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# 多年冻土区森林土壤可溶解性有机碳研究进展及影响因素

**朱宇奇**

哈尔滨师范大学地理科学学院，黑龙江 哈尔滨

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## 摘　要

**多年冻土区是典型的生态环境脆弱区和全球重要的土壤碳库。气候变暖引发的多年冻土融化加剧了土壤中可溶解性有机碳(DOC)的释放与迁移，对全球碳循环产生了显著影响，进而可能加剧全球气候变化。近年来，相关研究集中探讨了多年冻土泥炭地可溶性有机碳的季节变化特征，包括浓度变化、化学组成以及迁移特性，揭示了温度、土壤水分状况、植被变化、泥炭地排水及微生物活动等多种因素对可溶性有机碳的显著影响。随着全球气候变暖加剧，多年冻土的退化进一步加速了土壤活动层内微生物群落组成的改变，推动了碳的矿化过程，增加了向大气释放的潜在风险。当前广泛应用的紫外可见光谱与高分辨率质谱技术虽可揭示DOC的芳香性及腐殖质等特征，但仍然缺乏分子层面的深入解析。此外，针对中高纬度多年冻土泥炭地的研究仍然较为匮乏。因此，未来需进一步深入研究多年冻土泥炭地DOC特征的季节变化机制及其环境影响因素。**

## 关键词

**多年冻土，可溶性有机碳，气候变暖，森林土壤，泥炭地，碳循环**

# Seasonal Variation of Dissolved Organic Carbon Characteristics in Permafrost Forest Soils: Research Progress and Influencing Factors

**Yuqi Zhu**

School of Geographical Sciences, Harbin Normal University, Harbin Heilongjiang

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## Abstract

**Permafrost regions are ecologically fragile zones and important global soil carbon reservoirs. The thawing of permafrost induced by climate warming accelerates the release and migration of dissolved organic carbon (DOC), significantly impacting global carbon cycling and exacerbating climate change. Recent research has extensively examined the seasonal variations of DOC concentration, composition, and sources within forest soils in permafrost regions. Studies indicate substantial DOC variability influenced by factors such as temperature fluctuations, soil moisture, vegetation dynamics, microbial activities, and hydrological conditions. DOC in these regions demonstrates notable seasonal variation, influenced by factors including thaw depth, vegetation type, drainage patterns, and microbial activities. Techniques such as ultraviolet-visible spectroscopy and high-resolution mass spectrometry have been applied to evaluate DOC's chemical characteristics, particularly its aromaticity and humic components. However, these approaches have limitations in revealing molecular-level information, especially within mid-to-high latitude permafrost peatlands, where related studies remain scarce. Future investigations should focus on elucidating the underlying mechanisms of DOC seasonal variability and exploring environmental factors influencing DOC dynamics in diverse permafrost ecosystems.**

## Keywords

**Permafrost, Dissolved Organic Carbon, Climate Warming, Forest Soil, Peatlands, Carbon Cycling**



## 1. 引言

气候变化引起了极端气候事件的增加，同时也加剧了冻土的退化与消失[1]-[3]，全球范围内的多年冻土正在变暖，在 2007~2016 年，地表温度接近年变化深度的连续多年冻土区温度增加了 0.39℃ ±0.15℃，多年冻土变暖已经潜在的放大了全球气候变化[4]，极端的气候事件例如极端潮湿的夏季，若要沿着当前浓度路径所预测基于大气温度的升高，多年冻土会加快的退化和消失[5]。冻土区是典型的生态环境脆弱区和主要的土壤碳库[6] [7]。在青藏高原的相关研究表明气候变暖激发了冻土退化，改变了多年冻土区活动层微生物组成，群落稳定性、功能和生物化学相关过程的碳流失[6] [8] [9]。冻土融化也会加剧融化多年冻土区地下冰并且改变地表水文结构，导致了重要的变化在微生物的生态进化，生物化学过程和热效应[6] [10]。当冻土退化时，一些有机碳将会被矿化为二氧化碳和甲烷，尽管这种冻土碳反馈的时间和范围仍然不确定[11]。融化的有机质可能被矿化在原地或者之后迁移到下坡或者下游生态系统[12]-[14]。因此，研究这些离开原位的碳的命运对于预测冻土退化后当地和全球的相关后果是至关重要的，因为被迁移的碳可以被矿化至大气中，被存储在沉积物中或者并入水生或者海洋食物网之中[15]-[17]。可溶解性有机碳是溶解在水中可以通过 0.45 μm 滤膜部分的总的有机碳[18]，是土壤碳库中最可移动的和被生物反应的[19]。在多年冻土退化期间可溶解性有机碳的产生或释放可以被迅速的矿化或者迁移很长的距离[13] [20]-[22]。潜在的影响了河流、湖泊、和河口生态系统，也影响了陆地碳平衡[23] [24]。这种持续存在的多年冻土可溶解性有机碳的移动通过土壤和水文所决定的迁移时间和矿化比率[25]-[28]，在多年冻土区通过土壤到河网的水流路径和留存时间取决于融化的深度[29] [30]，以及与浅层融化深度相关的和小的储

水相关的在土壤和河流对于降水迅速的响应[31]-[34]。因此，融化深度影响了可溶解性有机碳向溪流河网中的传输[28] [29]。

在过去十年间，研究者逐渐将关注重点从可溶解性有机碳的浓度转向其特征，特别是在泥炭地生态系统中，可溶性有机碳特征受到排水过程的显著影响。这一因素甚至比浓度更为关键，因为其决定了可溶性有机碳在碳循环中迁移和转化的命运[35] [36]。由于可溶性有机碳具有高度的化学异质性，其不同组分及变化特征对于理解可溶性有机碳在环境中的行为至关重要，而这些特征主要受其化学组成的控制。例如，可溶性有机碳中高比例的芳香性化合物可显著抑制其分解[37]，而多酚类物质则能够降低微生物活性并抑制酶的产生[38] [39]。

尽管已有研究探讨了可溶性有机碳的基本特征，但仍有多个关键科学问题尚未解决。本研究综述的核心问题包括：(1) 不同环境因素(温度、土壤水分、植被类型等)如何驱动 DOC 浓度和组成的季节变化？(2) 气候变暖是否增强了 DOC 的迁移及转化速率？(3) 不同类型多年冻土生态系统(如森林、草甸、湿地)对 DOC 变化的驱动因子是否存在差异？基于已有研究，我们假设在多年冻土退化过程中，较高温度和水文变化可能加速 DOC 的释放和矿化，同时不同植被类型对 DOC 组成具有重要调控作用。

## 2. 多年冻土区可溶性有机碳的来源、化学组成及环境影响

多年冻土活动层和植被生长被认为很容易收到气候变暖的威胁[40]-[45]。近年来对于气候变化引起可溶性有机碳侧向迁移的相关研究显示，在多年冻土区，土壤、表层有机层和植被渗滤液是可溶性有机碳的主要来源[46]，植被通过落叶和根系分泌物主动释放有机碳，而降水后的直流和茎流导致了碳从叶片和根茎中的淋滤，根据对茎流的量化研究显示，在冠层下(直流和茎流)采集的水样中的有机碳含量(12 mg C $L^{-1}$)远高于冠层上采集的水样(2.4 mg C $L^{-1}$) [47]。而在西伯利亚中部落叶松林的可溶性有机碳直流的年平均输出量为 0.1~0.2 g C $m^{-2}$ [48]。土壤溶液中的可溶性有机碳和土层中储存的碳密切相关。土壤表层的有机层是陆地可溶性有机碳的主要来源，估计约 24 g C $m^{-2}$ [49]。在多年冻土区有机土壤层中估计有约 1%的土壤有机碳作为可溶性有机碳存在[50]，多年冻土区的深层土壤也包含了大量的可溶性有机碳，根据测量融化的多年冻土，原地采集的样品在实验室测定可溶性有机碳高达 116 mg C $L^{-1}$ [51]，根据相关研究在被隔离的冰的融水中也有很高的可溶性有机碳含量(48~1548 mg C $L^{-1}$) [52]，因此多年冻土退化会释放大量的可溶性有机碳。同时研究发现多年冻土区自然生态系统下可溶性有机碳具有很高的生物可降解性，多年冻土土壤中可溶性有机碳的生物利用性范围从 24% ± 1%至 71%，中位数约为 52% [13] [20] [21] [51]-[56]，然而另一项研究显示无论是否受到热熔喀斯特的影响，溪流中的可溶性有机碳的生物可利用性和改变以及浓度，都没有明显的不同[57]，在青藏高原的相关研究显示，热熔喀斯特主要引发微生物残体碳的流失[58]。多年冻土区可溶性有机碳的生物可利用性主要取决于自身的化学组成，简单有机物组成例如氨基酸，碳水化合物和脂肪酸，更加容易被快速分解，而可溶性有机碳中的复杂部分，例如腐殖酸物质则需要更长时间去分解[55]。土壤有机碳的根本来源是陆地生物，相关研究表明大多数枯落物和植被的渗滤液由低分子量分子组成，对于微生物分解具有很高的不稳定性[59]。在对多年冻土区地下水可溶性有机碳开展的相关研究发现，DOC 浓度约 0.7 mg C $L^{-1}$，主要由老的、具有疏水性和难分解性组分组成，主要由土壤中稳定有机质驱动。因此，在大兴安岭典型多年冻土区不同生态系统下开展相关研究十分必要[60]。

## 3. 多年冻土区可溶性有机碳的季节变化特征

可溶性有机碳(DOC)在俄罗斯 Kulingdakan 集水区的落叶松生态系统中表现出了非常强的年际变化和月变化，其中北坡可溶性有机碳浓度范围在 16~71 mg/$L^{-1}$，而南坡可溶性有机碳浓度显著的更高，范围达 29~215 mg/$L^{-1}$，在 2003~2004 的整个观测期内，南坡的可溶性有机碳浓度是北坡的两倍，浓度分别

为 91 mg/L$^{-1}$ 和 50 mg/L$^{-1}$。可溶性有机碳在南北坡均展现出了浓度的季节变化，具体为从春季到秋季逐渐增加，其中在热量条件较差的北坡更为明显[49]。

在环北极泥炭地中，低位泥炭地(fens)和高位泥炭地(bogs)可溶性有机碳季节浓度平均值在 20~40 mg/L$^{-1}$，与在黄石国家公园海狸坝观测到可溶性有机碳 19~38 mg/L$^{-1}$ 的季节浓度平均值相似[61]。

可溶性有机碳的浓度会随着土壤深度增加而逐渐减小[49]，但相关研究表明多年冻土区深层土壤中含有大量的可溶性有机碳[51]，深层土壤中可溶性有机碳平均浓度达 116 mg/L$^{-1}$。在分离冰融化水中，可溶性有机碳的浓度范围为 48~1548 mg/L$^{-1}$，这些结果都表明了冻土融化可能会释放大量的可溶性有机碳。

## 4. 多年冻土区可溶性有机碳的分子组成

可溶性有机碳是一种由高分子量和低分子量化合物组成的复杂混合物，来源于植被、凋落物、土壤淋滤液、根系分泌物和微生物酶及微生物生物量[62] [63]，主要由有机酸组成[64]，在水生系统中脂肪酸、氨基酸、碳氢化合物和碳水化合物及单宁类物质约占样品有机质组成的 10%~20%，复杂有机组分如腐殖酸(~10%)、富里酸(~40%)，亲水性酸和粘土腐殖质矿物质复合体[62]。

不同生态系统下可溶性有机碳在分子尺度上的成分有所不同，其中木质素化合物完全来源于陆地植物和化学稳定性高得醛酚聚合物[46]，其中从凋落物层淋滤出的水溶性有机碳主要以碳水化合物(~50%)和有机酸、类腐殖酸组成[65]。可溶性有机碳是微生物活动的基质[61] [66]，随着水分下渗，水溶性有机碳的含量和成分会经历重大变化[27] [60] [67]。其中碳水化合物会被微生物迅速分解，因此原位含有的碳水化合物较少，而羧酸和酚酸含量较高[46]。研究表明大多数植被或凋落物的淋滤液主要为低分子量的可溶性有机碳，对于微生物分解具有很高的生物不稳定性[59]。与活动层相比，多年冻土层中保存了更多的植物源，这主要表现在随着深度增加木质素碳在总碳中的贡献不断增加，且伴随酸(AC)与醛(AL)在丁香基(S)和香草基(V)单元中的下降，以及 S/V 和植物源糖类贡献的增加[68]。通过多年冻土区水溶性有机碳在活动层和多年冻土层的比较发现多年冻土层中低分子量水溶性有机碳同样占比很高[20] [69]。同时可溶性有机碳的化学组成决定了其生物可降解性，简单的有机组分如氨基酸、碳水化合物、和脂肪酸更容易被快速分解，而腐殖质等复杂组分则需要更长的时间去分解[46]。

## 5. 多年冻土区可溶性有机碳的生物可降解性

环极地森林生态系统中可溶性有机碳主要由疏水性有机酸组成，并且具有很强的芳香性，随着物种的变化可溶性有机碳的化学组成也展示出了显著变化，其中可溶性有机碳的生物可降解性与植被淋滤液的生物可降解性较相似，范围为 10%~90% [70]。另一项对于多年冻土区泥炭地泥炭芯的培养实验也同样表明了多年冻土层的水溶性有机碳具有很高的生物可降解性[20]。

在对于多年冻土层水溶性有机碳的生物可降解性的相关研究中，在阿拉斯加的相关研究表明古老的低分子有机酸同样具有很高的生物可降解性，会在融化后被封存的古细菌迅速矿化，在 200 小时的培养实验后水溶性有机碳浓度平均降低了 53% [69]，另外一项在阿拉斯加连续多年冻土区 Kolyma 河盆地的研究也展示在不足 7 天的培养实验中，水溶性有机碳的损失约为 50% [21]。

## 6. 研究技术与方法

由于不同的可溶解性有机碳组成有特定的光谱特征，紫外可见光吸收光谱(UV-Vis)被广泛用于表征 DOC 的质量。例如，紫外光在 254 nm 处的吸收($SUVA_{254}$)和可溶解性有机碳的芳香性具有很强的相关性，这一关系通过 $^{13}C$ NMR 被证明，现在被广泛用于表征可溶解性有机碳的芳香性上[71]。此外，400 nm 处的吸光度与可溶性有机碳的比值(C/C ratio)可以指示可溶解性有机碳中有色腐殖质和无色腐殖质的比率[72]。465 nm 和 665 nm 处的吸光度比值(E4/E6 ratio)已经被表明是富里酸和腐殖酸的比例指数[73]。并且

250 nm 和 365 nm 的吸光度的比值(E2/E3 ratio)和可溶解性有机碳的分子大小呈现负相关。基于光谱指标，研究者表明泥炭地排水可以提高泥炭地的氧化分解，导致可溶解性有机碳芳香性程度增高[74] [75]。

然而紫外可见光光谱法无法反应可溶解性有机碳的小变化，解析可溶性有机碳在分子层面上的特征。例如 E2/E3 或 E4/E6 在恢复和未恢复的泥炭地没有观察到区别[76]。此外，该技术仅能反映 DOC 的整体光学特征，无法提供其具体的分子组成、化学式或结构信息。然而，这些信息对于理解泥炭地排水对 DOC 命运的影响至关重要。因此，进一步的研究需要采用高分辨率的分析技术，以更精确地解析 DOC 在分子水平的组成和变化特征。

当前，高分辨率的质谱仪，包括傅里叶变换离子回旋分辨率质谱技术(FT-ICR MS)等，被广泛运用到研究可溶解性有机碳的分子组成[77]。先前的研究中傅里叶变换粒子回旋质谱仪被用于调查环北极和亚北极泥炭地[35] [78]。然而，现有研究主要集中在北极和热带泥炭地[76] [79]，而对于中高纬度多年冻土区泥炭地和山地泥炭地中 DOC 组成及其受排水影响的研究仍较为有限，这一领域需要进一步深入探索。

## 7. 结论与展望

由于落叶松生态系统中针叶含有较多的树脂和蜡质，且木质素含量较高，在分解的过程中会释放出较多的芳香性化合物和木质素衍生物[49]，因此可溶性有机碳可能含有较多的高分子量有机物，在低温和高酸性的土壤中分解较慢[80]。泥炭地中常见的如泥炭藓等草本植物，纤维素和半纤维素是常见的碳水化合物，因此其分解产物可能占可溶性有机碳的重要部分，含有如醋酸、丁酸和丙酸等低分子量有机酸[81]。同时厌氧环境导致泥炭地水溶性有机碳的分解速率更慢[20]。此外增温引起的植被变化和可溶解性有机碳的垂直淋溶，增加了可溶性有机碳的释放，并且潜在的造成了温室气体排放的增加[82]。

本综述总结了多年冻土区 DOC 的研究进展，探讨了 DOC 的来源、化学组成、季节变化特征及其对环境变化的响应。研究表明，DOC 受温度、土壤水分、植被动态和水文条件等多因素调控，且在不同生态系统中表现出显著的季节变化模式。然而，当前研究仍然存在以下不足：首先缺乏对不同生态系统(森林、湿地、草甸)中 DOC 变化机制的系统研究。未来应加强跨生态系统比较研究，探讨 DOC 在不同环境中的迁移与转化机制。其次分子水平解析技术的应用仍有限。未来应结合高分辨率质谱(FT-ICR MS)、稳定同位素示踪法($^{13}$C-NMR)等技术，深入解析 DOC 的分子组成及其生物可降解性。最后缺乏长期监测数据，难以评估气候变暖对 DOC 迁移和降解的长期影响。未来应采用长期监测和模拟实验结合的方法，以揭示 DOC 对气候变化的长期响应机制。总之，未来的研究应聚焦于生态系统差异、分子机制解析和长期监测，以更全面地理解多年冻土区 DOC 在全球碳循环中的作用，并为预测未来气候变化提供更可靠的数据支持。

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