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(SHENGTAI XUEBAO)

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封面图说:秋色藏野驴群——秋天已经降临在海拔 4200 多米的黄河源区,红色的西伯利亚蓼(生于盐碱荒地或砂质含盐碱土壤)铺满大地,间有的高原苔草也泛出了金黄,行走在上面的藏野驴们顾不上欣赏这美丽的秋色,只是抓紧时间在严冬到来之前取食,添肥增膘以求渡过青藏高原即将到来的漫长冬天。

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

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冰雪灾害对森林的影响

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摘要:冰雪灾害是一种常见的自然灾害,往往对森林造成很大破坏。随着冰在树冠上不断积累,产生的压力逐渐增大,最后超过该部位最大弯曲力矩时林木会受到伤害。受害程度与林分的多种特征,如树种组成和林分密度及林木的多种特征,如胸径、树高、树干尖削度、叶片表面积、树冠对称性、根系、林龄等有密切关系。影响冰雪灾害的外部因素有地形因子和土壤因子,包括海拔、坡度、坡向、坡位和土壤类型、土壤厚度、土壤水分含量。冰雪灾害对林下光照、土壤、凋落物、真菌和森林动物产生影响。冰雪灾害后的林下光照对树种更新、森林动态和恢复具有重要意义。研究冰雪灾害对天然林的影响,长期监测冰雪灾害后的森林动态、林下植物的光环境、森林的养分循环、土壤以及森林动物,特别是土壤微生物的变化,加强森林的防灾管理是今后该领域的研究方向。

关键词:冰雪灾害;林分特征;地形; 土壤

Effects of ice-snow damage on forests

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Abstract: Ice-snow damage is a common natural disaster, and it often caused huge damage to forests. The frequency of ice storms may increase in response to climate change. Typically, warm, moist air overruns a shallow body of cold air, rain from warm air may become supercooled when it falls from the warmer clouds, causing it to freeze immediately upon contact. Ice-snow damage occurs when the ice loaded on crown exceeds the maximum bending moment for a tree of given size and species. Ice-snow damage of forests dependents on ice accumulation. Accumulation ice can cause tree damage ranged from the loss of tissues to structural failure. Ice-snow damage to trees can range from mere breakage of a few twigs, to bending stems to the ground, to moderate crown loss, to outright breakage of the trunk. There is a close relationship between ice-snow damage and forest characteristics, such as stand density and species composition as well as tree characteristics, such as diameter at breast height, tree height, stem taper, leaf area, crowns symmetry, root system and stand age, etc. The stands with the highest density are the most vulnerable to ice-snow damage, especially for a few years after thinning. Softwoods suffer less damage from the same degree of ice loading than do hardwoods. Trees with branches that droop or have pliable stems and limbs are better withstand ice-snow damage. Dominant canopy trees incur more ice-snow damage than sub-canopy trees. Moreover, ice-snow damage is affected by some external factors, such as topography and soil conditions, including elevation, slope grade, slope aspect, slope position, soil type, soil thickness and soil water content. Higher elevations are more prone to freezing rain. Elevation and aspects increasing exposure to stronger winds result in higher damage. Ice-snow damage also exerts an impact on forest understory light, soil, litter, disease fungi and wildlife. The understory light condition that followed ice-snow damages has great significance to species regeneration, forest dynamic and

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recovery. A transient increase in understory light following an ice-snow damage may accelerate the conversion of early successional stands to more shade-tolerant species. The rapid decrease in understory light following an ice-snow damage is likely a result of the recovery of both the overstory and understory vegetation. An ice-snow damage indirectly impacts natural plant regeneration by its impact on fruit and seed production. Wildlife first must endure the perils of the ice-snow storm—low temperatures, ice buildup, falling debris, and reduced mobility. Birds are especially vulnerable. Wounds caused by ice-snow damages permit infection by a wide array of disease fungi and become breeding grounds for bark beetles or other pests, especially when the injuries are large and do not heal rapidly. Ice damages also increase potential fire risk by elevating fuel loads. Future research in the field of ice-snow damage to forests should focus on effects of ice-snow damage on natural forests and the long-term research of nutrient cycling and soil, especially microorganism, wildlife, forest dynamics and forest understory light, and reducing the risk of ice-snow damage through forest management.

Key Words: ice-snow damage; forest characteristics; topography; soil

冰雪灾害是一种常见的自然灾害。全球气候异常及人类对自然资源和环境的不合理开发和利用,导致冰雪灾害的地域发生变化,频率和强度呈现上升趋势[1-2]。美国和加拿大的一些地区时常发生冰雪灾害,每 50 年或更短的时间在这些地区的冰雪灾害核心区就会发生强度足以破坏森林的冰灾。我国的冰雪灾害多发生在东北,但是,我国南方地区 2008 年 1—2 月发生了长时间和大范围冰雪灾害,造成 19 个省区森林受灾面积达 1860 万 hm^2,占全国森林总面积的 1/10,森林生态系统遭到难以估量的破坏[3],给林业造成的直接经济损失达 573 亿元[4]。

冰雪灾害是森林生态系统重要的非生物干扰因子,对森林的经济、生态和社会价值都会产生影响。冰雪灾害对树木的伤害程度从断大枝、弯梢、断冠、断干、倒伏,直至翻蔸[5]。此外,冰雪灾害后森林中光照、土壤、凋落物等非生物因素的变化,以及病虫害的爆发,都将对森林生态系统造成更严重的损害。因此,许多学者就冰雪灾害对森林的影响进行了研究,如森林冰雪灾害的成因[6]、对树木的损害[7-9]、林分动态[10]、冰雪灾害对森林经营管理的影响[11]。2008 年我国南方发生冰雪灾害后,国内许多学者对亚热带森林的冰雪灾害进行了研究[12-17]。李秀芬等[18]和吴可可等[5]分别对森林的风/雪灾害和南方森林雨雪冰冻灾害进行过阐述。本文从冰雪灾害后林木的受害情况、内外影响因素、受损机理、林分发生的变化及恢复等方面进行综述,以期为降低冰雪灾害对森林的危害以及冰雪灾害后森林的恢复提供参考。

1　受害特征

重大冰雪灾害通过冰积累产生的压力破坏树木,或将树木连根拔起,对森林造成大范围伤害,一次冰暴使森林的受害面积可以达到成千上万平方公里[19],引发了许多短期及长期的生态问题[9,11]。

1.1　单株木

冰雪灾害对单株木的伤害程度,从仅损坏一些嫩枝,使茎弯曲至地面,到部分树冠受损,甚至使树干完全破裂[20]。

冰积累对树木有严重的物理伤害。冰积累的厚度达 0.6—1.3 cm 时会使小枝或有缺陷的树枝脱落,1.3—2.5 cm 时会产生明显的破损[21]。当冰覆盖在过分伸展树枝的倾斜幼树时,在其树皮光滑的外表上会形成硬结和很明显的损伤。例如,冰雪灾害后的南方松幼树严重弯曲且树枝受损,渗漏树脂[11]。严重受害时会引起单株木的树干腐烂、降低生长、形成应压木、年轮偏心及年轮间出现细胞空隙[22]。冰负荷还能严重地伤害树根,有时会将树木连根拔起。在冰冻解除后,仍然可以看到冰积累对树木的影响。在 1998 年的美国东北部冰暴中,长时间低温使发生弯曲树木的树冠被冻结在地面长达 3 周,在冰冻解除后,部分树木恢复直立姿态,而有一些树木两年后仍然弯曲[9]。树根严重受损坏的单株木会因为失去修复潜力较快死亡,一些树种因为可以再生根,即使完全倒伏依然可以存活下来。

1.2 林分

冰雪灾害为许多地区的主要冠层干扰[23]。由于林分组成、积冰厚度、地理位置和林分历史的差异,冰雪灾害对其造成的伤害特征不同,破坏程度可以从轻微、部分破坏到整片林分的完全损坏。在受害轻微的林分中,没有受害的树木通过增加树冠幅度来填充空余的生长空间,这样的林分会快速生长,进而恢复到受害之前的水平。中度受害的林分当叶面积恢复后才会正常生长。严重受害的林分几乎完全倒伏或大量树干折断。冰雪灾害对森林的损害特征随树种而异。陈红跃等[24]调查粤北冰雪灾害后的林分时发现,湿地松(*Pinus elliottii*)林折断的树木达88%,少量弯曲和倒伏,而杉木(*Cunninghamia lanceolata*)林没有弯曲和倒伏的树木,基本是折断和断头的类型。

冰雪灾害中,对林分边缘效应研究的结果常常是矛盾的。似乎在林中的树木比在林缘的树木更易受到雪害,因为处于林缘的树上的雪可能会被风吹走,或者林缘的树木的树枝拥有足够的力量去承担雪的负荷[9]。例如,Kienholz[25]发现沿着未疏伐种植园的外边缘生长的加拿大短叶松(*Pinus banksiana*)比生长在林分内部的受害小。但也有人认为,由于林缘风的强度大,树木所受到的伤害也大[26]。另外,沿着林窗边缘或道路边缘生长的树木,其树冠常常会不对称,增大了它们的易损性[27]。这些矛盾的结论源于当地环境条件和植被的复杂性及不确定性[28]。

2 林分或林木自身影响因素

生物力学可以解释单株林木在理想情况下的受害机理,但并不能完全说明其受到的实际损害。冰雪灾害对林分的破坏程度与树种组成、林分密度、林木的胸径、树高、尖削度、叶片表面积、树冠对称性、林龄和根系状况等多种林分或林木特征有密切关系。

2.1 树种组成

同一地区的不同树种抵抗冰雪灾害的能力存在差异[29-30]。陈红跃等[24]发现林分的生物量损失量为阔叶林>湿地松林>杉木林。乡土树种的抗灾能力强于外来树种[31]。在新英格兰1998年1月的暴风雪中,外来树种如刺槐(*Robinia pseudoacacia*)和柳属(*Salix*)树种遭受严重损伤,而乡土树种受到的伤害极小[9]。落叶树种比常绿树种抗压性强[32],所以受灾比后者轻,慢生树种比速生树种受害轻[33]。不同的林分组成对雪害的敏感性不同[34]。天然林结构稳定,抗干扰性强,抵御自然灾害的能力通常强于人工林[18,35]。纯林往往比混交林受灾严重[13,16]。

2.2 林分密度

许多研究者认为,密度大的林分受损严重[16, 36]。据彭险峰[35]报道,郁闭度达0.7以上后,林木高生长优势明显,极易折断和倒伏。许业洲[15]的研究表明,密度超过2 000 株/hm^2 的林分受灾个体是密度1 000 株/hm^2 以下林分的近3倍。Zeide 等[37]认为疏伐林分可以使树木从竞争中释放出来,更快地生长,因此抵抗冰雪灾害的能力更强,而 Nykänen 等[38]报道,疏伐几年后的林分抗灾能力下降,这可能是因为刚经过采伐的林分由于风的穿透更深, 进入树的冠层, 增加了树的风负荷量, 林木的稳定性较差[30]。也有研究表明,林分密度过大或过小均会使林木受灾程度加重[13,39],甚至林分受害程度与密度无关[40-41],而杨灌英等[42]发现密度大的毛竹林受损程度比密度小的要轻。郁闭度大的林分内风速较小, 受害较轻。天然林由于适应当地的气候条件,抗冰雪灾害能力往往比人工林强[18]。

2.3 胸径和树高

利用林木直径预测其所受冰雪灾害已经成为一项重要的研究内容。一般来说,随着林木单株径阶的增大,林木抵御冰雪灾害的能力增强,受害程度明显减少[16,40]。也有研究认为大径级的个体受损更严重[33]。Bragg 等[11]也指出平均胸径大约为18—25cm 的林木易受害。苏志尧等[43]认为胸径较大的林木受灾的比例更高,因为胸径大的林木往往占据林冠上层,更易直接受到破坏。李秀芬等[34]认为粗大林木因冠幅较大而易受折断的危害,而低矮、小径级的林木更趋向于被压弯。胸径大小影响林木的受害特征。薛立等[17]发现林木折断的树干部位随胸径的增加而显著升高。陈红跃等[24]指出胸径在9.0 cm 以下的杉木多数容易发生折干,

而胸径在 9.0 cm 以上的杉木则多数容易发生断头。在瑞典受冰雪灾害的欧洲赤松(*Pinus sylvestris*)林在 3m 或 5m 高处的直径和高径比是决定受害程度的重要因素[44]。

树高对冰雪灾害的影响主要是与风灾联系在一起的。一般情况下,风灾对结冰树木的影响随树高的增加而增加[45-46]。Peltola 等[47]的树干抗折断实验也证实了林木的树干抗折能力与树高呈负相关。然而,张志祥等[48]发现黄山松(*Pinus hwangshanensis*)胸径越大,林木越高,其受灾程度越轻,这可能是因为当林木成熟时,林木的高生长比直径生长衰退得快, 也可能是随着黄山松树龄的增加,木材强度随之增加的缘故。赵霞等[14]发现树高≤5.0 m 的林木大多表现为压弯和倒伏,而翻蔸的平均树高在 5.0 m 以上。

2.4　树干尖削度

尖削度可能是影响树木抗风能力最重要的因子之一[45,49]。尖削度越大的树木对风和雪压有更强的抗性[50],而尖削度小的林木易发生断裂,尤其是尖削度小于 1:90 或 1:100 的林木更易遭受雪灾的伤害[15,47-48]。在密度较大林分中生长的树木由于其尖削度小, 容易遭到冰雪灾害的破坏[16, 20, 32,36]。

2.5　叶面积

叶大而多的树种明显增加了冰雪负荷,更易受冰雪伤害[21]。例如,火炬松(*Pinus taeda* L.)的茎干柔韧性高及针叶较短,与湿地松或长叶松(*Pinus palustris* Mill)比不易受害[51]。但是,在冰负荷相同的情况下,针叶树比阔叶树易受害。王秋华等[52]发现针叶树种比阔叶树种受损严重,因为其枝叶密集,积累的冰雪多,负荷大。汤景明等[13]也得到同样的结论。芬兰的主要造林树种中,欧洲赤松最易受雪害,欧洲云杉(*Picea abies*)中等,桦木(*Betula* spp)因为落叶而不易受雪害[53]。

2.6　树冠

树冠的大小、相对高度和不均匀程度影响林木抵御冰雪灾害的能力[18,54]。通常认为树冠较窄或圆柱状的树冠抗倒伏能力强, 而开阔的树冠和不对称的树冠易被压断。例如,树冠狭窄的挪威云杉(*Picea abies*)抗冰雪灾害能力强于树冠宽大的欧洲赤松[38]。松树冠近塔形,树冠受力较为均匀,所以比树冠近椭圆形的湿地松抗冰雪灾害的能力强[55]。冠幅和树冠开度大的林木,积累降雪的表面积和受风的面积均较大,容易受冰雪灾害影响[56],树冠往往在巨大的重力下折断。例如宽伞形树冠且分枝较多的香樟 (*Cinnamomum camphora*)容易雪折,而椭圆形、圆锥状树冠的香樟受害程度相对较轻[57]。刘刚等[58]认为在相同的生境中能够占据林冠优势层的区系类型往往受灾更严重。因为树冠相对较高的林木位于群落上层,经过的风的速度较快,承受的风压大,树冠往往较易折断。冰雪荷载对树冠不均匀林木的树干造成了不平衡的压力,林木重心偏于一侧,容易发生翻蔸或断干。

树形密切影响着林木的受害程度。树枝下垂、木材密度较大或者茎和枝柔韧的树木,抗冰压能力更强,因为它们可以将由冰积累产生的弯曲力转移给树木的其它部分和地表,甚至是相邻树木[20]。有明显顶端优势的大部分塔形松树和阔叶树(例如,枫香 *Liquidambar formosana*)容易使冰和雪流到地表,而许多花瓶型的榆树(*Ulmus pumila*)和橡树(*Quercus palustris*)特别易受冰害[36]。枝条的分布影响冰积累,尤其是在茎或树枝较弱的分叉处或明显的分叉处存在一个冰积累支点[40],不利于抗冰雪灾害。

2.7　林龄

林龄对林木受冰雪灾害的影响随树种和环境而异。有研究认为冰雪灾害主要发生在老龄林[54],树龄越大所受到的伤害程度越大[20]。也有研究认为,幼树更易在冰冻中死亡[27],而高大的老龄树拥有更强的结构刚度,因此对伤害有更强的抵抗力[11,44],因此,抵御雪灾的能力随着林龄的增长而增强[12,15]。阿肯色州冰暴导致老龄(约 30 年林龄)种植园中部分树冠受损,只有零散的一些茎破损或翻蔸[11]。

2.8　根系状况

树干抗冰雪灾害的能力与它的根系抵抗翻蔸和树干抗折断的能力有关[47]。冰雪灾害期间,当林木的抗折断能力小于根在土壤中的固着力时,经常出现林冠和树干折断[59],而抗折断能力大于根在土壤中的固着力时,林木就会被连根拔起[60]。根系形态和分布特征也影响林分的抗灾能力。Warrillow 等[61]认为维吉尼亚州

松树的浅根性可能是导致它在冰暴后存活率很低的原因。许业洲等[15]指出,主要侧根数量较多、平均粗度较粗、根系生物量大的林木的抗倒伏能力较强。

3 外部影响因素

3.1 地形因子

一些地形特征(高海拔等)会加重冰雪灾害对树木造成的伤害[62]。一般情况下,冰雪灾害随海拔升高而加重[48,63],原因是高海拔地区的树冠上积雪量相对较多,再加上高海拔地区温度较低,冰凌较厚且融化速度缓慢,容易导致林木结冰而受灾,例如许业洲等[15]发现海拔 1800 m 以上地区的林分受灾程度是 1800 m 以下地区的 2 倍。

坡度、坡向和坡位在冰雪灾害中对树木也有着重要的影响。多数学者认为坡度越大林木受灾越严重[16,64-65]。杨灌英等[42]发现坡度较大的毛竹林损失严重,原因是生长在这些地点的林木的林冠不对称,承受的冰雪不均匀,容易造成大树枝折断和翻蔸[66]。Rhoades[67]认为,陡坡的林木更易遭受冰积累伤害是陡坡处的小团粒土壤结构和有限的根系长度共同作用的结果。汤景明等[13]、蔡子良等[62]报道北坡的雪折比南坡严重,可能与北坡的气温较低有关。有人报道冰雪灾害对上坡林木损伤更为严重,因为上坡有相对高的遭遇冰暴的风险的机会,风速较大,林木结冰也较为严重[5,13,20,43,68]。

3.2 土壤因子

土壤类型、土壤厚度、水分含量等土壤因子都影响着林木翻蔸危害的程度[6,69]。一般来说,泥炭地林分对雪和风有更强的抵抗能力。Oliver 等[70]研究发现,生长在泥炭土的欧洲赤松抵抗翻蔸的能力最强,棕壤土次之,砂土最差。生长在薄土层上的林木根系浅、固着力差,遇到瞬时强风时容易翻蔸[5]。土壤湿润且肥力丰富地段的林分受灾比土壤干燥且肥力较低林分要严重[57],原因是土壤湿润时,供给植物吸收的水分充足,导致体内含水量较高,容易结成冻害。土壤肥沃地的植物生长旺盛,枝、叶嫩软,易受冻害[68]。

4 冰雪灾害后的林分变化

4.1 光照

冰雪灾害通过对森林冠层结构的影响[71-72],间接影响林下光照[73]。Beaudet 等[74]发现,冰雪灾害后光量子通量密度(PPFD) 短暂增加,随后降低,光照呈倒“J”型,表明在受干扰后早期光照强,而后期引起林下光照迅速减少,原因可能是上层林冠和林下植被的修复[75]、枝发芽[76-77]、林冠下层被压抑幼苗的生长[72,77-78]。冰雪灾害后林下的光照暂时增加和随后降低,这有利于耐荫树种生长[79]。另外,冰雪灾害后,林下各处的光照都增强。林窗对林下光照的影响比林缘大[80-81]。当几个林窗同步形成,光照在林下相互联通,没有被林窗影响光照条件的区域就非常少[82]。

4.2 土壤

冰雪灾害对土壤理化性质有重要影响。冰冻作用改变土壤团聚体的大小和稳定性[83]。有报道称,冰雪灾害引起土壤自然含水量、孔隙度和可利用养分的降低[84]等。但是,陈凤霞等[85]的研究发现,冰雪灾害后由于大量的枝叶残体输入土壤,土壤有机质增加,导致土壤持水能力增强且容重减少。田大伦等[86]也指出冰灾后栾树(*Koelreuteria paniculata*)和杜英(*Elaeocarpus decipens*)混交林的土壤含水量显著增加。

冰雪灾害后林冠残体积累于地表,凋落物和树干残体在分解过程中增加了土壤有机质和养分。Rustad[87]的实验发现,凋落物的大量增加可以提高土壤 C 和 N 的含量。田大伦等[88]发现冰灾 1 个月后的栾树杜英混交林的土壤全 P、全 K 含量显著增加,而速效 N、速效 P、速效 K 含量明显减少,微量元素 Cu、Pb、Co 含量增加,Fe、Zn、Mn、Cd、Ni 含量减少。陈凤霞等[85]报道,冰雪灾害发生 1 a 后,由于林冠残体的分解,杉木林土壤有机质、全 N、全 P、全 K、碱解 N 和速效 P 含量比冰雪灾害刚刚结束时均显著增加,而速效 K 含量由于雨水淋洗而减少。薛立等[17]认为雨雪冰冻灾害造成的杉木林冠残体分解引起养分含量的增加。因为冰灾破坏冠层结构,使林冠开度增加,造成短期的林地太阳辐射水平提高和温度上升,加快了凋落物的分解速度[88-89],进而加速养分循环。

4.3　凋落物

极端天气、火灾或地质灾害等发生时,在外力作用下产生的植物个体或植物器官的新鲜残体被称为非正常凋落物[89-90]。Hooper 等[91]发现,魁北克冰雪灾害导致温带落叶森林调落物在每年正常的基础上增加了10—20 倍。吴仲民等[92]的调查表明,冰雪灾害造成粤北森林的非正常凋落物平均干质量在 20 t/hm^{2}以上,相当于南岭地区地带性森林植被 5—10a 正常凋落物量的总和。严重的冰暴会使林分产生大量的粗木质残体。冰雪灾害后的老龄橡树和山胡桃(*Cathayensis Sarg*)林产生的木质残体平均达 5m^3/hm^2(0—33 m^3/hm^2)[93]。与凋落物相比,粗木质残体的养分浓度低而释放速率慢[93],其养分缓慢的释放并储存于土壤有机质中,有利于林地长期的养分供应[85]。冰雪灾害造成的大量林冠残体积累于林地可以提高土壤肥力,科学地保护和管理将会增强受灾森林土壤的储碳功能[90]。

4.4　真菌

真菌会使树木在冰雪灾害中产生的伤口感染,伤口很大且不能很快愈合时尤为严重[94],一些真菌会通过这样的伤口进入树干,降低了树木价值[9]。伤口或冰暴后日灼易引起阔叶树腐烂。溃疡[74]和腐烂[95]伤口增加了树木在今后冰雪灾害中的敏感性。然而,Rexrode 等[96]发现,在冰积累造成树冠损伤后,产生了黑樱桃(*Prunus serotina*)髓腐病,但是没有长时期受害。大范围真菌病害会使与冰积累有关伤口感染,尤其当伤口很大而且不很快愈合时[91]。与冰暴相关的伤害导致真菌感染包括日灼和树皮应力裂纹[11]。伤口或冰暴后日灼尤其易引起硬木腐烂[91]。

4.5　动物

野生动物必须忍耐冰雪灾害带来的风险——低温、冰积累、掉落的残枝和移动性下降。鸟类尤其易受伤害,如冰雪灾害造成角鸊鹈(*Podiceps auritus*)大量死亡[97]。冰暴常常改变野生动物的栖息地[98],有利于新栖息地形成。粗木质残体数量的增加[99]和早期茎、枝的腐烂,为发展洞穴提供了有利条件[99]。冰积累降低果实和种子的产量,间接影响野生动物。

林分在冰雪灾害后易发生虫害。九成以上树皮严重受损的林木都受到小蠹虫(*Scolytidae*)的袭击[100]。松小蠹(*Tomicus* spp)是受冰雪灾害后林分的最大危害之一[101],极端天气情况及大量林木的死亡使啄木鸟(*Piculus*)无法生存,是松小蠹大量爆发的原因[102]。Cool 等[100]报道,南卡莱罗纳冰雪灾害后的雕刻小蠹和黑脂大小蠹只对健康林木造成了有限的伤害。Blanche 等[103]对火炬松做模拟的砍伐实验,发现松木受到物理伤害七个月以后,自身会产生更多的树脂,同时也降低了这些林木对小蠹虫伤害的敏感性。

一般来说,冰雪灾害对土壤动物群落结构的影响不明显,对数量的影响却很明显。冰雪灾害造成的大量林窗对有明显避光性的土壤节肢动物有抑制作用[104]。颜绍馗等[105]发现,冰雪灾害后大中型土壤动物多度下降,而土壤动物群落组成并无明显变化。另一方面,冰雪灾害产生大量的非正常凋落物,在分解过程中增加了林地养分的输入,会对土壤动物产生积极影响。肖以华等[106]报道凋落物现存量与大型土壤动物群落生物量显著相关。由于微生物对外界环境变化的反应要比植物和动物更敏感[107-109],冰雪灾害后形成的大林窗的土壤微生物群落的丰富度、多样性和均匀度都低于小林窗[110]。

5　恢复

5.1　冠层

一般来说,被冰雪灾害伤害的冠层树种有能力在重大的树冠损伤后存活下来[75],还可以及时不断地恢复叶面积和冠幅,但不是所有的冠层树种的恢复能力都相同。例如,受损严重的美洲椴(*Tilia americana*)的受损树冠枝条和树干基部具有很强的发芽能力,而加拿大铁杉(*Tsuga canadensis*)的树冠枝条没有发芽能力[111]。主冠层受损增加了林下光照,短期内刺激林下个体的快速生长。主冠层树枝的侧向伸长使林隙快速郁闭,林下光照降低,林分组成向更耐荫树种转变,这些树种会入侵冠层并持续生长,直到主冠层的林隙完全修复[76]。例如,冰雪灾害中未受损的糖枫(*Acer saccharum*)和山毛榉(*Fagus grandifolia*)幼苗可以利用合适的林窗生长至冠层高度[111]。

5.2 光照

林下光照对树种更新和森林动态具有重要意义。冰雪灾害后林内光照恢复到干扰前水平所需的时间小于其他干扰。例如,择伐后需要 8—13 a 林下光照才能恢复到受干扰前的水平[112],而冰雪灾害后仅需要 3—7 a[72]。冰雪灾害后 3 a,山毛榉和糖枫混交林的部分林窗闭合[113],冰雪灾害后 4 a,糖枫林的叶面积指数恢复到受害前而且较稳定[72]。

6 展望

随着人类对自然资源过度开发利用和气候变暖,未来气候变化的不确定性增加。因此,迫切需要研究冰雪灾害的发生、大小或强度与气候的关系,并以此为基础预测其对森林动态的影响。目前国外的冰雪灾害研究多集中在人工林,对天然林的研究很少,短期研究多,持续定位研究少。开展受灾森林的生物多样性变化、更新、演替的长期研究,对于预测森林的发展,合理经营管理森林资源具有重要的意义。目前,对生长中的林分结构特征,如林木受害程度和特点、树种丰富度以及树种组成等进行过较多的研究,对其功能特征,如养分循环、土壤,特别是土壤微生物研究较少,鲜有冰雪灾害后的森林动物、森林动态和林下植物光环境的报道。因此,开展以上内容的长期研究非常必要。

近年来冰雪灾害的发生有明显的上升趋势。虽然冰暴的发生时间是不可预知的,但可以预测它对不同森林的影响,并通过森林管理减少其危害。例如在冰雪灾害发生地区筛选抗冰雪灾害树种,根据林分遭受冰雪灾害后的研究结果实行适地适树,选择适宜的造林密度、立地和间伐模式,建立较大尖削度的林分等均能减少冰雪灾害对森林的危害。通过了解树木抵抗冰雪灾害的能力和生长的地形条件,对林分遭受冰雪灾害的危险进行评估模拟,可以预测其受害状况。对发生过冰雪灾害的林分,及时清理折断的林冠残体、倒伏林木和受损严重或死亡的林木,并进行林分改造,可以减轻或防止病虫害的爆发和蔓延和森林火灾的发生,有利于受害森林的可持续发展。

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