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青藏高原生态系统对气候变化的响应及其反馈

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摘要 近几十年来, 青藏高原正经历快速的气候变化, 高原生态系统因此发生了深刻变化, 并对周边地区产生了深远影响. 本文围绕青藏高原生态系统结构和功能对气候变化的响应与反馈这一主线, 系统总结了气候变化对物候、高山树线、生物多样性、植被生产力和生态系统碳汇功能的影响, 阐述了青藏高原植被变化对区域气候的反馈及对亚洲季风的远程影响的研究进展. 主要结论如下: 气候变暖导致植被返青期总体提前, 高原树线位置上升, 高寒草原植物物种丰富度和多样性下降; 气候变暖总体促进了高原植被生产力、增强了生态系统碳汇功能, 但受限于土壤极大的空间异质性和对深层土壤碳动态理解的匮乏, 目前对高原土壤碳库及土壤碳汇功能大小的估算仍具有较大不确定性. 同时, 青藏高原植被变化对近地表气温产生"负反馈"作用; 植被活动增强还对东亚季风产生远程影响, 导致我国东部夏季降水变化呈现"华南增加-长江黄河中间区域减少"的空间分异格局. 未来的研究需要在完善观测体系基础上, 加强对高寒生态系统对气候变暖的适应机理及生物地球物理反馈等过程的认知, 为优化生态系统管理和保障青藏高原的生态安全提供理论基础.

关键词 青藏高原, 气候变化, 植被变化, 碳汇, 反馈

青藏高原平均海拔4000 m以上, 是世界上平均海拔最高的自然地理单元, 是我国乃至亚洲重要的生态安全屏障[1]. 20世纪80年代以来, 全球变暖问题在青藏高原地区表现愈加突出, 其升温速率为全球平均升温速率的2倍左右[2,3], 青藏高原的生态安全面临前所未有的挑战. 在这一背景下, 青藏高原生态系统如何响应和反馈气候变化, 不仅关系到本区域的生态安全, 还会对其毗邻地区生态环境产生深刻影响. 因此, 长期以来生态系统对气候变化的响应与反馈都是国内外研究的热点之一.

自20世纪初以来, 青藏高原生态学研究走过了从个体到群落再到生态系统的漫长科学积累道路[4], 尤其是自1973年起的青藏高原综合科学考察, 历经20余载, 对青藏高原生态系统结构和功能进行了全面、系统的考察研究, 摸清了家底, 填补了空白[5]. 21世纪初以来, 随着多尺度综合联网观测、控制实验与模型模拟等新的研究方法和工具的应用, 我国科学家们在青藏高原生态学研究方面取得了大量有价值的成果, 增强了预测全球变化背景下青藏高原生态系统动态变化的能力[1]. 本文围绕青藏高原生态系统对气候变化的响

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应及反馈，拟系统总结气候变化对青藏高原物候、树线动态、生物多样性、生产力和碳汇功能的影响，以及青藏高原植被变化对区域气候的反馈作用等方面的研究成果，这些成果对开展青藏高原生态安全屏障建设, 保证青藏高原生态安全都有重要指导意义.

1 生态系统结构对气候变化的响应

1.1 高原植被返青期总体呈提前趋势，其返青期的温度敏感性低于全国平均水平

近几十年来，随着气候变暖青藏高原植被物候在物种、生态系统、景观、区域水平上均发生了显著变化. 基于长期物候观测数据的研究结果表明, 在物种水平上，20世纪80年代以来青藏高原典型优势物种如小嵩草(*Kobresia pygmaea*)等，其萌动期、展叶期、开花期均存在提前趋势，提前速率在0.17~1.9 d a^{-1}之间；而枯黄期呈推迟趋势, 速率在0.3~1.8 d a^{-1}不等[6~8]. 然而, 目前的地面物候观测点及物种数均局限于少数站点及部分物种，基于有限站点的少数物种的物候变化能在多大程度上代表广大高原上植物物候的动态变化及地理格局还存在较大疑问.

遥感技术的发展弥补了地面观测站点有限的缺陷, 为景观或更大尺度上的物候学研究提供了新的有效手段[9]. 基于遥感数据的物候研究发现，20世纪80和90年代青藏高原大部分地区植被返青期显著提前，平均提前速率约为0.31~0.88 d a^{-1}[10~12]，但围绕21世纪初青藏高原植被返青期变化趋势的时空变化特征则存在较大争论. Yu等人[10]指出在区域尺度上，不同于20世纪80~90年代的显著提前趋势，青藏高原植被返青期在2000~2006年间呈推迟趋势，这一发现得到了Piao等人[11]研究结果的支持. 但Zhang等人[13]认为，早期研究得出的“21世纪初青藏高原植被返青期推迟”结论是由其所使用遥感产品的数据质量导致，21世纪初青藏高原植被返青期仍在显著提前. 但也有研究指出Zhang等人[13]的分析中并没有剔除非生长季积雪覆盖对遥感植被指数数据的干扰，从而高估了植被返青期的提前幅度[14,15]. 通过校正积雪变化的干扰，Shen等人[16]发现2000~2011年间青藏高原植被返青期在区域尺度上并没有发生显著变化，但其变化趋势存在显著空间差异, 即青藏高原西南部植被返青期显著推迟，而东北部的植被返青期则持续提前.

温度是影响植被生长期变化的最主要驱动因子之一. 研究表明温度每升高1°C，青藏高原草地返青期平均提前约4.1 d[11]，这一数值显著低于中国温带地区植被返青期对温度敏感性的平均水平 (7.5 d $°C^{-1}$)[17]. 青藏高原植被返青期较低的温度敏感性可能与该地区温度波动较大有关: 通常温度波动越大的地区, 植物为了规避低温冻害，其春季物候对温度的敏感性也会下降[18]. 进一步研究发现, 不同于北半球高纬度大部分地区植被返青期主要受白天温度变化的影响[19]，青藏高原植被返青期的年际变化与夜间温度的关系更为显著[20]，表明青藏高原春季植被物候受白天温度以及辐射的限制较小. 一些植物的春季物候除了受春季温度影响之外，还可能受冬季温度影响. Yu等人[10]提出，青藏高原冬季温度的快速上升导致春季植被展叶期所需积温需求增加，从而抵消了春季升温对物候提前的促进效应. 但这一观点并没有得到大部分学者的支持，一般认为, 青藏高原冬季地表温度长期较低, 较好地满足了植物冬季休眠的低温需求，因此冬天温度对春季物候的影响可能并不大[6,18,21].

除了温度变化，在一些地区降水的变化也会显著改变植被物候. 例如, Li等人[22]发现西藏当雄嵩草属等广布优势物种的返青期对降水变化敏感，且与印度季风雨季来临时间同步. 据Shen等人[16]的研究, 21世纪初青藏高原西南部植被返青期推迟与印度季风减弱导致的该地区降水下降密切相关. 该研究发现, 在高原西南地区, 降水与植被返青期之间存在显著负相关关系，即降水的下降导致植被返青期的推迟. 此外, 积雪对植被返青期的影响亦不可忽视[23,24]，因为冬季积雪增多一般会增加春季土壤水分，从而促进植被春季物候的提前.

1.2 气候变暖导致高原树线位置呈上升趋势，但其上升幅度受种间关系和降水的调控

高山树线作为树木(树高2 m以上)分布的最高海拔界限，对气候变化十分敏感. 在过去100年的变暖背景下, 青藏高原高山树线有向更高海拔爬升的趋势 (图1), 但不同地区树线爬升幅度具有显著的空间差异 (图1). 例如，在祁连山区，青海云杉树线上升幅度为13~80 m[25]，而该地区祁连圆柏树线海拔保持相对稳定[26]. 在青海玉树、西藏昌都和林芝地区，川西云杉树线爬升25 m[27]，而急尖长苞冷杉树线仅上升0~9 m[28]. 在滇西北的横断山区，长苞冷杉和大果红杉树线爬升幅度分别为19~28和0~67 m[25,29,30]. 总之，过去100年来青藏高

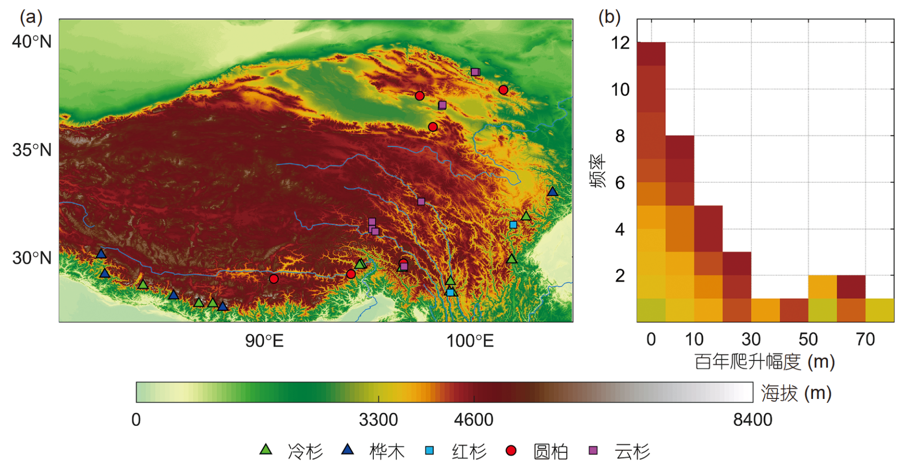

图 1 青藏高原不同类型树种高山树线的空间分布图(a)和近百年来高山树线的爬升幅度(b)

Figure 1 The spatial distribution of the treeline sites of different tree species over the Tibetan Plateau (a) and their upward shifts of the treeline position during the past 100 years (b)

原树线总体上处于上升趋势, 最高爬升了80 m. 大空间尺度上树线上升幅度并不存在显著的种间差异，但是相同树种的树线上升速率在同一山区却可能存在显著差异[25,31].

温度是高山树线变化的主要驱动因子，但温度变化并不能完全解释高山树线变化的空间异质性，需要进一步量化降水和非气候因素等对树线爬升变化的贡献. 对青藏高原6个关键区域云冷杉树线样地研究发现, 在树线显著上升的区域, 树线之上的植被普遍稀疏; 而当树线上升幅度较小或保持稳定时，树线之上普遍分布高盖度的灌丛[25]. 进一步分析发现，植被厚度指数(即灌丛的盖度乘以高度)作为种间竞争的量化指标可以解释过去100年来青藏高原树线位置变化的70%，从而证实了种间竞争对树线变化的调控作用. 此外, 在春季降水匮乏的喜马拉雅山中段高海拔山区，降水量变化是调控天然树线上升速率的主要因子[31]. 与青藏高原东部不同，在喜马拉雅山区海拔3000 m以上的地区, 降水量随海拔升高而下降，树线位置的树木和高山灌丛生长受春季降水的限制，而且树线之上灌丛分布稀疏，可以排除种间竞争对树线变化的限制作用[32,33]. 喜马拉雅山中段东部区域树线上升速率沿降水梯度呈显著空间差异，东部降水较丰沛的样地较之西部树线具有较高的上升速率. 模型结果进一步表明, 春季降水和年平均最高气温可以解释喜马拉雅山中段树线位置变化速率的61%.

干扰也是影响树线位置变化及其对气候变化响应的一个重要因素[34]. 基于青藏高原东部云杉树线样地网络(包括受放牧干扰、未受干扰两个梯度)以及历史气候和放牧资料的研究揭示，藏东云杉树线的上升速率受到放牧强度的调控[35]. 过度放牧改变了土壤理化性质和微环境状况，限制了树线之上矮灌丛的生长和树苗更新, 从而影响了树线变化[34]. 森林火也是驱动树线变化的干扰因素之一. 在滇西北横断山区, 20世纪60年代的轻度火干扰降低了灌丛覆盖度，减缓了树木与灌丛之间的种间竞争, 从而加速了树线的上升速率, 进一步验证了“物种关系机制”[25]. 自20世纪80年代以来, 受火干扰的树线位置爬升11~44 m，显著高于未受火干扰的对照样地(爬升幅度为0 m)[30]. 总之，除温度以外, 种间竞争、降水变化和干扰也影响着过去百年时间尺度上青藏高原高山树线动态变化格局，这也解释了气候变暖背景下青藏高原树线位置变化呈现较大区域分异的原因.

1.3 升温显著降低高寒草原植物物种丰富度和多样性, 但对高寒草甸群落的影响没有定论

气候变暖是全球生物多样性丧失的主要原因之一[36]. 通过综合分析青藏高原野外模拟增温实验结果, 发现温度升高显著降低了高寒草原群落植物物种丰富度和多样性，但增温对高寒草甸群落多样性没有显著影响(图2). 然而，单个站点实验也发现增温有降低高寒草甸群落物种丰富度的趋势[37]，主要是由于增温方法不一致或稀少物种的年际波动造成的[38]. 事实上增温区物种丰富度的变化是由新物种增加和丧失物种的净变化决定的，但目前有关原位增温实验的实验年限

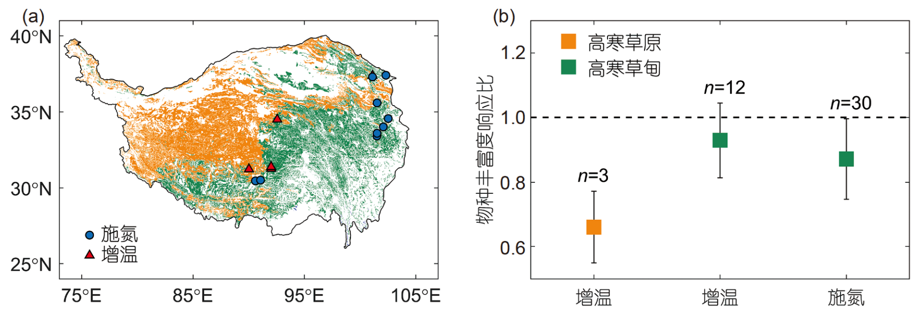

图 2 青藏高原增温、施氮实验站点的空间分布(a)和增温、施氮对青藏高原高寒草地物种丰富度的影响(b). 物种丰富度响应比为处理组和对照组的物种丰富度比值

Figure 2 The spatial distribution of the experiment sites of warming and nitrogen addition over the Tibetan Plateau (a), and the impacts of warming and nitrogen addition on the species richness of the alpine grassland (b). The species richness response ratio is the ratio between the species richness of the treatment experiment against that of the control experiment

普遍短, 可能没有观测到增温导致的新物种增加. 10年长期的海拔梯度移栽实验证明, 由于物种获得数量大于物种丧失数量, 使得增温和降温均提高了高寒草甸植物物种丰富度, 这种效应取决于追随气候变化的物种特性和数量[39].

随着人类活动的加剧, 青藏高原氮沉降速率呈逐年增加趋势[40,41]. 大气氮沉降的大幅增加将导致土壤和水体酸化、富营养化等问题, 从而严重威胁陆地生态系统健康和生物多样性[42]. 大量研究表明氮素添加会导致草地生物多样性显著下降[43,44], 其主要解释机制包括光限制[45,46]、土壤酸化[47,48]和稀有种灭绝风险增加等[44,49]. 对青藏高原草地施氮肥实验的整合分析结果表明, 氮素添加总体上显著降低了高寒草甸群落物种多样性和丰富度 (图2), 这与Fu和Shen[50]的整合分析研究结果一致. 然而也有研究表明氮素添加并没有对高寒草甸[51,52]和草原[31] 的物种多样性和丰富度产生显著影响. 造成这一结果的主要原因, 除了大部分实验年限较短之外, 也可能因为其他因素, 如土壤水分条件限制了氮添加的作用.

2 生态系统功能对气候变化的响应

2.1 高原植被生产力总体上呈增加趋势, 气候变暖是其主要驱动因子

植被生产力一直是青藏高原生态学研究的焦点之一. 近30年来, 卫星遥感信息的应用以及植被生产力模型的开发与应用使大尺度植被生产力的时间变化研究得到了迅猛发展. 基于遥感光能利用率模型(CASA)研究表明, 青藏高原植被年总净初级生产力(NPP)约为0.21 Pg C, 占全国植被NPP总量的十分之一左右[53]. 从变化趋势来看, 青藏高原植被生产力与全球大部分地区植被生产力的变化趋势基本一致, 即在过去30多年间呈显著增加趋势[4,54,55](图3(a)). 但植被生产力的动态变化在空间格局上存在很大差异: 植被生产力增加在青藏高原东部以及西南部地区尤为显著; 但在海拔较高、生态更为脆弱的藏北高原、西藏“一江两河”和三江源的部分地区, 植被生产力则呈下降趋势[4].

导致青藏高原植被生产力变化的驱动力大致可以分为以下两方面: 一是自然驱动, 即气候变化、大气中CO_2浓度升高以及氮沉降等; 二是人为驱动, 即放牧、退牧还草等生态保护和建设工程等. 由于植被生长变化同时受多因子影响, 其定量归因是长期困扰学术界的瓶颈问题. 最近, Zhu等人[57]利用10种不同生态系统模型, 结合遥感数据, 并通过引入气候变化领域的“指纹”法, 对与植被生产力密切相关的植被叶面积变化进行了归因分析. 结果表明, 气候变化尤其是气候变暖是20世纪80年代以来青藏高原植被生长增加的主要原因, 这与泛北极地区植被生长促进机制一致. 无论是青藏高原, 还是泛北极地区, 目前生长季平均温度低于其生长的最适合温度, 因此气候变暖会提高这些地区的植被生产力[58]. 野外控制实验也支持了升温整体上有利于青藏高原植被生长的观点. 基于青藏高原地区16个增温实验的综合分析结果显示, 大多数(68%)实验结果中升温对植被生产力的作用表现为正效应, 平均来看其温度敏感性为22.9±9.8 g m^{-2} $°C^{-1}$. 不同增温方式得到的植被生产力的温度敏感性差异大, 基于开顶式增温(OTC)方法得到的植被生产力对升温的敏感性(15.7±9.7 g m^{-2} $°C^{-1}$) 要低于基于红外增温的方法得到的敏感性(73.4 g m^{-2} $°C^{-1}$)(图3(b)). 升温对植被生产力的负效应则主要出现在较为干旱的地区, 这与增温导致生

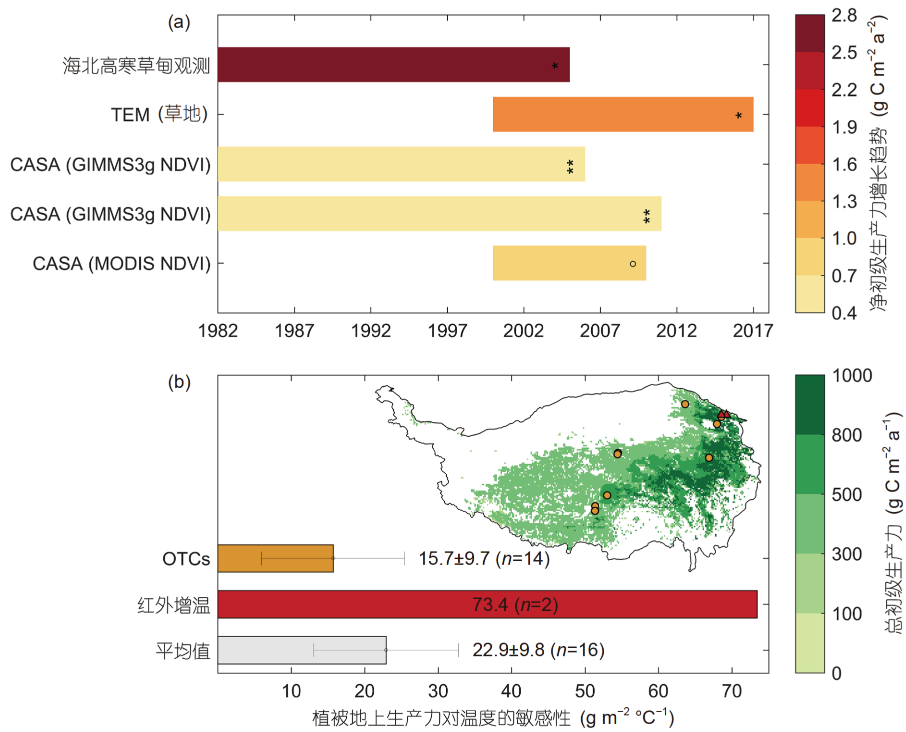

图 3 青藏高原植被净初级生产力(NPP)变化趋势(a)及植被地上生产力对温度变化响应的敏感性(b). (a)中NPP不同变化趋势来自不同数据源的估算, 主要包括站点观测(海北高寒草甸观测站)、过程模型估算(TEM模型)以及基于遥感过程模型的估算(GIMMS3g和MODIS NDVI). 图中**, *, °分别表示生产力变化趋势在P< 0.01, P< 0.05和P< 0.10水平上显著; (b)插入的小图表示青藏高原总初级生产力(GPP)的空间格局(数据来源: Yao等人[56])

Figure 3 The trends in net primary production (NPP) over the Tibetan Plateau (a) and the sensitivity of above-ground grassland productivity to temperature change (b). The trends of NPP are estimated from multiple sources of data including *in situ* observations at Haibei station, estimations from process-based ecosystem model (TEM model) and model simulations driven by remote sensing datasets (GIMMS3g and MODIS NDVI). The markers **, *, and ° illustrate the significance level at P < 0.01, P< 0.05 and P< 0.10. The inset of (b) shows the spatial pattern of the gross primary production (GPP) over Tibetan Plateau (Data sources: Yao et al.[56])

态系统蒸散发增加, 从而加剧土壤水分亏缺有关[59].

2.2 高原生态系统碳储量增加, 尤其是高寒草甸土壤碳储量增加显著

由于高寒环境的限制, 青藏高原植被生物量相对较小, 土壤碳库是青藏高原生态系统总碳库最主要组成部分. 围绕青藏高原碳储量大小的估算, 国内学者开展了大量样带调查研究[60~62], 但不同研究之间结果相差较大(表1). 根据已有研究报道, 青藏高原整个区域1 m深度以内土壤平均有机碳密度介于6~20.6 kg C m^{-2}之间, 存在3倍以上的差异. 值得注意的是, 青藏高原是中低纬度面积最大的多年冻土分布区[69,70], 由于反复的冻扰和沉积作用, 其深层土壤中的碳积累量非常可观[71]. 为了弥补青藏高原深层土壤碳储量信息的不足, 近年来一些学者相继开展了青藏高原深层土壤碳调查研究. 已有的研究结果表明, 青藏高原3 m深度土壤有机碳库大约为13.4~26.5 Pg C, 其中100~300 cm的深层土壤碳库占比接近一半[66~68].

表 1 不同研究估算得到的青藏高原土壤有机碳储量

Table 1 The soil organic carbon stock over Tibetan Plateau estimated by different studies

土壤深度 (m)	土壤有机碳密度 (kg C m^{-2})	文献
0~0.8	20.59	Wang等人[63]
0 ~ 1	6.48	Yang等人[64]
0 ~ 1.5	5.79	Wu等人[65]
0 ~ 1	13.84	Mu等人[66]
1 ~ 3	12.61	Mu等人[66]
0 ~ 1	6.48	Ding等人[67]
1 ~ 3	6.88	Ding等人[67]
0 ~ 2	11.45	Zhao等人[68]

植被和土壤碳库随时间的动态变化构成了生态系统碳源汇功能. 遥感观测、生态系统碳循环模型和大气反演模型模拟结果均表明, 青藏高原生态系统是一个碳汇, 其大小约为23.4~34.3 Tg C a^{-1}, 占我国陆地碳汇的10%~18%, 植被生产力的增加是青藏高原主要碳汇机制[72]. 通量观测和野外土壤碳调查数据也证实了青藏高原近年来的碳汇功能[60,73,74]. 例如, 来自大尺度的重复土壤调查研究表明, 过去10年间青藏高原高寒草地表层(0~30 cm)土壤碳库以28.0 g C m^{-2} a^{-1}的平均速率在积累[60], 但受限于土壤本身极大的空间异质性、野外调查方法的差异性以及对深层土壤碳动态理解的匮乏, 目前青藏高原生态系统特别是土壤碳汇功能大小的估算仍具有较大的不确定性[75].

青藏高原生态系统碳汇的空间分布也呈现明显的区域异质性, 表现为高原东部草甸碳汇显著高于西部高寒草原[60,76]. 青藏高原碳汇功能的空间异质性与水分状况有关. 相比于高寒草原, 高寒草甸生长所面临的干旱胁迫较低, 因此升温导致的高寒草甸植被生产力的增加大于高寒草原, 进而导致更多植被固定的有机碳输入到土壤中[60,77~79]. 青藏高原野外控制实验结果也表明, 升温对水分条件较好的草甸生态系统碳通量净交换表现为促进作用, 而对干旱草原的碳固定则表现为抑制作用, 并且生态系统碳通量净交换的变化量与土壤水分含量呈显著正相关[80].

面对21世纪的气候变暖, 青藏高原土壤碳储量是否还会增加, 是预测未来青藏高原生态系统碳源汇功能的关键. 碳循环过程模型的模拟结果显示, 在未来2°C升温情景下, 虽然青藏高原草地的生产力将增加9%, 但土壤碳储量会下降10%, 从而导致青藏高原生态系统由大气CO_2的汇转变为源[81], 但该模型模拟研究中并没有考虑气候变化对冻土碳的影响. 未来气候变暖可能加速冻土融化[82,83], 进而使原本被封存在冻土中的大量有机碳被微生物分解并释放到大气中. 青海省刚察县一处冻土退化序列的野外观测表明, 冻土融化造成的热融沉陷导致表层15 cm土壤有机碳含量在过去16年间下降了近21%[84]. 与此同时, 冻土退化还可能引发高寒生态系统的退化[85], 进而减少输入土壤的有机碳量. 根据这些研究成果推测, 青藏高原生态系统从当前的碳汇变成碳源的临界升温幅度可能低于2°C, 但由于模型模拟结果的不确定性, 对于未来气候变化下的青藏高原生态系统碳源汇功能转变还需要进一步深入研究.

3 青藏高原植被变化对气候的反馈

3.1 不同于泛北极地区, 青藏高原植被生长对气候变暖产生“负反馈”作用

青藏高原作为全球高寒草地的主要分布区域, 对气候变化敏感; 同时气候变化导致的青藏高原植被覆盖度和生产力的变化也将通过改变地表能量和水分平衡过程对近地表气温和降水产生反馈作用. 植被变化对近地表温度的反馈作用主要表现在以下几个方面: 一是植被变化在一定程度上能改变地面反照率[86], 从而影响地表吸收的净短波辐射总量[87]; 二是植被蒸腾以潜热的形式散发到大气中时会消耗大部分地表吸收的净辐射, 即植被生长增强 (或减弱) 会促进 (抑制) 地表净辐射通量在潜热和显热通量之间的分配关系[88~91]; 三是植被还将通过改变地表粗糙度影响潜热和显热通量大小[92]. 因此, 植被对局地气候尤其是近地表温度反馈的大小和方向一定程度上取决于地表反照率反馈和蒸散发降温作用这两大基本过程[93].

Shen等人[94]结合地面气象观测资料和遥感信息发现, 不同于高纬地区植被对气候变暖形成的“正反馈”作用, 1980年以来青藏高原草地植被生长增加对局地气候变化产生了“负反馈”效应. 植被覆盖度的增加显著降低植被生长季白天的地表温度, 而对夜间温度的影响并不显著, 因此表现为部分抵消了生长季平均温度的升高. 青藏高原植被增强的局地降温效应主要源于蒸散发的降温机制, 即植被覆盖度增加显著促进蒸腾作用, 使得净辐射通量用于地表向大气的感热通量显著减少.

3.2 植被生长的增加提高了土壤水源涵养能力

植被变化也可调节区域水循环过程, 即植被蒸腾、土壤水分和河川径流等[95~98]. 在全球变暖背景下, 大型生态保护和建设工程[99~101], 尤其植被恢复工程对青藏高原水资源变化有何影响, 是长期忽略的重要问题. 最近, Li等人[102]利用径流观测、水热耦合平衡理论和水汽再循环模型, 揭示了长江源近年来草地恢复工程显著促进了植被蒸腾作用, 减少了丰水期流量, 其减少量能占丰水期平均径流量的16.4%. 另一方面, 局地水汽再循环[103]和大气环流变化[104]是形成青藏高原降水的主要过程. 研究显示, 大气环流变化引起的降水增加明显高于草地恢复工程通过局地水汽再循环引起的降水增加, 主要抵消了由生态工程导致的径流减少, 因而长江源直门达水文站观测的径流量仍表现为增加

趋势. 这些结果表明有效分离出气候变化的作用是准确理解植被变化对水循环影响的关键. 另外, 不同于黄土高原植树造林工程降低了土壤含水量[105], 长江源草地恢复工程有效提高了土壤水源涵养能力[99,102]. 这一结论也得到了站点水平长期围栏封育试验的证实, 比如在长期围栏封育实验中未退化草甸的土壤含水量比严重退化的高18.3%~27.8%[106].

3.3 青藏高原植被生长增强导致我国东部夏季降水变化呈现“华南增加-长江黄河中间区域减少”的空间分异格局

由于青藏高原海拔高, 成为一个强大的大气热源, 这一热源在夏季达到最大[107~110]. 过去研究表明, 青藏高原热源变化不仅影响局地环流[111,112], 还能影响到亚洲[113,114]乃至整个北半球的气候变化[115,116]. 植被生长变化通过控制植被蒸腾作用, 改变净辐射通量在地表潜热和显热通量之间的分配关系, 从而影响青藏高原“感热气泵”的强弱[117,118], 进而引起下游气候变化. 在诸多青藏高原大气热源对气候的远程效应研究中, 青藏高原大气热源异常对中国东部夏季降水的影响受到学术界广泛关注[113~115,119,120]. Zuo等人[121]利用遥感信息和再分析产品, 揭示了青藏高原植被生长尤其是南部植被增强促进了植被蒸腾作用, 削弱了地表感热加热作用, 减弱了高原近地面气流的上升运动, 导致了南亚高压减弱并向西移动, 进一步引起西太平洋副热带高压减弱东移, 东亚夏季风环流减弱, 从而导致华南地区降水增多, 长江和黄河之间区域降水减少(图4).

4 结论与展望

自20世纪80年代以来, 科学家们利用从定位观测到遥感和模型模拟等多种研究手段和方法, 深入研究了青藏高原生态系统对气候变化的响应和反馈, 取得了丰硕的成果, 增强了预测青藏高原生态系统结构和功能响应全球变化的能力[54,122~124]. 然而, 面对不断加剧的人类活动和持续变暖的气候, 我们对青藏高原生态系统及其与气候变化的相互作用仍然存在诸多认识上的不足, 很多问题亟待解决. 本文拟扼要讨论以下几个独具青藏高原特色的重要问题, 愿能起到抛砖引玉的作用, 以进一步促进我国青藏高原生态学研究的持续发展.

首先, 生态系统不仅会被动响应外部环境变化和胁迫, 同时对环境变化也有一定的主动适应能力. 目前的青藏高原全球变化生态学研究主要集中在生态系统对气候变化的响应, 尤其是敏感性研究方面, 对高寒生态系统如何适应气候变化了解非常有限. 青藏高原生态系统长期处在低温环境, 其植被生长的最适温度全球最低, 且当前青藏高原生长季温度仍低于其植被生长最适温度[58]. 然而, 未来全球变暖背景下, 青藏高原生长季温度是否仍将保持在其生长最适合温度以下? 回答这一问题不仅取决于升温速率, 也取决于植被生长对气候变化的适应能力. 只有更好地认识和描述高寒生态系统对气候快速变暖的适应机理, 才能更准确地预测未来全球变暖可能引起的青藏高原高寒生态系统结构和功能变化. 迎接这一挑战不仅需要运用各种现有手段, 更需要创造性地发展新的方法来加深我们对青藏高原生态系统系统动力学和稳定性机制的理解.

其次, 青藏高原独特的气候、土壤、生物、生态系统特征为发展和检验基础生态学理论, 提供了独一无二的自然条件. 但无论是经典生态学还是全球变化生态学, 其基本理论均是以热带、温带和高纬度生态系统为基础发展起来的. 有关青藏高原生态系统的基础生态学理论研究仍然偏少, 对理论学说在高寒环境下的检验还存在较大不足, 遑论利用青藏高原的独特自然条件发展新的生态学理论. 利用青藏高原生态系统独特的“高、寒、旱”环境特征[4], 检验和发展生物物种适应环境的生活史对策理论、岛屿生物地理学理论、生态系统代谢理论等, 有可能在高寒生态系统领域提出新的观点甚至发展新的学说.

最后, 生态系统既响应和适应气候变化, 也通过生物地球物理过程反馈气候系统. 青藏高原地表反照率和蒸散发变化是影响青藏高原热泵效应的关键参数[117,118]. 以往的研究多注重相关关系分析, 对青藏高原植被变化和受亚洲季风影响区域之间气候波动之间的关系还没有全面量化. 比如, 虽然植被通过蒸散发过程对近地表气温和局地水循环过程产生重要反馈作用, 但由于区域气候模型存在较大模拟偏差, 有关青藏高原生态系统蒸散发如何影响局地水汽循环, 进而通过远程相关(tele-connection)影响整个中国乃至亚洲气候系统的水汽运输和分配仍缺乏有效验证和定量研究. 加强青藏高原生态系统对气候变化反馈方面的研究, 不仅会极大地丰富当前全球变化生态学的研究内容, 而且将推动青藏高原研究进一步向有机的地球系统科学方向发展. 当前正启动的青藏高原第二次综合科学考察有望进一步提升和扩大我国在相关研究领域的水平和话语权.

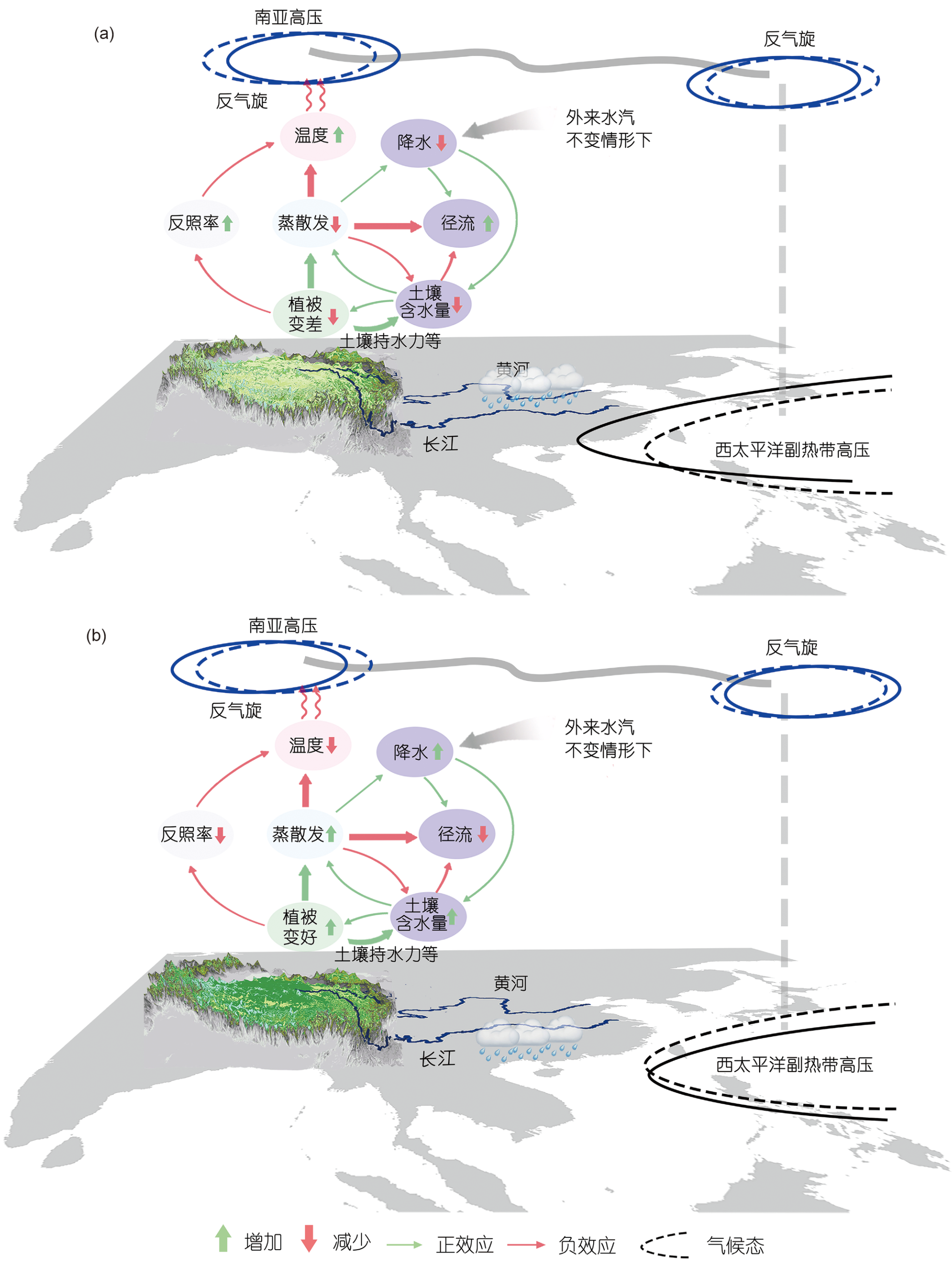

图 4 青藏高原植被变化对气候反馈机制的概念框架. 青藏高原上浅绿色和深绿色地表分别代表植被变差(a)和变好(b)情景. 变量旁边箭头表示变化方向(绿色和红色分别表示增加和减少); 变量间箭头表示反馈方向(绿色和红色分别表征正和负反馈), 箭头粗细表征反馈作用强弱. 椭圆形指示南亚高压(SAHP)、西太平洋副热带高压(WPSH), 或反气旋的空间位置, 其中虚线为气候态的空间位置, 实线则表示植被变化导致的SAHP, WPSH或反气旋的空间位置. 青藏高原地表两条蓝色曲线分别表示黄河和长江

Figure 4 The conceptual framework of the feedback of Tibetan Plateau vegetation changes to climate change. The light and dark green of Tibetan Plateau represent the browning (a) and greening (b) of alpine vegetation, respectively. The arrows beside the variable show increase (green, upward) or decrease (red, downward) of the variable; the arrows between variables show the positive (green) and negative (red) feedback loops. The thickness of the arrow indicates the strength of the feedback loops. The ovals are the spatial position of South Asia High Pressure (SAHP), Western Pacific Subtropical High (WPSH), or anticyclone. The dashed ovals illustrate the spatial position of climatological SAHP, WPSH or anticyclone, and the solid ovals show that Tibetan vegetation induced changes in positions of SAHP, WPSH or anticyclone. The two blue curves over the Tibetan plateau represent the Yellow River and Yangtze River, respectively

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Summary for "青藏高原生态系统对气候变化的响应及其反馈"

Responses and feedback of the Tibetan Plateau's alpine ecosystem to climate change

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The Tibetan Plateau, also known as the "third pole of the Earth", houses a diverse array of alpine-ecosystem types and serves as a critical ecological security shield for China and even for many other regions of Asia. In recent decades, the rapid climate change in the Tibetan Plateau has led to profound changes in the structure and functioning of its ecosystem. Such changes in the ecosystem of the Tibetan Plateau can not only profoundly impact the environment of the high plateau itself but also extend significant influence over that of surrounding areas. With the continuous growth of data obtained via long-term *in situ* monitoring, manipulative experiments, satellite remote sensing, and model simulations, scientists have recently made significant advances in the research on the responses and feedback of the Tibetan Plateau's alpine ecosystem to climate change. Aiming to identify knowledge gaps and to stimulate future research, we provide a comprehensive review of past efforts to understand how climate change has impacted the Tibetan Plateau's alpine ecosystem, which in turn also provides feedback to the climate. In particular, we focus on the impacts of climate change on the structure and functioning of the ecosystem, including vegetation phenology, treeline position, species biodiversity, ecosystem productivity, and carbon sink, along with feedback involving vegetation changes to the regional climate and hydrology through local and teleconnected biophysical loops.

A number of key findings emerge based on cumulative knowledge from old as wells as recent researches. (1) Climate warming during the past several decades has significantly advanced spring vegetation phenology in the Tibetan Plateau. (2) Further, warming has significantly shifted the treeline upward with varying amplitudes that may have been regulated by other factors such as precipitation and interspecific interactions. (3) The plant-community structure of the Tibetan Plateau's alpine steppe ecosystem is sensitive to climate change, with climate warming considerably reducing its biodiversity and species abundance. However, for the alpine-meadow ecosystem, the impact of climate warming on the diversity and species abundance is still inconclusive. (4) Furthermore, warming has significantly increased vegetation productivity, which can consequently lead to an enhanced carbon sink. Such warming-induced carbon accumulation by vegetation is higher in alpine meadows than in alpine steppes. However, the effect of climate change on soil carbon stock remains highly uncertain mainly because of the high spatial heterogeneity of soil properties and lack of information regarding deep-layer soil processes. (5) Warming-induced vegetation greening of the Tibetan Plateau provides an overall cooling effect countering the local warming and modulates the local and far-reaching precipitation patterns through teleconnected feedback to the East Asian monsoon. In particular, the modeling results suggest that this greening trend of the Tibetan Plateau increases precipitation in South China but reduces precipitation in the region between the Yellow and Yangtze Rivers.

Even with the recent significant progress in the study on the ecosystem-climate interaction in the Tibetan Plateau, many knowledge gaps remain. These gaps provide opportunities for future research, which needs to expand and optimize long-term ecological observation networks to improve the understanding of key ecological processes and deepen the comprehension of the response and acclimation mechanisms of the alpine ecosystem under the influence of climate warming. The knowledge enhancement thus obtained will provide important guidelines for improving ecosystem management and safeguarding the ecological security in the Tibetan Plateau.

Tibetan Plateau, climate change, vegetation changes, carbon sink, feedback

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