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火干扰对森林土壤斥水性的影响研究进展

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摘要:土壤斥水性是指水分不能或很难湿润土壤颗粒表面的现象,很多植被类型及气候带森林存在土壤斥水性。土壤斥水性受水分、温度、干湿交替、土壤质地、植被类型等生物和非生物因子的影响。而火干扰是森林生态系统土壤斥水性的重要影响因子,使森林土壤斥水性增强,渗透率降低,地表截留体减少,从而增加地表径流和土壤侵蚀。就火干扰对土壤斥水性的发生机理及其对水文过程的影响进行了较为全面的总结和讨论,并指出目前存在的问题和未来的研究重点。森林火灾后火烧迹地地表径流和土壤侵蚀显著增加,定量预测火灾后土壤斥水性对径流与侵蚀的影响比较困难,因此,基于不同尺度和自然降雨的火灾后斥水性对地表径流和土壤侵蚀的实验及长期定位观测是今后的研究方向与重点。

关键词:土壤斥水性;火干扰;地表径流;土壤侵蚀

Progress of the effects of fire disturbance on forest soil water repellency

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Abstract: Soil water repellency (SWR) is a phenomenon that occurs when the soil particles are unable or hard to be moistened by water. It refers to the inability of water to wet or infiltrate a dry soil, and this phenomenon has been documented in a wide range of vegetation types and climates, especially in soil affected by wildfire. SWR is affected by biotic and abiotic factors, such as water, temperature, alternation of dry and wet seasons, soil texture, vegetation type, etc. Fire disturbance is one of the important factors influencing the SWR of forest ecological system. It enhances the SWR of the forest soil, reducing the permeability and intercept body and increasing the surface runoff and soil erosion. Numerous studies have suggested that SWR is the primary cause of reduced infiltration rates of soils after burning. In order to understand the frontier of research in the field, this paper summarizes the effects of fire disturbance on SWR. Based on the recent achievements, the historical development of the issue was reviewed briefly. Meanwhile, its physical mechanism, influencing factors, as well as its potential effects on eco-hydrological processes before and after the fire, are discussed. The main aims

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of the future studies on this issue are also pointed out. The runoff and soil erosion increased significantly after forest fire, but it is difficult to predict the quantitative influence of SWR on runoff and erosion after the fire. Therefore, studying the effect of SWR of different scales and natural rainfall after the fire experiments on surface runoff and soil erosion and long-term observation are recommended as the future research direction and emphasis.

Key Words: soil water repellency; fire disturbance; runoff; soil erosion

土壤斥水性(Soil Water Repellency,简称SWR)是指土壤不能或者很难被水分湿润的现象,很多植被类型及气候带存在土壤斥水性现象,特别是火烧迹地[1-2]。不同土地利用方式和植被类型的土壤斥水性差异显著[3]。土壤斥水性通常在干燥条件下产生,而在长期湿润条件下减弱或消失,与土壤类型、火强度、湿润前土壤斥水性强度等有关。目前,相关研究主要集中在森林火灾和计划烧除对土壤斥水性的短期影响,而长期影响研究较少。大量研究表明,火干扰增强土壤斥水性,导致土壤入渗率下降,增加地表径流和土壤侵蚀[4-6]。近几十年来,火干扰对土壤斥水性的形成机理研究逐渐成为国外林火生态领域的研究热点之一,而国内研究报道极少。大量野外对照研究结果表明,森林火灾显著增加土壤斥水性,并得到实验室模拟和野外实验进一步证实[7-9],其主要机理是燃烧过程导致凋落物和土壤中的疏水化合物挥发并冷凝于土壤表层,或者高温高热导致土壤中某些有机化合物分解后具有斥水性。火干扰过程中,温度是斥水性变化的重要影响因子,当温度达到175—200℃时土壤斥水性加剧,当温度超过270—300℃时,土壤中的某些疏水性物质会遭到破坏[10-11]。

土壤斥水性在水平空间上分布不连续,在垂直空间上分布不均匀,基于同种植被类型的土壤斥水性持续时间和强度都不是一个固定值,呈现显著的时空异质性[12-15]。斥水土壤的时空变异给斥水性的测定带来不确定性。尤其基于大尺度的时空变异,难以定量研究火后土壤斑块、灰烬、生物扰动、孔隙及烧毁的根系变化对地表径流的影响。迄今为止的研究表明,斥水性严重影响火后地表径流和土壤侵蚀过程,定量预测火灾后土壤斥水性对水文过程的影响比较困难,因此,基于不同尺度和自然降雨的火灾后斥水性对地表径流和土壤侵蚀的实验及长期定位观测非常迫切。本文阐述了土壤斥水性概念、形成原因、火干扰后土壤斥水性的变化及其对地表径流和土壤侵蚀的影响,以期为火干扰后斥水性土壤的修复及植被恢复提供理论参考。

1 土壤斥水性研究历史

除南极洲外,从农田、草原到森林,各种气候带的土壤均发现斥水性土壤[6]。许多研究认为土壤斥水性是一种正常现象[16-17],但斥水性仅发生于表层几厘米的土壤,因为表层土壤中含有大量疏水性有机分子,如有的物种为了减少昆虫、微生物的入侵和保持叶面干燥,常常在叶表面产生一些耐降解的疏水化合物,这种疏水化合物也是形成土壤斥水性的原因之一。1910年对美国加州的土壤斥水性研究表明,火烧迹地森林土壤很难通过人为灌溉、自然降雨或地下水分运动而变潮湿[7]。Miyamoto等研究发现土壤斥水性与土壤特定有机化合物组合关系紧密[18]。某些土壤和植被组合特别容易产生强烈的土壤斥水性现象,如灌木林、松柏类和桉树林比阔叶落叶林更容易产生斥水性。另外,粗造土壤比细纹理土壤更容易形成斥水性,通常归因于土壤颗粒表面积大小。许多研究认为斥水性是由覆盖在土壤颗粒表面的疏水有机化合物引起的,表层土壤及土壤表面有机物燃烧产物在土壤中挥发和冷凝,诱发或加剧土壤斥水性[19]。总之,许多土壤类型在未经火干扰就具有斥水性,燃烧可以极大地影响土壤斥水性的规模和深度。

2 火干扰对土壤斥水性的影响

2.1 火干扰期间土壤斥水性变化

森林可燃物燃烧挥发疏水有机化合物,导致土壤斥水性,同时燃烧产生的热量形成压力梯度使土壤中化

合物向上推移,土壤温度随土层深度的增加而下降,促进疏水化合物冷凝于土壤表层。燃烧产生的热量不仅改变土壤中疏水物质,使某些化合物变成更具疏水性的结构,同时燃烧可以促进疏水化合物与土壤颗粒结合。火干扰期间温度的变化会改变土壤斥水性,土壤温度达 175—270℃时加剧土壤斥水性,达 270—400℃时土壤表层结构被毁,较长时间的低温加热会引起斥水性[20]。

森林可燃物燃烧后形成大量的矿物留存于土壤表面,而这些灰烬具有亲水性而不是疏水性物质,当灰烬被移走后,土壤表面具有斥水层。燃烧对土壤斥水性的影响随持续时间与火强度的变化而变化,主要取决于可燃物类型、可燃物消耗量、火持续时间和火强度等[21]。主要影响有:(1)燃烧可以使良好的土壤变成斥水性土壤[22];(2)含水率低的土壤受热后增强斥水性;(3)随火强度增加,土壤斥水性深度增加;(4)对于含水率非常高的土壤,低强度火可以改良斥水性土壤。

2.2　火干扰后土壤斥水性变化

火干扰后土壤斥水性因土壤水分变化而迅速改变,更与火后植被恢复的速度及类型有关。燃烧对土壤斥水性、渗透率及土壤侵蚀的影响分为短期和长期影响。随着土壤水分增加,过火林地土壤斥水性降低,甚至消失。斥水性土壤通常抵抗润湿时间从几秒到数天甚至数月[23],但强大的压力梯度和大孔隙可以使水进入土壤。一定的土壤含水量(即临界阈值)状态下土壤可以慢慢由斥水土壤变为湿润土壤,但时间很长,低有机物含量的沙质土壤的含水量阈值可以不到 5%,而细质地土壤的阈值可以超过 30%[24],研究表明,土壤水分阈值随着火强度的增加而增加,但这种变化关系的机制尚不清楚。火后长时间的湿润和干燥周期交替可引起土壤斥水性慢慢消失。大多数研究表明,燃烧产物对土壤斥水性的影响持续时间不相同。火灾对土壤斥水性的影响最长记录是俄勒冈州的松林高强度火烧迹地,土壤斥水性持续了 3—4 年,甚至达 6 年[25];撒丁岛灌木丛低强度火干扰后土壤斥水性增加,3 年内恢复到火干扰前的水平[26]。西班牙松树林火灾后产生土壤斥水性,3 年内基本恢复[27]。密歇根州混交林森林火灾后 1 年内 65%的过火面积土壤斥水性基本恢复[28]。加州混交林低强度火后 2 个月内土壤斥水性基本恢复到火烧前水平[29]。即使同一植被和土壤类型,火灾后土壤斥水性的持续时间高度可变。Huffmann 等研究发现,科罗拉多州松树林火干扰后土壤斥水性持续了至少 22 个月,而附近营林用火后土壤斥水性持续 1 年左右[0]。澳大利亚桉树林中、高强度火后土壤斥水性增加显著,两年内逐渐下降。MacDonald 等观测科罗拉多州火烧迹地,火干扰对 0—3 cm 层土壤产生斥水性[1],表层土壤斥水性减弱或消失主要归因于物理冻融循环,但也与土壤生物活动、植被恢复及其他因素有关。研究爱达荷州灌木林地表明,太阳照晒影响土壤水分差异,由此产生的土壤湿度差异影响土壤斥水性变化和植被恢复[32]。

火干扰对土壤斥水性的长期影响是由于各种物理和化学过程共同作用的结果。大量研究认为火干扰的持续时间越长,土壤斥水性更严重,但火灾后土壤斥水性随着时间变化的规律不够透彻。具体原因包括:(1)火灾后土壤斥水性的短期影响研究较多,长期跟踪调查相对较少;(2)影响土壤斥水性的因素较多(如土壤种类、含水率等),很少有人在一次实验或研究中涉及所有影响因子;(3)土壤斥水性的诊断技术研究时间不长,起步较晚,主要为滴水穿透时间法与酒精溶液入渗法。

3　火干扰后土壤斥水性对水文过程的影响

火干扰后林地水文过程与土壤斥水性密切相关,土壤斥水性对水文过程的影响主要包括:(1)渗透率降低和地表径流增加,(2)土壤渗透性和水分通量的空间变异性,造成土壤水分分布不均,(3)土壤侵蚀增加,(4)增加干燥土壤的风蚀,(5)降低土壤颗粒的凝聚力;(6)渗透率降低的次生影响主要表现在阻碍植物的萌发和生长(即影响火后植被恢复),从而影响火干扰后径流和侵蚀持续时间,火烧迹地比未烧林地土壤斥水性更强更持久,因此火干扰后土壤斥水性已经引起特别关注,如地表枯枝落叶的损失、土壤结构的变化、土壤孔隙减少导致渗透下降、上层植被损失减少截留体等,被认为是增加地表径流和土壤侵蚀的主要原因[3-34]。

3.1　土壤斥水性对水文效应的影响

最引人注目的土壤斥水性后果之一是渗透速率下降,斥水性土壤在强降雨期间也很难湿润。森林火灾过

后,土壤渗透速率降低,截留体被烧毁,因此火干扰后一旦降雨,火烧迹地比未烧林地更容易形成地表径流。如每小时 40—46 mm 的模拟降雨后,葡萄牙强斥水性森林土壤湿润程度很低[35],80 mm 模拟降雨,强斥水性土壤渗透率仍然很小,降雨持续 3 周,土壤下层仍保持干燥。DeBano 发现第一个 5 分钟渗透到斥水土壤的水分仅为饱和水的 1%,降雨后土壤斥水性引起径流,表面活性剂应用于裸露的强斥水性桉树林土壤,模拟降雨后入渗率比对照土壤增加 16 倍[15]。常年积雪地区,很少出现土壤斥水性,因为融雪速度比降雨慢,最初的融雪通常会慢慢湿润土壤到水分阈值,正好解释了为什么落基山脉中部和北部地区冬、春季火烧迹地几乎没有地表径流和土壤侵蚀。土壤水分低于临界阈值时,干燥季节土壤斥水性对渗透和径流影响更大[6-37]。特别干燥或火干扰后,澳大利亚桉树林土壤斥水性显著增强,导致地表径流比其他林地增加 10%[38]。

对 5 个火烧迹地和 1 个对照林地入渗率进行比较研究,两个火烧迹地对入渗率没有显著影响,而其他 3 个火烧迹地渗透速率大大降低。相同降雨量情况下,火灾后土壤斥水性导致地表径流增加。大部分未燃烧林地渗透速率大于降雨强度,暴雨径流主要为地下暴流及饱和坡面流[39]。在科罗拉多州低山林区,夏季雷暴雨强度达 60—65 mm/h 时,不会形成地表径流和土壤侵蚀,但火灾后两年内,降雨强度达 8—10 mm/h 就形成地表径流和侵蚀[40]。火灾后位于斥水层上的湿润表层土壤往往诱发浅层饱和坡面流。高强度火灾后,土壤颗粒表面粗糙度降低,增加坡面流的速度和峰值流量[41]。降雨使暴露于雨滴溅击、片蚀和细沟侵蚀的矿质土壤表面引起覆土,进一步降低渗透速率,这些变化的净效应使峰值流量增加一个或多个数量级,如夏季亚利桑那州森林[42]和科罗拉多州[43]杰克松林火灾后峰值流量是未烧林地的 5—15 倍。Scott 等研究发现,基于同样降雨量,南非松树林火灾后峰值流量比未烧林地增加 2 倍以上,这种差异与饱和坡面流有关[4]。燃烧损失上层植被,减少截留体和蒸腾速率,从而影响径流量,至少在年降雨量 450—500 mm 区域才容易形成地表径流,降雨量越大,径流量越大。

土壤渗透速率的空间变异阻碍了土壤斥水性的大尺度效应。在科罗拉多和蒙大拿的火烧迹地密集采样斥水性土壤后发现,自相关距离仅 2 m[44],土壤斥水性的空间变异性与大多数其他研究结果一致[45-46]。未烧林地土壤入渗率遵循对数正态分布,并显示低水平的空间相关性,表明坡面流的产生具有空间变异性,随着空间尺度的增大可能诱导较高的渗透速率,在火烧迹地斥水区域产生的地表径流也有部分通过被烧毁的植物根系形成的孔隙入渗到土壤下层[47]。

土壤斥水性的时空变异性是很难确定土壤斥水性对地表径流的影响。火干扰后的径流中含有大量沉积物和燃烧剩余物,很难精确测定森林火灾后流域尺度径流量[48]。Doerr 等比较了葡萄牙未烧林地的峰值径流没有显著差异[1],但潮湿条件下(无或弱斥水性)峰值径流持续时间比火烧迹地大大减少。科罗拉多杰克松林燃烧后的强地表径流和侵蚀率持续一年左右,火后一年大幅减弱。结果表明,土壤斥水性可以增加流域地表径流,但土壤斥水性只是影响地表径流的众多因素之一,因此综合多因素下火灾对土壤斥水性的影响及灾后水文过程研究非常迫切。

3.2 土壤斥水性对侵蚀的影响

火干扰烧除保护土壤表面的枯枝落叶,高强度火甚至消耗矿质土壤表层的有机物,降低土壤表面粗糙度,增加地表径流速度,将进一步增加表面侵蚀率[49]。一般情况下,土壤斥水性对侵蚀的最大影响归因于地表径流。随着地表径流量的增加,速度增快,冲刷能力和运输能力也增大,径流受区域地形影响,变成许多细流,造成细沟侵蚀[50]。陡坡林地高强度火后,一旦降雨,表土层容易湿润而变得饱和,孔隙压力增加会降低剪切强度,在重力作用下,引起滑坡和小型泥石流[51]。对科罗拉多杰克松林火烧前后调查表明,高强度火后的第一次暴雨引起广泛的细沟侵蚀,冲走地表约 80%的泥沙[52-53],河道与洼地的沉积物显著增加[54],坡面样地移去地表覆盖物与高强度火后导致的细沟侵蚀和土壤侵蚀量相当。然而某些土壤类型不容易发生细沟侵蚀,主要原因:(1)流水切应力比水滴溅小几个数量级[55];(2)一旦地表径流集中,流水层可以减少水滴滴溅,但细沟侵蚀速率可能较高;(3)火烧后斥水土壤容易发生细沟侵蚀,归因于地表的裂缝、烧毁的根洞及昆虫和动物的洞穴对坡面流的拦截[56]。土壤斥水性直接影响土壤侵蚀率,实验室测试表明,斥水土壤比湿润土壤产生较

少、较慢的移动喷射液滴,但斥水土壤上的水滴含有更多的沉淀物[57],连续降雨后,斥水土壤表面保持干燥和无粘性,尽管有水膜覆盖,土壤颗粒容易被雨滴溅散,相反,模拟降雨引起的湿润土壤表面密封和压实,增加土壤被溅散的抵抗性。实验室和野外对长期未烧斥水林地进行模拟降雨,得到结果一致[58],但自然降雨对刚刚过火的裸露斥水土壤的影响研究较少。

火干扰后土壤侵蚀率和土壤斥水性之间高度相关,表明火灾后土壤斥水性强度和林地植被恢复决定了灾后土壤侵蚀的动态。除了保护植被盖度,土壤斥水性对表面侵蚀率的影响不仅取决于土壤斥水性强度和持久性,而且取决于时空分布与连续性,当然也与土壤质地、降水季节、融雪与降雨形成的地表径流等有关。流水驱动表面侵蚀的情况下,燃烧大大增加风蚀率,归因于森林火灾消耗了林地植被及枯枝落叶,减少表层土壤水分,从而降低土壤颗粒凝聚力,林内风速增大,土壤斥水性在火烧迹地的风蚀中起重要作用[59]。

4 结论与展望

土壤斥水性是一个普遍存在的现象,火干扰特别是高强度火显著增加土壤斥水性。火灾破坏地表截留体,燃烧高温(大于 300℃)使有机化合物蒸发,部分疏水性化合物冷凝于土壤表层,形成极强的疏水层,导致渗透速率降低,从而引起地表径流和侵蚀。火干扰增强土壤斥水性,降低渗透速率,是导致峰值流量和土壤侵蚀的主要原因,同时火干扰引起表层土壤和植被等一系列变化,也是增加地表径流和土壤侵蚀的因素。

当前,火干扰对土壤斥水性影响研究存在的问题及对策可归纳为以下 3 个方面:(1)火干扰后土壤斥水性持续时间及植被恢复有待进一步研究;(2)由于土壤斥水性的时空变异性,很难定量研究,土壤斥水性对不同尺度生物扰动、植被恢复、地表径流及土壤侵蚀等的影响,需要运用定量方法来获取土壤斥水性的时、间变异特征;(3)森林火灾后不同尺度、自然降雨条件下土壤斥水性及其对径流和侵蚀的动态变化研究很少,因为火灾后影响径流和侵蚀的干扰因素较多,需要加强控制条件下的实验研究。森林火灾后经常产生土壤斥水性,或火烧增加土壤斥水性且持续时间更长,因此,不同植被类型火干扰后土壤斥水性持续时间及改良土壤斥水性的主要物理、化学和生物因素有待进一步研究。同时,火干扰后土壤斥水性与渗透速率之间的关系、不同尺度范围内的径流率预测、综合多因素的土壤斥水性变化规律的研究没有报道,因此,加强火干扰后不同尺度、自然降雨条件下土壤斥水性的动态变化及其与地表径流和土壤侵蚀的关系研究是今后的研究重点与方向。

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