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植被物候的遥感提取及其影响因素研究进展*

崔林丽[1],史　军[1,2],杜华强[3]
(1.上海市生态气象和卫星遥感中心,上海　200030;2.上海城市气候变化应对重点开放实验室,上海　200030;3.浙江农林大学环境与资源学院,浙江　临安　311300)

摘　要:植被物候是反映植被动态的重要指标和气候变化对生态系统影响的重要感应器,它影响着地表反照率、粗糙度、蒸发散、CO_2通量以及人类生产活动。首先论述了基于遥感的植被物候提取方法和植被物候变化的影响因素两方面的研究进展,然后指出气候变化背景下植物物候研究存在的突出问题,包括遥感难以直接获取常绿植被叶片和冠层结构物候、尺度效应阻碍遥感产品与地面观测的匹配、气候要素(降水和日间、夜间温度等)和城市化对物候的影响及协同作用机制不清楚、缺少针对植被类型的物候产品和模型以及未将物候间滞后效应纳入考虑等。开展常绿植被物候指标的遥感提取方法及算法研制,探索气候变化、极端天气气候对物候的影响机制及未来预估,分析城市化、植被类型对物候的影响以及与气候变化的协同效应,建立综合考虑降水、滞后效应和尺度效应的群落尺度物候模型,是未来工作关注的重点。

关　键　词:植被物候;遥感提取;影响因素;气候变化;城市化
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1　引　言

植被物候是指植物生活史事件受环境因子(主要是气象条件)的季节性变化而出现的变化,如发芽、抽枝、展叶、开花、结果、落叶和休眠等[1],它是反映植被动态的重要指标[2]和气候变化影响的高度敏感指标[3]。植被物候影响着陆地与大气之间的碳、水和能量交换[1,4~6],并与农业生产、旅游、花粉过敏等人类活动息息相关[4,5,7]。许多研究表明,近几十年来,全球变暖导致了北半球中高纬度地区植被生长季开始提早、结束推迟和生长季延长[8~11]。因此,植被物候及其相关环境因子的时空格局在全球变化研究中受到越来越多的关注[4,9~11]。准确、详细的物候信息对于区域到全球陆地生物地球化学循环研究和气候变化、生态环境评估都具有重要价值[4,12]。

2　植被物候期遥感提取技术

卫星遥感数据具有时间序列连续、观测范围大、特征提取容易等特点[13],可用于监测从区域到全球尺度大规模植被物候动态[14]。植被物候提取中常用的遥感植被指数(Vegetation Indices, VIs)以归一化植被指数(Normalized Difference Vegetation Index, NDVI)和增强型植被指数(Enhanced Vegetation Index, EVI)应用最为广泛[6,8,15]。由于云和气溶胶等大气效应、传感器性能和观测条件差异

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作者简介:崔林丽(1975-),女,山西长治人,研究员,主要从事植被遥感和大气遥感研究. **E-mail:**cllcontact@163.com

等干扰,卫星遥感获取的VIs时间序列含有明显的噪声[16],需要先采用一些平滑方法,如Savitzky-Golay滤波法等进行VIs数据预处理和重构[16~18]。经过预处理的VIs数据再通过一定的算法,如阈值法[1,19]、变化点检测法[17]和混合算法[15,20,21]等可以提取植被物候指标。但不同方法提取的物候日期间相关性较差,并存在很大的不确定性[1,19,22,23]。开展不同植被VIs的滤波方法和物候指标提取算法的对比目前已有较多研究和文献综述[1,16,19,23~25],但对于常绿植被物候期的遥感提取以及尺度效应对物候提取的影响还较缺乏。因此,下面着重论述这两方面的研究进展。

2.1 常绿植被物候期的遥感提取

由于温带地区植物物候变化显著,且观测资料比较丰富,所以,国内外有关遥感植被物候的研究集中于温带落叶植被[24~28],而对亚热带和热带地区的研究相当有限[29]。在这些地区,广泛分布着林冠绿度季节变化较小[18,30]的常绿针叶、阔叶林及混交林。基于NDVI和EVI的物候提取方法应用潜力有限[12,26,31],常绿林物候遥感提取目前还存在很大的挑战性。考虑到不同卫星VIs对绿度动态以及地面亮度和湿度变化有不同的响应[32],反映了植被生长某一特定方面的敏感性[33]。因此,一些研究结合来自多个VIs的互补信息,并引入气温或地表温度等辅助数据,采用混合算法开展常绿植被物候的提取[20,33,34]。该方法在北美中部取得较为理想的物候反演结果[21],也改善了对我国常绿植被春季展叶期[34]和加拿大常绿针叶林秋季生长期结束[35]的估计。

传统的VIs主要反映植被绿度的季节变化,不能反映真实的植被光合(作用)物候[36]。近年来,一些研究通过挖掘现有卫星遥感对叶片色素含量的探测信息,如欧洲极轨平台搭载的中分辨率成像光谱仪的陆地叶绿素指数(MERIS Terrestrial Chlorophyll Index, MTCI)、叶绿素/类胡萝卜素指数(Chlorophyll/Carotenoid Index, CCI)和植被释放的日光诱导叶绿素荧光(Solar-Induced Chlorophyll Fluorescence, SIF)等[37,38],从冠层功能(生理)的角度来构建适合常绿植被的物候指标提取算法并估计常绿植被光合物候[6,32]。叶绿素浓度变化对植被物候变化具有较好的指示作用,MTCI指数被用于推断常绿林物候的变化[24,37]。常绿针叶林叶片色素含量的季节性变化,即叶绿素/类胡萝卜素值,与常绿植被光合活性具有紧密的对应关系,CCI也可用来监测常绿林光合物候[39]。

作为植被光合作用的指示物,SIF近年来也被用于植被物候研究[40~42],它不局限于对叶片表观颜色变化的观察,而是监测植被内在的光合作用过程[43]。在我国长白山温带红松阔叶林以及北半球中高纬度积雪覆盖的常绿针叶林,SIF数据对物候期的表征都优于NDVI与EVI数据,可以较好地反映出植被季节变化特征[6,40]。在我国亚热带常绿针叶林,卫星SIF估计的春季和秋季物候期滞后时间也短于传统VIs,能更好地追踪常绿林生长阶段和光合作用的季节性[18]。在巴西热带生物群落,卫星SIF数据还可以区分不同植被类别的季节性物候差异[41]。对不同的常绿生物群落和植物功能类型,可以尝试从冠层绿度和功能角度出发,开展多个传感器和/或多个数据源的植被结构物候信息和光合物候信息的提取和对比,但在某些特定条件下,比如影像分辨率和植被本身属性等的制约下,常绿植被物候仍然是无法利用遥感提取的。

2.2 遥感物候期提取的尺度效应

卫星遥感物候提取结果与地面物候站或通量站观测结果的对比都会受到观测空间尺度的影响。遥感物候产品如何反映物种特有的物候指标,尺度效应仍是一个难题[44]。尺度效应是指从低空间分辨率卫星图像中提取的物候指标并不一定等于同一地理足迹内较高分辨率物候指标的平均值[12,22]。不均匀的植被覆盖(植被异质性)也是决定卫星获得的物候日期与地面观测之间差异的主要因素[12,45,46]。由于卫星数据的空间分辨率较低,一个像素可能包含许多植物物种,卫星反演的物候期实际上代表了一个像素内所有植物的平均绿度增长,与基于对单个植物的物候事件(如爆芽或展叶)观察得出的度量标准有所不同[47]。在大多数情况下,由于空间覆盖范围和物候事件定义的差异,卫星获取的植被物候数据不能直接与野外物候观测结果进行比较,除非有少数物种在一个像素点上表现出同步的物候(如农田)[48]。

空间观测和地面观测之间的空间尺度差异阻碍了在卫星影像像素水平上植被群落级物候模式与地面单个植株级数据之间的联系[25]。已有多项研究探讨了尺度效应[22,49,50],并提出了若干空间升尺度(up-scaling)技术,帮助解决基于地面和卫星观测之间的空间尺度差异[22,51,52],如Studer等[51]提出多物种物候指数(multispecies phenology index)用来评估瑞士阿尔卑斯山(Swiss Alpine)春季物候的年

际变化和趋势。Liang等[52]使用一种景观升尺度方法，从样地水平的观测中提取景观物候指数用来验证中分辨率成像光谱仪（MODIS）地表物候（Land Surface Phenology，LSP）的有效性。Zhang等[22]指出，低空间分辨率像素内生长季开始日期（Start of Growing Season，SOS）提取结果更多的是由高分辨率中SOS较早的像素决定的，而不是较晚的SOS像素，并提出“百分位聚集”方法，即当高分辨率图像中30%像素的植被开始展叶，在低分辨率图像中就可以监测到SOS。一般来说，对于物种特有的物候监测或空间异质性景观区域，应选择空间分辨率较高的卫星图像[25]，并根据不同的研究目的来选择相应的VIs滤波方法和物候指标提取算法。

3　植被物候期变化的影响因素

3.1　气候要素及其变化对物候期的影响

气候变量，包括气温、降水和日照时数等被用于解释植物物候的年际变化。研究表明，气候条件对植被物候的影响具有明显的滞后效应，季前（物候事件发生前）温度和降水在调节植被物候方面起着关键作用[10,47,53,54]。温度长期以来被认为是决定中高纬度地区植被物候的主要控制因素。我国温带植被春季物候开始日期与季前2~3个月的平均气温有非常显著的负相关[8,55]，早春（3~5月上旬）气温升高1 ℃，植被物候期提前7.5天[8]；季前60天平均温度上升1 ℃，春季SOS提前1.2天[55]。Wu等[56]也表明我国温带地区SOS与季前1~3个月平均温度相关性较大，春季（2~4月）温度是驱动春季物候变化的主要因素。对内蒙古鄂温克旗典型草原物候研究表明[57]，3~4月气温是影响牧草返青最主要的气候因子，气温升高返青期提前。温暖的春季可以提前解冻表土，带来早期融雪，促进早春植被萌发[53]。

冬季降水对水分限制生物群落（如温带草原和温带荒漠）春季物候具有重要的调节作用[8,56]。在北半球寒温带和温带草原及森林，植被展叶期的热量需求与季前降水间存在广泛的正空间相关性[58,59]，因而在典型荒漠草原，干旱可能会消除气候变暖对植被返青期提早的贡献[60]。对我国东北样带干旱半干旱区研究表明，温带典型草原SOS日期与季前2~4个月的降水关系最为显著[61]，内蒙古荒漠草原2000—2016年返青期主要受季前降水控制[53]。Piao等[8]也发现我国温带植被SOS与季前5个月降水呈显著负相关。由于卫星反演的物候期总体上反映了植被在水资源限制下的状态，因此，在干旱和半干旱环境中，一些基于温度而忽视水分有效性的物候估计与基于卫星的结果相比，包含较少的物候空间变化细节，而且显示出不同的、有时甚至是相反的空间格局[62]。

以往研究主要考察日平均温度和降水量对物候的影响，一些基于卫星、现场观测或实验的研究揭示了植被SOS受日间和夜间温度的不对称影响[2,9,63~65]，表明日间温度（T_{max}）对树木展叶期物候的影响大于夜间温度（T_{min}）和日平均温度（T_{mean}）的影响[9]。控制实验也指出，日间温度对3种温带树种展叶期物候的影响是夜间温度的3倍[63]。然而，植被物候事件对日间和夜间升温的不对称响应因地区而异，与当地的水热组合相关[2]。在我国黄河流域[66]和青藏高原[65]，T_{min}对植被返青期的影响大于T_{max}，增加T_{min}能够在高达36%以上的青藏高原面积大大提早植被返青期[47]。而且，不同季节T_{max}和T_{min}增暖对植被物候也存在不对称影响，如我国温带草原SOS主要受冬季T_{max}增暖和春季T_{min}增暖影响[2]。目前，对不同地区植被物候是如何响应季节（冬季与春季）和昼夜（白天与夜间）时间尺度的升温，在很大程度上还是未知的[47]。

3.2　城市化和人类活动对物候期的影响

城市化和气候变化是21世纪两个主要的全球环境问题[67,68]。由于城市化与增温[69]、CO_2浓度上升有关，城市气候条件被认为与未来全球变暖下的气候相似，城市成为模拟未来气候变化对物候影响的良好试验场[66]。在城市环境中，植被物候由于对公众健康（如过敏）和能源需求（如降温效应）等的影响而受到广泛关注[7]。城市化对物候的影响从城市向乡村地区衰减[3]，城乡物候差异与距离城市中心的远近呈现出对数[66]或指数[3,70]关系。对北美东部和我国研究表明，城市化对植被物候影响的平均范围距离城市周边不超过20 km[3]。一些研究也通过人口密度[71]、不透水面覆盖率（Impervious Surfaces Percentage，ISP）[72]和城市热岛[70]等城市化相关因子来解释城市植被物候的空间变化，表明城乡物候差异与城乡地表温度（Land Surface Temperature，LST）差异或城市热岛强度（Urban Heat Island，UHI）显著相关[66,70]。

目前对城市化引起的ISP增加、人口变化等如何与气候变化共同影响城市物候变化以及各自的贡献尚不清楚[73,74]。现有研究表明，气候变量（包括温度、降水和日照等）在调节城市植被物候的时间变化中起主导作用，当控制了气候因素的影响，SOS

提早和生长季结束日期(End of Growing Season，EOS)延迟与城市化幅度(ISP增加)显著相关，城市化可以补偿气候变化对植被物候的负面影响(延迟SOS或提早EOS)，并放大气候变化对物候的正面影响(提早SOS或延迟EOS)[74]。Li等[71]的研究也表明，城市化对植物物候的影响随区域温度的变化而变化，在寒冷地区高人口密度会提早植物物候，但在温暖地区这种影响消失甚至逆转。进一步研究发现，植被物候对城市环境的响应取决于城市中心的纬度和城市白天、夜间温度[75]，城市人口密度和物候之间的关系是通过夜间温度的差异来实现的，夜间温度随着人口密度的变化而变化[73]。因此，除了全球变暖之外，未来的人口增长也应该被考虑到人类引起的环境变化的生态系统评估中[73]。

此外，大多数研究均侧重于城市温度或LST对植被物候变化的影响，而忽视了其他同时发生显著变化的环境因素，如大气CO_2浓度等。Wang等[36]研究表明，植被光合物候开始期和峰值期提早的主要影响因素是温度和大气CO_2，而植被光合物候结束期延迟的主要影响因素是大气CO_2，全球变暖和CO_2浓度升高对植被不同物候期的影响不同。深入研究气候变化、CO_2浓度升高以及城市化引起的土地覆盖变化、人口密度变化等对植被不同物候期的综合影响及各自贡献，对于制定城市化对植被物候影响的评价指标、预测城市植被物候期动态都至关重要。

4 展 望

植被物候是控制陆地生态系统生物地球化学循环的重要因素，也是各种生态系统过程模型的重要输入和驱动参数。本文从植被物候期的遥感提取技术和植被物候期变化的影响因素两个方面，阐述了当前国内外最新研究进展，并针对目前研究中面临的挑战，给出了今后植被物候研究的重点方向，主要包括以下几个方面：

(1)*常绿植被物候指标的遥感提取及算法研制*。由于常绿林冠层绿度的季节性变化不显著[26]，常规VIs，如NDVI和EVI对常绿林林冠细微的绿度变化信息几乎不敏感，无法从叶片和冠层结构角度探测植被物候。如何基于遥感技术监测常绿植被物候变化是卫星遥感应用领域的一大难点。近年来，一些学者尝试利用多传感器的优点和一些辅助信息，建立适合于特定植被类型或局部区域的方法[12]，如混合算法模型[20,21,35]，或根据叶片色素含量变化[39]或植被释放的日光诱导叶绿素荧光[6,18,40,42]。集成多源卫星传感器和气候等多种辅助数据，开展常绿植被结构物候和光合物候的提取和多种物候提取算法的对比，对热带和亚热带广大区域植被生长动态监测和碳源/汇评估具有重要的意义。对于中、高纬度地区常绿针叶林，需要综合评估目前已有的或重新构建考虑融雪效应的物候指数，从而提高积雪影响下常绿植被春季物候遥感反演的精度[6]。

(2)*气候条件对物候演变的影响机制及未来预估*。物候是一个综合反映环境变化的生物指示因子，季前气温、降水、日照等气候要素以及这些要素的不同方面(如T_{max}和T_{min})均会对植被物候产生不同影响，并与植被类型、降水梯度等密切相关[54,66]。在全球变暖背景下，极端气温和降水事件很可能增加[76]，极端天气气候事件对环境和物候的影响较平均气候变化更为直接和严重[76,77]。已有研究多集中于物候与平均气候要素的关系，对极端天气气候事件和大尺度气候振荡对物候的影响考虑较少[77~79]。从天气、气候角度深入分析植被物候对增暖的敏感性在纬度、海拔高度和气候区之间差异和对季前气温、降水变化的滞后响应，以及对昼夜升温不对称、极端天气气候事件和气候振荡的响应规律和响应机制，并预估未来全球变暖背景下植被物候可能变化，可以为理解区域植被—大气相互作用过程、支撑气候变化适应策略提供科学依据。

(3)*城市化和土地利用/土地覆盖变化对物候的影响*。在全球变化背景下，了解植被物候和生产力对自然环境变化和人类活动的综合响应是非常重要的[80,81]。多数研究认为，城市化对物候的影响模式与城市化气候效应(主要是温度)密切相关[71,72,74,75]，城市热岛导致城区及周边植被春季绿叶始期明显提早、绿叶终期延迟和生长期变长[3,70]，但在认识城市化对植被物候的影响方面，仍存在较大的知识空白。在我国快速城市化和主要大城市高速扩张的背景下，弄清城市化发展，如城市空间增长与人口密度变化等对城市及周边植被物候期的影响机制，分离城市化过程与气候变化、CO_2浓度升高对植被不同物候期的综合影响及各自贡献，可以加深对城市系统中人与自然交互作用(或反馈)规律的理解，并为城市规划布局和对未来变暖背景下植被物候合理预估提供借鉴。

(4)*综合考虑降水、滞后效应和尺度效应的群落物候模型*。对于冬季干燥寒冷的干旱/半干旱地区，如青藏高原和内蒙古高原，必须考虑春季物候与季前降水量之间错综复杂的联系[5,55]，在基于温

度的物候模型中纳入降水驱动效应，以提高模型在区域尺度和复杂气候条件下的适用性。同时，探索春季和秋季物候期之间滞后效应以及在多样化气候区、植被类型之间的差异，改进的物候模型要将前一个物候期对接下来物候期的影响纳入考虑[11,48,82]。为了进一步提高物候模拟的精度，有必要利用具有较高时空分辨率的卫星遥感数影像提取物候指标和建立针对不同土地覆盖类型（植被类型）的物候模型，并利用物候相机（如 PhenoCam 网络）[83]等手段加密地面同步对比观测，探索多种空间升尺度技术，实现在像素水平上物种尺度物候模拟和群落尺度物候模型的发展。

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Advances in Remote Sensing Extraction of Vegetation Phenology and Its Driving Factors*

CUI Linli[1]，SHI Jun[1,2]，DU Huaqiang[3]

（1.*Shanghai Ecological Forecasting and Remote Sensing Center*，*Shanghai* 200030，*China*；2.*Key Laboratory of Cities Mitigation and Adaptation to Climate Change in Shanghai*（*CMACC*），*Shanghai* 200030，*China*；3.*College of Environmental and Resource Sciences*，*Zhejiang A&F University*，*Lin'an Zhejiang* 311300，*China*）

Abstract：Phenology is considered as an important indicator for understanding the vegetation dynamics and the impact of climate change on ecosystem. It has significant influences on surface albedo，roughness，evapotranspiration，CO_2 flux，and human activities. This study presents the progress on the phenology extraction methods based on satellite，and the driving factors of vegetation phenology dynamics. The key weaknesses in our current understanding of vegetation phenology in the context of climate change are also raised，including the difficulty in estimating the phenology of evergreen vegetation based on remote sensing directly from the perspective of leaf and canopy structure，the low comparability between satellite products and ground-based measurements due to the scale effect，the unclear synergistic mechanisms between climate factors（rainfall and day/night temperature）and urbanization，the lack of phenological products and models for specific vegetation types，as well as the inconsideration of lag effect of phenology. So，it is important to focus on the following four aspects in future research：① the development of satellite phenology extraction methods for evergreen vegetation；② the research on the mechanisms and forecast of climate change and extreme weather on phenology；③ the study of the impact of urbanization and vegetation types on phenology，together with their synergistic effects；④ the establishment of phenological model at community scale which considers precipitation，lag effect and scale effect.

Key words：Vegetation phenology；Remote sensing extraction；Influencing factors；Climate change；Urbanization.

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First author: CUI Linli（1975-），female，Changzhi City，Shanxi Province，Professor. Research areas include remote sensing of vegetation and the atmosphere. **E-mail**：cllcontact@163.com