植物生态学报　2018, **42** (1): 1–5
Chinese Journal of Plant Ecology
DOI: 10.17521/cjpe.2018.0048
http://www.plant-ecology.com

全球变化背景下的高寒生态过程

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杨元合 (2018). 全球变化背景下的高寒生态过程. 植物生态学报, 42, 1–5. DOI: 10.17521/cjpe.2018.0048

Ecological processes in alpine ecosystems under changing environment

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Yang YH (2018). Ecological processes in alpine ecosystems under changing environment. *Chinese Journal of Plant Ecology*, 42, 1–5. DOI: 10.17521/cjpe.2018.0048

青藏高原是世界上海拔最高和面积最大的高原, 被誉为"地球第三极"(姚檀栋等, 2017), 也是我国重要的生态安全屏障和战略资源储备基地(孙鸿烈等, 2012)。高原气候整体上呈现"寒" "旱"特征, 且存在自东南向西北逐渐降低的降水梯度。沿着这一降水梯度, 分布着森林、灌丛、高寒草甸、高寒草原和高寒荒漠等植被类型(张宪洲等, 2015)。同时, 该地区孕育了约占我国国土面积1/6的冻土(周幼吴等, 2000)。过去几十年, 青藏高原经历了显著的气候变化。该地区的年平均气温在以每年0.05 ℃的速率增加, 年降水量也在以每10年增加10.2 mm的速度波动上升(图1)。除了气候变化, 青藏高原地区的大气氮沉降速率在持续增加(Liu *et al*., 2013), 冻土活动层厚度也在以每年1.8 cm的速率增加(Wu & Zhang, 2010)。这些环境变化已经并将持续改变高寒生态系统的结构和功能, 进而对当地居民的生存环境乃至整个国家的经济发展产生重要影响(秦大河, 2014)。因此, 开展全球变化背景下的高寒生态过程研究不仅对认识高寒生态系统对气候变化的响应与适应等方面具有重要的科学意义, 而且在国家生态文明建设等方面具有重要的实践价值。

近20年来, 国内学者基于定位观测、样带调查、控制实验、室内培养、模型模拟等多种手段(图2), 围绕全球变化背景下的高寒生态系统结构与功能等主题开展了大量工作, 取得了重要进展, 相关研究成果引起国内外学术界的广泛关注。通过梳理近20年来的文献资料, 不难发现以往的研究呈现以下两个特点。第一, 以往的研究多以样带调查等大尺度研

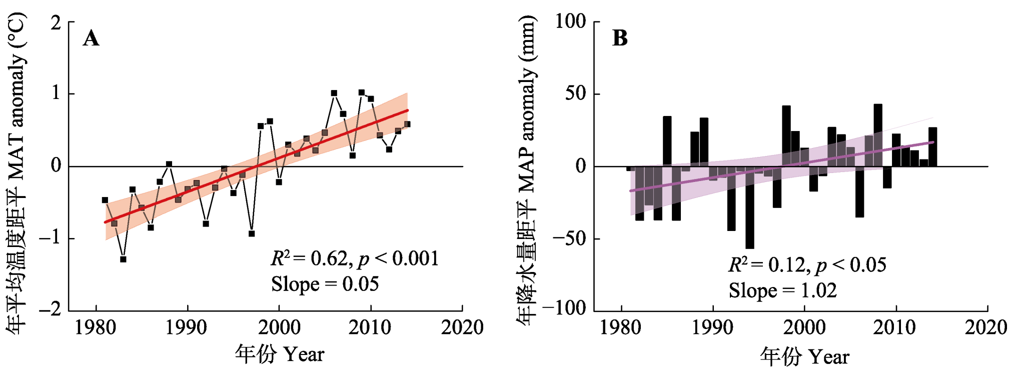

图1　青藏高原年平均气温(**A**)和年降水量(**B**)的变化。
Fig. 1　Changes in mean annual temperature (MAT, **A**) and precipitation (MAP, **B**) on the Qinghai-Xizang Plateau during the past three decades.

收稿日期Received: 2018-01-02　接受日期Accepted: 2018-01-10
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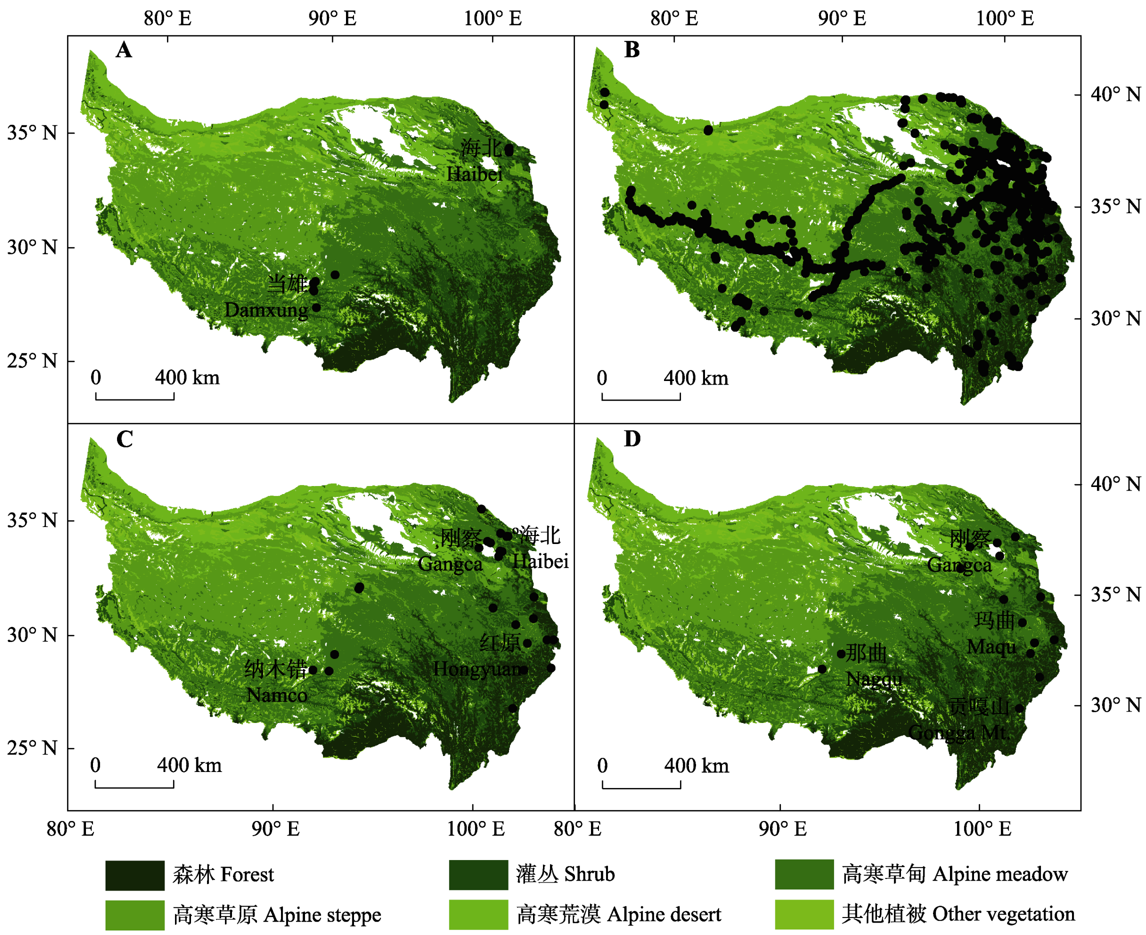

图2 青藏高原地区开展的定位观测(**A**)、样带调查(**B**)、控制实验(**C**)以及本专辑中的样点分布(**D**)。底图为青藏高原植被类型的空间分布，源自1:1 000 000的中国植被图(中国科学院中国植被图编辑委员会, 2001)。需要说明的是，图中样点的经纬度来自附件I中的文献。

Fig. 2 Location of long-term observations (**A**), transect studies (**B**), manipulative experiments (**C**) on the Qinghai-Xizang Plateau, and research sites in this special issue (**D**), shown on the background of China's vegetation atlas at a scale of 1:1 000 000 (Editorial Committee for Vegetation Map of China, 2001). Notably, geographic information for each site in this figure was derived from literatures synthesized in Appendix I.

究为主，而基于定位观测和室内培养的研究较少。通过样带调查等大尺度研究，基本阐明了青藏高原高寒植被属性(He *et al*., 2009)、土壤特征(Yang *et al*., 2008)、微生物属性(Chen *et al*., 2017)以及主要生态系统功能(Jin *et al*., 2015)的空间分布规律及其影响因素。然而，与样带调查相比，青藏高原的定位观测和室内培养研究较为薄弱。实际上，这两种方法正是开展生态过程研究的重要手段。这一研究现状说明青藏高原生态学研究有必要从格局研究向过程研究转变。第二，青藏高原的控制实验研究近年来不断增加，主要集中在增温和施氮等少数全球变化因子上。同时，受技术手段(核磁共振分析、^{14}C同位素、微生物功能基因等)的限制，过去的控制实验研究重点还是在阐述不同生态过程对各种全球变化因子的响应上，尚未从机制上剖析全球变化要素对高寒生态系统的影响途径。这一研究现状意味着高寒生态学研究在从格局研究向过程研究转变的同时，亟需应用新技术加强机制研究。

为了进一步促进学术界对高寒生态过程的认识，我们组织了“高寒生态过程”专辑。本专辑收录了13篇文章，内容涉及增温、养分添加、草地退化等全球变化要素，包括森林、灌丛和草地等生态系统，涵盖高寒植物、土壤和微生物过程。在植物属性方面，有3篇文章揭示了功能群或者不同物种对环境变化的响应存在差异的现象，分别发现禾本科和杂类草植物的化学计量特征对养分添加的响应模式不同(孙小妹等, 2018)，不同功能群的多样性和生产力对草地退化的响应存在差异(陈宁等, 2018)，繁殖物候对气候变暖的响应在不同繁殖阶段、不同物种间存在差异(张莉等, 2018)。还有两篇文章重点关

注树木生长和凋落枝分解。其中, 宋文琦等(2018)针对“干旱、半干旱区高山林线处, 究竟是温度还是水分是限制树木生长的主控因子?”这一问题, 对比了青藏高原东北部不同降水梯度下高山林线祁连圆柏(*Sabina przewalskii*)径向生长与气候的关系, 发现水分不是青藏高原东北部干旱区高山林线树木径向生长的限制因素, 但会影响树木生长与温度的关系。基于“以往研究多集中在凋落叶分解”的现状, 郭彩虹等(2018)重点关注了川西亚高山森林林窗对凋落枝分解的影响, 发现林窗环境变化显著影响亚高山森林凋落枝分解, 但其影响取决于林窗面积和分解时间。其余的两项研究则注重新方法的引用或者长期的定位研究: 字洪标等(2018)基于微根管法研究了氮添加对川西北高寒草甸群落根系动态的影响, 发现氮添加缩短了高寒草甸植物根系寿命, 加快了根系周转并促使根系向表层集中; 柴曦等(2018)基于连续5年的通量观测发现, 灌丛草甸起着碳汇作用而草原化草甸基本呈碳中性状态, 这种差异主要由两类生态系统中碳利用效率、归一化植被指数(*NDVI*)以及湿润程度和水热匹配性的差异所致。

在土壤和微生物过程方面, 有3篇文章分别关注了增温、水分条件变化以及氮添加背景下土壤养分状况的变化: 马志良等(2018)揭示了模拟气候变暖对窄叶鲜卑花(*Sibiraea angustata*)高寒灌丛土壤无机氮的影响, 发现增温导致硝态氮含量在生长季中期增加、末期降低, 使生长季中期铵态氮含量升高; 苟小林等(2018)比较了不同水分条件下两种沙地植物根际土壤养分特征, 发现半湿润条件下沙蒿(*Artemisia desertorun*)根际土壤养分含量高于半干旱条件, 而中国沙棘(*Hippophae rhamnoides* subsp. *sinensis*)却呈现相反趋势; 秦书琪等(2018)则针对“碱性土中交换性盐基离子对氮添加的响应”研究匮乏的现状, 考察了紫花针茅(*Stipa purpurea*)草原土壤交换性盐基离子对氮添加的响应, 发现氮添加能促进植被生长进而加速盐基离子吸收, 也能提高土壤无机氮含量、促进NH_4^+交换与NO_3^-淋溶进而导致盐基离子损失。这一结果与以往在酸性土得出的“缓冲土壤酸化导致盐基离子损失”的结论有所不同。其余的3篇文章重点关注了微生物群落及其介导的生物地球化学循环过程。其中, 来自高寒草原的两项研究显示, 增温导致的土壤干旱抑制了紫花针茅草原土壤微生物的群落组成(王军等, 2018)以及土壤N_2O通量(王冠钦等, 2018)对气候变暖的响应。此外, 石国玺等(2018)考察了高寒草甸退化过程中的植物-土壤-微生物反馈作用, 发现土壤微生物功能多样性改变诱发的氮限制是导致黄帚橐吾(*Ligularia virgaurea*)种群数量增加的重要机制。这些文章大多来自长期从事青藏高原研究的团队, 在一定程度上能够反映我国在高寒生态过程方面的最新研究进展。

尽管本专辑的出版有望促进学术界对全球变化背景下高寒生态过程的认识, 但仍有很多问题尚未解决。未来的研究值得关注以下几个方面: (1)通过开展长期定位观测和室内培养研究, 揭示植被和土壤过程的长期变化及其机制。从图2可以看出, 目前青藏高原长期定位观测的研究主要集中在海北站等少数研究点, 在区域尺度上的长期联网观测处于空白状态, 进而使得区域尺度上一些基本但又重要的生态参数(如物种组成, 物候, 地上、地下生产力等)的长期变化趋势仍不清楚。同时, 室内培养是解析地下生态过程(如土壤碳维持机制)的重要手段, 但目前这方面的研究在青藏高原十分薄弱。作为我国陆地碳库的重要组成部分, 青藏高原土壤中储存了大量有机碳(Ding *et al*., 2016)。这部分碳在气候变暖背景下的稳定性如何, 受哪些机制调控等问题的解决离不开室内培养实验。(2)依托野外控制实验平台, 结合同位素、微生物功能基因等技术, 揭示高寒生态过程对各种全球变化要素的响应及其生态学机制。如上所述, 青藏高原是全球变化的敏感区, 出现了“气候变暖、降水波动中上升、氮沉降增加、冻土融化”等全球变化现象。然而, 目前的全球变化控制实验主要集中在增温和养分添加上, 对其他要素如降水格局变化、冻土融化等不够重视, 对多种全球变化要素间的交互作用的认识也十分有限。同时, 未来的控制实验研究应当注重同位素、微生物功能基因等技术的应用, 着力于解析青藏高原独特的高寒生态过程及其对全球变化的响应机制。令人鼓舞的是, 随着国家对青藏高原研究的重视, 上述问题有望在不久的将来得以解决。

致谢 感谢主编方精云老师在此次专辑组织过程中给予的大力支持; 感谢编辑部谢巍、李敏、王葳老师为专辑中每篇文章所做的辛勤付出; 感谢高寒生

DOI: 10.17521/cjpe.2018.0048

态格局与过程研究组的寇丹、刘富庭、张典业、彭云峰、陈蕾伊、陈永亮等的长期讨论，这些讨论对本文的写作起到了重要作用。

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附件I　青藏高原地区开展的定位观测、样带调查和控制实验研究

Appendix I　Literatures about long-term observations, transect studies, and manipulative experiments on the Qinghai-Xizang Plateau

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Appendix I Literatures about long-term observations, transect studies, and manipulative experiments on the Qinghai-Xizang Plateau

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