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生态学报

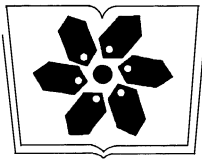
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封面图说: 草丛中的朱鹮——朱鹮有着鸟中“东方宝石”之称。洁白的羽毛, 艳红的头冠和黑色的长嘴, 加上细长的双脚, 朱鹮历来被日本皇室视为圣鸟。20 世纪前朱鹮在中国东部、日本、俄罗斯、朝鲜等地曾有较广泛地分布, 由于环境恶化等因素导致种群数量急剧下降, 至 20 世纪 70 年代野外已认为无踪影。1981 年 5 月, 中国鸟类学家经多年考察, 在陕西省洋县重新发现朱鹮种群, 一共只有 7 只, 也是世界上仅存的种群。此后对朱鹮的保护和科学研究做了大量工作, 并于 1989 年在世界首次人工孵化成功。

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周文昌, 牟长城, 刘夏, 顾韩. 火干扰对小兴安岭白桦沼泽和落叶松-苔草沼泽凋落物和土壤碳储量的影响. 生态学报, 2012, 32(20): 6387-6395.
Zhou W C, Mu C C, Liu X, Gu H. Effects of fire disturbance on litter mass and soil carbon storage of *Betula platyphylla* and *Larix gmelinii*-*Carex schmidtii* swamps in the Xiaoxing'an Mountains of Northeast China. Acta Ecologica Sinica, 2012, 32(20): 6387-6395.

火干扰对小兴安岭白桦沼泽和落叶松- 苔草沼泽凋落物和土壤碳储量的影响

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摘要: 火干扰在湿地生态系统中起着重要的作用, 尽管湿地占全球陆地生态系统很小一部分, 却是陆地生态系统一个重要的碳汇。然而关于火干扰对我国小兴安岭森林沼泽生态系统土壤碳库影响的研究鲜有报道。因此选取两种森林沼泽典型地段进行土壤取样, 研究火干扰对小兴安岭白桦 (*Betula platyphylla*) 沼泽和落叶松 (*Larix gmelinii*)-苔草 (*Carex schmidtii*) 沼泽地表凋落物和土壤碳储量 (0—50 cm) 的影响。研究结果表明: ① 重度火烧使得白桦沼泽地表凋落物量和碳储量降低了 36.36% (0.50 kg/m²) 和 35.52% (0.23 kg C/m²), 而轻度火烧无显著影响; 轻度火烧和重度火烧落叶松-苔草沼泽地表凋落物量和碳储量分别减少了 45.32% (0.99 kg/m²) 和 44.66% (0.42 kg C/m²)、50.42% (1.10 kg/m²) 和 49.71% (0.47 kg C/m²); ② 白桦沼泽和落叶松-苔草沼泽两者对照样地、轻度火烧样地、重度火烧样地的土壤碳储量 (0—50 cm) 分别为 (23.55±6.34) kg C/m²、(18.50±8.16) kg C/m²、(32.50±7.22) kg C/m² 和 (20.89±2.59) kg C/m²、(23.52±16.03) kg C/m²、(21.75±6.60) kg C/m², 然而火干扰对两种森林沼泽土壤碳储量 (0—50 cm) 影响不显著。研究结果可为我国东北开展森林湿地计划火烧和碳管理提供理论依据。

关键词: 火干扰; 凋落物; 土壤碳储量; 森林沼泽; 小兴安岭

Effects of fire disturbance on litter mass and soil carbon storage of *Betula platyphylla* and *Larix gmelinii*-*Carex schmidtii* swamps in the Xiaoxing'an Mountains of Northeast China

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Abstract: Fire disturbance plays an important role in wetland ecosystems. Although wetlands account for a small percentage of the earth's land surface, they are an important global terrestrial carbon sink. A large amount of carbon stored in wetland soils could be released as carbon dioxide into the atmosphere after fire and this could have a significant impact on global warming. It is for these reasons that soil carbon storage in wetlands after fire disturbance has attracted much research attention in recent years. Previous studies on the influence of fire disturbance on forested swamp ecosystems in the Xiaoxing'an Mountains of Northeast China have lacked adequate reports. Therefore, the objective of this study was to describe both the litter mass and soil carbon storage changes after fire disturbance in two different forested swamp ecosystems to provide a theoretical basis for restoration of forested swamp ecosystems and sustainable wetland management. Soil samples from *Betula platyphylla* and *Larix gmelinii*-*Carex schmidtii* forested swamps in the Xiaoxing'an Mountains of Northeast China

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were collected from plots disturbed by different intensities of fire and control plots to comprehensively investigate the effects of fire disturbance on litter mass and soil carbon storage (within 0—50 cm depth) of the ecosystems. The results showed the following: 1) The surface litter mass of the control plots, the low intensity fire plots and the high intensity fire plots were 1.37 kg/m^2 (0.65 kg C/m^2), 1.36 kg/m^2 (0.62 kg C/m^2), and 0.87 kg/m^2 (0.42 kg C/m^2), respectively, in the *B. platyphylla* swamps and 2.19 kg/m^2 (0.94 kg C/m^2), 1.20 kg/m^2 (0.52 kg C/m^2), and 1.09 kg/m^2 (0.47 kg C/m^2), respectively, in the *L. gmelinii*-*C. schmidtii* swamps. The surface litter mass and carbon storage in the *B. platyphyll* swamp decreased by 36.36% (0.50 kg/m^2) and 35.52% (0.23 kg C/m^2), respectively, after high intensity fire disturbance but no significant changes were detected after low intensity fire disturbance. The surface litter mass and carbon storage of the *L. gmelinii*-*C. schmidtii* swamps decreased by 45.32% (0.99 kg/m^2) and 44.66% (0.42 kg C/m^2), respectively, after low intensity fire disturbance and 50.42% (1.10 kg/m^2) and 49.71% (0.47 kg C/m^2), respectively, after high intensity fire disturbance. 2) The soil carbon storage of the control plots, low intensity fire plots and high intensity fire plots was $(23.55 \pm 6.34) \text{ kg C/m}^2$, $(18.50 \pm 8.16) \text{ kg C/m}^2$, and $(32.50 \pm 7.22) \text{ kg C/m}^2$, respectively, in the *B. platyphylla* swamps and $(20.89 \pm 2.59) \text{ kg C/m}^2$, $(23.52 \pm 16.03) \text{ kg C/m}^2$, and $(21.75 \pm 6.60) \text{ kg C/m}^2$, respectively, in the *L. gmelinii*-*C. schmidtii* swamps. There was no significant difference between different sampling plots at 0—50 cm depth. However the soil carbon storage of the high intensity fire plots at 0—10 cm in the *L. gmelinii*-*C. schmidtii* swamps was decreased by 62.58% (4.61 kg C/m^2) and 60.51% (4.22 kg C/m^2) compared with the control plots and low intensity fire plots, respectively, at the same depth. There were significant ($P < 0.01$) differences between the high intensity fire plot and the control plot and between the high intensity fire plot and low intensity fire plot ($P < 0.01$). This study aimed to provide useful information for the carbon management and prescribed fire disturbance in the development of the forested wetland ecosystems in Northeast China.

Key Words: fire disturbance; surface litter; soil carbon storage; forested swamps; Xiaoxing'an Mountains

泥炭地约占到全球陆地地表面积的 3%—4% (3.5×10^8 — $4 \times 10^8 \text{ hm}^2$), 却大约储存了 $4.55 \times 10^{17} \text{ g C}$, 相当于陆地土壤碳库的 $1/3$ ^[1]。Gorham^[1] 估计北极和亚北极泥炭地每年吸收大气中碳的速率为 23 g C/m^2 , 且认为全球泥炭地是大气二氧化碳 (CO_2) 的净碳汇 ($7.6 \times 10^{13} \text{ g C/a}$)。但是这些估计泥炭地作为碳汇的结论未考虑干扰的影响^[2], 以前的研究都是假设湿地未干扰而计算得来的数据, 当湿地受到排水或开垦后, 地下水位降低, 土壤温度升高, 湿地碳分解速率加快^[3-4], 以至于几千年储存的碳在很短时间内被分解而释放到大气中。加拿大橡树岭 (Oak Hammock March) 碳固存工作组对北美 204 块湿地研究表明, 原始状态的湿地是开垦后湿地碳储量的 2 倍, 即湿地被开垦后将损失 50% 的土壤有机碳^[5]。然而, 湿地土壤碳库是碳循环的主要场所之一, 与全球气候变化息息相关。因此, 湿地因干扰后, 会严重影响湿地土壤碳库和碳循环, 以及应对干扰的响应机制。

火烧干扰也会对湿地生态系统群落结构与功能造成严重的影响^[6-10]。例如, 严重的火烧会引起湿地微地形、水文、植被和泥沼的性质变化^[11-15], 不管是自然火还是人为管理火都会引起生态系统中的碳释放到大气中^[12, 16] 和增加可溶性有机碳 (Dissolved Organic Carbon, 简称为 DOC) 流出生态系统^[17-18]。有资料研究表明: 在北美地区泥炭地通过生物质的燃烧而从泥炭释放到大气中的碳为 $(3.2 \pm 0.4) \text{ kg C/m}^2$ ^[2]; 在阿拉斯加北方森林地带因火烧土壤有机质损失 2.5 — 3.0 kg C/m^2 ^[19]; 在欧洲芬兰东部泥炭损失在 2.5 kg C/m^2 ^[20]; 在西伯利亚西部白桦泥炭沼泽土壤有机质损失 42 kg C/m^2 ^[21]。湿地生态系统这种大量土壤碳损失而释放到大气中, 可能引起一个不预测的气候反馈作用^[1-2, 22-23]。因此, 进一步研究火干扰对湿地生态系统碳储量的影响显得尤为重要。

目前, 关于火烧影响湿地碳储量变化和植被恢复方面在北方泥炭地和欧洲有着广泛的报道^[1-2, 10, 23-26]。然而, 就目前针对我国泥炭沼泽在火烧干扰后生态系统的研究, 仅在大小兴安岭森林沼泽与三江平原开展了

火烧后植被的恢复和土壤性质^[27-28]、以及温室气体排放的少量研究^[29-30],对火烧干扰后湿地土壤碳储量的研究少有报道。小兴安岭是我国东北山区湿地三大分布区(大、小兴安岭和长白山)之一,湿地总面积 106.96 万 hm^2 ^[31],主要为沼泽湿地。同时,又作为我国森林火烧频繁发生地区,是研究火干扰对森林沼泽湿地影响的优良基地。最近一次火灾发生于 2009 年 4 月下旬,过火面积近万公顷,本文分别选取白桦沼泽和落叶松-苔草沼泽典型地段,建立火烧样地(地表火和林冠火)和未火烧样地标准地,随机挖取土壤剖面 and 采集地表凋落物层,进行取样,带回实验室烘干、分析,定量评价火烧后小兴安岭白桦沼泽和落叶松-苔草沼泽地表凋落物层碳储量和下层土壤碳储量,对深入理解火干扰对森林沼泽土壤碳(C)循环起着重要的作用,为我国东北开展湿地碳管理提供理论依据。

1 研究区概况与研究方法

1.1 研究区概况

研究地点位于小兴安岭中段的黑龙江省伊春市友好林业局岭峰林场($48^{\circ}13'7''-48^{\circ}33'15''\text{N}$, $128^{\circ}10'15''-128^{\circ}33'25''\text{E}$),海拔为 436—546 m。该地区属温带大陆湿润季风气候,年平均气温 -1°C ,年平均降水量 629.6 mm,全年有两个降水高峰期:冬季降雪和 7—8 月的降雨,占全年降水量的 70%。无霜期约 100 d,霜期在 9 月上旬,晚霜期在翌年 5 月中旬结束。本实验主要以白桦(*Betula platyphylla*)沼泽和落叶松(*Larix gmelinii*)-苔草(*Carex schmidtii*)沼泽为研究对象,土壤类型为泥炭沼泽土,因火灾频繁发生,火干扰是该区域主要干扰类型之一,最近一次火灾发生于 2009 年 4 月下旬,研究区过火面积近万公顷。

1.2 样地设置

本研究于 2010 年 5 月底进行样地踏查,为了解森林沼泽火灾地段与未火灾地段,便于在 10 月开展实验取样。在相同海拔高度、地势平坦地段分别设置白桦沼泽与落叶松-苔草沼泽火烧样地与未火灾地段,火烧样地以轻度火烧(地表火)和重度火烧(林冠火)(下同)为研究对象。轻度火烧指的是火烧仅烧毁了草本、灌木层,以及部分乔木;重度火烧指的是火烧灼伤高度达到乔木林冠层,且大量乔木烧死的林分。轻度火烧白桦沼泽乔木致死率为 15%,而重度火烧样地为 75%;轻度火烧落叶松-苔草乔木致死率为 13%,而重度火烧样地为 60%。白桦沼泽乔木层以白桦为优势群落,灌木层主要是柴桦(*Betula fruticosa*)为优势种,伴生种为柳叶绣线菊(*Spiraea salicifolia*),草本层主要是修氏苔草(*Carex schmidtii*)和小叶樟(*Calamagrostis angustifolia*);落叶松-苔草沼泽乔木层以落叶松为优势群落,灌木层是油桦(*Betula ovalifolia*)为优势种,伴生种有笃斯越橘(*Vaccinium uliginosum*)、细叶杜香(*Ledum palustre* var. *angustum*),草本层主要有修氏苔草(*Carex schmidtii*)、小叶樟(*Calamagrostis angustifolia*)、白毛羊胡子草(*Eriophorum vaginatum*)。在两种森林沼泽火烧地(轻度火烧、重度火烧)与未火烧地分别建立 1 公顷的标准样地。

1.3 样品采集及测定方法

2010 年 10 月,在两种森林沼泽每个标准样地随机重复取 3 个土壤剖面。在取土壤样时,首先用小刀取土层上面的凋落物层,按 20 cm×20 cm 取样,用袋子装好,带回实验室内,在 70°C 下烘干至恒定质量,称其干质量。在取土样时,考虑到小兴安岭森林沼泽土壤约 50 cm 以下为冻土层,下层取样深度到 50 cm 为止。确定土壤剖面后,用土壤环刀(100 cm^3) 在 0—50 cm 每 10 cm 为一层取样,土样用铝盒装好,带回实验室,在烘箱 105°C 下烘干 24 h 后,测定其土壤容重;同时在同一土层深度取约 500 g 土样装入样品袋,带回实验室,风干后,去除样品袋内大于 2 mm 的根系或岩石后,在 70°C 下烘干 24 h。然后,研磨粉碎,过 100 目筛,采用分析天平(0.1 mg)称取凋落物 50—60 mg、土壤 50—100 mg 左右的样品,利用碳/氮分析仪 Multi N/C 3100 和 HT 1500 Solids Module (Analytik Jena AG, Germany) 分析,计算其各层土壤有机碳(Soil Organic Carbon, 简称为 SOC)含量和凋落物碳质量分数,计算 2 种森林沼泽的凋落物碳储量和土壤碳储量^[32]。

土壤碳密度是指单位面积一定深度的土层中 SOC 的贮量,某一土层 i 的碳密度($\text{SOC}_i, \text{kg C/m}^2$)的计算公式为^[32]:

$$\text{SOC}_i = C_i \times D_i \times E_i \times (1 - G_i) / 100$$

式中, C_i 为土壤有机碳含量 (g C/kg), D_i 为容重 (g/cm^3), E_i 为土层厚度 (cm), G_i 为直径大于 2 mm 的石砾所占的体积百分比 (%)。

如果某一土壤剖面由 k 层组成, 那么该剖面的碳密度 ($\text{SOC}_i, \text{kg C/m}^2$) 为:

$$\text{SOC}_i = \sum_{i=1}^k \text{SOC}_i = \sum_{i=1}^k C_i \times D_i \times E_i \times (1 - G_i) / 100$$

1.4 数据处理

文中数据均采用 SPSS 16.0 软件进行单因素方差分析 (one-way ANOVA), 采用最小显著差异法 (LSD) 分析不同数据组间的差异性, 显著性水平设置为 $\alpha=0.05$ 。用 Origin 8.0 软件作图。

2 结果与分析

2.1 火干扰对森林沼泽地表凋落物量和碳储量的影响

火干扰对小兴安岭 2 种森林沼泽地表凋落物量有影响 (图 1)。重度火烧白桦沼泽样地地表凋落物量为 (0.87 ± 0.07) kg/m^2 , 较对照样地 ($(1.37 \pm 0.05) \text{ kg/m}^2$) 和轻度火烧样地 ($(1.36 \pm 0.09) \text{ kg/m}^2$) 减少了 36.36% (0.50 kg/m^2) 和 35.89% (0.49 kg/m^2), 且均极显著差异 ($P < 0.001$), 然而轻度火烧对白桦沼泽样地地表凋落物量无显著影响 ($P > 0.05$)。轻度和重度火烧落叶松-苔草沼泽样地地表凋落物量为 (1.20 ± 0.08) kg/m^2 和 (1.09 ± 0.09) kg/m^2 , 分别较对照样地 ($(2.19 \pm 0.18) \text{ kg/m}^2$) 减少了 45.32% (0.99 kg/m^2) 和 50.42% (1.10 kg/m^2), 且该森林沼泽火烧样地与对照样地之间均极显著差异 ($P < 0.0001$), 但是轻度火烧样地与重度火烧样地之间无显著差异 ($P > 0.05$)。

小兴安岭 2 种火烧森林沼泽样地地表凋落物碳质量分数与对照地之间无显著差异 ($P > 0.05$), 且地表凋落物碳质量分数分布在 (431.19 ± 14.58)—(478.69 ± 10.24) g C/kg 之间 (图 2)。重度火烧白桦沼泽样地地表凋落物碳储量为 (0.42 ± 0.03) kg C/m^2 , 较对照样地 ($(0.65 \pm 0.02) \text{ kg C/m}^2$) 和轻度火烧样地 ($(0.62 \pm 0.04) \text{ kg C/m}^2$) 减少 35.52% (0.23 kg C/m^2) 和 32.48% (0.20 kg C/m^2), 且均极显著差异 ($P < 0.001$), 然而轻度火烧对白桦沼泽样地地表凋落物碳储量影响不显著 ($P > 0.05$)。轻度和重度火烧落叶松-苔草沼泽样地的地表凋落物碳储量为 (0.52 ± 0.03) kg C/m^2 和 (0.47 ± 0.02) kg C/m^2 , 分别较对照样地 ($(0.94 \pm 0.09) \text{ kg C/m}^2$) 减少了 44.66% (0.42 kg C/m^2) 和 49.71% (0.47 kg C/m^2), 该森林沼泽火烧样地与对照样地之间均极显著差异 ($P < 0.0001$), 但是轻度火烧样地与重度火烧样地之间无显著差异 ($P > 0.05$)。

2.2 火干扰对森林沼泽土壤容重及土壤有机碳含量的影响

重度火烧白桦沼泽土壤容重为 (0.65 ± 0.10) g/cm^3 , 较对照样地 ($(0.99 \pm 0.17) \text{ g/cm}^3$) 降低了 33.74%, 且显著差异 ($P < 0.05$), 其它组间不显著 ($P > 0.05$); 轻度和重度火烧落叶松-苔草沼泽土壤容重为 (0.91 ± 0.05) g/cm^3 和 (0.98 ± 0.12) g/cm^3 , 与对照样地 ($(0.88 \pm 0.07) \text{ g/cm}^3$) 相互比较, 各组间均不显著 ($P > 0.05$) (表 1)。

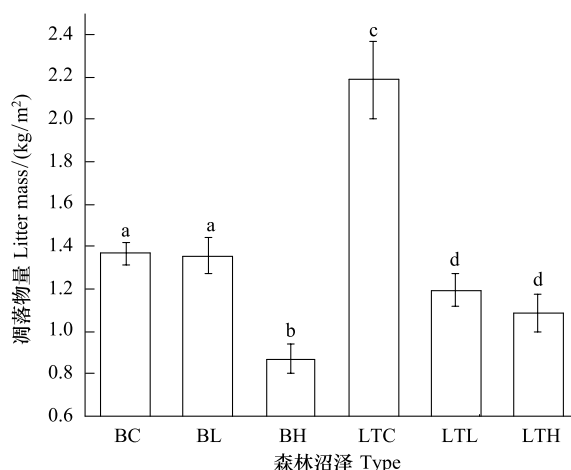


图 1 火干扰对 2 种森林沼泽凋落物量的影响

Fig. 1 Effects of fire disturbance on litter storage from two forested swamps

BC: 白桦沼泽对照 (*B. platyphylla* swamp-Control); BL: 白桦沼泽轻度火烧 (*B. platyphylla* swamp-Low intensity burned); BH: 白桦沼泽重度火烧 (*B. platyphylla* swamp-High intensity burned); LTC: 落叶松-苔草沼泽-对照 (*L. gmelinii-Carex schmidtii*-Control); LTL: 落叶松-苔草沼泽-轻度火烧 (*L. gmelinii-Carex schmidtii*-Low intensity burned); LTH: 落叶松-苔草沼泽-重度火烧 (*L. gmelinii-Carex schmidtii*-High intensity burned); 误差线表示该数值的标准差; 图形中不同的小写字母表示同种湿地类型显著差异 ($P < 0.05$)

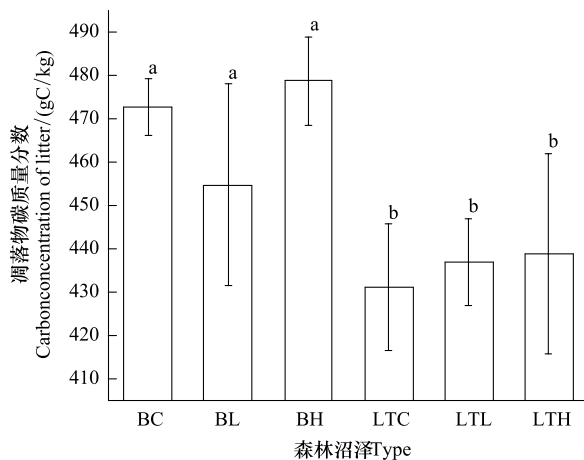


图2 火干扰对2种森林沼泽凋落物碳质量分数的影响

Fig. 2 Effects of fire disturbance on carbon concentration of litter from two forested swamps

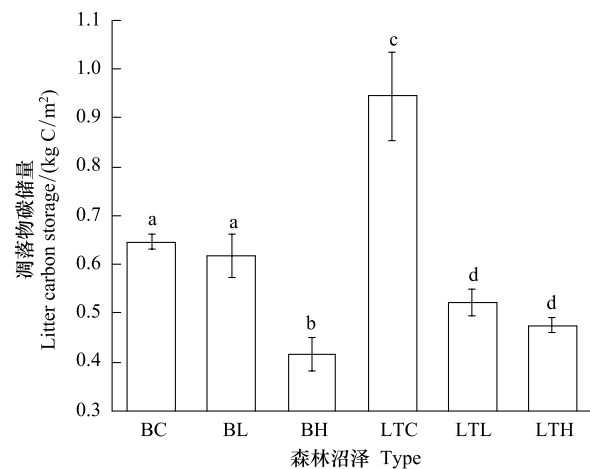


图3 火干扰对2种森林沼泽地表凋落物碳储量的影响

Fig. 3 Effects of fire disturbance on litter carbon storage from two forested swamps

表1 火干扰对2种森林沼泽土壤容重的影响

Table 1 Effects of fire disturbance on soil bulk density from two forested swamps

类型 Type	土壤容重 Soil bulk density/(g/cm³)				
	0—10 cm 土壤容重 Bulk density from 0 to 10 centimeter	10—20 cm 土壤容重 Bulk density from 10 to 20 centimeter	20—30 cm 土壤容重 Bulk density from 20 to 30 centimeter	30—40 cm 土壤容重 Bulk density from 30 to 40 centimeter	40—50 cm 土壤容重 Bulk density from 40 to 50 centimeter
BC	0.44±0.05Aa	0.93±0.38Ab	1.12±0.38Ab	1.27±0.06Ab	1.19±0.15ABb
BL	0.28±0.01Ba	0.63±0.42Aa	1.24±0.35Ab	1.09±0.20Ab	1.35±0.10Ab
BH	0.25±0.03Ba	0.40±0.02Aab	0.59±0.25Ab	0.93±0.24Ac	1.03±0.08Bc
LTC	0.26±0.01Aa	0.32±0.04Aa	1.13±0.20Ab	1.31±0.23Ac	1.37±0.07Ac
LTL	0.33±0.07Aa	0.70±0.43Aa	1.14±0.16Ab	1.26±0.15Ab	1.28±0.14Ab
LTH	0.65±0.07Bab	0.52±0.11Aa	0.94±0.41Ab	1.36±0.02Ac	1.41±0.05Ac

表中数值为平均值±标准差,每列不同大写字母表示同种湿地类型同一土壤深度土壤容重差异显著($P<0.05$),每行不同小写字母表示不同土壤深度土壤容重差异显著($P<0.05$)

但是进一步对小兴安岭两种森林沼泽不同土层土壤容重采用单因素方差分析,得到火干扰对两者表层土壤容重有影响(表1)。轻度和重度火烧白桦沼泽表层(0—10 cm)土壤容重分别较对照样地降低了35.63%和42.73%,且极显著差异($P<0.01$),而轻度火烧白桦沼泽与重度火烧之间无显著差异($P>0.05$)。重度火烧落叶松-苔草沼泽表层(0—10 cm)土壤容重较轻度火烧和对照样地提高94.50%和150.85%,且极显著差异($P<0.001$)。

轻度和重度火烧白桦沼泽土壤有机碳含量为(87.24 ± 30.07) g C/kg 和(154.05 ± 45.16) g C/kg,而仅有重度火烧白桦沼泽土壤有机碳含量较对照地((70.32 ± 25.06) g C/kg)增加了119.06% (83.73 g C/kg),且显著差异($P<0.05$);轻度和重度火烧落叶松-苔草沼泽土壤有机碳含量为(85.66 ± 42.03) g C/kg 和(65.19 ± 27.86) g C/kg,与对照样地((108.33 ± 11.76) g C/kg)比较,各组间数据均不显著($P>0.05$)。

进一步对白桦沼泽和落叶松-苔草沼泽不同土层土壤有机碳含量分析,得到火干扰对两者不同表层土壤有机碳含量有影响。由表2可知,重度火烧白桦沼泽表层(0—20 cm)土壤有机碳含量((259.24 ± 48.56) g C/kg)较对照样地((119.00 ± 30.78) g C/kg)增加了117.86% (140.24 g C/kg),且差异极显著($P=0.01$)。轻度和重度火烧落叶松-苔草沼泽表层(0—10 cm)土壤有机碳含量分别较对照样地减少了25.89% (73.41 g C/kg)和84.89% (240.76 g C/kg),而重度火烧落叶松-苔草沼泽表层(0—10 cm)较轻度火烧减少了79.61% (167.35 g C/kg),且各组间均显著差异($P<0.05$)。

表2 火干扰对2种森林沼泽土壤有机碳含量的影响

Table 2 Effects of fire disturbance on soil organic carbon concentration from two forested swamps

类型 Type	土壤有机碳含量 SOC concentration/(g C/kg)				
	0—10 cm 有机碳含量 SOC concentration from 0 to 10 centimeter	10—20 cm 有机碳含量 SOC concentration from 10 to 20 centimeter	20—30 cm 有机碳含量 SOC concentration from 20 to 30 centimeter	30—40 cm 有机碳含量 SOC concentration from 30 to 40 centimeter	40—50 cm 有机碳含量 SOC concentration from 40 to 50 centimeter
BC	171.05±13.26Aa	66.95±51.92Ab	60.10±69.22Ab	22.86±9.25Ab	30.65±28.97Ab
BL	229.54±26.87ABa	147.24±105.52ABa	33.46±40.60Ab	20.55±26.22Ab	5.40±3.98Ab
BH	284.25±81.60Ba	234.23±19.94Bab	152.88±113.50Abc	61.50±52.62Ac	37.38±19.01Ac
LTC	283.61±30.90Aa	195.95±63.28Ab	42.13±33.83Ac	8.93±1.09Ac	11.02±3.57Ac
LTL	210.20±49.30Ba	124.67±99.35Aab	35.49±33.74Ab	28.91±28.55ABb	29.06±33.59Ab
LTH	42.85±8.54Ca	145.87±54.82Ab	114.76±14.18Ab	17.41±1.81Bc	5.07±3.27Ac

表中数值为平均值±标准差,每列不同大写字母表示同种湿地类型同一土壤深度土壤有机碳含量差异显著($P<0.05$),每行不同小写字母表示不同土壤深度土壤有机碳含量差异显著($P<0.05$)

2.3 火干扰对森林沼泽土壤碳储量的影响

经单因素方差分析,火烧对两种森林沼泽土壤碳储量(0—50 cm)影响不显著($P>0.05$),以及两者森林沼泽土壤碳储量(0—50 cm)之间差异不显著($P>0.05$) (表3)。进而对白桦沼泽和落叶松-苔草沼泽地一定土壤深度土壤碳储量采取单因素方差分析。火干扰对2种森林沼泽土壤表层土壤碳储量一般无显著影响,仅有重度火烧落叶松-苔草沼泽表层(0—10 cm)土壤碳储量较对照样地与其轻度火烧样地同一层土壤碳储量降低了62.58% (4.61 kg C/m²)和60.51% (4.22 kg C/m²),且极显著差异($P<0.01$),其它影响不显著($P>0.05$)。

表3 火干扰对2种森林沼泽土壤碳储量的影响

Table 3 Effects of fire disturbance on soil carbon storage from two forested swamps

土壤深度 Depth range/cm	BC	BL	BH	LTC	LTL	LTH
0—10	7.43±0.46	6.43±0.56	6.93±1.27	7.37±0.90	6.98±1.92	2.76±0.31 *
0—50	23.55±6.34	18.50±8.16	32.50±7.22	20.89±2.59	23.52±16.03	21.76±6.60

表中数值为平均值±标准差(kg C/m²); * 代表这种湿地该数值与其轻度火烧样地 and 对照地的值显著差异($P<0.01$)

3 讨论

3.1 火干扰对森林沼泽地表凋落物量和碳储量的影响

火干扰对小兴安岭两种森林沼泽地表凋落物量和碳储量有影响,重度火烧减少了白桦沼泽地表凋落物量和碳储量,而轻度火烧对其无显著影响。火干扰减少了落叶松-苔草沼泽地表凋落物量和碳储量,两种森林沼泽就地表凋落物量和碳储量减少程度来说,重度火烧减少程度大于轻度火烧(图1,图3)。而针对不同森林沼泽,火干扰对两种森林沼泽地表凋落物量和碳储量的影响程度不一致,重度火烧白桦沼泽地表凋落物量和碳储量减少约1/3,而2种火烧强度对落叶松-苔草沼泽地表凋落物量和碳储量减少约1/2(图1,图3)。分析其原因,在火烧期间,火烧直接燃烧掉了湿地地表大量未分解掉的地表凋落物,使得地表凋落物量及碳储量减少;同时火烧也烧掉了全部草本、灌木及部分乔木,使得凋落物的来源减少,从而使得地表凋落物量及碳储量减少;此外,在火烧结束后,增加了地表辐射,温度上升,进而加速了地表凋落物的分解^[28-29, 33-34],也可能导致地表凋落物量及碳储量的减少。本研究结论与现有火干扰减少了湿地地表凋落物量的研究结论基本一致^[35],与其他学者研究北方泥炭地火烧直接烧毁地表有机质碳储量损失一致^[12,24]。由于落叶松-苔草沼泽一般位于森林沼泽生态交错带上位,在沿着沼泽至毛赤杨、白桦、落叶松森林沼泽群落方向上,环境梯度相对高于白桦沼泽^[36],可能地表水位低于白桦沼泽,地表凋落物湿度较小,而适合可燃物燃烧的量较多,可能是导致落叶松-苔草沼泽地表凋落物量和碳储量减少程度大于白桦沼泽的原因。因此,今后有必要从微地形(水文)、可燃物类型等进一步去研究火烧后地表有机质的变化。

3.2 火干扰对森林沼泽土壤碳储量的影响

小兴安岭白桦沼泽和落叶松-苔草沼泽两者对照样地与火烧样地的土壤碳储量(0—50 cm)范围分布在(18.50±8.16)—(32.50±7.22) kg C/m²之间。本文研究结果大于蔡体久等^[37]研究小兴安岭泥炭藓湿地土层0—60 cm 土壤有机碳储量(16.61 kg C/m²),该学者认为湿地土壤有机碳储量比其他学者研究的湿地土壤有机碳储量小是因土壤容重(0.027—0.097 g/cm³)较小所致。同理,本文研究的湿地土壤容重(0.25—1.45 g/cm³)与其比较大,导致土壤有机碳储量较大。比张文菊等^[38]研究相同纬度三江平原典型湿地(常年积水的腐殖质沼泽)土层0—60 cm 土壤有机碳储量(36.6 kg C/m²)小,可能是由于本文研究的森林沼泽为季节性积水,通气状况在非积水时期有所改善,植物残体分解程度较高,导致土壤有机碳储量较小;也有学者认为湿地土壤有机碳含量较其它生态系统(森林或草原)高,然而可能因湿地更低的土壤容重(或泥炭密度),也可能引起湿地更低的土壤碳库^[39]。因此,要搞清楚不同湿地类型土壤有机碳储量的精确数据,必须对不同湿地类型、分布及生境因子开展系统的调查和研究。

从不同火烧强度、不同林型下分析两种森林沼泽土壤有机碳储量的差异性,唯有重度火干扰落叶松-苔草沼泽表层(0—10 cm)的土壤碳储量有显著的下降(4.61 kg C/m²)。这与 Turetsky 等^[24]研究北方泥炭沼泽火烧3个月后表层(0—30 cm)土壤有机质碳储量下降((2.2±0.5) kg C/m²)一致,但不同之处是该研究者的结论在火烧地与未火烧地间土壤表层有机质碳储量之间差异不显著。本研究也与 Meigs^[40]研究在不同火烧强度下森林生态系统土壤碳储量(土层0—20 cm 或甚至达到100 cm)之间影响不显著相吻合。其可能原因:火烧后,草本、灌木生物量以及地下细根生产力的增加^[40-42],使得干扰后土壤碳得以恢复^[43];另一个是,本文研究地段火烧时间(2009年4月下旬)为小兴安岭森林沼泽土壤层还未冻融,火烧期间可能未烧毁下层土壤有机碳,仅仅是烧毁了两种森林沼泽地表长期积累较厚的凋落物层(图1),短期内,未对其土壤碳储量造成显著性影响。火干扰对土壤有机碳储量的影响是一个相当复杂的过程,要搞清楚火干扰对生态系统土壤碳储量的影响,尚须进行长期定位研究和监测。例如,有学者认为不同生态系统之间土壤碳储量的差异性的关键因子可能与以前生态系统受到家畜和野生动物干扰密切相关^[39]。因此,火烧前生态系统干扰的历史原因与火烧后细根变化量可能加大了土壤碳储量的空间异质性。

4 结论

火干扰(不同火干扰强度)一般是减少小兴安岭白桦沼泽和落叶松-苔草沼泽两者地表凋落物储量和碳储量。除了轻度火烧白桦沼泽减少不明显外,其它火烧强度是显著地减少了地表凋落物量和碳储量,且有重度火烧减少的程度较大的趋势。火干扰对小兴安岭白桦沼泽和落叶松-苔草沼泽两种森林沼泽土壤碳储量(0—50 cm)影响不显著,但是重度火烧对落叶松-苔草沼泽表层(0—10 cm)土壤碳储量有显著地减少。本结论将为我国东北开展湿地土壤碳管理和计划火烧提供理论的依据。

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