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基于稳定同位素的干旱半干旱区 SPAC 水分运移过程研究进展

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摘要:土壤-植物-大气连续体(SPAC)是生态水文学的重点研究对象,其水分运移过程对于干旱半干旱区生态植被建设和水资源综合管理具有重要意义。氢氧稳定同位素较高的灵敏性和准确度有助于揭示这一过程。介绍了氢氧稳定同位素在土壤-大气界面、土壤-地下水界面、土壤-植物界面和植物-大气界面水分补给传输过程中的应用,包括土壤水分来源和蒸发;水分补给入渗机制和滞留时间;植物水分来源和水力再分配;蒸散发分割和叶片吸水的相关研究,同时明确了氢氧稳定同位素技术在应用过程中存在的一些不确定性以及未来亟需加强的方面,以期为利用稳定同位素技术对生态水文过程的研究提供参考依据。

关键词:稳定同位素;土壤-植物-大气连续体(SPAC);土壤水;水分来源

A review of water movement process in SPAC in the semi-arid and arid regions based on stable isotopes

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Abstract: Soil-plant-atmosphere continuum (SPAC) is one of the important research objects in ecohydrology, and its water movement process is of great significance for ecological vegetation construction and integrated water resources management in arid and semi-arid regions. With higher sensitivity and accuracy, hydrogen and oxygen stable isotopes were used to trace water transport processes. This paper focused on the application of hydrogen and oxygen stable isotopes in water recharge and transport at soil-atmosphere interface, soil-groundwater interface, soil-plant interface, and plant-atmosphere interface, including source and evaporation of soil water; water infiltration mechanism and residence time; plant water source and hydraulic redistribution; evapotranspiration partitioning and leaf water absorption. In addition, this paper clarified the uncertainties and limitations of hydrogen and oxygen stable isotope technology and discussed the future research direction, which might provide a reference for the study of ecohydrological processes using stable isotope techniques.

Key Words: stable isotope; soil-plant-atmosphere continuum(SPAC); soil water; water source

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干旱半干旱区占我国陆地面积一半以上,是陆地生态系统的重要组成部分[1],降水稀少、蒸发强烈、区域生态环境脆弱[2],水分是限制该区域植物生长发育的关键因子。研究表明,近年来我国干旱半干旱区的极端气候事件呈现出多发、强发态势[3],这改变了区域水循环过程,严重影响生态环境发展[4]。相比全球概念的一般水文循环模式,即降水、径流或入渗、蒸发或蒸腾过程,干旱半干旱区的水循环主要以土壤-植物-大气间的垂直循环为主[5]。这种垂直循环在区域内部的水分运动中起着重要作用,影响着干旱、半干旱区植被分布和生长等多个方面。因此,研究干旱半干旱区土壤-植物-大气间的水分垂直循环对于气候变化背景下生态植被建设和水资源综合管理具有重要意义[6]。

澳大利亚学者 Philip[7] 1966 年首次提出了较为完整的土壤-植物-大气连续体(Soil-Plant-Atmosphere Continuum,简称 SPAC)概念,认为系统各个界面之间互相衔接,是一个连续的整体,系统内的水分运动依靠能量转化来实现。这对于以往孤立、静止的水分传输观点来说是一次重要的突破。我国对 SPAC 水分运移的研究始于 20 世纪 80 年代。康绍忠等人[8]从水分中的能量输送与转化、水分传输过程中的力能关系、植物根系吸水、水分在植物体内的传输和计算机仿真等方面阐述了 SPAC 系统水分运移,提出了土壤水分动态模拟、作物根系吸水、蒸发蒸腾模拟 3 个子系统的 SPAC 水分运移模拟,但是并没有考虑到地下水在整个系统中的作用。因此,刘昌明[9]将 SPAC 的概念进一步扩展为“五水”转化,即大气、植物、地表、土壤和地下含水层中的水之间相互作用和相互影响,最终达到平衡状态。基于水循环原理,本文将 SPAC 水分运移过程进一步概括为四个层面:(1)大气-土壤界面水分的来源及蒸发;(2)土壤-地下含水层之间的水分入渗和滞留时间;(3)土壤-植物界面的根系吸水;(4)大气-植物界面的蒸散发分割和叶片吸水[9—10]。

目前,SPAC 系统水分运移过程已成为土壤学、水文学和生态学等学科的重点关注对象之一[11]。水分运移过程的研究多使用模型模拟,如 SVAT、Coup-Model、Eco-Hat、Swap、Waves 等。氢氧稳定同位素作为水分子的组成部分,被称为水的“指纹”,是示踪水循环的天然示踪剂[12—13]。因其记录了大量的环境信息,现已广泛地应用于揭示降水水汽来源[14—15]、土壤蒸发[16—17]、土壤水和地下水补给运移[18—19]、植物水分来源[20—21]以及蒸散发分割[22—23]等诸多方面,极大地促进了对 SPAC 系统水分运移过程的认识。基于此,本文进一步归纳总结了稳定同位素在干旱半干旱区土壤-大气界面、土壤-地下水界面、土壤-植物界面和植物-大气界面水分运移过程中的相关研究(图 1),展望了未来研究中亟需加强的方面,以期为利用稳定同位素技术研究生态水文过程提供参考,明确干旱半干旱区生态系统水分迁移转化过程,维持生态系统的稳定性和可持续性。

1　土壤-大气界面的水分运移

1.1　土壤水补给来源

降水作为土壤水天然补给来源,入渗的降水可能部分或完全与原先滞留在土壤中的旧水混合,这种新旧水的混合可能会使得土壤水保留新水(降水)信号[24]。受环境因素、水汽来源和对流活动的影响,降水同位素存在明显的季节性周期变化[25],这使得受降水补给的土壤水同位素也存在明显的季节变化。干旱半干旱区,植被覆盖是限制土壤水分来源的关键因子,不同土地利用方式下的土壤水受不同强度降水补给[26],如农田和草地受小降水事件补给,沙柳地和杨树地受夏秋季强降水事件补给[27]。降水对土壤水的补给深度受降水量和降水强度的直接影响,即降水量越大、降水强度越高,对土壤水的补给深度越大[28—29]。

1.2　土壤蒸发

大气降水进入陆地生态系统后通过蒸散发返回到大气中,其中土壤蒸发量占总降水量的 10%—60%[30]。同位素的二阶变量指标,氘盈余(*d*-excess)[31]和水线氘差(lc-excess)[32]通常用作定性揭示蒸发损失规律。*d*-excess 值越小,表明受到的蒸发分馏程度越强。lc-excess 指示的是由蒸发引起的非平衡动力分馏过程,降水 lc-excess 值存在极小的或无季节变化,长期平均值为 0‰。其他水体如土壤水、河水等受蒸发影响,同位素发生分馏,其 lc-excess 值通常小于 0‰。通常 lc-excess 值越低,表征的蒸发程度越强烈。值得注意的是,水体的 *d*-excess 不仅受到蒸发过程的影响,还受到水汽源及源地相对湿度的影响,lc-excess 仅仅指示蒸发引起的非平

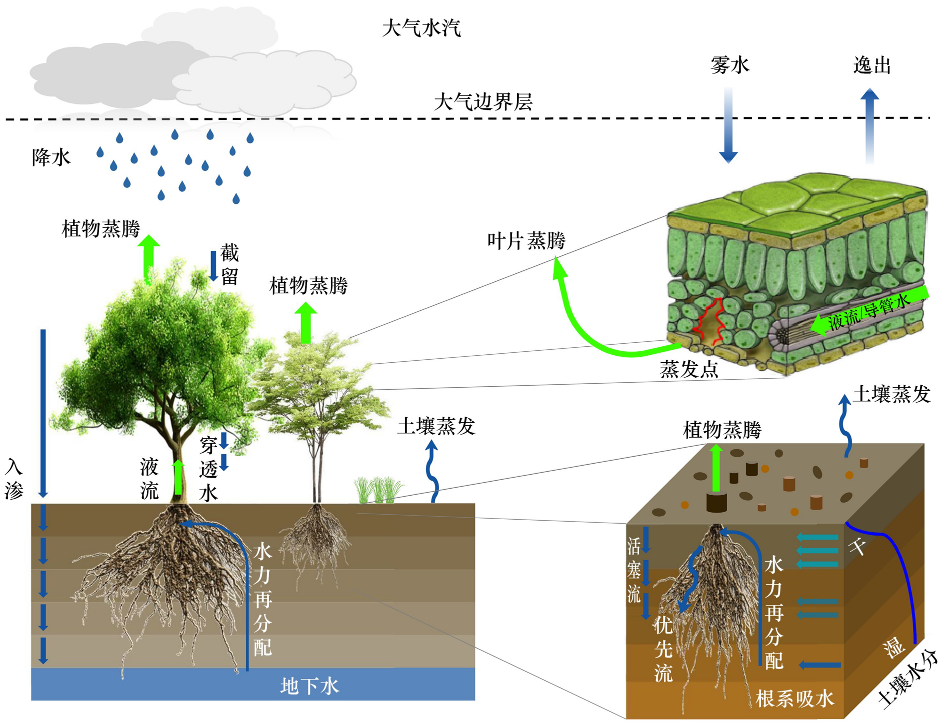

图 1 土壤-植物-大气连续体水分运移过程示意图[6]

Fig.1 Schematic diagram of water transport processes in soil-plant-atmosphere continuum[6]

衡动力分馏过程。因此,lc-excess 较 *d*-excess 在指示土壤蒸发规律方面更具优势[16]。此外,局地蒸发线斜率(Slope of Local Evaporation Line,简称 S_{LEL})也是判断蒸发分馏强弱的指标,蒸发线的斜率越小,表明水体受到的蒸发分馏越强[33]。Gibson 等[34]应用全球湖水和土壤水的 S_{LEL} 揭示了蒸发分馏的季节性差异,并总结出开放水体的 S_{LEL} 一般在 4.0—5.0 之间,而土壤水的 S_{LEL} 相对开放水体一般更低,通常小于 3。除上述的几个定性揭示土壤蒸发的指标外,Craig-Gordon 模型通常用于定量计算土壤蒸发损失率(进入土壤的降水通过蒸发返回到大气的比例)[17,35—36]。由于温度和相对湿度的季节性变化,土壤蒸发存在明显的季节性变化[33]。车存伟等人[36]在兰州市南北两山的研究,李华非[37]在青海湖沙柳河流域的研究均证实了这一点。受气候条件、地表植被覆盖和海拔高度等因素的影响,土壤蒸发在空间上也存在一定的差异。如祁连山上游西营河流域,位于山麓的西营、铧尖土壤蒸发损失率大于位于山坡的宁缠和山顶的冷龙[38]。除 Craig-Gordon 模型外,也可基于瑞利分馏模型量化水体的蒸发损失率[39]。Hu 等人[40]耦合 *d*-excess 和瑞利分馏模型评估了 5 个模拟小流域的蒸发损失率。向伟[41]进一步采用 lc-excess 耦合瑞利分馏模型评估了黄土高原 33 个采样点深层土壤蒸发损失率(11.3%—23.9%)。目前哪种方法的表现性更优,尚未形成统一的定论,在实际应用过程中可将两种方法结合起来,实现对土壤蒸发损失率的准确评估。

2 土壤-地下水界面的水分运移

2.1 土壤水分入渗机制

干旱半干旱区降水稀少,蒸散发量较高,地下水的补给速率较慢,评估其补给来源和入渗方式对于水资源的可持续管理具有重要意义[42]。由于分馏作用,不同水体的稳定同位素组成存在较大的差异。因此,可以通过比较地下水和潜在补给来源的同位素相似性判断地下水的补给来源。如鄂尔多斯盆地地下水的主要补给来源并不是当地降水,而是氢氧同位素值较低的其他地区的降水[43]。库姆塔格沙漠地下水来源于流域之外的径流补给[44]。车臣河流域地下水受到南部高山冰川融雪水和降雨的补给[45]。黄土高原土层深厚,地下水

接受降水补给,但只有高强度的大降水事件才能补给深层土壤水和地下水[18—19]。

降水进入土壤后主要以活塞流和优先流两种方式下渗补给地下水。活塞流模式中土壤水分缓慢成层推进,即新水取代旧水并将其推向深层土壤最终补给地下水[46—47]。因此,具有不同 δ^2H、δ^{18}O 特征峰值的降水在入渗过程中得以保留在土壤剖面中,随着入渗深度的增大,在混合及扩散作用下逐渐消失。然而,裂缝、裂隙、植物根系和生物孔隙等会促进优先流的发生,使得新水能够迅速到达深层土壤,与上层旧水的混合作用有限[48]。黄土高原土层深厚,土壤水分入渗机制较为复杂,有学者认为黄土高原土壤水分入渗以活塞流为主[49—53]。然而,黄土中存在的裂缝、裂隙、植物根系和生物孔隙提供了优先流发生的快速通道[54],Li 等人[55]在黑河流域,Huang 等人[56]在洛川塬区的研究证实了优先流的主导。也有研究发现土壤水分并非以单一的活塞流或优先流方式入渗,这两种流可能同时存在[53,57—58],如长武塬区活塞流和优先流补给量分别占地下水总补给量的 45%—62% 和 38%—55%[59]。通过活塞流形式流动的水是连通水,其在水文系统中的比例决定了水文连通性[30],而优先流形式的下渗影响着地下水的补给[60],因此明确优先流的发生条件对于评估地下水量至关重要。研究发现优先流的发生与土地利用方式存在一定关系[61—62],高耗水型人工林草(如苹果林地、苜蓿草地)因水分负平衡形成的土壤干层将减小优先流发生的可能性,而农田、荒草地等土地利用方式均易发生优先流形式的降水入渗,从而对深层土壤水分或地下水形成补给[63]。此外,优先流的发生与大降雨事件的出现有关,土壤湿度和降雨强度共同影响优先流的发生[64]。多雨年份土壤水的优先流入渗会被激活从而补给地下水,而在少雨年份地下水则是以土壤水的活塞流入渗补给的[65]。

氢氧稳定同位素为地下水的补给运移研究提供了新的视角,但是由于水样测定、环境因素等方面的影响可能存在误差[66],因此可与亮蓝染色剂、环境示踪剂(如^{3}H 同位素和 Cl^-)和模型模拟(如 Hydrus-1D)等方法结合起来研究土壤-地下界面的水分补给运移过程。

2.2　土壤水分滞留时间

水分进入流域内,经过混合、扩散、运移到某一观测位置的平均时间称为平均滞留时间(Mean Residence Time,MRT 或 Mean Transit Time,MTT)[67—68]。因其观测对象的不同,多集中在流域地下水(渗流、泉水、井水等)和地表径流等。土壤水的平均滞留时间指的是降水入渗到达特定土壤深度的平均时间[69]。滞留时间越长,表明土壤中溶质运移、污染物迁移的时间越长。准确评估土壤水滞留时间有助于深入了解土壤水龄、流动路径、关键带不同水文组分之间的联系以及地下水文系统的连通性。

估算 MRT 需要确定滞留时间分布(Transit Time Distribution,TTD),多使用集总参数法[67,70—71],如指数模型(Exponential Flow Model,EM)、活塞流模型(Piston Flow Model,PM)、指数活塞流模型(Exponential-Piston Flow Model,EPM)、弥散模型(Dispersion Model,DM)和伽马模型(Gamma Model,GM)等(图 2)。研究发现,不同水文组分的季节性变化遵循正弦曲线变化[72—73]。因此,可以根据振幅和相位位移等参数计算出输入和输出波正弦曲线拟合的同位素季节性变化,进而根据模拟函数振幅的差异估算 MRT[74—76]。但是由于水文系统的异质性和非平稳性,基于季节性示踪周期估计的 MRT 容易受到聚类偏差的影响,对真实的 MRT 产生低估。而新水比例,即小于 0.15—0.25 年(即 2—3 个月)的水流组分(Young Water Fraction,F_{yw}),在异质性水文系统中可以更为准确的估算 MRT[71,73]。因此,通常使用 TTD 和 F_{yw}来描述水文组分的 MRT。

我国水分滞留时间的研究主要集中在青藏高原中部永久性冻土区和亚热带湿润气候区,包括青藏高原中部永久性冻土区的冻土层上水和河水[77—78];东南湘江流域的土壤水、植物木质部水、河水和地下水[73];西南岩溶集水区的土壤水、泉水和溪水[76,79—80];西南永安河流域的河水和地下水[81],西南沱江流域的河水[82],西南元阳梯田土壤水[69]。由于干旱、半干旱区水文过程复杂,气候条件恶劣,水资源短缺,数据采集受到一定的限制,研究尚不多见。研究发现土壤水滞留时间随土壤深度的增加而增加,浅层土壤水的滞留时间为几天,深层土壤水的滞留时间为几个月,深剖面土壤水滞留时间甚至可以达到几年[67,73,79]。受地形和植被覆盖的影响,土壤水分滞留时间存在差异[83]。地形通过可垂直入渗的长度来影响土壤水分滞留时间[74]。植被覆盖通过改变土壤入渗能力、导水性、储水能力等影响土壤水滞留时间[84],如 Ma 等人[69]在元阳梯田的研究发现,

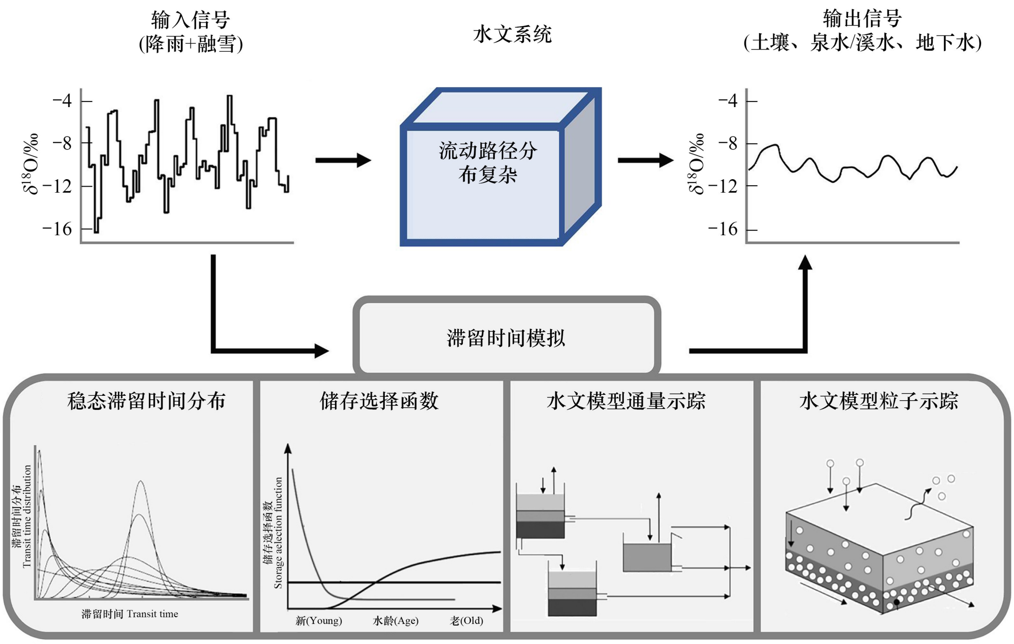

图 2　基于示踪剂的输入-输出关系估算滞留时间分布[67]

Fig.2　Transit time distributions (TTDs) estimated from tracer input-output relationships[67]

0—100 cm 深度范围内林地土壤水 MRT 为 53—94 d(7.6—13.6 周),0—100 cm 深度范围内灌丛土壤水 MRT 为 76—142 d(10.9—20.1 周)。

尽管稳定同位素方法估算土壤水分滞留时间可以在采样频率不高、不规则的数据集上应用,但不是所有水文组分的正弦波拟合效果较好。而且在估算以“旧水”为主导的水文组分滞留时间时存在一定的局限性[73],只能用于判断水龄小于 4 年的水分滞留时间[85—86],而^{3}H 同位素和 Cl^-可以用于评估土层深厚、水龄较长的黄土高原深剖面土壤水龄。因此,未来的研究可使用多种示踪剂评估土壤水分滞留时间。

3　土壤-植物界面的水分运移

3.1　植物水分来源

土壤-植物界面水分运移的关键问题是植物根系吸水,利用同位素研究植物水分来源的基本假设是:除了极少数的盐生[87]和旱生植物[88],水分从植物根系及沿导管向上传输的过程中,不存在同位素分馏现象。因此,通过比较植物木质部水与潜在水源的同位素值,可以估算出植物对不同来源水分的相对使用量,进而明确植物的水分来源[12,89]。目前利用氢氧稳定同位素技术研究植物水分来源的方法主要有直接对比法、二元或三元线性混合模型、多元线性混合模型(IsoSource)[90]、贝叶斯混合模型(MixSIR、SIAR、MixSIAR)[91—93]、吸水深度模型等[94]。直接对比法只能定性判断植物的吸水层位,吸水深度模型可以判断植物吸收土壤水的平均深度,其余模型均能定量计算潜在水源对植物的贡献率。但是由于模型算法的不同,且输入数据具有不确定性,因此不同模型的计算结果之间存在差异[95—96]。经过对比分析,认为目前贝叶斯混合模型 MixSIAR 是判断植物水分来源的最优模型[89,97—102]。

干旱半干旱区相同生境下的不同植物种之间通常存在一定的水分竞争,如青海共和盆地沙柳(*Salix psammophila*)和乌柳(*Salix cheilophila*)能够根据不同水源的可利用性,在不同季节选择利用不同深度的土壤水分或者地下水,二者之间存在一定程度的水分竞争[103]。此外,不同生境下的同种植物水分来源也存在明显的差异,如生长在山坡的柽柳(*Tamarix ramosissima*)以深层土壤水(80—150 cm)为主要水分来源,而河漫滩生境下柽柳主要利用浅层土壤水(0—30 cm),这反映了植物对环境的适应性[104]。植物主要依靠根系吸收水

分,不同林龄的植物根系分布状况有所不同,因此水分来源也存在一定的差异[105—106]。降水作为限制干旱半干旱区植物生长的关键因子,植物水分来源受降水模式的影响较大,植物用水策略对降水的敏感性受到降雨类型、干/湿期和植被类型的影响[107—108]。前人在利用氢氧稳定同位素研究植物水分来源的过程中发现,当使用单一同位素(^{2}H 或^{18}O)或双同位素(^{2}H 和^{18}O)示踪时结果存在差异,这是由于木质部水与土壤水之间的同位素偏移导致的[109]。这种同位素偏移最早出现在盐生[87]和旱生植物[88],近年来在半干旱灌丛[110]、针叶林[111—112]、阔叶林[113—115]、城市绿化植物[116]、热带雨林[98,117]、稻田[118]和盆栽植物[119—120]中均有发现。越来越多的研究证实了植物-土壤水同位素偏移并非个别现象,可能是普遍存在的,而这种广泛存在的偏移现象给利用同位素技术判断植物水分来源带来了极大的不确定性。因此,厘清植物-土壤水之间同位素偏移的机理是继续利用同位素技术研究植物水分来源的前提[113,121—122]。

3.2　根系水力再分配

植物根系水力再分配(Hydraulic Redistribution,HR)是指在水势梯度的驱动下,植物根系将水分从湿润的土壤层运输到干燥土壤层的过程[123]。包括水分由深层土壤向浅层的水力提升[124]、浅层土壤向深层的逆向水力提升[125]以及在水平方向上的侧向再分配[126](图 3)。利用同位素示踪主要是给植物根区浇灌重水,观测植物本身及周围相邻植物根系土壤以确定 HR 现象的存在。Caldwell 等[128]对三齿蒿(*Artemisia tridentata*)施加重水,首次发现根系吸收深层土壤水分后释放到浅层土壤中供给相邻植物沙生冰草(*Agropyron desertorum*)蒸腾,进一步证实了水力提升的存在。Schulze 等[129]利用同位素技术在美国的卡拉哈里沙漠观测到了当浅层土壤湿润而深层土壤干燥时,植物根系将水分运输到深层的逆向水力提升现象。截至目前,已有超过 150 种的植物存在 HR 现象[130]。特别是在干旱半干旱区,具有二态型根系的植物能够灵活利用不同深度的土壤水,这比只依靠单一浅层土壤水的植物更具有竞争优势[110]。因此,明确植物根系水力再分配对于干旱胁迫下营林措施的制定至关重要。

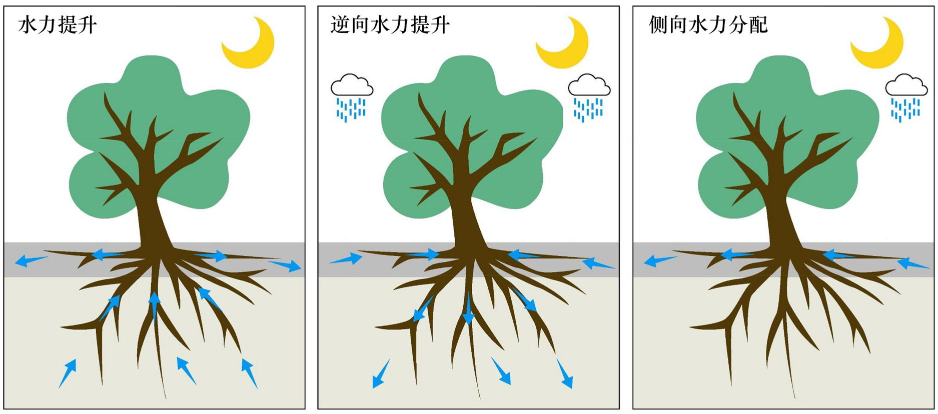

图 3　根系水力再分配的示意图[127]

Fig.3　Schematic diagrams of hydraulic redistribution of roots[127]

水力提升:干旱时期水分由深层土壤运移到浅层土壤;逆向水力提升:雨后水分由浅层土壤运移到深层土壤;侧向水力分配:土壤不均匀湿润后水分由湿润土壤运移到干燥土壤

4　植物-大气界面的水分运移

4.1　蒸散发分割

蒸散发(Evapotranspiration,ET)是陆地生态系统水循环的重要环节,影响着陆地生态系统水分收支和能量平衡[131—133],主要包括土壤蒸发(Evaporation,E)和植物蒸腾(Transpiration,T)两个部分。拆分蒸散发通量有助于更好地了解陆地生态系统水汽交换过程。由于土壤蒸发过程中发生的非平衡动力学分馏作用,表层土

壤水富集重同位素,土壤蒸发水汽重同位素值相比土壤水更加贫化。当蒸腾处于同位素稳态(ISS)条件下,植物蒸腾水汽同位素组成近似于木质部水同位素组成[134—135]。因此,基于植物蒸腾水汽和土壤蒸发水汽同位素组成存在的明显差异,可利用二元混合模型可以实现蒸散发的分割[22,136—137]。土壤蒸发水汽同位素组成多使用 Craig-Gordon 模型进行计算[35]。在自然条件下,植物叶片水同位素受环境因素的影响,往往表现为非稳态(NSS)[138—139],仅在蒸腾作用强烈的中午或较长时间尺度才能达到同位素稳态[140—141]。因此,基于同位素稳定态假设的蒸散拆分研究多选择植物生长季日照强烈、气温高的典型晴天以减小同位素非稳态的影响。此外,也有研究使用考虑了 Péclet 效应修正后的 Craig-Gordon 模型来计算蒸腾水汽同位素组成[139,142—144]。蒸散水汽同位素组成多使用 Keeling plot 法进行计算[145],该直线描述了大气水汽同位素组成与其浓度倒数之间的线性关系,其在 y 轴的截距表示蒸散水汽的氧同位素组成[146]。此外,通量梯度法和涡度相关法也可用于确定蒸散水汽同位素组成[147]。

氢氧稳定同位素技术为陆地生态系统水分通量的拆分提供了有力工具[148],目前广泛地应用在农田[149—150]、草地[151—153]、森林[154—155]等生态系统中。如袁国富等[149]利用原位测定水汽同位素值和 Keeling Plot 法分割了麦田蒸散,发现生长旺盛期麦田 94%—99%的蒸散来源于植物蒸腾。Good 等[151]在旱地斑块状草地的研究发现,在草地增绿期间,植物蒸腾从 0%增加到 40%,随后下降,平均占比为 29%。彭文丽等[156]在黑河上游的研究发现,植物蒸腾是青海云杉林蒸散发的主要组成部分,占 52.2%—88.4%。Sun 等人[157]在华北石质山地栓皮栎生态系统利用离轴积分腔输出光谱技术和 Keeling Plot 法在日尺度上拆分了蒸散各组分。武昱鑫等[144]利用 Craig-Gordon 模型和 Keeling Plot 法结合 ISS 和 NSS 模型模拟了侧柏生态系统蒸散各组分,并比较了两种模型分割的结果,发现植被蒸腾在林地蒸散中起主导作用。尽管稳定同位素在分割生态系统蒸散发方面具有独特的优势,但仍然存在一些不确定性[22]。要提高蒸散发分割的精度,前提条件是准确评估 δ_E、δ_T和 δ_{ET}三个分量,因此可将同位素和水文学、植物生理学和微气象学中的传统方法相结合,通过修正参数和改进公式实现蒸散组分的准确量化[144]。

4.2 叶片吸水

研究发现,一些植物可以通过叶片吸水改善植物的水分状况,延长其在干旱胁迫下的存活时间[158—160]。目前,已在超过 200 个植物种、6 个生态系统中均发现了叶片吸水现象[161]。利用稳定同位素研究植物叶片吸水主要是通过模拟凝结水浸润处理,将叶片暴露在富集/贫化重同位素的标记水模拟的湿润环境中,一段时间后测量叶片中是否出现这种标记水,并与木质部水的同位素值进行对比[162]。Berry 等[163]利用氢氧稳定同位素研究发现凝结水对欧洲云杉的贡献率可达 31%。Hill 等[164]利用同位素计算出内盖夫沙漠三种植物 *Salsola inermis*、*Artemisia sieberi*、*Haloxylon scoparium* 对露水的利用率分别为 56%、63%、46%。桂子洋等[165]在毛乌素沙地利用同位素示踪和荧光标记法证实了黑沙蒿(*Artemisia ordosica*)和北沙柳(*Salix psammophila*)叶片能够吸收凝结水。虽然氢氧稳定同位素在探究植物叶片吸水方面得到了广泛的应用,但在叶片内外水汽浓度平衡的条件下,仍然存在叶片水和大气水汽之间的同位素交换过程,因此需重新审视叶片吸水的问题[166]。

5 总结与展望

近年来,氢氧稳定同位素技术因其较高的准确性和灵敏度在 SPAC 系统水分运移过程的研究中得到了广泛的应用,极大地推动了同位素生态水文学的发展,但仍然存在着诸多限制。因此,本文从野外观测、实验方法、机理解释三方面总结了以下不足:(1)前人研究大多集中在 SPAC 系统中的某一环节,缺乏从整体上对这一过程的研究,特别是各个环节是如何相互作用、相互影响的? 而在植物-大气界面,许多动态过程集中在几分钟或几小时内;土壤-植物界面,动态过程发生在小时到日尺度;土壤-大气界面的水分入渗和蒸发发生在从日到月尺度;土壤-地下界面的水分运移,多发生在从日到月甚至年尺度上的变化。因此,SPAC 系统水分运移过程实际上是一个时间尺度问题,那么如何获取高时间分辨率的同位素数据就显得尤为重要。土壤和植物水稳定同位素的原位测量技术可以弥补采样周期和频率不足,未来可作为解析 SPAC 系统水分补给传输过程的

有效手段。(2)土壤-植物木质部水之间的同位素偏移现象使得在利用^{2}H 和^{18}O 示踪植物水分来源时产生了偏差,这极大地增加了同位素技术应用的不确定性。未来研究应明确产生这种偏移的原因,建立统一的标准化流程,以降低同位素技术的不确定性,获得与生态水文过程高度匹配的同位素数据。(3)当前研究多关注同位素数据本身的变化,而植物生理特性和土壤理化性质差异会导致同位素数据的异质性变化,如菌根植物的水交换[120,167],植物有机物中的羟基与水分子之间的氢交换作用[168],粘粒矿物和阳离子之间的相互作用[169—170],根尖根毛处的土壤孔隙水蒸气冷凝等[119]。未来研究可考虑多学科如水文学、植物生理学和大气科学等相结合,从更微观的视角审视 SPAC 系统水分补给传输过程。

基于以上不足,未来干旱半干旱区 SPAC 水分运移的四个界面过程应重点关注以下内容:(1)土壤-大气界面:前人在研究过程中关于土壤蒸发深度的定义并不一致,因此准确判断不饱和带中蒸发锋面的位置是前提条件。此外,利用 Craig-Gordon 模型和瑞利分馏模型均可判断土壤蒸发损失率,但两种方法的表现性和适用性尚未可知,未来可与传统方法相结合对其进行评估。(2)土壤-地下水界面:采用多种示踪剂相结合以明确干旱半干旱区土壤水分入渗机制,特别是优先流的发生条件,深入探究优先流的产生对植物根系吸水、土壤水龄、地下水文系统连通性的影响。(3)土壤-植物界面:明晰植物-土壤水之间同位素偏移的原因,通过建立统一的校正方程,提高植物水分来源识别和划分的准确性。此外,加强从"同位素生态位"解释干旱半干旱区物种间的共存机制。(4)植物-大气界面:加强对干旱半干旱区的蒸散发分割定量研究,蒸散发的分割中蒸腾水汽同位素值的估计是基于植物蒸腾的稳态假设,利用植物茎干水同位素进行代替。但自然条件下往往是非稳态的,在非稳态条件下多使用模型来模拟蒸腾水汽同位素值。因此可将同位素和水文学、植物生理学和微气象学中的传统方法相结合,通过修正参数和改进公式准确量化非稳态时段下蒸散组分。

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