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桉树人工林区水体泛黑机理研究进展

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摘要: 围绕桉树人工林区水体突发性泛黑的形成机理,参考国内外关于缺氧性黑水事件的主要研究成果,重点从桉树人工林区泛黑现象的表征,致黑物质特性及来源,水体突发性泛黑的驱动因素,模拟预测及适应性调控等 5 个方面,讨论了桉树林区水体泛黑机理的研究进展。研究认为,桉树人工林区的黑水是一种出现在林区洼地、溪流、水库等不同规模水体的颜色如墨的水,其致黑物质主要为桉树茎叶残体浸出液富含黑色溶解性有机碳(DOC)、单宁酸等,单宁酸与金属离子结合形成的黑色络合物,以及当水体缺氧时形成的黑色金属硫化物。气象条件骤变,水文情势突变,沉积物的累积与运移等因素驱动了水体泛黑:对受水温分层结构影响的大中型水库等深水水体而言,致黑物质累积在水体底层,当气温骤降,水温分层结构失稳,水体内部多种化学反应及物质的运移过程发生变化,此时水体变黑。水文情势突变时,以潜流形式进入水库的径流将林区大量 DOC、植物残渣、泥沙携带进入水体,导致水体泛黑。沉积物中微生物分解及氮、磷等的释放加重了水体底部缺氧,为致黑物质形成创造了环境。为了更好地预测和调控黑水,建立黑水运移模拟模型及对黑水进行适应性调控也尤为重要。目前现有研究大多集中于小规模水体(如溪流、河道等),而对会发生分层现象的大规模水体(如深水湖库等)的黑水发生机理仍不完全明晰,流域层面上的黑水模拟与预测还需进一步研究,桉树人工林区水库泛黑机理研究是未来重要方向。

关键词: 桉树人工林;水体泛黑;溶解性有机碳;黑水模拟模型;适应性调控

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Review on the mechanism of blackwater in eucalyptus plantation

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Abstract: Ecological impact of Eucalyptus plantation is a key scientific topic of global concern, especially its deforestation and water safety problem. Present research findings have evolved around the black water mechanism, its characteristics and the source of the dark component. The driving factor of black water, its prediction and adaptive control have been analyzed in this study. Research has indicated that black water appeared in depressions, streams and reservoirs of different scale in the eucalyptus forest. This was mainly caused by dissolved organic carbon and tannic acid that was extracted from eucalyptus leaf. Black complex formed by the combination of tannic

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acid with metal ions, and ferrous metal sulfides formed when the water was oxygen deficient. Besides, black water formation was triggered by either a change in meteorological conditions, hydrological situation or sediment accumulation, and migration. For deep waters (large and medium-sized reservoirs), which are affected by thermal stratification, dark matter accumulated in the water bottom. The water's thermal stratification structure lost its stability when the temperature dropped, hence allowed the mixing of the water along the column in the reservoir leading to various chemical reactions, then finally caused the appearing of black water. Additionally, when the hydrological regime suddenly changes, the flood water that flows into the reservoir in the form of underflow will bring large amounts of DOC, plant residue and sediment into the water, resulting in the black water. The decomposition of microorganisms and the release of nitrogen as well as phosphorus in sediments aggravated oxygen deficiency at the bottom of the water, and created an environment for the formation of black matter. To predict and control the black water, it is very important to establish a model to simulate the transportation and regulate the adaptability of it. Present research was focused on the small-scale water (such as streams, rivers, etc.), so the formation mechanism of large-scale water that results in stratification (such as deep lakes and reservoirs, etc.) is still not entirely clear. Therefore, further study on the simulation and prediction of black water at the basin level is needed. At last, the mechanism of reservoirs in eucalyptus forest area will be an important topic in the future.

Key words: eucalyptus plantation; black water; dissolved organic carbon; mathematical simulation of black water; adaptive regulation

桉树(Eucalyptus)原产于澳大利亚,因生长速度快、轮伐周期短、经济效益高等优点,已被全球120多个国家引种,目前种植面积已高达全球人工林总面积的1/3[1]。然而桉树种植背后的生态环境问题逐渐显现,该树种被认为是“抽水机”“绿色沙漠”,甚至被传言“有毒”,这些争议引起了中央和地方政府、主流媒体(CCTV)、学术界以及群众的高度关注[2],其中桉树人工林区砍伐迹地及其周边水体大面积突发性泛黑引发的水量水质安全问题更是新的关注焦点[3-4]。桉树人工林对水量水质的影响在时空上具有多层次、多过程的特点,桉树经营活动、林区土壤特性、气象水文条件、水体规模等均对黑水时空分布和演变格局产生重要影响[5-8]。总结国外桉树人工林区水体的泛黑机理,主要是溶解性有机碳(DOC)、单宁酸等致黑物质在洪水淹没时从桉树叶等植物残渣中大量浸出,并在气温适宜条件下被微生物等分解代谢,因分解代谢过程消耗了大量氧气,使得水体出现缺氧甚至厌氧环境,造成鱼虾死亡。目前国内对于水体泛黑现象的研究主要集中在城市黑臭河道、太湖“湖泛”,以及红枫湖和百花湖黑水事件方面,而对本身存在争议的桉树的人工林区水体突发性泛黑鲜有报道,仅有的研究只针对桉树砍伐迹地洼地等小规模水体,但我国桉树人工林区其他水体(如水库等)也发生了泛黑现象。为推进对桉树人工林区水体泛黑现象的研究,本文拟重点对黑水形成的研究进展进行回顾性总结。

本文简要概述了桉树人工林区泛黑现象的表征,通过介绍桉树人工林区水体泛黑的致黑物质及来源和突发性泛黑的驱动因素,综述了林区水体泛黑的形成机理,在此基础上,介绍了黑水模拟与预测模型的研究进展,并针对桉树人工林区水体突发性泛黑提出了具有一定参考价值的调控措施,这对指导我国南方地区水库流域内桉树人工林科学种植及保障饮用水安全意义重大。最后展望了桉树人工林区水体泛黑现象未来的研究方向及发展趋势。

1 桉树人工林区水体泛黑现象表征

水质恶化现象具有不同的表现形式[9-10],包括河道黑臭[11-12]、海洋赤潮[13]及湖库富营养化[14-15]等。水质恶化引起的水体颜色变化给人的感觉最为直接[16],桉树人工林区出现的黑水是一种出现在林区不同规模水体的颜色如墨的水。在桉树采伐或凋落物密集的季节,桉树等植物残渣经过雨水或林间溪水浸泡,使得林区洼地[17]、溪流等小规模水体变黑,后汇入池塘、水库导致池塘、水库等中到大规模水体颜色变黑,水中鱼类死亡[6,17]。澳大利亚、美国、巴西、欧洲等地区的桉树人工林区水体均发生过此类泛黑现象,林区凋落物等堆积在低洼处,形成洼地黑水,并溢流出黑色径流,造成流域泛黑[6,17]。如2011年澳大利亚墨累达令河流域发生严重泛黑事件,长期干旱后的一场洪水将累积于墨里达令盆地的上百吨DOC冲刷进了墨里河[18],造成了大量鱼虾死亡[19],持续时间长达6个月[18],影响河段长度超过2 000 km。由于这些国家地广人稀、水资源开发利用程度不高,桉树人工林区水库数量有限,现有报道集中在河道、洼地或池塘等泛黑研究[20-22],而针

对水库泛黑的研究较少。而在我国南方桉树人工林种植地区,人口密度大,水库众多,很多水库都承担了生活饮用水水源的功能,如南宁市有 50 座生活饮用水水源地水库,其中 45 座都种植了桉树,如此大规模和高比例的桉树种植使得水库水体突发泛黑出现频率高、影响范围广[23],对水库周边居民的生活饮用水安全构成了严重的威胁[24]。但水库与河道、洼地等水体在气象水文条件、温度和溶解氧(DO)垂向分层特性、水动力结构、沉积物运移规律方面,以及桉树凋落物或残体在水体中的运移、腐解和转化特征方面,都存在较大差别,所以国外针对河道、洼地等水体泛黑的研究成果还很难直接借鉴到水库泛黑研究中。

2　桉树人工林区水体泛黑的致黑物质及其来源

2.1　桉树茎叶残体浸出液富含黑色溶解性有机碳

桉树人工林区黑水的特点是含有高浓度的溶解性有机碳,有机碳被微生物分解代谢导致水体 DO 偏低,从而造成鱼类和甲壳类动物死亡[25]。有机碳等营养物质对水生态系统的运转起着重要作用[26],水体对溶解性有机碳(DOC)有一定的承载能力,当其中有机碳含量达到一定程度时就容易引发黑水[27]。Francis 等[28]指出桉树人工林区黑水是林区有机物(主要是凋落物)堆积在低洼处,在水分过饱和(或淹水)条件下分解,并溢流出富含溶解性有机碳(DOC)而形成[28]。溢流出的 DOC 绝大多数来自植物残体[25],植物残体在被水淹没时,浸出大量 DOC;DOC 浸出量和许多因素相关,如树种、树龄、河滩上凋落物的累积量[26]以及叶片新鲜程度[28]。在桉树人工林区,DOC 等含碳化合物的浸出就主要来自桉树叶而非树皮、树枝[29-30],且叶片越新鲜,DOC 浸泡释放量越大[6]。桉树叶在被洪水淹没的 24 h 内就能浸出较多的 DOC[28],且桉树凋落叶质量损失率显著大于杂交相思、马尾松和软阔林[31]。澳大利亚 Edward-Wakool 系统中,凋落物在夏季末,也就是 12 月到次年 1 月时达到峰值,最高值为 11.8 $g/(m^2 \cdot d)$。凋落物多的时候,31 d 就能使一条窄的小溪流出现缺氧性黑水,然后再汇入河道,高落叶量和高温增大了黑水发生的概率[25]。

对于常规水体[32]和黑色水体[33],有机物在周边土壤和沉积物中都有储存[34]。土壤中凋落物的浸出速率与土壤类型及土壤污染程度有关[35]。Rixen 等[36]在对印度尼西亚苏门答腊 Siak 河的长期观测中发现,长期淋溶作用使土壤中腐殖质等深色或黑色有机颗粒物质迁移进入水体,致使水体变黑。杨钙仁[17]对桉树人工林采伐迹地黑水发生规律的研究发现,土壤层和凋落物层是影响林区水质的关键环节,施肥后,林区土壤层的养分元素会通过淋溶、交换、冲刷等物理化学过程随水迁移;桉树凋落物淋溶水的有机物含量高,且颗粒大小比较均匀,使得水体浊度高。

2.2　水体的缺氧环境导致黑色金属硫化物形成

黑色金属硫化物在缺氧厌氧的水环境中富集可导致水体变黑。位于美国中西部的 Illinois 州的 Big Pit 露天矿湖水体变黑就是由于缺氧厌氧环境促生了黑色金属硫化物[37],Duval 等[38]也发现了类似的现象和规律;夏品华等[39]研究表明,缺氧环境下使得沉积物中氮磷等物质释放,水体营养盐含量升高,且缺氧环境下有机质分解伴随了还原态 S^{2-} 形成,刘国峰等[40]和 Duan 等[41]认为在缺氧厌氧环境下,水环境中具备形成黑色金属硫化物的客观条件,水体中存在大量以黑色 FeS 为代表的金属硫化物可能是水体显黑的主要原因。桉树人工林区水体泛黑的致黑物质除了溶解性有机碳含量过高外,也可能与其他因素有关。如土壤或沉积物中较高含量的铁、锰等物质,这些物质(同时也包括桉树叶)在降雨径流作用下从土壤中迁移进入水体[42],桉树叶使得水体中有机物增加,有机物在水中分解大量消耗 DO,导致水体缺氧严重[1],沉积物中硫类污染物释放。同时铁、锰是氧化还原条件中的敏感性元素[17],它们在一定条件下在水中还原成铁、锰等低价离子,同时在缺氧环境下,水中还原成铁、锰等低价离子,形成金属硫化物等黑色不溶性物质,造成黑水现象发生。

2.3　桉树茎叶浸出单宁酸与金属离子结合形成黑色络合物

我国广西人工林区桉树林区的黑水发源于新鲜叶和嫩梢,新鲜叶累积越多,黑色越明显,且桉树较马尾松、杂交相思等的单宁酸含量高、易分解[17]。张娟等[43]在对什邡地震灾区茶水变黑现象的调查研究发现,该地井水中含有大量的二价铁离子,在泡水时与茶叶中的单宁酸反应,形成紫黑色单宁酸亚铁络合物,使得水变黑色。连成叶[44]的研究也表明,单宁酸可与二价铁离子反应变黑,并在氧化作用下黑色会更加明显,且黑色程度与含铁量多少有关,含铁量越多颜色越深,反之越浅。广西地区土壤铁、锰等金属含量本身较高,在雨期来临时,特别是恰好遇到桉树采伐,雨水将树叶及土壤中铁、锰带入河道或水库中,在缺氧、还原性条件下,水体由于黑色单宁酸亚铁的形成而变黑,当水体复氧后单宁酸亚铁被氧化成单宁酸铁黑色沉淀[45]。

桉树人工林区水体泛黑的致黑物质及其来源涉及过程多且反应复杂,目前已有研究只涉及以上三个方面,这些方面对黑水产生的贡献程度还有待进一步研究。

3 桉树人工林区水体突发性泛黑的驱动因素

桉树人工林区黑水的孕育、累积、触发和消亡受林区水温、水文情势和沉积物运移的复合影响。对小规模水体(如溪流、河道等)而言,高温高湿、久旱甘霖的气象水文条件极易引发黑水[27],而对中到大规模水体(如湖、库等),气象或水文条件突变引起的水体热分层结构在短期内失稳破坏而导致的上下层水体物质交换可能是其突发性泛黑的触发条件。

3.1 气象条件骤变对黑水生消演变的驱动机制

水温与水体内部的物理化学特性与密切相关,水温变化一定程度上影响了 DO 浓度[46]、微生物分解速率[47]及水体分层结构,微生物分解速率影响了 DOC 浸出的快慢[25, 48],水温分层结构的形成与失稳影响了水体内部多种化学反应变化及物质的运移过程[49],因此水温变化对桉树人工林区水体泛黑具有重要的驱动作用。夏季水温升高加快了微生物对桉树叶等植物残渣的腐解速率,过程中消耗了大量的氧气,造成了水体厌氧,使水体成为一个还原环境,促发了铁、锰等黑色硫化物的形成[50],同时也造成了大量鱼类死亡。另外,DOC 的溶解度随温度变化而变化,因此非生物碳的浸出率增大[51]。对与水深超过一定深度的中到大规模水体,如水库:夏季强烈的太阳辐射使得表层水体温度升高,由于水深,热量无法传递到下层水体,从而导致水体水温分层结构形成[52]。稳定的温度分层结构使得水体中物质的上下交换受阻,DO 的消耗大于补充,导致底层水体缺氧甚至厌氧,富集在底部沉积物中的营养盐等物质在厌氧环境中被释放,致黑物质在厌氧环境中形成,底层水质恶化[53]。当秋冬季气温下降时,上层水温也随之降低,水体密度增大,水体分层结构失稳,下层恶化水体因密度流扩散至整个水体,引发了水体出现季节性水体泛黑事件[39]。

3.2 水文情势突变对黑水生消演变的驱动机制

水文情势突变也是黑水的促发因素[27, 54]。洪水冲刷下,河流、水库等水体与被冲积平原或山地之间的相互作用对水质关键驱动有重要的影响[55]。Whitworth 等[56]、Howitt 等[26]的研究表明,雨前干旱以及降雨水量对桉树人工林区黑水的发生具有重要影响。雨前干旱给被冲积的平原和山地一定的时间积累桉树等植物残渣,洪水的来临浸润了这些植物残渣,并将其浸出的大量溶解性有机碳、剩余植物残渣及平原、山地土壤中的悬浮颗粒态物质和泥沙携带进入径流、河道及水水库,尤其是在降雨早期阶段,这种现象尤为突出[57]。汛期强降雨径流也能显著改变入库条件,尤其在入流量大小和紊动性方面,对库区水体造成了一定程度上的冲击,使得强降雨条件下水体的热分层结构与平时差异显著。大量研究[57-59]表明汛期降雨径流一般以密度异重流形式潜入水库水体,表层流、间层流、潜流是异重流在水体中主要存在的 3 种流态[60]。径流携带了林区大量 DOC、植物残渣、泥沙,通过表层流及间层流形式进入库区水体的径流直接影响水体水质,通过潜流形式进入库区水体的径流将 DOC、植物残渣、泥沙等带入水库底层,在底层缺氧环境中发生一系列的化学反应,待水温分层结构消失时,导致整个水层水质恶化[61]。

3.3 沉积物的累积与运移对黑水生消演变的驱动机制

沉积物跨界面运移对水体水质产生了重要影响,一定程度上促进了黑水的爆发。在澳大利亚桉树人工林区,桉树等树木的树皮、树叶在夏季大量凋落,此时粗颗粒有机质(CPOM)(包含了氮、磷等物质)[62]在溪流底质中逐渐累积,且当凋落物中树枝和树皮所占比重大时,CPOM 的累计量增多[63]。此外,桉树叶较其他落叶林区树叶重,影响了林区水体底质的 CPOM 的更新,使其更新时间变长。对小规模的溪流、河道等水体而言,CPOM 的更新缓慢大大增加了水体泛黑几率[62]。但当林区河道坡度较大时,CPOM 便由河道迁移到了湖库等中到大规模水体中[64]。湖库等中到大规模水体在夏季容易产生分层现象,所以当 CPOM 在沉积物中累积时,不会立即促发湖库水体变黑。当湖库分层时,底层处于缺氧状态,水体沉积物内源磷释放的风险增大[65],当分层现象消失时,由于水动力等作用,湖库水体的上下水层发生交换[66],最终使得整个水体变黑。

桉树人工林区水体泛黑因水体规模不同,促发黑水发生的因素也略有差异,目前的研究成果主要集中在针对桉树人工林区水体泛黑的单个驱动因素,而对多因素复合驱动研究还不够深入,尤其是对桉树人工林区水库的研究。

4　桉树人工林区水体泛黑关键过程数学表征及黑水运移模拟模型

桉树林区发生的黑水事件,尤其是缺氧黑水事件对水环境造成了灾难性的影响[19, 56],因此对黑水事件的模拟预测也尤为重要。黑水事件的模拟预测最常见的方法是建立黑水运移模拟模型。在黑水运移模拟模型方面,现有算法已有了较大的进展[67-68]。Howitt 等[69]开发的黑水运移模型以模块为单位运行,各子模块分别预测了洪泛区在洪水来临前凋落物累积量、在洪水期间的凋落物输入量及 DOC 浸出量、水体 DO 等,以此描述黑水在河道中的产生、累积、释放和运移过程。Hladyz 等[70]通过对澳大利亚 Edward Wakool 河流系统的研究,提出了一种碳负荷运算方法,该方法可以确定 DOC 的主要来源以及干涸河道中 DOC 的累积途径和累积时间,并根据 DOC 在最大累积速率下的累积时间重新确定干涸河道中的水流时间。King 等[71]所开发的模型,将与上场洪水的时间间隔、洪水的持续时间和规模、洪泛区碳的输出和分解、森林下游指定点的 DO 预测等进行耦合,优化了模型框架,通过各耦合成分的模拟计算,合理判定水资源分配的结果,以限制洪水对森林下游水质的负面影响。针对澳大利亚东南部的河漫滩,Whitworth 等[48]建立了一种黑水风险评估模型,该模型涵盖了河滩上凋落物的累积和衰减率,以及碳浸出率、微生物降解、耗氧率、复氧过程和水体中溶解性有机碳和 DO 的影响[20, 27],后期又分析了凋落物中碳的浸出、分解与温度之间的相关关系,并修正了已有的关键参数和算法。与此同时,Whitworth 等[5]将修正后的黑水风险评估模型进行了通用化调整,使得所有算法和常量都可以应用在平原系统的黑水运移模拟中[20],并运用此模型预测了桉树林洪泛区洪水淹没期间水体中 DO 和 DOC 的浓度分布状况以及森林洪泛区河滩对于 DO 和 DOC 的承载能力。但现有的黑水运移模型主要针对河道水体,还没有关于水库黑水生消演变的模拟模型。水库独特的热分层现象、沉积物蓄积与释放效应等都导致水库中的黑水运移过程不同于河道水体,因此建立气象、水文、底泥等多因素耦合下的水库黑水运移模拟模型十分必要。

5　桉树人工区水体泛黑的适应性调控

桉树人工林区水体泛黑给饮用水水源地安全及鱼类等生存造成了严重威胁[19, 56],因此对其做适应性调控十分必要。澳大利亚已有研究将水体泛黑的适应性调控分为流量调节、降低粗颗粒有机碳浓度和加快复氧速率三个方面[46]。流量调节主要是季节性流量控制,水温是水中 DO 浓度的重要影响因素,气温低时洪水将 DOC 带入河道或水库中不易造成溶氧消耗大于输入[72],所以可以在暖天气和枯落物高峰开始之前调节环境流量。粗颗粒有机碳主要来源于林区土壤及桉树凋落物,为降低粗颗粒有机质浓度,可将桉树砍伐期安排在洪水期后,并在洪水来临前,及时对桉树人林区凋落物进行清理减少林区溪流河道等发生黑水的概率;也可在径流入库点设置集水渠,沉淀过滤泥沙后汇入水库,或在林区设置隔离栏,防止散落的速生桉茎叶流入库区,保障饮用水水源地安全[46]。加快复氧速率可通过降低河道、水库等水位的方式促进底部复氧,使得黑水尽快复原,或将洪水当作增大流量的一个工具[73],增大流量,水体流动增大了表层水体扰动和混合,从而增大了复氧率[27],避免水体因缺氧而导致黑物质的生成。

6　结论与展望

桉树人工林区水体泛黑现象在林区不同规模水体都有发生,小到砍伐迹地洼地,大到林区饮用水水源地水库,溶解性有机碳等致黑物质和金属离子氧化还原反应生成黑色物质是林区水体致黑的主要物质,水温与 DO 条件变化、水文情势突变、沉积物的累积与运移是林区水体泛黑的驱动因素。

现有研究成果主要集中在河道、洼地或池塘等泛黑,而针对水库泛黑的研究不足。水库与河道、洼地等水体在气象水文条件、温度和 DO 垂向分层特性、水动力结构、沉积物运移规律等方面存在较大差别,所以国外针对河道、洼地等水体泛黑的研究成果还很难直接借鉴到水库泛黑研究中。目前国内对于水库水质恶化驱动因素的研究多为单因素驱动研究,而对多因素复合驱动研究还不够深入,尤其是对桉树人工林区水库的研究。

在科学制定桉树人工林区水库水质保障措施方面,缺乏专门针对水库且耦合气象-水文-底质多因素的黑水运移数值模拟技术,不能高精度的反演和预测多情境组合下水库泛黑物质在大气-水体-底泥界面间的运移机制和黑水生消过程,并以此提出泛黑水库水质保护的最优化适应性调控措施。

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