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非降水研究进展

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摘 要: 非降水对于干旱和半干旱区的水平衡和生态非常重要。本文归纳总结了非降水的测量和模拟方法, 分析并综述了研究现状。非降水为陆气间较小的通量, 时空变异强, 直接测定存在困难。利用专门的冷凝器可获得可观的结露量。露水研究集中于干旱与半干旱区的站点尺度, 雾水研究集中在沿海和山区, 水汽吸附研究主要在旱地。非降水的收集利用及其对生态环境的影响是研究热点。然而, 露水研究较多, 雾水和水汽吸附研究明显偏少。同时, 自然表面结露、大空间尺度和长期的研究较少。在非降水的时空变化规律认识方面存在明显的知识缺口。

关键词: 非降水; 露; 雾; 水汽吸附

非降水(non-rainfall water)指自然降水和人工灌溉以外, 来自大气并以露、雾和水汽吸附等形式附着在地表和地物表面的液态水^[1-4]。当地物表面温度低于或等于露点温度时, 潮湿空气中的水汽凝结成露水^[5-6]。需要注意, 露水不是在空气中形成后再沉积到表面上, 因此使用“露水形成”比“露水沉积”更恰当^[7-8]。雾水的形成与地物表面条件无关。当大气中的水汽达到饱和时雾就会发生, 其本质是形成悬浮在空气中的微小水滴。由于雾滴的沉降和地物的拦截作用^[9], 雾水沉积在表面上, 故可用“雾水沉积”描述该过程。水汽吸附是水汽从大气向土壤扩散并吸附在土壤颗粒表面的过程。土壤表面温度高于露点温度且大气相对湿度高于土壤空气相对湿度, 形成指向土壤的水汽梯度^[10-12], 是水汽吸附发生的必要条件。基于微气象条件可以区分雾、露和水汽吸附^[13]。发生雾的大气条件在大陆内部较少满足, 因此大多数雾形成于相对湿度高、水汽易于饱和的沿海和山区^[14]。区分露和水汽吸附较为困难^[15]。露水受特定气候条件限制较小, 在大多数条件下都可能发生, 广泛发生于世界各地^[16-17]。与露水相比, 水汽吸附对表面温度和大气湿度的要求更低, 更容易发生^[18]。传统上, 陆面凝结水同样包括露水、雾和水汽吸附形式的水。国内有学者将非降水称为凝结水^[19]。然而, 两者

的水汽源不同, 不是等同的概念。形成非降水的水汽直接来自大气, 是陆面和大气间的通量。陆面凝结水的水汽来源包括大气和深层土壤向上扩散的水汽^[20]。

非降水是干旱和半干旱区的重要水源, 是干旱缺水时期植物、昆虫、小动物和生物结皮不可或缺的重要水源^[3-5, 21]。干旱期缺水会使植物生长受限, 有些幼苗甚至会受到死亡的威胁^[22]。非降水减轻了植物水分亏缺, 增加了植物的水量^[23-24], 缓解了植被的水分胁迫, 促进了植物的生长, 延长了光合作用。一些小动物(如黄粉虫、壁虎)可以利用自己的身体来收集露水、雾水并供其使用。非降水是干旱和半干旱区陆地水平衡的重要组成部分^[25-26]。旱季非降水补充了降雨量, 将非降水与降雨结合可以满足植物蒸散需求。本文回顾了已有研究, 总结了非降水的观测和定量方法, 评价了常用方法的特点, 并综述了非降水的研究进展, 提出了目前研究的知识缺口以及未来研究方向, 为非降水的进一步研究提供了参考。

1 观测与估算方法

1.1 露

露水的实际测量较为困难。目前仍然没有普

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适的露水标准测量方法和模型。已有方法可以分为测量法和估算法两大类^[27]。

过去几十年内开发了许多方法和仪器来测量露水量。例如,布板法^[28-29]、称重法^[30]、叶片湿度传感器^[31-32]和蒸渗仪^[33-34]等。布板法简单、成本低,便于比较不同位置和高度的露水量^[29],但其测定结果受冷凝板材质的显著影响^[28,35]。称重法是常用的测量自然结露量的方法,但需要在清晨手动收集,增加了人力成本^[30]。叶片湿度传感器可检测叶片表面是否存在露水,与数据收集器连接可自动记录数据^[36]。蒸渗仪/微蒸渗仪具有足够的灵敏度和精度来测量露水量^[26,35],但是实际上表层土壤更容易从空气中吸收水汽^[37],导致很难区分露水和在水汽吸附量,此外蒸渗仪成本较高^[38]。由于露水一般出现在夜晚,所以大多数测量方法都需要在凌晨进行观测,这增加了获得长期和连续的露水量的困难^[39]。

已有研究进行了露水收集实验并讨论了露水的应用^[40-44]。国际露水利用组织(International Orga-

nization For Dew Utilization-OPUR)推荐的露水冷凝器被认为是收集露水最有前途的方法^[34,43]。通过比较冷凝器表面不同的箔材料、放置的角度和位置增加收获的露水量^[45]。国际雾露协会(International Fog and Dew Association, IFDA)组织的国际会议(International Conference on Fog, Fog Collection, and Dew)也展示了一些用于露水收集的新材料。露水收集器的目的是增加收获的露水量以供使用,并不能反映真实的露水产量。

经验模型、分析模型和人工智能模型用来估算露水量^[46],以有效地量化露水的形成。经验模型构建了露水与气象变量之间的关系。典型的经验模型 Beysens 模型^[22,42,47]刻画了云量、风速、空气温度、露点温度、场地高程等与露水产量的关系(表1)。露水凝结伴随向表面的负潜热通量,是蒸发的逆过程^[38],因此可以使用基于物理原理的模型来估算露水量。物理模型可以应用于不同地点,但由于热交换和辐射交换模拟的困难,使得构建过程更加复杂

表1 露水产量估算模型

Tab. 1 Dew Yield Estimation Model

模型	公式	解释
Beysens 模型 ^[22,42,47,45,49-50]	$\frac{dh}{dt} = \begin{cases} \left\{ 0.37 \times \left[\frac{1 + 0.204323H - 0.0238893H^2 - (18.0132 - 1.04963H + 0.21891H^2) \times 10^{-3}T_d}{\left(1 - \frac{N}{8}\right) \exp\left(-\frac{u}{4.4}\right)} \right] \times \right. \\ \left. \left[b(T_d - T_a) \right] \right\} +, \text{ if positive} \\ 0, \text{ if negative} \end{cases}$ $\frac{dh}{dt} = \begin{cases} \left\{ 0.37 \times \left[\frac{1 + 0.204323H - 0.0238893H^2 - (18.0132 - 1.04963H + 0.21891H^2) \times 10^{-3}T_d}{\left(1 - \frac{N}{8}\right) \left(\frac{T_d + 273.15}{285}\right)^4} \right] \times \right. \\ \left. 0.06(T_d - T_a) \times [1 + 100 \times (1 - \exp[-\left(\frac{u}{u_0}\right)^{20}])] \right\} +, \text{ if positive} \\ 0, \text{ if negative} \end{cases}$	H是高程;T _d 是露点温度;N是云量;u是10 m处风速,u ₀ =4.4 m·s ⁻¹ ;T _a 是气温;b是T _d -T _a 与露水产量的斜率
能量平衡模型 ^[34,51-52]	$\frac{dT_c}{dt}(C_c m_c + C_w m_w + C_i m_i) = P_{rad} + P_{cond} + P_{conv} + P_{lat}$ $\frac{dT_c}{dt}(C_c m_c + C_w m_w) = P_{rad} + P_{cond} + P_{conv} + P_{lat}$	dT _c /dt是冷凝器温度的变化率;C _c 、C _w 和C _i 是冷凝器、水和冰的比热容;m _c 、m _w 和m _i 是冷凝器、水和冰的质量;P _{rad} 是进出辐射;P _{cond} 是冷凝器表面与地面之间的传导热交换;P _{conv} 是对流热交换;P _{lat} 是水的冷凝释放的潜热
PM 方程 ^[23,27,36]	$\lambda E = \frac{[S(R_n - G) + \rho_a \times C_p \times \delta_e \times g_a]}{\gamma + S}$ $\lambda E = \frac{[S(R_n - G)]}{\gamma + S}$ $\lambda E = \frac{0.408\Delta(R_n - G) + \gamma \frac{C_n}{T + 273} U_2 (e_s - e_a)}{\Delta + \gamma(1 + C_d U_2)}$	R _n 是净辐射;G是土壤热通量;δ _e 是水蒸汽压差;ρ _a 是空气密度;C _p 是空气热容;S是蒸汽压与温度曲线的斜率;γ是湿度常数;g _a 是蒸汽传导率;Δ是饱和蒸汽压随温度的增加;C _n 和C _d 是随参考类型和计算时间步长而变化的常数;U ₂ 是2 m处风速;e _s 是饱和蒸汽压;e _a 是实际蒸汽压
波文比能量平衡模型 ^[39]	$\lambda E = \frac{R_n - G}{1 + \gamma \frac{\Delta T}{\Delta e_a}}$	R _n 是净辐射;G是土壤热通量;γ是湿度常数;ΔT和Δe _a 分别是温度和蒸汽压差

和不确定^[40,48]。目前使用最广泛的物理模型是能量平衡^[34,45,49-50]、PM方程(Penman-Monteith)^[23,27,36,51-52]和波文比能量平衡方程^[39]。基于能量平衡的物理模型集中应用于人工冷凝表面。在量化露水的实际应用中所需参数不同。模型的一些参数,如土壤热通量、热交换系数较为复杂且难以获得^[46]。PM方程广泛应用于不同表面的露水形成,其最初是用于计算蒸散的,考虑了大气中能量和水汽的传输^[27]。与其他方法比较PM法的优点是不需要表面温度变量^[38]。波文比是显热通量与潜热通量之比,该方程能够在相对较大的面积上测量表面能通量^[51],与其他方法相比它在获得正确的热和蒸汽传导率方面表现优秀^[38]。使用人工智能模型也可以估计露水的产量^[40],虽然该模型可以应用于开发全球露水图,但需要大量的样本数据,在实践中存在困难。

1.2 雾

雾水不易发生且悬浮在空气中,难以直接测量。通常用雾水收集器收集后由雨量计测量。不同形式的雾收集器性能差异较大。平板式雾收集器比圆柱形雾收集器具有更好的雾收集能力^[53]。雾水收集器的位置非常重要,一般面向风向安装。风速是对雾水收集器影响最大的因素^[54],当风速超过一定阈值时,形成雾的可能性会大大降低。阈值大小存在地区差异。

Katata^[55]总结了陆地生态系统的雾水沉积模型,将其分为阻力模型、解析模型和复杂模型3种。阻力模型大多基于Lovett模型及其变式,其中一些物理量测量困难需要进行估计。Chang等^[56]基于Lovett模型,通过雾沉降率与可见度的关系建立了经验模型,提供了估算长期雾沉积率的方法。解析模型建立了雾水沉积与一些参数的公式,计算简单,但这些参数(如:风速、相对湿度)多为经验参数,需要进行实验或统计。Körner等^[57]仅用温度和相对湿度两个变量提出了REAL-Fog方法计算雾,该方法简单、性能优秀,但存在一定高估倾向。复杂模型常与三维气象模型结合进行雾水模拟,预测精度高。Katata等^[58]耦合了气象模型MM5和地表模型SOLVEG,对树木的雾沉积进行了估算。

数值天气预报模型(Numerical Weather Prediction, NWP)在预测沿海雾方面应用广泛。三维天气研究和预报模型(Weather Research and Forecasting Model, WRF)最为常用^[59-60]。该模型包括微物理、积

云参数化、表面物理、行星边界层物理、大气辐射和陆地表面模型等模块^[61]。WRF模型在很大程度上可以得到较好的预测结果,但仍有许多需要改进的地方,如:难以预测短期微尺度上的雾状况、不能很好的捕捉雾的垂直分布以及预测值偏低等^[62-63]。遥感卫星(如中分辨率成像光谱仪、云气溶胶激光雷达和红外探路者卫星观测、Himawari-8葵花八号等)提高了海岸地区沿海雾观测精度,是目前在大范围长时间尺度上监测海雾的最有效手段^[64]。人工智能技术在预测沿海雾方面也具有重要作用。

1.3 水汽吸附

关于土壤水汽吸附观测和估算方法较少。目前测量水汽吸附主要是基于蒸渗仪的观测^[65-66],但是蒸渗仪不能直接得出水汽吸附量,还需要对其进行水分通量分割^[18]。估算水汽吸附的方法主要包括两大类:水汽吸附等温线法^[67-68]和土壤水分保持曲线法^[65,67,69]。使用水汽吸附等温线能够有效的估算蒸汽吸附数据,但数据分辨率不够高,可能存在较大误差。充分表征土壤水分保持曲线的最干燥部分对研究水汽吸附具有重要意义,能够很好的模拟土壤水分通量振荡。除此之外,也有文献利用梯度法计算水汽吸附^[12]。该方法仅产生有限的土壤扰动,但高度依赖于扩散系数,需要进行校准以提高准确性。

2 研究进展

非降雨水研究集中于沿海及干旱与半干旱地区。20世纪90年代以色列内盖夫沙漠是非降雨水研究的一个重点区域。近年来关于沿海雾等的研究显著增多。同时,非降雨水的收集以及非降雨水对生态环境的影响仍然是研究热点。

20世纪中叶以来,露水研究的数量逐渐增加。大多数研究集中于干旱与半干旱站点,应用测量和模拟方法研究短期露水量(表2)。研究结果表明露水量是一种较小的通量^[51],但不同的露水收集方法可以获得不同的露水量。例如,倒金字塔冷凝器比平面冷凝器的收集效率高^[41]。已有研究比较和验证了不同的露水量模拟方法,结果表明表面能量收支模型好于空气动力学模型^[41]。蒸渗仪测量的露水量与波文比能量平衡估算的露水量在中国巴丹吉林沙漠具有良好一致性,但波文比能量平衡的值始终低于测量值^[39]。人工智能模型也可以有效地预测旱

表2 近年的露水产量研究

Tab. 2 Recent study on main dew yield

地点	气温/℃	降水量/mm	时间/年-月	植被	方法	露量
中国科学院伊犁流域 ^[28] (43°20'N, 84°00'E, 1157 m)	—	200~800	2021-07—2021-08; 2021-09—2021-10	禾本科、豆科、 菊科	布板法	2.50 mm 0.05 mm·d ⁻¹
甘肃省白银市平埠村 ^[32] (36°25'N, 104°25'E, 1461 m)	8.9	238	2018-04—2018-09; 2019-04—2019-09; 2020-04—2020-09	玉米	叶片湿度传感器	0.10 mm·d ⁻¹
维科萨联邦大学 ^[42] (20°77'S, 42°87'W, 665 m)	—	—	2018-08—2018-10	—	冷凝器	0.05~0.15 mm·d ⁻¹
甘肃省河西走廊黑河流域 ^[70~71] (39°24'N, 100°07'E, 1405 m)	7.6	117	2016-06—2016-10	灌木、草本物种	微蒸渗仪	0.06 mm·d ⁻¹
肯尼亚马克陶 ^[34] (3°25'S, 38°08'E, 1060 m)	—	—	2016-04—2017-03	—	冷凝器(PVC、 PE、OPUR)	0.07~0.10 mm·d ⁻¹ 18.90~25.30 mm
古尔班通古特沙漠 ^[46] (44°48'N, 85°33'E)	6.6	70~180	2015-08—2018-12	生物结皮	叶片湿度传感器	0.10 mm·d ⁻¹ 12.21 mm·a ⁻¹
中国宁夏-北京林业大学 ^[36] (37°42'N, 107°14'E, 1530 m)	8.3	291	2015-05—2015-12	黑沙蒿和 北沙柳	叶片湿度传感器、PM	0~0.04 mm·d ⁻¹
陕西省三元县 ^[72] (34°33'N, 108°54'E, 420 m)	13.6	533	2014-01—2016-12	—	叶片湿度传感器	0~0.88 mm·d ⁻¹ 32.80 mm·a ⁻¹
内蒙古多伦县 ^[30] (42°04'N, 116°32'E, 1318 m)	1.6	385	2014-07—2014-10	榆树林, 草原	称重法	0.12 mm·d ⁻¹ 0.24 mm·d ⁻¹
黎巴嫩贝丁 ^[22] (920 m)	—	—	2014-03—2014-10; 2013-07—2013-10	—	冷凝器(PE)	0.13 mm·d ⁻¹
马达加斯加西南沿海 ^[73] (24°04'S, 43°42'E, 10 m)	24.0	360	2013-04—2014-09	稀疏的草	天平称重	0.12 mm·d ⁻¹
巴丹吉兰沙漠 ^[39] (39°21'N, 100°07'E, 1374 m)	7.6	117	2013-06—2013-10	灌木为主, 梭梭林	微蒸渗仪	16.10 mm 0.13 mm·d ⁻¹
毛乌素沙漠 ^[74] (37°42'N, 107°13'E, 1530 m)	8.1	292	2012-04—2012-10	黑沙蒿	涡度相关	0.05 mm·d ⁻¹
墨西哥哈利斯科州 ^[75] (21°46'N, 101°36'W, 2240 m)	15.1	424	2011-01—2016-12	草原, 格兰马草	PM	0.20 mm·d ⁻¹ 16.50~69.00 mm·a ⁻¹
西班牙卡塔赫纳技术大学 ^[44] (37°41'N, 0°57'W, 30 m)	17.5	350	2011-01—2012-01	—	冷凝器 A级盘	17.42 mm·a ⁻¹ 7.84 mm·a ⁻¹
塔克拉玛干沙漠 ^[37] (40°28'N, 87°51'E, 842 m)	11.5	35	2011-06—2011-10	杨树林	涡度相关	0.12 mm·d ⁻¹ 12.87 mm.
中国科学院三江平原 ^[76] (47°35'N, 133°31'E, 56 m)	1.9	550~600	2010-05—2010-10	黄杨、苔草、 大豆、水稻	冷凝器	4.25~30.18 mm
河北石家庄栾城 ^[77] (37°31'N, 114°24'E, 50 m)	12.8	366~598	2008-04—2008-09; 2009-04—2009-09; 2010-04—2010-09	小麦、玉米	涡度相关	7.61 mm·a ⁻¹
中国临泽内河流域研究站 ^[29] (39°21'N, 100°07'E)	7.6	—	2008-08—2008-09; 2007-01—2007-12	灌木	布板法	0.05~0.06 mm·d ⁻¹
西班牙阿尔梅里亚 ^[52] (36°56'N, 2°01'W, 208 m)	18.0	220	2007-01—2010-12	草原	叶片湿度传感器 和PM	182.00 mm 0.15 mm·d ⁻¹
印度科塔拉 ^[78] (23°14'N, 68°45'E, 21 m)	—	300	2004-10—2005-05	—	冷凝屋顶(18 m ²)	6.30 mm 0.09 mm·d ⁻¹
荷兰瓦赫宁根大学 ^[41] (51°58'N, 5°38'E, 7 m)	—	—	2003-12—2005-05	多年生黑麦草 和普通早熟禾	冷凝器(OPUR、 PVC)	0.10~0.20 mm·d ⁻¹

季露水量^[70]。考虑露水量评估干旱,有助于对不同地区的干旱做出更准确的评估^[27]。

已有研究中存在两方面的不足,即缺乏长期观测和大空间尺度研究。长期观测有利于深入了解

露水的形成和变化规律,露水对维持区域水和生态平衡的作用。然而,露水形成的长期测量几乎是不可能的,同时由于估算方法的局限性对露水量的长期趋势进行评估十分困难^[28,45]。已有研究结果展示

了长期观测研究的重要性。塔克拉玛干沙漠的露水量在1960—1968年减少,1969—2000年稳步增加,2001—2011年再下降;6—10月的多年平均露水量占同期平均降雨量的64%和全年平均降雨量的50%,露水在维持该地区水平衡方面发挥了重要作用^[37]。库内斯河6—10月露水量在1980—2002年略微增加,2002—2013年急剧下降,2013—2021年略微增加;露水是维持该地区生态稳定的重要水源^[28]。大空间尺度的露水研究非常有限,获得大空间尺度上连续的露水时空分布十分困难。露水量的时空分布规律有助于识别露水收集潜力大的地区,有助于高效利用露水资源,可以极大地促进陆地水循环研究,同时可以加深对气候变化影响的认识。Tomazskiewicz等^[17]预测了2013年旱季地中海周边142个站点的露水产量,并结合地统计插值确定了地中海的露水产量图,确定了地中海露水产量高的地区,为其利用露水资源减少对地下水的依赖奠定了基础。Atashi等^[50]使用能量平衡模型对伊朗7个地点的露水量进行模拟以分析其时空变化,发现伊朗北部山区露水产量大,形成频繁,南部和中部水资源贫乏地区露水也可以作为替代性水源。由于伊朗水资源短缺,此研究有助于进行露水收获的科学规划。1975—2018年中国露水量在东北和西北高,中部和南部低^[27]。Vuollekoski等^[49]利用1979—2012年的气象再分析数据和能量平衡模型绘制了全球露水量图,研究了全球露水收集潜力,结果表明在一些缺水地区(北非和阿拉伯半岛沿海部分地区)具有大规模收集露水的潜力。

雾水研究多集中在沿海地区。为了增强对沿海雾的理解以及提高对沿海雾预测的准确性,2018年发起了海岸雾研究计划项目(Coastal-Fog, C-FOG)。该项目的核心内容是2018年8月至10月在加拿大东部和美国东北部的海岸线进行的研究活动^[62-63,79],包括对沿海雾产生的天气气象条件、微观物理学、动力学以及建模模拟的研究。雾事件大都发生于气旋和反气旋系统^[80-81]。评估雾水的微物理参数化观测结果(如:液滴浓度、液态含水量等),进一步开发能见度(雾水强度)的参数化,为模型模拟雾的有效性做出了贡献。Chisholm等^[82]研究了海洋气溶胶颗粒的运动过程,强调了边界层对于沿海雾形成的作用。在模型估算雾水量的研究方面,Dimitrova等^[59]将沿海雾水量的观测结果与WRF模型模

拟结果进行了比较,发现WRF模型在计算海洋上的雾水量和气象条件时具有良好的性能。我国对于20世纪60—70年代研究了黄渤海地区沿海雾。山东半岛沿黄海地区雾的出现常伴有海陆风环流,通过WRF模型模拟发现夜间陆风环流促进海雾形成,而白天海风环流则减缓了海雾的发展^[83]。田梦等^[84]观测了环渤海沿海雾,总结了环渤海地区沿海雾形成的天气条件和动力学特征。对其他地区也进行了海雾研究,福建沿海地区的持续性海雾过程可以分为3个阶段:辐射雾影响、平流雾影响和海雾遇冷消散^[85]。珠江口海雾的发生得益于边界层的稳定以及适宜的天气和水文条件^[86]。因此,充分考虑天气气候以及边界层特征,对理解沿海雾的形成与发展有重要意义,增加了预测沿海雾的精度。

山区的雾水量研究大多基于山地云林的云水拦截。树木可以充当雾捕集器拦截云水,佐法尔山脉的森林拦截的雾水可增加15%~150%的树冠下水输入量^[87]。山地云林冠层对海拔高度不同的雾的截留存在差异^[88]。山地不同位置的雾水收集潜力也明显不同。在玻利维亚进行的为期1a的实验评估了雾水收集潜力的空间变异性^[89]。

水汽吸附通常发生在旱地,尽管水汽吸附通量被认为非常小,但是在特殊环境中水汽吸附可能是主要的非降雨水形式。Kool等^[24]在纳米布沙漠的沙丘上使用14个微蒸渗仪进行非降雨水量的观测,确定了水汽吸附是沙子中主要的非降雨水输入。受土壤特性空间变异性强影响,土壤水汽吸附也显示强的空间变异性。Verhoef等^[65]使用8个微蒸渗仪对西班牙南部的一个橄榄园的裸露土壤进行了水汽吸附测量发现离树干最远的地方显示出最大的水汽吸附值。Saaltink等^[69]使用3种不同的土壤水分保持曲线模拟西班牙南部沙丘沉积物的水汽吸附数据,证明双孔隙率水分保持曲线模拟的结果与实测数据最吻合,并且在年尺度上的拟合效果最好。目前,土壤水汽吸附的模拟仍然是一个严峻的挑战,需要更多的研究来解决这一问题。

稳定同位素示踪技术为评价非降雨水的生态水文过程研究提供了独特的手段,在雾水研究中的应用较多。不少研究发现露水或雾水相对于降水来说更加富集重同位素,这种同位素组成差异使得稳定同位素技术成为研究露水和雾水生态水文效应的有效方法。目前雾水稳定同位素研究旨在探

究雾水的补给作用^[90],露水稳定同位素的研究集中于露水形成过程中的蒸发问题,二者都回答了植被如何利用非降水的问题。旱季赤水林区的雾水D和¹⁸O同位素比降水富集,补给了该地区的地下水和地表径流^[91]。捷克共和国的雾水³H和¹⁸O同位素比降水和穿透水富集,雾中含有的大量离子对大气沉积具有巨大贡献^[92]。过量¹⁷O可以从水样中提取蒸发信息,揭示露水形成过程中不同蒸发过程(平衡和动力学分馏)^[93]。在控制露水同位素组成方面,平衡分馏相对于动力学分馏起到了更重要的作用^[94]。通过测量植物叶片水的同位素可以确定植物水分来源。通过测量木质部水的同位素发现西双版纳森林植物在旱季以雾水作为重要补充,且藤本植物的雾水利用率高于乔木^[95]。中国东北部小叶白杨叶面水分主要来源于露水^[96]。

近年来,关于非降水与生物结皮之间相互关系的研究明显增多。非降水是干旱半干旱区重要的水源,而生物结皮覆盖了干旱半干旱区面积的70%以上^[97],二者对于干旱半干旱区都有重要意义,且相互间存在密切的联系。生物结皮是土壤生物(苔藓、地衣、藻类等)与表土的联合体,因其对环境的敏感可以作为研究干旱半干旱区的模型生态系统(Model Ecosystems)。生物结皮对非降水具有潜在的积极影响,通过改善土壤质地、调节土壤水分平衡增加了非降水的量,增强了非降水的循环^[98]。非降水激活了生物结皮的生理活性,延长了生物结皮的代谢,减轻了干旱胁迫,但导致了负碳平衡和低固碳率^[11]。非降水是否为生物结皮的重要水源取决于其能否达到生物结皮活动所需的阈值。虽然大多数学者认为非降水是所有生物结皮的重要水源,但目前的研究证明,苔藓或地衣结皮可更有效地利用非降水,而蓝藻结皮相反,甚至还可能造成碳的损失导致负面作用^[99]。造成这种现象的原因可能是蒸渗仪高估了非降雨水量,而实际非降雨水量大大低于蓝藻的阈值。干旱半干旱区非降水和生物结皮的关系影响到水循环和碳的生物地球化学循环,其相互作用机理和影响程度需要进一步的研究。

3 研究展望

非降水研究已经取得了大量的研究成果,但是仍然处于起始阶段,存在许多待解决的问题,包

括:(1)自然表面的露水难以测定和估算。(2)大空间尺度和长期的露水研究较少。(3)雾水和土壤水汽吸附的研究明显偏少,且零星分布在不同的区域和特定的时段。已有的非降水研究尚无法提供对其时空变化规律的整体认识。

未来的研究需要从如下3个方面逐步开展,以深入认识非降水这种非传统水资源。首先,丰富对不同区域自然表面非降水的研究。寻找和开发新技术和新方法对自然表面的非降水进行收集、观测和模型模拟。该项研究有助于在更广空间尺度和更大时间尺度上更加准确地估算非降雨水量。其次,探索大空间尺度和长期的非降水观测和模拟研究,深入揭示非降水的时空分布和变化规律,促进非降水资源的合理评估和收集利用。最后,以地球系统理论为指导,实现对非降水的水循环意义、生态水文意义、气候意义的深入探讨和研究。这将有助于陆面过程模型和地球系统模型的完善和模拟精度的提高,加深非降水对未来气候变化响应和反馈的理解。

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Research progress in non-rainfall water: A review

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Abstract: In dry and semi-arid environments, non-rainfall water is crucial for water balance and ecology and enhances regional water intake. To preserve ecological equilibrium, non-rainfall water may be a crucial water supply. However, owing to the longer wetting period of leaves, non-rainfall water may also contribute to the spread of diseases. This work discusses the measurement and modeling methodologies of dew, fog, and water vapor adsorption, examines the research development of dew, fog, and water vapor adsorption, and does a dynamic analysis of bibliometric hot spots to enhance our knowledge on non-rainfall water. The findings indicate that there is a minor movement of non-rainfall water between the ground and the atmosphere. Utilizing unique condensers will result in significant condensation. Pyramid condensers are more effective in collecting dew than plane condensers. Since non-rainfall water exhibits clear temporal and geographical fluctuation, it is difficult to monitor in real-world settings, which restricts relevant research. The regional focus is on non-rainfall water research. Studies on fog water mostly concentrate on coastal and mountainous locations, whereas studies on dew primarily concentrate on the site scale in arid and semi-arid regions. Water vapor adsorption typically takes place on dry ground. A hub for research on non-rainfall water is the Negev Desert in southern Israel. The focus of this study is on the collection and use of non-rainfall water and its impact on the environment's ecology. The water cycle and the carbon biogeochemical cycle in arid and semi-arid regions are affected by the interaction between non-rainfall water and biological crust. Recently, the study on the interaction between non-rainfall water and biological crusts has grown radically. Understanding the origins and evolution of coastal fog is crucial to enhance the precision of coastal fog forecasts by considering all relevant meteorological, climatic, and boundary layer factors. The modeling of soil moisture adsorption remains a significant obstacle, nevertheless. Precipitation is less concentrated in heavy isotopes than dew or fog water. The stable isotope technique is a useful tool for researching the ecohydrological impacts of dew and fog water due to the variation in isotope composition. More research has been done on dew than on fog water or soil moisture adsorption. However, extensive regional research is limited, including long-term studies on non-rainfall water or studies on natural surface condensation. Current studies on non-rainfall water are unable to provide a comprehensive grasp of its spatiotemporal variance. Future research must discover and develop new technologies and new methods to collect, observe, and model non-rainfall water on natural surfaces, investigate the large spatial scale and long-term non-rainfall water observation and simulation, and reveal influences of non-rainfall water on the water cycle, eco-hydrology, and climatic change to deepen the understanding of non-rainfall water as a nontraditional water resource.

Keywords: non-rainfall water; dew; fog; water vapor adsorption