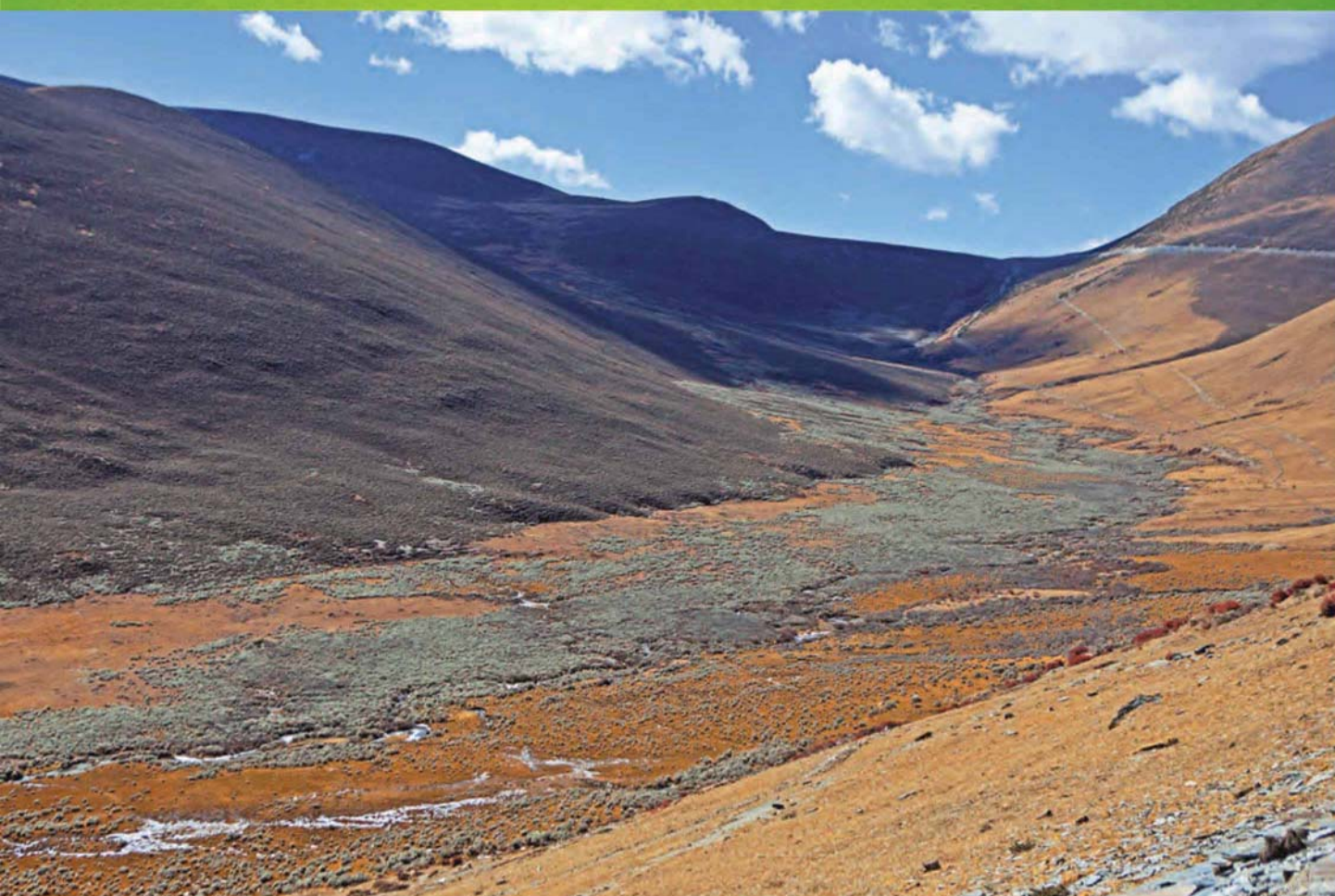


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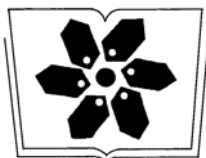
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封面图说: 川西高山地带土壤及植被——青藏高原东缘川西的高山地带坡面上为草地,沟谷地带由于低平且水分较充足,生长有很多灌丛。川西地区大约在海拔 4000m 左右为林线,以下则分布有亚高山森林。亚高山森林是以冷、云杉属为建群种或优势种的暗针叶林为主体的森林植被。作为高海拔低温生态系统,高山-亚高山地带土壤碳被认为是我国重要的土壤碳库。有研究表明,易氧化有机碳含量与海拔高度呈显著正相关,显示高海拔有利于土壤碳的固存。因而,这里的表层土壤总有机碳含量随着海拔的升高而增加。

彩图及图说提供: 陈建伟教授 北京林业大学 E-mail: cites.chenjw@163.com

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秦纪洪, 王琴, 孙辉. 川西亚高山-高山土壤表层有机碳及活性组分沿海拔梯度的变化. 生态学报, 2013, 33(18): 5858-5864.

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川西亚高山-高山土壤表层有机碳及 活性组分沿海拔梯度的变化

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摘要:青藏高原东缘亚高山-高山地带土壤碳被认为是我国重要的土壤碳库, 作为高海拔低温生态系统, 土壤碳对土壤暖化的响应可能也更加敏感。该区域亚高山森林一般分布在海拔 3200 m 以上, 上缘接高山树线和灌丛草地, 土壤有机碳含量高。海拔梯度上变化的土壤环境因子是主要土壤温度, 海拔梯度上高寒土壤有机碳及活性有机碳组的分布格局, 可体现海拔梯度上温度因子对土壤碳动态的影响。对沿海拔 3200 m(亚高山针叶林)、3340 m(亚高山针叶林)、3540 m(亚高山针叶林)、3670 m(亚高山针叶林)、3740 m(亚高山针叶林)、3850 m(高山林线)、3940 m(高山树线)、4120 m(高山草地)的土壤表层(0—20 cm)有机碳和活性有机碳组分含量进行分析, 结果表明在该海拔范围内, 表层土壤总有机碳含量随着海拔的升高而增加, 显示高海拔有利于土壤碳的固存; 土壤活性有机碳组分中, 颗粒态有机碳含量及其占总有机碳比例与海拔呈显著正相关, 在海拔最高的 4120 m 含量和占有有机碳总量比例分别达到 50.81 g/kg 和 56.52%。在该海拔范围内海拔越高颗粒态有机碳占有有机碳比例越高, 显示高海拔土壤有机碳更多以土壤颗粒态碳形式贮存。微生物量碳、水溶性碳、轻组分有机碳与海拔高度没有明显的相关性, 表明这些活性有机碳组分受海拔因素影响不大; 易氧化有机碳含量与海拔高度显著正相关。因此, 颗粒态有机碳含量及其比例可作为高海拔地带土壤活性有机碳库动态的特征指标, 表征高海拔地带土壤有机碳动态与贮量受温度影响的指标。

关键词: 亚高山-高山土壤; 土壤有机碳; 土壤活性有机碳; 颗粒态有机碳; 海拔梯度; 土壤暖化

Changes of organic carbon and its labile fractions in topsoil with altitude in subalpine-alpine area of southwestern China

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Abstract: The alpine-subalpine area of the eastern Tibetan Plateau, as typical high-altitude low-temperature ecosystem, is one of the most important soil carbon pools in China. The soil there has high content of organic carbon due to abundant biomass of the alpine forest and shrub land distributed in the area, and is considered to be more sensitive to soil warming than that in the tropic or subtropical area. The spatial distribution pattern of soil carbon and its labile fractions with altitude could reflect the combined effects of altitudinal biological and environmental factors, particularly the temperature, on soil carbon dynamics. In this study, total organic carbon and its labile fractions including particulate organic carbon, microbial biomass carbon, light fraction of organic carbon, easily oxidized organic carbon, and water soluble organic carbon in topsoil (0—20 cm) were determined with an aim to understand changes of their characteristics with elevational gradients. The investigated altitude range was from 3200 to 4120 m that was covered by subalpine coniferous forest at 3200, 3340, 3540, 3670 and 3740 m, timberline at 3850 m, alpine tree line at 3940 m, and alpine meadows at 4120 m. The results showed that content of total organic carbon in topsoil increased significantly with altitude in the studied range, indicating that high

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altitude and low temperature are conducive to carbon sequestration in soil. Content of particulate organic carbon content and its ratio to total organic carbon showed significantly positive correlations with altitude, with its concentration reaching up to 50.81 g/kg and accounting for 56.52% of total organic carbon, as measured at the highest elevation of 4120 m. Therefore, particulate organic carbon had become the major component of total organic carbon with its ratio gradually increased with altitude. On the other hand, microbial biomass carbon, water-soluble carbon, light fraction of organic carbon, as the group of less affected labile fractions, did not change significantly within the studied altitude range, while the fraction of easily-oxidized organic carbon tended to increase with altitude. To sum up, concentrations of particulate and easily-oxidized organic carbon fractions in topsoil could be used as indicators of labile organic carbon dynamics and balance in subalpine-alpine area at different altitudes. Moreover, soil warming may exacerbate the mineralization of particulate organic carbon, resulting in the decrease of the proportion of total organic carbon in soil. The elevational gradient study offered useful insights into the dynamics of high-altitude soil carbon and the differentiation of its labile fractions. It is indicated that soil carbon pool at high altitude could become a new carbon source under future warming scenarios.

Key Words: subalpine-alpine soil; soil organic carbon; soil labile organic carbon; particulate organic carbon; altitudinal gradient; soil warming

土壤碳是全球陆地生态系统最大的碳库,是陆地植被碳储量的 3 倍和大气碳库的 2 倍^[1]。高海拔/纬度(极地与高山)低温土壤因其具有更高的碳密度而在全球土壤碳库中具有重要地位^[2],同时高海拔和高纬度地带在全球变化中增温更加显著^[3-4],因而温度对低温土壤的影响可能更加明显^[5-6],这可能使高海拔地带比低海拔地带的土壤碳更易受全球增温的影响^[7-8]。对同类植被而言海拔梯度实质上是温度的梯度变化,海拔梯度上有机碳状况反映温度梯度作用的结果,土壤碳储量在分布方面没有明显规律^[7,9];但是土壤颗粒态有机碳占有有机碳总量的比例随着海拔升高而升高,颗粒态有机碳周转时间随着海拔升高而降低^[9-10]。近年来,低温土壤碳对全球变化的响应引起越来越受到关注,尽管对于土壤碳库中惰性组分(Resistant SOC)和活性组分(Labile SOC)的温度敏感性还有争论^[11-13],但基本上都认为低温土壤有机碳对温度的敏感性比热带亚热带土壤更高。

青藏高原东缘高山-亚高山地带主要分布着高山草甸-亚高山森林,其中海拔 3200 m 以上是亚高山暗针叶林,暗针叶林上缘(川西高原多在 3700—3900 m)是高山灌丛和高山草甸。高山-亚高山地带是我国重要的土壤碳库^[14-15],温度在垂直梯度上分异明显,有利于开展土壤碳动态对温度变化的响应特征的原位研究。近年来,对亚高山森林或者高山草甸土壤碳储量与组分^[16-19]、土壤酶活性^[20-21]、微生物量与土壤呼吸^[22]等特征与动态进行了很多研究,逐步揭示了高山或者亚高山土壤生态系统的碳过程与动态及对冻融与温度变化等的响应特征,以及环境梯度上凋落物周转(贡嘎山 2100—3900 m)^[23]、酶活性(毕棚沟 3023—3582 m)^[24]区别于其他低海拔土壤的生态与生物化学过程与动态。青藏高原及其周边区域作为全球平均海拔最高的高寒生态系统,对其海拔梯度上土壤有机碳的分异及其在气候变化中的响应特征方面的研究还显得不足。本研究对不同海拔梯度上,川西典型的亚高山森林及高山下部邻接区的土壤碳及活性组分的自然分异特征开展研究,探索该区域与其他高寒土壤和高纬度土壤的异同,对于了解全球暖化背景下青藏高原东缘高寒生态系统土壤有机碳可能的响应特征及变化趋势具有重要意义。

1 实验材料与方法

1.1 研究区域概况

野外定位实验点位四川阿坝梦笔山,地处小金川支流抚边河上游玛嘉沟小流域,为典型的高山深谷地形,溪沟两侧坡向分别为东北和西南,坡度 35°左右;土壤从下至上分别为山地棕色针叶林土和高山草甸土。研究区亚高山针叶林主要是岷江冷杉(*Abies faxoniana*)和紫果云杉(*Picea balfouriana*)为建群种的暗针叶林,林龄 200a 至 50a 左右;除乔木树种外,林下和林窗零星分布有细枝茶藨子(*Ribes tenue*)、四川忍冬(*Lonicera szechuanica*)、红毛五加(*Acanthopanax giraldii*)、杜鹃花多个种(*Rhododendron* spp.)、柳属几个种(*Salix* spp.)等灌木植物。高山灌丛草地一般分布在海拔 3800—4100m,主要是高山杜鹃(*Rhododendron delavayi*)、千里香杜鹃(*Rhododendron thymifolium*)灌丛呈丛状散生,逐渐向高山草甸过渡。海拔梯度上的环境异质性体现在植被和温度的梯度分布,同一类型植被下主要是温度的差异。2010—2012 年期间在不同海拔高度实测的土壤温度状况见表 1。

1.2 采样方法

选择邻近的坡向和坡度相近的 4 个坡面,作为 4 个重复;4 个相邻的坡面之间为溪沟间隔,垂直采样线之间的水平距离在 800m 至 1500 m 之间,坡度介于 30°—52°,坡向均为东北,范围介于 E31.515—31.533°,N102.343—102.434°之间。在每个坡面的 3200—4100 m 海拔,每隔 100—200 m 设置一个横向 10 m 的采样断面,在采样断面上每隔 1 m 设置一个采样点,共 5 个采样

点(为5个平行采样点)。每个坡面采样断面须包括亚高山针叶林、林线边缘、树线、乔木上限、高山草甸这5个典型关键环境梯度,根据实地情况确定所有剖面均在海拔3200 m(亚高山针叶林)、3340 m(亚高山针叶林)、3540 m(亚高山针叶林)、3670 m(亚高山针叶林)、3740 m(亚高山针叶林)、3850 m(高山林线)、3940 m(高山树线)、4120 m(高山灌丛草地)植被未被扰动的土壤进行采样。采样时间为2012年7月份,采样时去掉地上植被和凋落物覆盖层,采集0—20 cm矿质土壤,土壤样品用冰盒带回实验室。过2 mm筛,4℃保存或者立即分析。

表1 研究区域不同海拔高度的土壤温度状况(2010-07—2012-06)

Table 1 Soil temperature regime at different altitude of the study area

海拔/m Altitude	年均气温/℃ Annual average temperature	5 cm 土壤年最低温/℃ Minimum soil temperature at 5 cm	5 cm 土壤年均温/℃ Annual soil average temperature at 5 cm	5 cm 土壤月均温≤0℃月份 Month average temperature ≤ 0℃
3200	8.1	-5.0	7.9	12月—1月
3450	5.5	-5.0	5.6	12月—2月
3670	4.3	-4.3	4.3	12月—3月
3850	4.0	-4.5	3.9	12月—3月
4120	3.7	-5.0	3.4	11月—3月

1.3 分析方法

颗粒态碳(POC)采用 Cambardella & Elliott 的方法测定^[25];水溶性有机碳(DOC)采用 Jones 方法测定^[26];轻组分碳(LFOC)采用 Janzen 等的密度为1.7 g/cm³的NaI溶液浮选法测定^[27];易氧化有机碳(EOC)采用 Blair 的KMnO₄(333 mmol/L)氧化法测定^[28];微生物量碳(MBC)采用 Vance 等的熏蒸-浸提法测定^[29]。数据采用 SPSS 11.0 软件包进行多重比较以及相关分析。

2 实验结果与分析

本次采样分析了西南亚高山-高山土壤表层(0—20 cm 矿质土壤层)的有机碳总量及活性有机碳组分含量(图1),结果显示海拔因子(温度)对不同的活性有机碳组分的影响是有差异的。从图1可以看出,有机碳总量沿海拔梯度在同一植被类型中逐步升高到稳定水平,但是在林缘以上的高山灌丛草地土壤则显著下降;土壤活性有机碳组分中,水溶性有机碳和轻组分有机碳含量波动幅度最大而且没有明显变化,颗粒态有机碳和易氧化有机碳含量沿海拔升高增加的趋势明显,微生物量碳沿海拔没有明显的变化规律。

2.2 表层土壤有机碳组分之间及与海拔梯度的关系

土壤有机碳与活性组分之间的相关性见表2。总有机碳、颗粒态有机碳以及易氧化有机碳与海拔呈显著正相关,表明在亚高山-高山梯度上,表层土壤总有机碳、颗粒态有机碳和易氧化有机碳库受到海拔因素的显著影响。对于高山-亚高山表层土壤有机碳组分而言,颗粒态有机碳和易氧化有机碳与总有机碳极显著正相关,显示土壤总有机碳含量受二者的影响显著;而微生物量碳、水溶性有机碳以及轻组分有机碳受海拔高度的影响未达到显著水平。就活性有机碳组分之间的关系来看,只有颗粒态有机碳与易氧化有机碳之间相关性达到了极显著水平,显示在高山-亚高山土壤有机碳组分中,颗粒态有机碳与易氧化有机碳作为活性有机碳的指标,二者可相互替代或者部分替代。

表2 亚高山-高山表层土壤有机碳、微生物量碳、水溶性碳、颗粒态碳以及易氧化碳海拔高度之间的相关性

Table 2 Correlation between altitude, total organic C, microbial biomass C, dissolved organic C, particulate organic C, light fraction organic C and easily oxidation organic C of subalpine-alpine topsoil

	海拔 Altitude	土壤有机碳 Total organic C (TOC)	微生物量碳 Microbial biomass C (MBC)	水溶性碳 Dissolved organic C (DOC)	颗粒态碳 Particulate organic C (POC)	易氧化碳 Easily oxidation organic C (EOC)
土壤有机碳 TOC	0.510 *					
微生物量碳 MBC	0.112	0.204				
水溶性碳 DOC	0.074	-0.180	0.343			
颗粒态碳 POC	0.487 *	0.834 **	0.049	-0.180		
易氧化碳 EOC	0.481 *	0.867 **	-0.043	-0.329	0.873 **	
轻组分碳 LFOC	0.078	0.278	-0.501 *	-0.542 *	0.412	0.481 *

Pearson 相关分析,双侧检验,相关系数后标有*为显著相关($P<0.05$),标有**为极显著相关($P<0.01$)

2.3 活性有机碳比例

不同海拔高度土壤表层活性有机碳所占土壤总有机碳的比例见表3。结果显示,微生物量有机碳(MBC)、水溶性有机碳

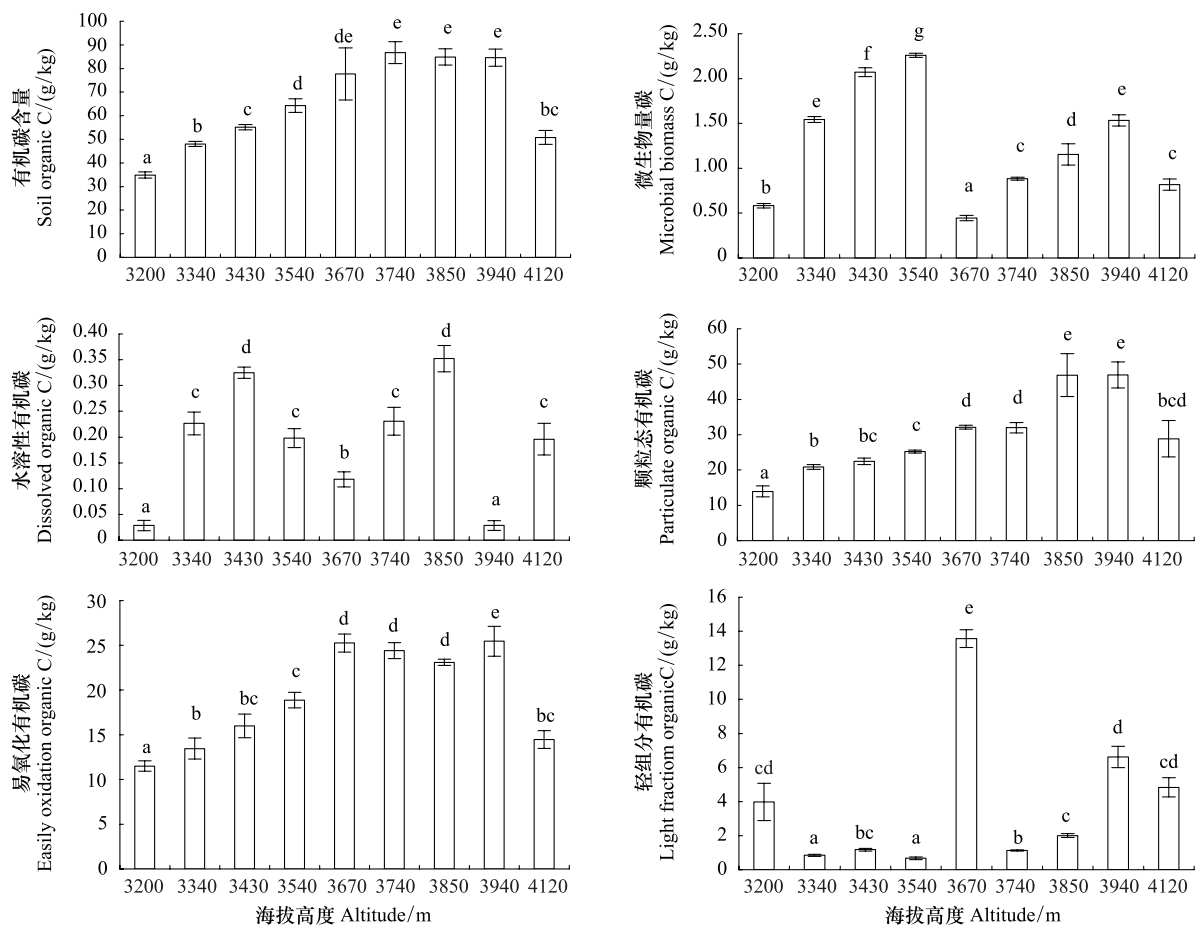


图1 亚高山-高山海拔梯度上土壤表层(0—20 cm)有机碳及活性有机碳组分含量

Fig.1 Organic C and labile fractions concentration in subalpine-alpine topsoil (0—20 cm) along an elevational gradient

误差线为标准差,字母相同则表示差异不显著($P<0.05$)

(DOC)、轻组分有机碳(LFOC)占该层土壤总有机碳的比例较小,而且在海拔梯度上没有明显的变化趋势,其中MBC所占比例均低于2%,DOC比例除海拔3430 m为2.7%外均低于2%,LFOC尽管比例最高达到17.76%,但是没有明显的海拔分异。EOC比例尽管很高,但是在海拔梯度仍然没有明显的变化趋势。POC除个别海拔高度(3670m)外,比例随着海拔升高,在海拔4120m达到最高为56.52%。

表3 亚高山-高山土壤不同活性有机碳组分占该层土壤有机碳全量的百分比

Table 3 Percentage of labile fractions in total organic C of subalpine-alpine topsoil along an elevational gradient

海拔/m Altitude	微生物量碳/% MBC	水溶性碳/% DOC	颗粒态碳/% POC	易氧化有机碳/% EOC	轻组分碳/% LFOC
3200	0.92(±0.03)	0.17(±0.01)	36.41(±2.10)	16.54(±0.62)	5.74(±0.16)
3340	1.67(±0.12)	0.08(±0.01)	40.08(±1.89)	33.03(±1.13)	11.49(±0.27)
3430	0.72(±0.04)	2.70(±0.18)	50.42(±1.67)	31.75(±1.08)	13.12(±1.02)
3540	0.70(±0.04)	0.06(±0.01)	51.01(±1.52)	32.38(±0.92)	9.41(±0.33)
3670	0.58(±0.01)	0.15(±0.01)	41.96(±0.93)	32.85(±0.57)	17.76(±0.41)
3850	0.95(±0.02)	0.22(±0.01)	52.10(±2.23)	34.59(±0.33)	17.70(±0.52)
3940	1.82(±0.09)	0.13(±0.00)	55.46(±1.58)	30.12(±0.61)	7.82(±0.13)
4120	1.61(±0.12)	1.96(±0.21)	56.52(±2.09)	28.58(±0.28)	9.54(±0.31)

表中值为平均值(±标准差)

3 讨论

与温带土壤相比,高海拔和高纬度的低温土壤有机碳含量更高^[27],在海拔梯度上树线附近矿质土壤中有机碳含量随着海拔升高而增加,而随着年均温升高而降低^[30]。本文研究表明川西高寒森林土壤表层有机碳含量随着海拔梯度升高,与一些研

究认为土壤有机碳在海拔梯度上分布无规律^[7,9]不同,实际上本文中高寒针叶林土壤有机碳是随着海拔升高而增加的,而高山草地(4120 m)土壤碳含量明显降低。有研究显示高海拔土壤活性有机碳高于低海拔土壤^[9,31],本研究的结果也证实了这一观点。尽管对颗粒态有机碳形成的机理还不是很清楚,但是颗粒态有机碳占有有机碳总量的比例随着海拔升高而增加的趋势应该是高海拔土壤一个显著的特征。由于低温土壤的活性有机碳组分对暖化的响应明显^[32],作为有机碳活性组分之一的颗粒态有机碳对增温的效应也可能更加显著。因此,颗粒态有机碳在高海拔土壤中含量高,空间分异规律性强,加上高海拔地带土壤温度的高度异质性,那么颗粒态有机碳可以作为气候暖化背景下,研究高寒土壤有机碳时空动态结果的指标之一。

活性有机碳不同组分周转时间不同,土壤微生物量碳等快速周转的活性有机碳周转时间从 24d 到 102d^[33],而土壤自由态颗粒态有机碳等周转时间则达到数年至上百年^[31]。对于高寒土壤,海拔越高,作为活性组分之一的颗粒态有机碳占有有机碳总量比例越高,土壤有机碳的潜在活性也越高,因此受到土壤温度的影响可能更大,这可能是导致高海拔土壤碳在升温情形下稳定性降低的原因之一^[34]。已有证据显示,颗粒态有机碳平均周转时间随着海拔降低而缩短^[31],长期持续增温使低温土壤的活性有机碳含量降低^[35],本文的结果也间接证实了这一趋势。因此,如果高海拔地带的土壤暖化成为事实,则颗粒态有机碳的潜在活性更容易转化为实际的矿化作用,但还需对不同区域的高海拔土壤开展更多的研究,寻求不同组分活性有机碳周转时间的量化证据。

全球暖化对高寒生态系统的效应是比较确定的,如 Harsch 对 1900 年以来的 103 份关于全球 166 个观测点树线动态的数据进行分析,结果显示 52% 的观测点树线上移,1% 出现树线后退,47% 保持稳定,在保持树线位置稳定的情形下多出现乔木密度的增加^[36]。对于高寒土壤,有研究认为土壤有机碳稳定组分也和活性有机碳组分一样对增温产生动态响应^[12-13],而且山地土壤有机碳温度敏感性随着稳定组分的增加而升高^[8],但是关于低温土壤有机碳的温度敏感性随着稳定组分增高是不是由于高比例颗粒态有机碳间接引起的效应,以及有机碳稳定组分与活性组分之间转化的定量关系,这方面还少见研究。因此,对于同一植被类型的高寒土壤生态系统而言,海拔梯度的差异实际上是土壤温度的差异(表 1),如果高寒土壤的颗粒态有机碳比例是特定温度条件下产生的结果,那么目前较低海拔土壤总有机碳和颗粒态有机碳的现状,可能是未来全球暖化导致的较高海拔土壤增温的情形,使高海拔地带土壤表层中高含量(多超过 20 g/kg)、高比例(超过该层总有机碳含量 50%)的颗粒态有机碳可能加快释放,从而成为新的土壤碳源。

4 结论

通过对海拔 3200—4120 m 西南高山-亚高山海拔梯度上土壤表层(0—20 cm)有机碳和活性有机碳组分的研究,海拔梯度实质上体现了温度对有机碳及不同活性组分的影响,得到以下结论:

(1) 高寒森林表层土壤总有机碳随着海拔的升高而增加,高海拔低温环境有利于高海拔森林土壤碳固存;活性有机碳组分中,颗粒态有机碳含量及其占总有机碳比例与海拔呈显著正相关,随着海拔的升高而上升,在海拔最高的 4120 m 含量和占有有机碳总量比例分别达到 50.81 g/kg 和 56.52%;而微生物量碳、水溶性碳、轻组分有机碳与海拔高度没有明显的相关性,表明这些活性有机碳组分受海拔因素影响不大。

(2) 颗粒态有机碳含量及易氧化有机碳含量与海拔高度显著正相关,同时颗粒态有机碳与易氧化有机碳含量显著相关,表明颗粒态有机碳与易氧化有机碳之间的密切关系,土壤有机碳在高海拔上更多是以颗粒态有机碳(易氧化有机碳)形式存在;以颗粒态有机碳为主的活性有机碳比例高暗示了高海拔土壤有机碳的不稳定性也更高。因此,颗粒态有机碳(易氧化有机碳)的含量和比例可能是表征高海拔地带土壤有机碳及活性组分动态特征及受海拔因素(土壤温度)影响的有效指标。

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