碳活性最差的坡位分别是坡下和坡中,而平原低地区不同坡位间无显著变化。研究结果为黑土坡耕地生态建设与保护技术的针对性设计奠定了理论基础。

关键词:典型黑土区;坡耕地;生态建设与保护;土壤总有机碳;土壤活性有机碳

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Characteristics of Changes in Active Organic Carbon in Surface Soil of Sloping Farmland in Typical Black Soil Areas

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Abstract: Taking the surface soil at different slope positions of sloping farmland in three typical types of landforms (overtopping and overtopping areas, hilly and overtopping areas, and plain low areas) in the black soil areas of Northeast China as the research object, the change characteristics of surface soil active organic carbon at different slope positions of slope land in black soil area were analyzed by measuring total organic carbon, highly active organic carbon, moderately active organic carbon, and low active organic carbon, exploring the differences in soil active organic carbon change characteristics of slope farmland in different landform types. The results showed that the variation range of total organic carbon content in the surface soil of slope farmland was 26.57 - 38.61 g/kg and the variation range of soil active organic carbon content was 1.85-5.67 g/kg. The change characteristics of total organic carbon and active organic carbon content in different slope positions of sloping farmland in three types of landforms were different. The variation characteristics of total organic carbon, medium active organic carbon and low active organic carbon content in the overtopping and overtopping areas were: slope up and slope middle significantly greater than slope down, and there was no significant difference between the slope up and slope middle. The variation characteristics of high active organic carbon content was the highest in slope middle and the lowest in slope down, and the high active organic carbon content was significantly different among different slope positions. The contents of total organic carbon and low active organic carbon in the hilly and overtopping areas were significantly different at different slope positions, and the slope down was significantly greater than slope up, slope up was significantly greater than slope middle. The changes in the content of high active organic carbon and medium active organic carbon were: slope up and slope down significantly greater than slope middle, and there was no significant difference between slope up and slope down. The content of total organic carbon and three levels of active organic carbon in the plain low areas had no significant difference among different slope positions. There were differences

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in the distribution patterns of active organic carbon in the surface soil of typical black soil areas among different landforms. The slopes with the worst activity in the overtopping and overtopping areas and the hilly and overtopping areas were slope down and slope middle, respectively. There was no significant change between different slope positions in the plain low areas. The research results have laid a theoretical foundation for the targeted design of ecological construction and protection technologies for black soil sloping farmland.

Keywords: Typical black soil areas; sloping farmland; ecological construction and protection; soil total organic carbon; soil active organic carbon

0 引言

有机碳作为土壤重要的组成部分,不仅起到维系植物生长的作用,同时还表征着土地的生产力^[1-7]。活性有机碳是土壤有机碳中较为活跃的部分^[8],是土壤碳库动态变化的早期指示指标^[9]。Loginow 等^[10]模拟有机碳被微生物、酶等的氧化分解作用,将活性有机碳能被 3 种不同浓度(33、167、333 mmol/L)的 KMnO_4 氧化的数量,分为高活性、中活性、低活性 3 种不同活性有机碳。由于不同活性有机碳中含碳有机化合物形态的不同,导致 3 种活性有机碳的化学性质、存在方式、生物有效性、稳定性及周转时间不尽相同,对外部环境干扰的反应程度也存在差异^[11]。因此,对不同活性有机碳进行定量研究,能够更加准确、细致地反映出土壤碳库的变化情况。

东北黑土区是我国重要的粮食生产基地,每年为国内市场提供近 40% 的商品粮^[12]。由于多年来高强度集约式耕作,东北黑土区坡耕地普遍存在土壤有机碳含量下降的问题,严重威胁国家粮食安全^[13]。在此背景下,铸牢北方生态安全屏障、持续加强黑土区生态建设与保护,不仅是新时代赋予林业行业的新使命,更是应对黑土地保护战略、国家粮食“压舱石”维护的重大需求。开展黑土区坡耕地土壤活性有机碳变化特征的研究,是科学认识坡耕地土壤质量与功能退化的基础,也是制约针对性设计黑土坡耕地生态建设与保护技术的瓶颈。虽然东北黑土区地处松嫩平原,但区内地形有着不同

程度的变化,不同地形作用下导致土壤侵蚀-沉积规律在坡面上的变化有所差异。目前,关于黑土区坡耕地土壤活性有机碳变化特征的研究主要集中在单一的地貌类型区内^[14],而忽略了黑土区拥有多种地貌类型这一重要的自然因素差异^[15]。关于黑土区多种地貌类型区内坡耕地不同坡位土壤活性有机碳变化特征的研究相对缺乏,制约了对于黑土区坡耕地活性有机碳变化特征的全面认识以及退化黑土的针对性修复。因此,本研究以典型黑土区 3 种地貌类型区(漫川漫岗区、丘陵漫岗区、平原低地区)坡耕地不同坡位(坡上、坡中、坡下)表层土壤为研究对象,通过测定土壤总有机碳、高活性有机碳、中活性有机碳和低活性有机碳等指标,探究不同地貌类型区坡耕地土壤活性有机碳变化特征的空间差异,旨在为系统揭示黑土坡耕地侵蚀退化机制、针对性设计研发生态修复与保护技术提供理论依据。

1 材料与方法

1.1 研究区概况

研究区为松嫩典型黑土区^[16],位于小兴安岭南侧的山前冲积台地上,是小兴安岭余脉向平原过渡地带,区内有漫川漫岗、丘陵漫岗和平原低地等多种地形。在典型黑土区内分别选择漫川漫岗、丘陵漫岗、平原低地 3 种地形区内开垦 60 a 的坡耕地为研究样地。坡耕地的坡度、坡向、坡长基本一致,均为大豆玉米轮作,现茬作物为大豆,前茬作物为玉米。研究区基本信息见表 1。

表 1 采样点基本信息

Tab. 1 Basic information of sampling points

地貌类型区 Landform type area	采样地点 Sampling location	地理位置 Geographical position	海拔/m Altitude	坡长/m Slope length	坡度/(°) Slope	年平均温度/°C Annual average temperature	年均降水量/mm Annual average precipitation
漫川漫岗区 Overtopping and overtopping areas	克山农场	48°11'~48°23' N 125°07'~125°36' E	240~340	410	4.1	1.3	503
丘陵漫岗区 Hilly and overtopping areas	鹤山农场	48°46'~49°02' N 124°53'~125°27' E	250~384	370	5.6	0.8	500
平原低地区 Plain low areas	赵光农场	47°54'~48°12' N 126°26'~127°6' E	240~330	450	2.8	0.5	570

1.2 研究方法

野外采样于2021年6月进行,在选定坡耕地的垄沟上沿平行于坡的方向设3条样线,每条样线按照坡上、坡中、坡下3个坡位设置取样点,在每个取样点表层(0~10 cm)采集0.5 kg土样装入塑料袋中带回实验室。将3条样线相同坡位的土壤样品均匀混合后分成3份,剔除石块和根系,放在室内自然风干后用于测定土壤总有机碳和活性有机碳。土壤总有机碳采用重铬酸钾容量-外加热法测定^[17];土壤活性有机碳采用高锰酸钾氧化法测定^[18],具体方法为:称取含15~30 mg碳的土样放入50 mL的离心管中,加入333、167、33 mmol/L的KMnO₄溶液25 mL,密封振荡1 h后,放入离心机以4 000 r/min的转速离心5 min,取离心后的上清液用去离子水按1:250比例稀释,然后将稀释液在分光光度计于565 nm波长处进行比色测定,利用KMnO₄消耗量来计算高、中、低3种活性有机碳含量,每个指标重复3次。

1.3 指标计算

土壤高、中、低活性有机碳含量计算公式如下^[19]

高、中、低活性有机碳含量(g/kg) = $(V \times 25 \times 250 \times 9) / (m \times 1000)$

式中:V为KMnO₄浓度变化值,mmol/L;25为KMnO₄用量,mL;250为稀释倍数;9为KMnO₄浓度变化1 mmol/L消耗的碳量,mg;m为烘干土质量,g。

土壤非活性有机碳含量为土壤总有机碳含量与土壤活性有机碳含量之差;土壤不同活性有机碳含量占比为土壤不同活性有机碳含量在土壤总有机碳含量中所占百分比^[2]。

1.4 数据处理

采用SPSS Statistics 27.0的单因素方差分析(ANOVA)和最小显著差异法(LSD)进行差异分析($P < 0.05$)。使用Pearson相关系数检验法对各指标进行相关性分析。采用Origin 2021软件绘图。

2 结果与分析

2.1 土壤总有机碳含量变化特征

由表2可知,坡耕地各坡位土壤总有机碳含量变化范围为26.57~38.61 g/kg,3种地貌类型区坡耕地不同坡位土壤总有机碳含量变化特征不同,漫川漫岗区土壤总有机碳含量变化特征为:坡上和坡中显著大于坡下,坡上和坡中无显著差异;丘陵漫

岗区土壤总有机碳含量变化特征为:坡下显著大于坡上、坡上显著大于坡中;平原低地区土壤总有机碳含量在不同坡位之间均未见明显差异。

表2 不同坡位土壤总有机碳含量

Tab. 2 Total organic carbon content of soil at

地貌类型区 Landform type area	different slope positions			g · kg ⁻¹
	坡上 Slope up	坡中 Slope middle	坡下 Slope down	
漫川漫岗区 Overtopping and overtopping areas	33.51±0.46a	34.21±0.84a	26.57±0.13b	
丘陵漫岗区 Hilly and overtopping areas	29.85±0.57b	26.76±0.22c	32.91±0.94a	
平原低地区 Plain low areas	36.50±0.99a	38.61±0.94a	37.57±0.97a	

注:数据为平均值±标准差;数据后不同字母表示坡位间差异显著($P < 0.05$)。

Note: The data in the table is the mean ± standard deviation; different letters after the data indicate significant differences between slope positions ($P < 0.05$).

2.2 土壤高活性有机碳含量变化特征

由表3可知,坡耕地各坡位土壤高活性有机碳含量变化范围为1.85~2.30 g/kg,3种地貌类型区坡耕地不同坡位土壤高活性有机碳含量变化特征不同,漫川漫岗区土壤高活性有机碳含量变化特征为:坡中显著大于坡上,坡上无显著大于坡下;丘陵漫岗区土壤高活性有机碳含量变化特征为:坡上和坡下显著大于坡中,坡上和坡下无显著差异;平原低地区土壤高活性有机碳含量在不同坡位之间均未见明显差异。

表3 不同坡位土壤高活性有机碳含量

Tab. 3 High active organic carbon content of soils

地貌类型区 Landform type area	at different slope positions			g · kg ⁻¹
	坡上 Slope up	坡中 Slope middle	坡下 Slope down	
漫川漫岗区 Overtopping and overtopping areas	2.22±0.03b	2.30±0.03a	1.88±0.03c	
丘陵漫岗区 Hilly and overtopping areas	2.15±0.05a	1.85±0.03b	2.09±0.05a	
平原低地区 Plain low areas	2.11±0.06a	2.10±0.09a	2.19±0.06a	

注:数据为平均值±标准差;数据后不同字母表示坡位间差异显著($P < 0.05$)。

Note: The data in the table is the mean ± standard deviation; different letters after the data indicate significant differences between slope positions ($P < 0.05$).

2.3 土壤中活性有机碳含量变化特征

由表4可知,坡耕地各坡位土壤中活性有机碳含量变化范围为3.62~4.43 g/kg,3种地貌类型区坡耕地不同坡位土壤中活性有机碳含量变化特征不同,漫川漫岗区土壤中活性有机碳含量变化特征为:坡上和坡中显著大于坡下,坡上和坡下无显著差异;丘陵漫岗区土壤中活性有机碳含量变化特征为:坡上和坡下显著大于坡中,坡上和坡下无显著差异;平原低地区土壤中活性有机碳含量在不同坡位之间均未见明显差异。

表4 不同坡位土壤中活性有机碳含量

Tab. 4 Medium active organic carbon content of soils at different slope positions $g \cdot kg^{-1}$

地貌类型区 Landform type area	坡上 Slope up	坡中 Slope middle	坡下 Slope down
漫川漫岗区 Overtopping and overtopping areas	3.90±0.06a	4.06±0.07a	3.62±0.12b
丘陵漫岗区 Hilly and overtopping areas	4.33±0.05a	3.63±0.09b	4.30±0.08a
平原低地区 Plain low areas	4.29±0.06a	4.38±0.09a	4.43±0.12a

注:数据为平均值±标准差;数据后不同字母表示坡位间差异显著($P<0.05$)。

Note: The data in the table is the mean ± standard deviation; different letters after the data indicate significant differences between slope positions ($P<0.05$).

2.4 土壤低活性有机碳含量变化特征

由表5可知,坡耕地各坡位土壤低活性有机碳含量变化范围为4.21~5.67 g/kg,3种地貌类型区坡耕地不同坡位土壤低活性有机碳含量变化特征不同,漫川漫岗区土壤低活性有机碳含量变化特征为:坡上和坡中显著大于坡下,坡上和坡中无显著差异;丘陵漫岗区土壤低活性有机碳含量变化特征为:坡下显著大于坡上、坡上显著大于坡中;平原低地区土壤低活性有机碳含量在不同坡位之间均未见明显差异。

2.5 土壤不同活性有机碳含量占比的变化特征

不同地貌区均为非活性有机碳占比最大,均超过50%,活性越大,比例越小,如图1所示。丘陵漫岗区各活性有机碳在不同坡位的占比变化较为明显,低活性有机碳比例相对较高且不同坡位之间变异性最大。漫川漫岗区高活性有机碳在不同坡位之间无显著变化,中、低活性有机碳含量占比变化表

表5 不同坡位土壤低活性有机碳含量

Tab. 5 Low active organic carbon content of soils at different slope positions $g \cdot kg^{-1}$

地貌类型区 Landform type area	坡上 Slope up	坡中 Slope middle	坡下 Slope down
漫川漫岗区 Overtopping and overtopping areas	4.87±0.11a	4.97±0.03a	4.21±0.07b
丘陵漫岗区 Hilly and overtopping areas	5.42±0.03b	5.18±0.05c	5.67±0.03a
平原低地区 Plain low areas	5.07±0.32a	5.15±0.07a	5.08±0.30a

注:数据为平均值±标准差;数据后不同字母表示坡位间差异显著($P<0.05$)。

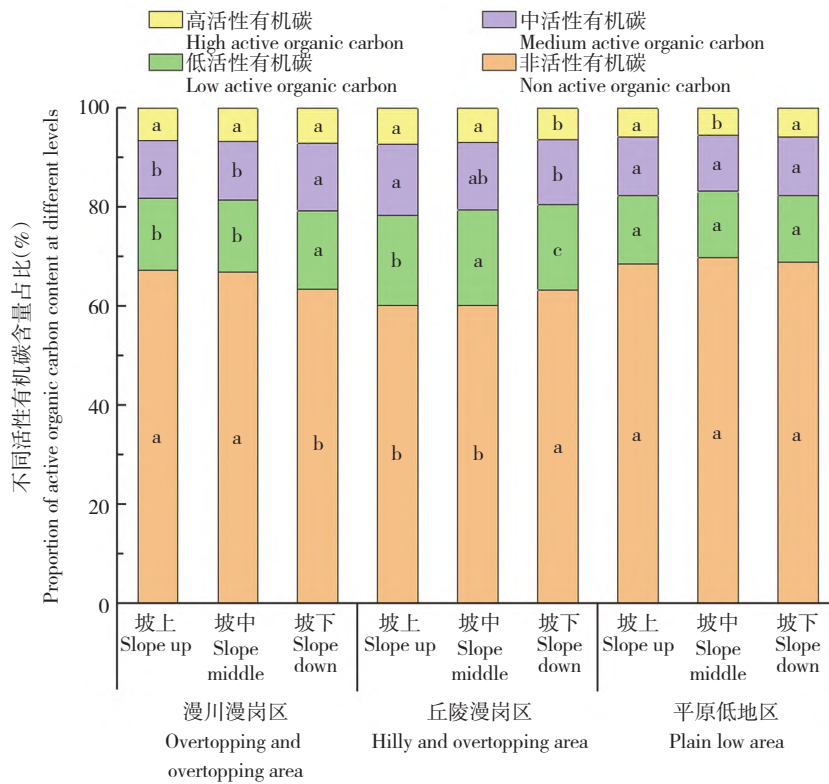
Note: The data in the table is the mean ± standard deviation; different letters after the data indicate significant differences between slope positions ($P<0.05$).

现为坡下显著大于坡上和坡中。平原低地区除坡中高活性有机碳显著小于坡上和坡下外,其他坡位中、低活性有机碳含量占比在不同坡位之间均未见明显差异。

3 讨论

活性有机碳是土壤有机碳中最为活跃的部分^[19],将活性有机碳分为高、中、低3种不同活性的有机碳,能够细致量化土壤活性有机碳在坡面上的变化情况^[20]。研究发现,3种地貌类型区坡耕地各坡位土壤高、中、低活性有机碳占土壤总有机碳比例由大到小表现为:低活性、中活性、高活性,这与齐思明^[21]研究结果相符合。相关分析表明(表6)土壤高活性有机碳和中活性有机碳与土壤总有机碳呈极显著正相关,这也说明了高活性有机碳和中活性有机碳与土壤总有机碳之间的紧密联系。

3种地貌类型区坡耕地不同坡位土壤总有机碳和高、中、低活性有机碳变化特征存在差异,漫川漫岗区坡耕地土壤总有机碳和高、中、低活性有机碳含量均表现为坡下最低,这是由于在漫川漫岗区,坡耕地坡下位置处于整个坡面的径流汇集区域,受到较强的径流冲刷力,加剧团聚体破碎的同时加快了有机碳的矿化,导致坡下土壤总有机碳含量要低于坡上和坡中^[22];丘陵漫岗区坡耕地土壤总有机碳和高、中、低活性有机碳含量均表现为坡中最低,这是因为有相关研究表明:坡中位置的水蚀速率要大于坡上,使坡中受到更严重的水力侵蚀,导致土壤有机碳的流失^[23];平原低地区土壤总有机碳和高、



不同字母表示同一地貌类型区、同一活性有机碳含量占比在坡位间差异显著 ($P < 0.05$)。

Different letters in the figure indicate significant differences in the proportion of the same active organic carbon content in the same geomorphic type area between slope locations ($P < 0.05$).

图 1 不同坡位土壤各活性有机碳含量占比

Fig. 1 Proportion of active organic carbon content in different levels of soil at different slope positions

表 6 土壤总有机碳及活性有机碳之间的相关系数

Tab. 6 Correlation coefficient between soil total organic carbon and active organic carbon

指标 Index	土壤总有机碳 Soil total organic carbon	高活性有机碳 High active organic carbon	中活性有机碳 Medium active organic carbon	低活性有机碳 Low active organic carbon
土壤总有机碳 Soil total organic carbon	1.000	0.661 **	0.743 **	0.258
高活性有机碳 High active organic carbon		1.000	0.553 **	0.239
中活性有机碳 Medium active organic carbon			1.000	0.571 **
低活性有机碳 Low active organic carbon				1.000

注: ** 表示极显著相关 ($P < 0.01$)。

Note: ** indicates an extremely significant correlation ($P < 0.01$).

中、低活性有机碳含量在坡上、坡中、坡下无显著差异,这可能是因为:平原低地区地势较为平坦,在较大的地貌背景下,坡耕地坡面上的起伏变化幅度相对较小,各坡位受到的侵蚀程度基本一致,导致各坡位土壤总有机碳和高、中、低活性有机碳含量没

有显著差异的原因^[24]。虽然黑土区地势平坦,但区内仍存在多种地貌类型,不同地貌类型区坡耕地不同坡位受到侵蚀营力类型、侵蚀-沉积规律的变化皆不同^[25],从而导致不同活性有机碳的变化特征存在差异^[26]。因此在黑土坡耕地修复过程中,建议考

考虑地貌类型以及坡位等因素的差异,有针对性地开展修复相关工作。

4 结论

3种地貌类型区坡耕地不同坡位表层土壤总有机碳和活性有机碳含量变化特征存在差异,漫川漫岗区总有机碳、中活性有机碳和低活性有机碳含量变化特征为:坡上和坡中显著大于坡下,坡上和坡中无显著差异;高活性有机碳含量变化特征表现为:坡中显著大于坡上、坡上显著大于坡下。丘陵漫岗区总有机碳和低活性有机碳含量变化特征为:坡下显著大于坡上、坡上显著大于坡中;高活性有机碳和中活性有机碳含量变化特征为:坡上和坡下显著大于坡中,坡上和坡下无显著差异。平原低地区总有机碳、高活性有机碳、中活性有机碳、低活性有机碳含量变化在不同坡位间均未见明显差异。研究结果不仅为系统揭示黑土区坡耕地土壤侵蚀退化机制积累了数据,而且为进一步开展黑土地生态修复以及黑土区生态建设与保护技术研发奠定了理论基础。

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