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荒漠绿洲典型天然植被与环境水分关系研究进展

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摘要: [目的] 水分是荒漠绿洲植被稳定存在的基础,荒漠绿洲天然植被是长期适应其水分环境变化的产物,具有稳定的结构组成和自我修复能力,能够有效应对环境变化的影响。[方法] 通过整理荒漠绿洲天然植被及其水分环境关系研究的文献资料,从荒漠绿洲天然植被分布格局、适应能力、群落结构特征、土壤水分、地下水位等方面,系统分析天然植被与其水分环境间的关系。[结果] 水分条件决定荒漠绿洲天然植被的组成结构和分布格局,天然植被又影响其水环境变化过程。土壤水分条件和地下水埋深决定荒漠绿洲天然植被的演替过程、结构特征和分布格局。荒漠绿洲天然植被对水资源的消耗和再分配过程影响土壤水分循环过程,引起的水环境变化反过来又影响到天然植被的演替和发展,二者间存在明显的互馈作用。[结论] 总结了近年来我国荒漠绿洲天然植被与水文过程方面的研究进展,系统梳理荒漠绿洲天然植被与水文过程间的互馈作用,分析荒漠绿洲天然植被稳定性维持的水分调控机制,明确其在维持荒漠绿洲生态系统稳定中的作用,建议根据荒漠绿洲天然植被与水分环境互作关系,指导荒漠绿洲生物防护体系构建及水资源管理;关注全球变化背景下的荒漠绿洲天然植被及其水分环境关系变化的研究,加强从不同尺度下开展荒漠绿洲天然植被与水分关系研究,同时引进新的研究技术和方法,为荒漠绿洲人工防护系统构建和水资源合理利用提供理论支撑。

关键词: 荒漠绿洲; 天然植被; 植被演替; 水文过程; 互馈机制

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Research Progress on Relationship between Typical Natural Vegetation and Environmental Water in Desert Oases

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Abstract: [Objective] Water is the foundation for the stable existence of vegetation in desert oases. The natural vegetation in desert oases is the result of long-term adaptation to changes in their water environment. It has a relatively stable structural composition and self-repairing ability, enabling it to effectively cope with the impact of environmental changes. [Methods] By reviewing the literature on the relationship between natural vegetation and water environment in desert oases, this study systematically analyzes the relationship from aspects such as the distribution patterns, adaptability, community structure characteristics, soil moisture, and groundwater level of natural vegetation in desert oases. [Results] Moisture conditions determine the compositional structure and spatial distribution patterns of natural vegetation in desert oases, while the natural vegetation, in turn, affects the variation processes of its water environment. Soil moisture conditions and groundwater depth determine the succession process, structural characteristics, and distribution patterns of natural vegetation in desert oases. The consumption and redistribution processes of water resources by natural vegetation affect the soil water cycling process in desert oases. The resulting changes in the water environment, in turn, influence the succession and

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development of natural vegetation, demonstrating a strong mutual feedback mechanism between the two. [Conclusion] This study summarizes the research progress on natural vegetation and hydrological processes in desert oases in China in recent years, systematically reviews the mutual feedback between them, analyzes the water regulation mechanisms that maintain the stability of natural vegetation in desert oases, and clarifies its role in sustaining the desert oasis ecosystem. It is recommended to guide the construction of biological protection systems and water resource management in desert oases based on the interaction between the natural vegetation and water environment in desert oases. Future research should focus on the changes in the relationship between the natural vegetation and water environment in desert oases under the background of global change, strengthen the research on the relationship between natural vegetation and water in desert oases at different scales, and introduce advanced research technologies and methods. This will provide theoretical support for the construction of artificial protection systems in desert oases and the rational utilization of water resources.

Keywords: desert oasis; natural vegetation; vegetation succession; hydrological processes; feedback mechanism

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荒漠绿洲天然植被的组成结构是长期适应环境和演变的结果,其组成结构具备区域特色、生境特色及物种结构特色等,代表不同荒漠绿洲区自然生态系统的特征^[1-3]。荒漠绿洲天然植被物种组成结构合理,空间层次丰富,乔灌木物种比例适宜,具备多层次的树冠结构,在防风固沙、水土保持、水源涵养、土壤改良、生态系统环境改善、维持生态系统稳定等方面具有独特的生态功能^[4-6],对荒漠绿洲人工防护体系构建具有较高的参考价值。水分是荒漠绿洲生态系统的关键调控因素,水分条件决定荒漠绿洲天然植被的组成结构、分布格局及持续稳定^[7-8];同时,荒漠绿洲天然植被对其水分环境也产生反馈作用,决定水分的分配格局及数量关系^[9-10]。在荒漠绿洲植被演替进程中,天然植被与其水分环境形成相互作用的协调稳定系统,维系着荒漠绿洲天然植被生态系统的长期稳定^[11-13]。

我国在荒漠绿洲天然植被与土壤水文过程研究方面已开展多方面研究,在天然植被结构特征、天然植被演变过程、分布格局、环境因素对天然植被影响及其相互作用等方面取得较为丰富的研究成果^[14-18],重点开展天然植被演替过程对土壤水文过程的影响研究^[19-23],明确天然植被区土壤水分变化特征、降雨水分再分配过程、植物水分利用特征等,同时,也系统分析环境水分变化对天然植被结构、分布和演变格局的影响^[24-26]。上述研究对我国荒漠绿洲天然植被与土壤水文关系的研究产生了显著的推动作用,但通过文献检索分析发现,目前此方面的研究进展还缺乏系统的梳理和总结分析。本文基于我国主要荒漠绿洲区天然植被及其土壤水环境关系的文献资料,系统总结目前天然植被与其土壤水环境间的相互作用关系研究进展,提出今后可能的研究重点和

面临的关键挑战,为我国荒漠绿洲天然植被保护和绿洲人工防护植被构建提供理论支撑。

1 我国主要荒漠绿洲天然植被的基本情况

我国的荒漠绿洲主要分布于西北地区,可以划分为南疆绿洲区、北疆绿洲区、河西走廊绿洲区、河套平原绿洲区、柴达木盆地绿洲区和阿拉善绿洲区^[27]。荒漠绿洲天然植被主要受到地带性植被分布和环境条件的共同作用,不同荒漠绿洲区形成各具特色的天然植被类型,既存在着区域相似性,也具备各自的独特性^[10,28-29]。我国荒漠绿洲天然植被与水分环境关系研究主要在我国西北地区开展,特别是在新疆地区、河西走廊地区和河套地区等地开展广泛深入的研究,取得丰硕的研究成果^[30-32]。

分析我国西北地区荒漠绿洲天然植被组成结构^[33-35]发现,乔木类型多以胡杨(*Populus euphratica* Oliv.)为主,灌木类型包括梭梭[*Haloxylon ammodendron* (C. A. Mey.) Bunge]、白刺(*Nitraria tangutorum* Bobrov)、怪柳(*Tamarix chinensis* Lour.)、骆驼刺(*Alhagi sparsifolia* Shap.)等;草本植物以芦苇[*Phragmites australis* (Cav.) Trin. ex Steud.]、花花柴[*Karelinia caspia* (Pall.) Less.]、沙蓬[*Agriophyllum squarrosum* (L.) Moq.]、沙蒿(*Artemisia desertorum* Spreng.)等为主;盐生植物主要以怪柳(*Tamarix chinensis* Lour.)、红砂[*Reaumuria soongorica* (Pall.) Maxim.]、沙冬青[*Ammopiptanthus mongolicus* (Maxim. ex Kom.) Cheng f.]、盐爪爪[*Kalidium foliatum* (Pall.) Moq.]等盐生物种为主(表1)。上述物种在多个荒漠绿洲区可见分布,在以往研究中观察到上述物种的跨区域分布现象,但在不同的荒漠绿洲环境条件背景下,

某些物种会成为当地天然植被的主体,在区域内成为优势分布物种,如在新疆南疆的绿洲区,胡杨成为优势物种;在河西走廊绿洲区,梭梭、白刺等形成优势物种;在土壤盐碱的绿洲区,柽柳、红砂等成为优势种。我国荒漠绿洲天然植被整体上物种分布相互重叠覆盖,但在局部特定环境下,形成某些物种的优势分布。

表 1 我国西北主要荒漠绿洲天然植被物种构成

Table 1 Species composition of natural vegetation in major desert oases of Northwest China

区域	天然植被典型物种构成
新疆绿洲区	<p>典型乔木物种:胡杨 典型灌木和草本物种:梭梭、铃铛刺[<i>Caragana halodendron</i> (Pall.) Dum. Cours.]、白刺、骆驼刺、罗布麻(<i>Apocynum venetum</i> L.)、对节刺(<i>Horaninowia ulicina</i> Fisch. & C. A. Mey.)、沙拐枣(<i>Calligonum mongolicum</i> Turcz.)、花花柴、多枝柽柳(<i>Tamarix ramosissima</i> Ledeb.)、芦苇、芨芨草、苦豆子(<i>Sophora alopecuroides</i> L.)、猪毛菜(<i>Salsola collina</i> Pall.)、红砂、无叶假木贼(<i>Anabasis aphylla</i> L.)、驼绒藜[<i>Krascheninnikovia ceratoides</i> (L.) Gueldenst.]和樟味藜(<i>Camphorosma monspeliaca</i> L.)、雾冰藜[<i>Grubovia dasyphylla</i> (Fisch. & C. A. Mey.) Freitag & G. Kadereit]、叉毛蓬[<i>Petrosimonia sibirica</i> (Pall.) Bunge]、盐地碱蓬[<i>Suaeda salsa</i> (Linn.) Pall.]、盐爪爪、盐节木、小獐毛[<i>Aeluropus pungens</i> (M. Bieb.) C. Koch]、新疆绢蒿[<i>Seriphidium kaschgaricum</i> (Krasch.) Poljakov]、白茎绢蒿[<i>Seriphidium terrae-albae</i> (Krasch.) Poljakov]、羽毛三芒草(<i>Aristida pennata</i> Trin.)、沙独尾草[<i>Eremurus inderiensis</i> (Steven) Regel]、囊果碱蓬(<i>Suaeda physophora</i> Pall.)等</p>
南疆绿洲区	<p>典型乔木物种:胡杨、灰杨(<i>Populus pruinosa</i> Schrenk)、白榆(<i>Ulmus pumila</i> L.) 典型灌木和草本物种:白刺、梭梭、柽柳、花花柴、骆驼刺、芦苇、红柳、沙棘(<i>Hippophae rhamnoides</i> L.)、甘草(<i>Glycyrrhiza uralensis</i> Fisch.)、铃铛刺、盐穗木、骆驼蓬(<i>Peganum harmala</i> L.)、罗布麻、黑果枸杞(<i>Lycium ruthenicum</i> Murr)、沙拐枣、芨芨草、苦豆子、小獐毛、盐爪爪、盐节木、苦马豆、羽毛三芒草、盐生草[<i>Halogeton glomeratus</i> (M. Bieb.) C. A. Mey.]、碱蓬[<i>Suaeda glauca</i> (Bunge) Bunge]、毛车前(<i>Plantago asiatica</i> L.)、高枝假木贼[<i>Anabasis elatior</i> (C. A. Mey.) Schischk.]、叉枝鸦葱(<i>Scorzonera divaricate</i> Turcz.)、猪毛菜、碱地肤[<i>Kochiascoparia</i> (Linn.) Schrad. var. <i>sieversiana</i> (Pall.) Ulbr. ex Aschers. et Graebn.]、叉毛蓬[<i>Petrosimonia sibirica</i> (Pall.) Bunge]、驼绒藜、蒲公英(<i>Taraxacum mongolicum</i> Hand. Mazz.)、大蓟(<i>Cirsium japonicum</i> Fisch. ex DC.)、沙漠绢蒿[<i>Seriphidium santolinum</i> (Schrenk) Poljakov]、狗尾草[<i>Setaria viridis</i> (L.) P. Beauv.]、虎尾草(<i>Chloris virgata</i> Sw.)、狗牙根[<i>Cynodon dactylon</i> (L.) Persoon]、赖草[<i>Leymus secalinus</i> (Georgi) Tzvelev]、合头藜(<i>Sympegma regelii</i> Bunge)、裸果木(<i>Gymnocarpus przewalskii</i> Maxim.)、膜果麻黄(<i>Ephedra przewalskii</i> Stapf)、刺沙蓬(<i>Salsola tragus</i> L.)、沙生针茅[<i>Stipa caucasica</i> subsp. <i>glareosa</i> (P. A. Smirnov) Tzvelev]等</p>
河西走廊绿洲区	<p>典型乔木物种:胡杨、二白杨(<i>Populus gansuensis</i> C. Wang et H. L. Yang)、灰杨 典型灌木和草本物种:白刺、柽柳、梭梭、盐爪爪、红砂、骆驼蓬、沙蒿、沙枣(<i>Elaeagnus angustifolia</i> L.)、旱柳(<i>Salix matsudana</i> Koidz)、芦苇、芨芨草、苦豆子、雾冰藜、沙蓬、盐穗木、泡泡刺、沙拐枣、沙冬青、黑果枸杞、骆驼刺、罗布麻、花花柴、白茎盐生草(<i>Halogeton arachnoideus</i> Moq.)、柠条锦鸡儿(<i>Caragana korshinskii</i> Kom.)、花棒(<i>Hedysarum scoparium</i> Fisch. & C. A. Mey.)、珍珠猪毛菜(<i>Salsola passerine</i> Bunge.)、甘草、小针茅、獐茅、膜果麻黄、猫头刺(<i>Oxytropis aciphylla</i> Ledeb.)、沙蓬、小叶锦鸡儿(<i>Caragana microphylla</i> Lam.)、大针茅(<i>Stipa grandis</i> P. A. Smirn.)、冰草[<i>Agropyron cristatum</i> (L.) Gaertn.]等。</p>
柴达木盆地绿洲区	<p>典型乔木物种:胡杨、小叶杨(<i>Populus simonii</i> Carrière) 典型灌木和草本物种:梭梭、白刺、柽柳、沙拐枣、骆驼刺、芦苇、花花柴、甘草、苦豆子、黑果枸杞、罗布麻等</p>
阿拉善高原绿洲区	<p>典型乔木物种:胡杨 典型灌木和草本物种:白刺、梭梭、红柳、红砂、骆驼刺、骆驼蓬、沙拐枣、多枝柽柳、沙枣、沙蒿、花花柴、芦苇、芨芨草、苦豆子、麻黄(<i>Ephedra sinica</i> Stapf)、沙蒿、绵刺、霸王、沙竹、驼绒藜、沙蓬、猪毛菜、虫实(<i>Corispermum hyssopifolium</i> L.)、蓝刺头(<i>Echinops sphaerocephalus</i> L.)、小叶锦鸡儿、柠条锦鸡儿、猫头刺等</p>
河套平原绿洲区	<p>典型乔木物种:胡杨、大果榆(<i>Ulmus macrocarpa</i> Hance) 典型灌木和草本物种:白刺、柽柳、梭梭、花棒、红柳、沙枣、骆驼蓬、黑沙蒿(<i>Artemisia ordosica</i> Krasch.)、沙蓬、沙冬青、盐爪爪、芦苇、沙蒿、芨芨草、苦豆子、雾冰藜、虫实、猪毛菜、沙蓬、霸王[<i>Zygophyllum xanthoxylum</i> (Bunge) Maxim.]、驼绒藜、红砂、泡泡刺、沙拐枣、猫头刺、珍珠柴[<i>Caroxylon passerinum</i> (Bunge) Akhani & Roalson]、短脚锦鸡儿(<i>Caragana brachypoda</i> Pojark.)、柠条锦鸡儿、绵刺(<i>Potania mongolica</i> Maxim.)、蒙古扁桃(<i>Prunus mongolica</i> Maxim.)、红砂、沙生冰草[<i>Agropyron desertorum</i> (Fisch.) Schult.]等</p>

2 荒漠绿洲水分环境对天然植被的影响

水分条件是荒漠绿洲天然植被组成和结构特征的重要决定因素,同时,天然植被对其土壤水文过程也产生相应的影响作用。

2.1 土壤水分对荒漠绿洲天然植物的影响

荒漠绿洲天然植物能够适应从极端干旱到相对湿润的生存环境,构成荒漠绿洲特有的天然植被空间分布和物种结构特征。

荒漠绿洲天然植物对环境水分条件存在较宽的适应范围,且在不同荒漠绿洲表现出不同的土壤水分适应能力^[36-38],如胡杨能在土壤水分体积分数0.44%~40.00%生存,土壤水分适应的变化幅度大,表现出其极强的适应能力,可在土壤水分体积分数低于0.50%条件下生存(塔里木河流域绿洲和石羊河下游绿洲区),在2.00%~3.00%的土壤水分体积分数条件下能够生长良好(多数绿洲区),在土壤水分体积分数达到20.00%~40.00%的湿地及河湖周边区域也可正常生长(额济纳绿洲、轮台绿洲等地区的湿地环境)。灌木类型的荒漠绿洲植物种一般具备更强的干旱适应能力,梭梭可在0.16%的极端土壤水分体积分数条件下生存,一般情况下可以耐受0.50%~0.90%的土壤水分环境。白刺可以耐受的最低土壤水分体积分数为

0.50%~0.80%,土壤水分体积分数在1.00%~2.00%能够正常生长,耐受的土壤水分体积分数最高可以达到16.70%;柽柳作为耐盐碱的荒漠绿洲植物种类,土壤水分体积分数为0.66%~47.06%。其他荒漠绿洲天然物种如羊柴、柠条锦鸡儿、沙拐枣等生存环境中土壤水分体积分数为1.00%~3.00%。芦苇能够适应干旱沙丘和湿地生存环境,土壤水分体积分数适应范围为0.27%~37.00%(表2)。由于荒漠绿洲区存在较大的土壤水分环境差异,即从绿洲核心区的湿地过渡到外围的荒漠区,土壤水分呈现逐渐降低的梯度分布特征,这种环境促进荒漠绿洲天然植物的水分适应能力提升,使得其既能在干旱的荒漠环境下生长,也可在湿润的绿洲内生存,这是荒漠绿洲天然植物适应其生存环境和自然进化选择的结果。

表 2 我国荒漠绿洲典型天然植物的土壤水分适应范围

Table 2 Soil moisture adaptation ranges of typical natural plants in desert oases of China

典型植物	分布区域及土壤水分条件	备注
胡杨	石羊河下游荒漠绿洲区0.50%~8.38% ^[39] ;塔里木河流域荒漠绿洲区0.44%~21.01% ^[40] 、2.28%~13.00% ^[41] ;塔里木河中游轮台县0.46%~39.74% ^[12] ;艾比湖流域荒漠绿洲区2.10%~6.11% ^[42] ;额济纳绿洲区3.00%~40.00% ^[43] ;策勒绿洲区1.90%~8.10% ^[44]	荒漠区及湿地
梭梭	艾比湖流域荒漠绿洲区0.72%~6.80% ^[42] ;石羊河下游民勤荒漠绿洲区0.55%~2.01% ^[45] ;古尔班通古特荒漠绿洲区3.80%~6.20% ^[46] 、3.20%~11.80% ^[47] 、3.54%~8.92% ^[48] ;库布奇沙漠荒漠绿洲区2.00%~8.00% ^[49] ;民勤荒漠绿洲区13.80%~15.50% ^[50] 、0.80%~4.20% ^[51] 、0.60%~1.00% ^[21] ;临泽荒漠绿洲区1.30%~2.82% ^[52] 、1.00%~4.00% ^[53] 、0.95%~3.10% ^[54] ;乌兰布和沙漠荒漠绿洲区0.36%~3.59% ^[55] ;额济纳荒漠绿洲区2.00%~18.00% ^[56] ;和田荒漠绿洲区0.16%~19.50% ^[57]	荒漠区为主
白刺	甘肃民勤荒漠绿洲区1.28%~5.03% ^[58] 、1.20%~2.80% ^[59] 、1.10%~2.20% ^[21] 、1.70%~2.20% ^[60] 、1.80%~3.10% ^[61] 、1.10%~4.10% ^[62] ;青土湖湿地,沙堆内部7.00%~16.00% ^[63] ;乌兰布和沙漠荒漠绿洲区,白刺沙堆间黏土区7.50%~16.70%,白刺沙堆内部土壤水分0.50%~1.20% ^[64] ;青海海西柴达木盆地荒漠绿洲区,沙堆内部土壤水分体积分数0.65%~3.15%,平均值为2.09% ^[65] ;毛乌素沙地南缘荒漠绿洲区2.17%~2.71% ^[66] ;腾格里沙漠东南缘荒漠绿洲区0.80%~7.00% ^[67]	沙堆形态较多,堆间及沙堆土壤水分体积分数差异较大
柽柳	甘肃民勤荒漠绿洲区1.70%~2.30% ^[21] 、7.00%~12.00% ^[68] ;石羊河下游1.87%~3.48% ^[69] ;青土湖湿地9.15%~13.23% ^[63] ;额济纳荒漠绿洲区11.12%~47.04% ^[20] 、11.10%~35.00% ^[70] ;巴丹吉林沙漠荒漠绿洲区0.75%~2.67% ^[71] ;库木塔格沙漠东南敦煌荒漠绿洲区3.20%~11.80% ^[72] ;河西走廊酒泉荒漠绿洲区12.50%~18.20% ^[73] ;宁夏吴忠黄河灌区荒漠绿洲区1.98%~7.55% ^[74] ;艾比湖流域荒漠绿洲区0.66%~2.82% ^[42] ;张掖黑河河岸带荒漠绿洲区5.30%~43.30% ^[75] ;和田荒漠绿洲区0.69%~15.40% ^[57] ;黄河腾格里沙漠过渡区5.20%~22.10% ^[76] ;准格尔盆地阜康荒漠绿洲区0.90%~22.30% ^[77] 、3.10%~15.20% ^[78] ;甘肃张掖临泽荒漠绿洲区1.40%~3.20% ^[79] ;策勒荒漠绿洲区0.70%~4.20% ^[80] 、1.80%~8.30% ^[44] ;轮台荒漠绿洲区1.40%~16.10% ^[81]	荒漠及土壤偏碱性区为主
芦苇	艾比湖流域荒漠绿洲区4.98%~9.21% ^[42] ,湿地14.00%~23.00% ^[82] ;甘肃临泽荒漠绿洲区,沙丘到湖畔湿地1.93%~23.13% ^[83] ;敦煌绿洲湖畔湿地,按距离湖泊远近,8.59%~37.32% ^[84] ;民勤荒漠绿洲区,覆沙地0.27%~3.72%,盐碱地2.00%~5.76%,盐沼地4.59%~8.57% ^[85]	荒漠区及湿地为主要分布区
沙枣	库布奇沙漠荒漠绿洲区1.43%~7.40% ^[86] ;宁夏平罗荒漠绿洲区4.50%~9.20% ^[13] ;额济纳荒漠绿洲区6.89%~11.37%(黏性土),5.10%~9.20%(沙性土) ^[87] ;民勤荒漠绿洲区4.50%~8.90% ^[88]	荒漠区为主
骆驼刺	艾比湖流域荒漠绿洲区4.20% ^[89] ;古尔班通古特荒漠绿洲区3.98%~9.56% ^[48] ;策勒荒漠绿洲区1.80%~7.10% ^[43] 、3.20%~6.80% ^[80] ;额济纳荒漠绿洲区2.10%~24.50% ^[90]	荒漠区为主
红砂	额济纳荒漠绿洲区1.46%~17.12% ^[20] 、0.90%~2.2% ^[91] ;张掖荒漠绿洲区0.74%~2.75% ^[11] ;甘肃兰州黄土丘陵区,4.20%~7.60% ^[92]	盐碱区
沙拐枣	策勒荒漠绿洲区1.60%~6.90% ^[43] 、1.60%~4.20% ^[80] ;古尔班通古特荒漠绿洲区1.50%~2.30% ^[93] ;腾格里沙漠阿拉善荒漠绿洲区0.40%~0.70% ^[94] ;民勤荒漠绿洲区1.20%~4.90% ^[21] ;临泽荒漠绿洲区1.50%~2.20% ^[95] ;河西走廊黑河中游荒漠绿洲区1.50%~3.50% ^[96]	荒漠区
羊柴	库布奇沙漠荒漠绿洲区0.78%~1.56% ^[86] ;腾格里沙漠阿拉善荒漠绿洲区0.40%~0.80% ^[94]	荒漠区

2.2 地下水对荒漠绿洲天然植被影响

荒漠绿洲天然植被对地下水有很强的依赖性,地下水对维持植被生存、保护具有不可替代的重要作用^[97],是荒漠绿洲天然植被生长和分布格局的关键决定因素,稳定的天然植被群落是地下水、土壤、植被相互之间动态平衡的结果。

1) 荒漠绿洲天然植被对地下水埋深的适应

环境条件影响荒漠绿洲天然植被的地下水适应能力,天然植物对地下水位的适应范围存在差异。在区域尺度上,樊自立等提出地下水水位适宜埋深,在温带荒漠区为 1.5~4.0 m,在暖温带荒漠区为 2.0~4.5 m^[98]。郝兴明等^[99]研究指出,塔里木河下游地区地下水位维持在 4.0~6.0 m 时,有利于植被的恢复;张惠昌等^[100]研究提出,荒漠绿洲区沙进人退的原因在于绿洲区地下水位的持续降低。在个体尺度上,马兴华等^[101]给出疏勒河流域下游绿洲区不同天然植物的

适宜地下水位;钟华平等^[102]研究表明,额济纳绿洲区不同的植物群落有各自适宜的地下水位埋深范围,并且确定红柳的适宜水位为 2.0~3.0 m,胡杨为 2.5~3.5 m,沙枣为 2.0~3.0 m,芦苇为 0.5~1.0 m,白刺为 3.0~4.0 m。在天然植被与地下水关系方面,张丽等^[103]建立塔里木河干流域几种典型植物生长与地下水埋深关系的分布模型得出,典型植物的最适地下水埋深、适宜地下水埋深区间及其对环境因子的忍耐度;郭占荣等^[97]对塔里木河流域的天然植被与地下水关系进行分析,并根据生长状况提出所需的地下水埋深范围;翟家齐等^[104]在此基础上系统地总结荒漠绿洲不同地区不同植被的地下水生态位阈值。由表 3 可知,乔木类型中的胡杨可适应的最大地下水埋深阈值为 3.5~4.7 m,灌木类型植物种可适应的最大地下水埋深阈值为 3.0~5.0 m,草本植物种可适应的最大地下水埋深阈值为 1.6~4.0 m。

表 3 不同类型植物在不同地域适应地下水埋深阈值^[104]

Table 3 Adaptation thresholds of groundwater depths for different plant types in different regions^[104]

植被类型	出现区域及适宜地下水埋深阈值
乔木	胡杨 新疆塔里木河流域 3.0~4.7 m; 甘肃疏勒河流域 1.0~4.0 m; 甘肃石羊河流域 2.5~3.5 m; 内蒙古额济纳绿洲区 2.5~4.0 m
	沙枣 甘肃石羊河下游 2.0~3.0 m; 甘肃疏勒河流域 1.0~3.0 m; 内蒙古额济纳绿洲 2.0~3.0 m
灌木	怪柳 新疆玛纳斯河谷 1.0~5.3 m; 新疆准噶尔盆地 2.3~5.0 m; 新疆塔里木河下游 3.5~4.0 m; 新疆焉耆盆地绿洲 3.0 m; 甘肃石羊河下游 2.0~5.0 m; 甘肃疏勒河流域 1.0~6.0 m; 内蒙古额济纳绿洲 < 5.0 m; 青海柴达木盆地 3.0~5.0 m
	梭梭 新疆吐鲁番盆地 2.5~7.0 m; 甘肃石羊河流域 2.0~4.0 m; 青海柴达木盆地 3.0~4.0 m; 内蒙古乌兰布和沙漠 1.8~4.0 m
	白刺 甘肃石羊河下游 < 5.0 m; 甘肃疏勒河流域 2.0~3.5 m; 青海柴达木盆地 1.0~4.1 m; 内蒙古乌兰布和沙漠 1.8~4.0 m
	骆驼刺 新疆塔里木河 3.0~4.0 m; 甘肃疏勒河流域 1.0~4.0 m; 青海柴达木盆地 3.1~4.2 m; 内蒙古额济纳绿洲 2.84 m
	罗布麻 新疆塔里木河 1.5~3.0 m; 甘肃疏勒河流域 1.0~4.0 m; 内蒙古额济纳绿洲 2.5 m; 青海柴达木盆地 1.0~3.0 m
	沙柳 内蒙古鄂尔多斯高原 1.5~5.0 m
草本	芦苇 新疆玛纳斯河谷 0~1.6 m; 新疆塔里木河 < 2.5 m; 新疆阜康 2.0 m; 新疆准噶尔盆地 2.3~4.0 m; 甘肃临泽 1.5~4.0 m; 青海柴达木盆地 1.5~3.1 m; 内蒙古额济纳绿洲 1.4 m
	芨芨草 新疆玛纳斯河谷 0.5~1.7 m; 黑河流域 3.0~4.0 m; 内蒙古鄂尔多斯高原 1.0~3.0 m; 青海柴达木盆地 0.8~3.4 m
	甘草 新疆塔里木河 1.5~3.5 m; 内蒙古额济纳绿洲 2.4 m; 甘肃疏勒河流域 1.0~3.0 m

2) 地下水水位变化对荒漠绿洲天然植被的影响

地下水水位变化影响天然植被演替、分布和结构特征。地下水水位通过影响土壤水分变化影响天然植被数量与组成^[10,30],天然植被的退化和物种的减少在很大程度上与地下水埋深的持续增加有着密切的联系^[12,31]。

地下水水位变化影响荒漠绿洲天然植被的演替进程。在干旱区典型的地下水水位梯度变化生境中(新疆荒漠绿洲区),如沿河及环湖地段,从河湖沿岸到外围戈壁,随地下水埋深的增加,天然植被演变的一般趋势为:芦苇、芨芨草草甸-胡杨、沙枣乔木林-红柳

灌木林-苏枸杞、盐爪爪、耐旱盐草-梭梭、红砂等戈壁荒漠植被。在湖盆地带,从湖心到沙漠,植被演变规律为芦苇沼泽-金代代、水葫芦草甸-芦苇草甸-芦苇盐土草甸-零星芦苇盐壳-梭梭、白刺、沙拐枣沙地-梭梭沙漠^[13,99]。

地下水水位变化影响天然植被结构构成和群落特征。地下水水位变化引起天然植被空间分布格局改变,随着地下水位的降低,河西走廊荒漠绿洲区芦苇种群的分布格局逐渐变成不连续的、斑块状的分布特征^[83]。地下水水位变化引起天然植被生长状况改变,地下水埋深的增加显著降低物种丰富度、地上生

物量、群落覆盖率、群落高度和叶面积指数^[105]。地下水位变化引起天然植被结构特征变化,额济纳绿洲区随着地下水位降低,胡杨林过熟林比例增加,林分退化严重,更新力降低,伴生物种锐减,植被盖度降低^[106];地下水位下降和土壤水分丧失是引起塔里木河流域绿洲天然植被退化的主导因子,随着地下水位下降,天然植物群落由乔灌草组成结构(胡杨、多枝怪柳、白刺、铃铛刺、甘草、罗布麻、芦苇等)逐渐演变为单一的灌木群落(怪柳)^[107]。塔里木河中下游地下水位在2.0~3.5 m时,群落组成以胡杨-怪柳-芦苇群落和芦苇+怪柳-甘草群落为主,植被盖度一般为40%;地下水位在3.5~5.0 m时,群落组成类型以胡杨+怪柳-罗布麻群落和沙棘-怪柳群落为主,植被盖度为10%~30%;当地下水位在5.0~12.0 m时,群落组成以胡杨+怪柳群落或者单一的胡杨林为主,植被盖度在20%以下^[108];在西北内陆盆地平原区,当地下水埋深>7.0 m时,绝大多数天然植物已不能生存,仅剩个别极耐旱的植物勉强维持生存,而当地下水埋深>9.0~10.0 m时,任何天然植物都将无法生存^[97]。

3 荒漠绿洲天然植被对土壤水分环境的影响

荒漠绿洲天然植被影响土壤水分环境变化。天然植被在退化演替进程中,土壤水分环境多呈现不同的变化趋势。一种变化趋势是随着天然植被退化演替进程,土壤水分条件逐渐恶化,如王宏燕等^[109]在塔里木绿洲发现,随着胡杨林退化程度加剧,土壤水分含量呈现下降趋势,土壤持水贮水性能和调节水分供应的潜在能力降低。另一种变化趋势是随着天然植被退化演替进程,土壤水分呈现波动性周期变化趋势,如赵鹏等^[69]在石羊河下游荒漠绿洲对多枝怪柳群落研究发现,从轻度退化到重度退化过程中土壤水分呈增加趋势。本研究在天然白刺群落退化演替过程中也发现,其土壤水分也呈规律性的循环变化特征,即随着群落衰退,土壤水分又恢复达到较高点,为下一个循环演替进程的开始提供水分条件。其原因可能在于退化后期植物减少,盖度降低,其对土壤水分消耗减少,在同等水分环境条件下,有可能使得土壤水分呈增加趋势,也对应退化后期阶段植被降雨利用率较低,更多降雨补充到土壤贮水量中。退化后期的土壤水分环境改善为后续植物的侵入和定居提供有利环境,促进天然植被演替的循环发生,进而深入阐释荒漠绿洲天然植被存在自我稳定性维持机制,通过

水环境的周期变化维持天然植被的循环演替存在,说明荒漠绿洲天然植被的演替进程与土壤水分存在多种互作模式,同时该作用方式对荒漠绿洲天然植被循环演替提供保障。

荒漠绿洲天然植被组成和结构影响土壤水分环境变化。由于天然植被群落物种及结构的差异,其水分利用特征存在差别,使得不同天然植被对土壤水分影响存在差异。在策勒绿洲,张鹤年等^[32]研究发现,不同天然植被土壤水分呈现明显差异,骆驼刺群落土壤水分体积分数为0.65%,叉枝鸦葱群落土壤水分体积分数为0.59%,花柴群落土壤水分体积分数为0.42%;在额济纳绿洲,席海洋等^[110]研究发现,天然植被群落土壤水分体积分数由高到低为怪柳群落(23.10%)、胡杨群落(22.80%)、苦豆子群落(18.10%)、裸地(9.90%);萨如拉等^[111]研究发现,沙枣林和怪柳林的土壤水分体积分数明显高于胡杨林土壤水分体积分数。在民勤绿洲,天然植被土壤水分体积分数由高到低依次为怪柳+白刺群落、怪柳+沙拐枣群落、怪柳群落、白刺群落、梭梭群落^[21];王兵等^[112]研究也发现,天然植被红柳群落土壤水分体积分数高于白刺群落;陈宏祥等^[96]也研究发现,天然植被土壤水分体积分数由大到小为泡泡刺群落、沙拐枣群落和梭梭群落。在临泽绿洲,方桥等^[95]研究发现,土壤水分体积分数呈现高低为泡泡刺群落、沙拐枣群落和梭梭群落;麻进等^[113]也发现类似趋势,天然植被区土壤含水率和土壤持水能力表现为梭梭+泡泡刺群落>泡泡刺+沙拐枣群落>沙拐枣+梭梭群落。天然植被物种及组成结构间的水分利用差异是导致天然植被间土壤水分差异的关键因素。

4 存在问题与展望

荒漠绿洲区天然植被具备独特的地域特征,在荒漠绿洲防护体系构建、水资源可持续利用等方面具有重要的借鉴和参考意义,可为荒漠绿洲人工防护体系构建、绿洲资源可持续开发利用等提供重要的理论支持。

参照荒漠绿洲天然植被结构和水分环境特征建立植被防护体系。根据荒漠绿洲天然植被演替和水分环境变化特征,依据近自然恢复理论框架,提出适宜的荒漠绿洲植被防护体系构建模式。以往建立荒漠绿洲防护体系过程中多采用单一或较少物种以较高的栽植密度实施,往往造成防护体系结构简单,系统水分收支失衡,稳定性降低,很难长期维持其有效的防护效果。建议在构建荒漠绿洲植物防护体系过程中,系统分析荒漠绿洲天然植物的水分适应能力及天然植被的物种组成结构特征,模拟天然植被特征构

建荒漠绿洲外围生物防护体系,建立一种近自然的、维持系统水分平衡的、持续稳定的防护体系模式。同时,加强荒漠绿洲天然植被的保护,减少人为影响,利用其自身的演替和水分循环变化特征,保持绿洲外围区域天然防护体系的长期稳定存在,有效提高绿洲防护体系的持续性,降低防护成本,增加防护效果。

在全球变化背景下加强荒漠绿洲天然植被与水分关系研究。荒漠绿洲天然植被与水分关系受到环境因素变化影响,随着气候变化、人为活动影响力的不断增强,其生存环境中的降雨、土壤水分、地下水位、地表水资源等均在不断改变,势必影响到植被与水分关系,特别是在我国西北地区,因受全球气候变化的影响,区域降雨呈现增加趋势,温度升高引发冰川雪水流量增加,必然引起荒漠绿洲区的水分环境变化,在此变化背景下天然植被与水分环境关系问题亟须深入探究。建议加强在不同变化背景下的荒漠绿洲天然植被-水分关系研究,从动态变化的角度分析二者的关系及作用机制的变化,根据气候变化引起的温度和降雨变化阈值范围,更加精准地预测环境变化对二者关系的影响。

在研究方法和技术方面实现创新和突破。现有的方法多采用局地的现场观测方式收集荒漠绿洲天然植被的土壤水分和地下水位数据,在空间尺度上和时间尺度上存在明显不足,较难精准反馈荒漠绿洲区域尺度下的水文过程特征。建议在今后的研究中,从微观上探究降雨-土壤水分-地下水-植物利用过程的水分运移过程和调控机制,重点探究土壤水分的运移机制;在宏观上,扩大到区域尺度下开展土壤水-地下水-地表水之间的跨尺度运移过程和调控机制,重点量化景观单元间的水分运移数量和调控机制。

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