

# 植被物候遥感监测关键问题

谢志英<sup>1</sup>, 朱文泉<sup>2</sup>, 付永硕<sup>1</sup>

1. 北京师范大学 水科学研究院, 北京 100875;

2. 北京师范大学 地理科学学部, 遥感科学国家重点实验室, 北京 100875

**摘要:** 植被物候是陆地生态系统响应全球气候变化最灵敏的生物学指示指标, 也是影响陆地生态系统碳循环的重要因子。因此, 植被物候的准确监测对模拟陆地生态系统碳循环以及理解陆地生态系统响应气候变化至关重要。物候学发展至今, 已有包括人工观测、物候相机观测和通量监测在内的地面观测以及遥感监测等多种植被物候监测手段, 并形成卫星遥感监测为主要手段、地面观测为验证的区域和全球尺度植被物候监测体系。植被物候遥感监测通用技术流程中的每个处理环节都会造成物候监测的不确定性。本文重点梳理了遥感时序数据、物候指标提取和遥感物候真实性检验3个物候监测关键环节, 深入探讨了地表背景对遥感指数的干扰、不同物候指标提取方法的差异以及物候验证中遥感物候指标与参考物候指标之间的匹配问题。最后, 探讨了解决这些关键问题的两个重要发展方向: (1) 发展抗地表背景干扰的植被物候遥感监测方法; (2) 构建结合地面多传感器协同观测和“天—空—地”多尺度一体化观测的联合观测网络。

**关键词:** 遥感, 植被物候, 遥感时序数据, 植被指数, 验证, 尺度效应

**中图分类号:** TP701/P2

**引用格式:** 谢志英, 朱文泉, 付永硕. 2024. 植被物候遥感监测关键问题. 遥感学报, 28(9): 2131–2143

Xie Z Y, Zhu W Q and Fu Y S. 2024. Key issues of remote sensing-based vegetation phenology monitoring. National Remote Sensing Bulletin, 28(9): 2131–2143 [DOI: 10.11834/jrs.20233088]

## 1 引言

物候是生物有机体长期适应气候条件而形成的周期性变化 (Xiao 等, 2009; Schwartz, 2013)。植被物候是表征陆表植被生长变化的重要参数, 是植被对全球气候变化响应的最直接指示 (Walther 等, 2002; Cleland 等, 2007; Richardson 等, 2013; Piao 等, 2019), 其调节了陆地生态系统对气候系统反馈的诸多路径 (Richardson 等, 2013), 几乎影响着生态和进化的所有方面 (Forrest 和 Miller-Rushing, 2010)。因此, 植被物候的准确监测, 对模拟陆地生态系统碳循环以及理解陆地生态系统响应和反馈气候变化至关重要。

物候学发展至今, 已经发展了多种植被 (植物) 物候观测和预测手段。这些方法大致可归纳为3类: 地面观测 (人工观测、物候相机监测和通量监测)、遥感监测和物候模型预测 (图1)。

人工观测是传统的植物物候观测手段, 其通常以植株个体为观测对象, 直接观测和记录植物发芽、展叶、开花、结果及落叶等物候事件发生的具体日期 (葛全胜 等, 2010)。目前, 中国、法国、美国 and 欧洲等多个国家和地区建立了以人工记录为主要观测手段的物候观测网 (Schwartz, 2013)。例如, 中国物候观测网 CPON (<http://www.cpon.ac.cn/> [2023-03-27])、法国物候观测网 (<http://www.obs-saisons.fr/> [2023-03-27]) 和美国国家物候网 USA-NPN (<http://www.usanpn.org/> [2023-03-27]) 等。

通量塔利用涡度相关技术提供了对近地面陆地生态系统与大气间 CO<sub>2</sub>、水分和能量交换的高频次观测, 这些通量观测数据实时记录了陆表植被光合作用和植被生长动态 (于贵瑞 等, 2004; Aubinet 等, 2012)。通量观测提供了多个时间尺度的净生态系统碳交换量 NEE (Net Ecosystem Exchange) 以及由 NEE 分解得到的总初级生产力 GPP (Gross

收稿日期: 2023-03-27; 预印本: 2023-10-17

基金项目: 国家重点研发计划 (编号: 2020YFA0608504); 国家自然科学基金杰出青年科学基金 (编号: 42025101)

第一作者简介: 谢志英, 研究方向为植被与生态遥感。E-mail: xiezy@bnu.edu.cn

通信作者简介: 朱文泉, 研究方向为植被与生态遥感。E-mail: zhuwq75@bnu.edu.cn

Primary Productivity) (Pastorello 等, 2020)。目前, FLUXNET2015 ([https://fluxnet.fluxdata.org/data/fluxnet2015-dataset/\[2023-03-27\]](https://fluxnet.fluxdata.org/data/fluxnet2015-dataset/[2023-03-27])) 收集了全球 212 个通量塔的观测数据, 并对其进行了统一的数据处理。基于 NEE 和 GPP 时序数据, 研究者开展了大量的陆表植被物候研究 (Gu 等, 2009; Richardson 等, 2009, 2010; Gonsamo 等, 2013; Wu 和 Chen, 2013; 赵晶晶和刘良云, 2013; Xie 等, 2019; Yang 和 Noormets, 2021; Xie 等, 2022)。基于 NEE 获取的物候被定义为“碳通量物候”(Carbon Flux Phenology) (Gonsamo 等, 2012b; Wu 等, 2012; Zhu 等, 2013), 基于 GPP 获取的物候被定义为“植被光合物候”(Vegetation Photosynthetic Phenology) (Gu 等, 2009)。目前, Yang 和 Noormets (2021) 已基于 FLUXNET2015 数据集获取了标准化的物候数据。

为了在机理层面更好地理解植被冠层和碳通量季节性变化间的关系, Baldocchi 等 (2005) 建议在通量塔上安装物候相机 (Richardson 等, 2007), 对植被冠层进行小时尺度的连续观测。物候相机是连接人工观测物候和遥感物候的桥梁 (Browning 等, 2017), 其既可提供个体尺度的照片信息, 也可提供景观尺度的冠层绿度信息。物候相机以倾斜摄影的方式对地表植被进行连续观测, 通过对影像的处理和分析获取能够表征植被冠层绿度季节性变化的冠层绿度指数。例如, 根据红 (R)、绿 (G)、蓝 (B) 波段计算的相对绿度指数 GCC (Green Chromatic Coordinate;  $GCC = G / (R + G + B)$ ) 和绝对绿度指数 ExG (Excess Green;  $ExG = 2G - (R + B)$ ) 等 (Richardson 等, 2007; Sonnentag 等, 2012)。目前, PhenoCam Dataset v 2.0 数据集 ([https://daac.ornl.gov/cgi-bin/dsviewer.pl?ds\\_id=1674\[2023-03-27\]](https://daac.ornl.gov/cgi-bin/dsviewer.pl?ds_id=1674[2023-03-27])) 提供了 2000 年—2018 年主要分布于北美和部分欧洲地区不同生态系统 393 个站点的物候相机观测时序和物候指标数据。已有专门针对物候相机观测数据开发的物候提取软件包“Phenopix” (Filippa 等, 2016)。

植物物候模型是准确模拟和预测植物物候期的重要方法, 其以植物生长发育对水、热和光等自然环境条件的需求或响应为基础, 基于这些环境因子建立方程以模拟植物物候期 (李荣平等, 2005; 周广胜等, 2023)。目前, 已发展了很多植物物候模型。然而, 受限于对植物物候响应气候

变化机制的有限认识, 物候模型对物候期的模拟及预测精度有限 (付永硕等, 2020)。此外, 不同植物生长对水、热和光等因子敏感性的差异及其空间异质性, 限制了其在区域尺度的应用。

卫星遥感是区域及全球尺度监测陆表植被物候的有效手段。基于卫星遥感获取的植被物候一般是景观尺度的植被冠层物候, 通常称为陆表物候 LSP (Land Surface Phenology), 表征遥感观测的陆表植被冠层的季节性变化 (de Beurs 和 Henebry, 2004; Reed 等, 2009; Schwartz, 2013; Helman, 2018)。陆表物候通常基于遥感获取的植被参数时序数据 (例如, 归一化差值植被指数 NDVI (Normalized Difference Vegetation Index) 的季节性变化特征获取物候指标。不同于传统观测的萌芽、展叶、开花和结果等物候事件, 基于遥感的物候监测一般得到的是景观尺度植被的生长季起始期 SOS (Start of Growing Season)、结束期 EOS (End of Growing Season) 及其长度 GSL (Length of Growing Season) (Caparros-Santiago 等, 2021)。目前, 研究者已基于遥感时序数据生产了数十种区域及全球的陆表植被物候产品 (王敏钰等, 2022)。

综合来看, 地面观测可在站点尺度获得较为准确的植被物候数据, 但其在大区域空间连续的植被物候监测中受到极大的制约。物候模型外推能力的局限性, 极大地制约了其在区域尺度的应用。卫星遥感是现阶段区域及全球尺度植被物候监测最为有效的手段。基于不同监测手段的特点, 逐渐形成了以卫星遥感为主要监测手段, 地面观测为验证手段的区域和全球尺度的陆表植被物候监测模式 (图 1)。

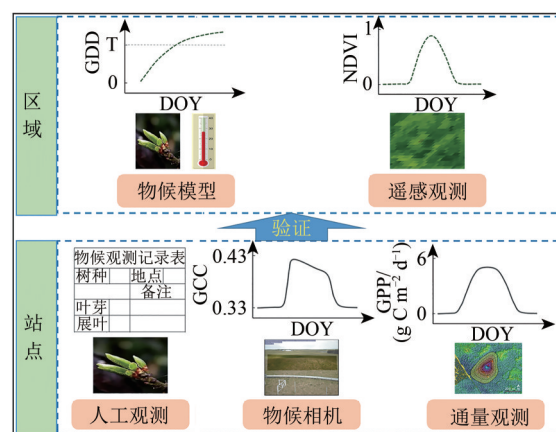


图 1 植被物候监测/预测方法

Fig. 1 Common methods of vegetation phenology monitoring/prediction

## 2 陆表植被物候遥感监测流程简述

陆表植被物候遥感监测发展至今已逐渐形成了一套通用处理流程(图2),其关键步骤包括遥感时序数据构建(或遥感指标筛选)、遥感时序数据重建、物候指标提取和精度验证。

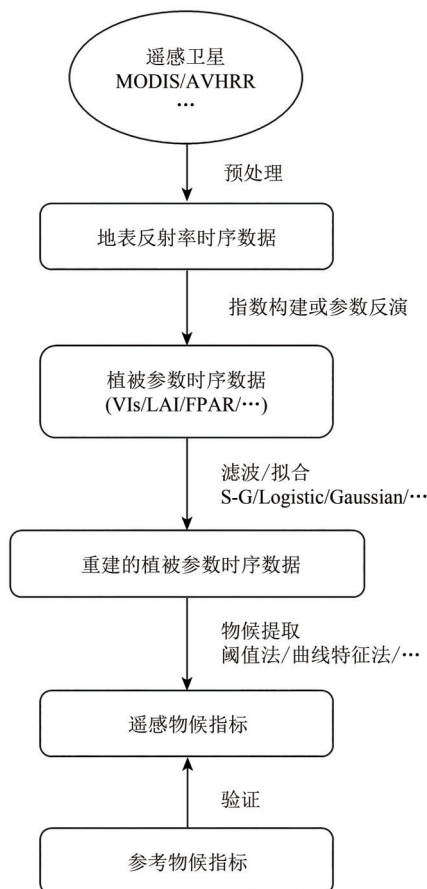


图2 植被物候遥感监测通用技术流程

Fig. 2 General technical flow of remote sensing-based phenology monitoring

基于卫星遥感光谱反射率构建的NDVI和增强植被指数EVI(Enhanced Vegetation Index)等植被指数及衍生的叶面积指数LAI(Leaf Area Index)和光合有效辐射吸收比率FPAR(Fraction of absorbed Photosynthetically Active Radiation)等表征了植被结构、生理和生化等方面的季节性变化,这些植被参数被广泛应用于陆表植被物候监测(Zeng等, 2020; Caparros-Santiago等, 2021)。需要注意的是,不同遥感参数所表征的植被特征存在差异,其获取的物候指标存在生物物理含义的本质差别。植被物候监测对遥感指数非常敏感(Berra和Gaulton, 2021),不同遥感指数监测的植被物候存

在明显的差异(White等, 2014; Karkauskaite等, 2017; 王聪等, 2017; 左璐等, 2018; Yang等, 2019; Xie等, 2022; 孙莉昕等, 2023)。Kowalski等(2020)基于Sentinel-2和Landsat时序数据测试了两种常用的时序数据拟合方法(薄板样条和logistic)以及两种最常用的植被指数(NDVI和EVI)监测阔叶林SOS的潜力,结果表明遥感指数选择比时序数据函数拟合模型选择更重要。遥感指数(或是其他植被遥感参数)的构建或选择是陆表植被物候遥感监测的基础环节,其从复杂地表背景中捕捉植被季节性动态变化的能力直接决定植被物候遥感监测的精度。

遥感时序数据重建(滤波和拟合等)的目的是消除噪声(云和气溶胶等)对遥感时序数据的污染并对其进行时间插值。目前,应用于时序数据拟合的方法较多,基于不同拟合方法获取的物候指标之间可能存在一定差异(de Beurs和Henebry, 2010; Atkinson等, 2012; Lara和Gandini, 2016; Li等, 2020)。各时序数据拟合方法有其各自的优缺点(王敏钰等, 2022),在现有研究中尚未就最佳拟合方法达成一致,在拟合方法选择时需谨慎。从深化陆表植被物候认知的角度来看,时序数据拟合对深化陆表植被物候认知的促进作用相对较小。

物候指标提取是陆表植被物候遥感监测的关键环节,其主要根据重建时序数据的特征值(例如,阈值、曲率变化率和曲线导数的极值等)来定义SOS、EOS和GSL等物候指标。陆表植被物候遥感监测发展至今,仍没有对陆表植被物候形成统一的严格定义(de Beurs和Henebry, 2010)。不同研究所定义的物候指标,其含义存在本质上的区别。例如,阈值法和曲线特征法所定义的物候指标存在本质区别,而不同阈值所定义的物候指标所表征的物候阶段同样存在本质差异。物候指标提取不仅是区域尺度陆表物候遥感监测的核心内容,在根据通量数据和物候相机数据获取物候参考数据中同样至关重要。

如何客观、有效地评价植被物候遥感监测精度是陆表植被物候遥感监测的关键问题。真实性检验是定量遥感应用最重要的一个环节,对定量遥感产品的推广应用至关重要(方红亮等, 2021; 高海亮等, 2021)。植被物候监测精度评价不仅受到物候指标提取方法的影响,不同观测手段获取



物候指标的本质含义差异和尺度差异都会影响物候指标监测精度。现有大多数植被物候遥感监测结果真实性检验基于地面观测的参考物候开展,其受到物候本质差异和尺度效应的影响需深入探讨。

从遥感卫星数据获取到植被物候指标提取的各个环节都会影响陆表物候遥感监测精度(夏传福等, 2013; 范德芹等, 2016; Li等, 2021)。已有多篇综述文章从不同角度分析了植被物候遥感监测的现状、存在的问题及未来发展方向(夏传福等, 2013; 范德芹等, 2016; Helman, 2018; Zeng等, 2020; Caparros-Santiago等, 2021), 但针对植被物候遥感监测中地表背景对遥感指数的干扰、物候指标提取方法差异及物候监测结果精度验证中的物候匹配等3个关键问题仍有待深入探讨。这3个关键问题直接决定遥感所监测的物候是否为植被物候(背景干扰时通常为融雪等伪物候)、物候指标所表征的本质含义及其与地面观测物候多尺度关联性的评价, 影响对植被物候遥感监测结果的深入理解。

### 3 陆表植被物候遥感监测关键问题

#### 3.1 遥感时序数据中的背景干扰问题

由于计算简便及数据易于获取, NDVI和EVI已成为区域和全球尺度植被物候研究中应用最为广泛的遥感时序数据(Zeng等, 2020; Caparros-Santiago等, 2021)。然而, 基于光谱反射率线性或非线性组合的不同植被指数, 容易受到土壤或冰雪背景、太阳入射—观测几何、大气效应、自身饱和性、地形阴影效应、非线性指数尺度效应、传感器老化、数据预处理、产品版本号等诸多因素的影响(Zeng等, 2022), 进而导致植被物候遥感监测的不确定性。

影响植被指数的诸多因素中, 土壤、雪和干枯植被等地表背景信息对植被指数的干扰是影响陆表物候准确监测的重要因素, 尤其是对于植被生长季起始期和结束期的监测。例如, Studer等(2007)在瑞士的研究结果表明, 基于NDVI监测的植被物候非常容易受到积雪的影响; 刘啸添等(2018)在长白山温带红松阔叶林的研究表明, 与基于日光诱导叶绿素荧光的监测结果相比, 基于NDVI监测的植被生长季起始期提前而结束期滞

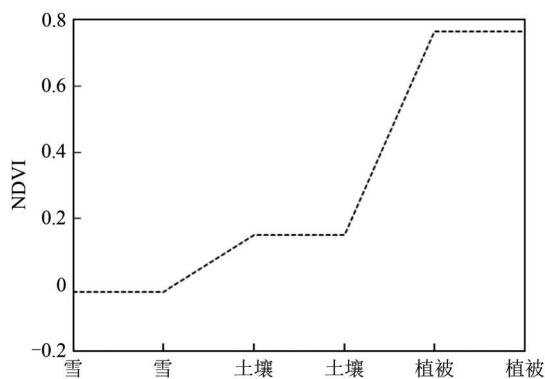
后, 这极有可能是由于NDVI中包含的积雪造成的误差。为了清楚地展示地表背景对植被物候遥感监测的影响, 本文根据典型地物高光谱数据(数据源自ENVI光谱库)模拟不同地物类型变化引起的植被指数变化(图3)。植被返青阶段, 一种典型的地表类型变化为: 积雪→土壤→植被(需特别注意雪、土壤和植被等典型地物间NDVI并非线性变化), 其对应的NDVI值会逐步的上升(图3(a))。积雪消融(雪变为土壤)所引起的NDVI上升, 将导致物候监测误差。类似地, 在植被衰老阶段, 一种典型的地表类型变化为: 绿色植被→干植被→土壤→积雪(图3(b)), 引起的NDVI数值变化将导致物候监测误差。Zhang(2015)利用近地面空气质量网络高频次获取的现场图片, 证实了地表背景信息变化会导致植被指数的变化。

复杂地表背景对NDVI的影响, 导致陆表植被物候时空变化遥感监测存在较大不确定性。例如, 21世纪以来青藏高原植被物候的变化趋势存在较大的争论(朴世龙等, 2019)。Yu等(2010)以及Piao等(2011)基于1982年—2006年NDVI时序数据的研究均表明青藏高原植被春季物候在2000年以前呈显著提前趋势, 而在2000年之后呈推迟趋势。然而, Zhang等(2013)的研究结果表明1982年—2011年青藏高原植被春季物候呈持续提前趋势, 同时指出NDVI数据质量问题导致2000年之后青藏高原植被春季物候呈推迟趋势。之后, Shen等(2013)的研究指出Zhang等(2013)的研究并没有剔除非生长季积雪对遥感植被指数的干扰; 在剔除积雪干扰后发现2000年—2011年青藏高原高寒植被春季物候没有发生显著变化。

为了克服传统植被指数在陆表植被物候监测中存在的不足, 研究者针对植被物候监测专门设计了多种遥感物候指数, 以期提高植被物候监测精度。例如, Gonsamo等(2012a)结合了NDVI和NDII(Normalized Difference Infrared Index)的优势, 提出了物候指数PI(Phenology Index), 旨在去除土壤和雪对植被物候监测结果的影响。Jin和Eklundh(2014)基于辐射传输方程, 利用红光和近红外波段, 提出了一种植被物候指数PPI(Plant Phenology Index), 其能够很好地减少雪对植被物候监测结果的影响。虽然PPI理论上可用于表示任

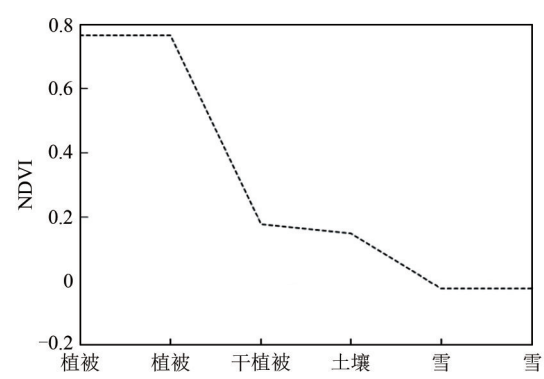
何绿色陆表植被的冠层动态,但它对季节性积雪覆盖的北半球高纬度针叶林的物候监测更为有用。针对植被春季物候监测, Wang 等 (2017) 基于红外、近红外和短波红外发展了归一化差值物候指数 NDPI (Normalized Difference Phenology Index), 其有效减少了融雪对落叶生态系统植被春季返青物候监测结果影响。针对苔原和草地生态系统, Yang 等 (2019) 利用绿光、红光和近红外波段构建了归一化差值绿度指数 NDGI (Normalized

Difference Greenness Index), 有效提高了苔原和草地春、秋季物候监测精度。相比传统的植被指数, 新发展的物候指数有效提高了部分典型植被的物候监测精度 (Cao 等, 2020; Gan 等, 2020)。然而, 这些遥感物候指数是针对特定目标 (如, 特定地表背景、植被类型以及物候) 设计, 其普适性较差。例如, PI 对稀疏植被的物候监测能力不足, NDPI 很难消除干枯植被的影响。



(a) 植被返青过程 NDVI 变化模拟示意图

(a) Simulation schematic of NDVI changes during vegetation greenness rising



(b) 植被枯黄过程 NDVI 变化模拟示意图

(b) Simulation schematic of NDVI changes during vegetation greenness falling

图3 植被返青和枯黄过程 NDVI 变化模拟示意图

Fig. 3 Simulation schematic of NDVI changes during vegetation greenness rising and falling

针对各遥感指数监测植被物候能力的对比研究表明, 现有物候指数在不同地理环境和植被类型的监测能力仍有待进一步提高 (孙莉昕 等, 2023)。在北半球中高纬度地区的对比发现, 即便是在草地物候监测中表现最好的 NDGI 在有效削弱复杂背景干扰方面仍然存在不足 (图4; 所用数据为 500 m 分辨率的 MODIS MOD09A1, 雪根据“QC”文件标记)。不同地表背景变化所引起的遥感指数数值变化, 导致复杂背景条件下植被物候遥感监测存在较大不确定性。而地表背景的时空异质性, 进一步增加了全球范围内植被物候遥感监测的难度。因此, 如何有效降低甚至消除复杂地表背景信息对植被物候遥感监测的影响是陆表植被物候遥感监测需要解决的首要关键问题。

### 3.2 物候指标提取方法差异问题

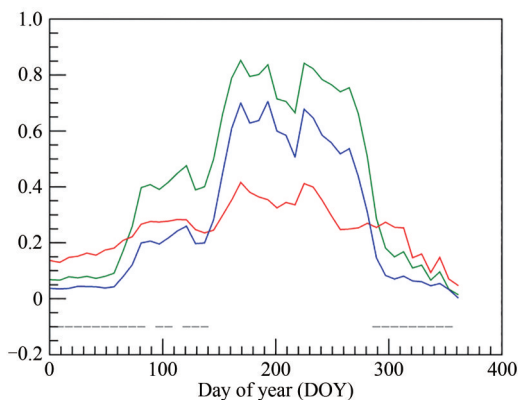
物候指标提取是陆表植被物候遥感监测的核心。不同于传统人工观测的发芽、开花和结果等非常具体的物候事件, 遥感物候监测需要根据遥

感指数时序曲线定义陆表植被物候。SOS 和 EOS 是陆表植被物候研究中最常用的物候指标, 其表征了绿色植被从复杂地表背景中出现和消失的时间。目前, 使用最广泛的物候指标提取方法主要包括阈值法和曲线特征法 (Caparros-Santiago 等, 2021)。

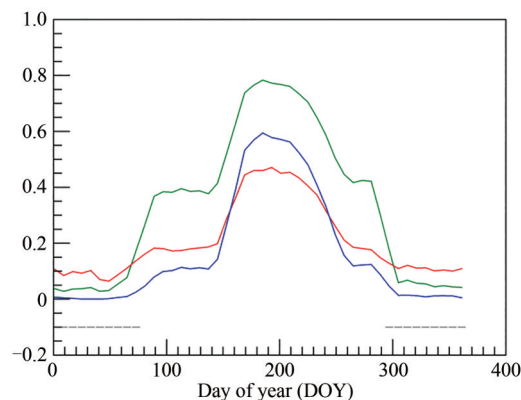
阈值法包括固定阈值和动态阈值。阈值法的提出在一定程度上是为了解决地表背景信息对遥感指数的干扰。固定阈值通过设置遥感指数的固定值, 以遥感指数到达该数值的日期定义物候指标。例如, 基于对特定区域地表背景信息的分析, Lloyd (1990) 以 NDVI 固定阈值为 0.099 监测物候。由于陆表背景信息的时空异质性, 固定阈值在大范围植被物候监测中并不适用 (Tan 等, 2011; Zeng 等, 2020)。动态阈值通过遥感指数季节性变化幅度的百分比设置。例如, White 等 (1997) 以植被指数季节性振幅的 50% 为阈值提取物候指标。由于动态阈值的选择并没有严格的依据, 不同研究所使用的阈值不同 (Richardson 等, 2010, 2012; Wu 等, 2013; Klosterman 等, 2014; Kross

等, 2014; Xie 等, 2019)。动态阈值法在一定程度上解决了固定阈值存在的不足, 但是其所定义的物候期没有明确的物理含义 (Tan 等, 2011)。

另外, 动态阈值法容易受到时序数据最大值的影响, 理论上讲, 植被生长季开始的时间不应受到植被生长盛期状况的影响。



(a) 常绿针叶林植被指数季节动态示例(91.22°E, 59.82°N)  
(a) Example of seasonal dynamics in the vegetation indices in evergreen needleleaf forest (91.22°E, 59.82°N)



(b) 稀树草原植被指数季节动态示例(115.16°E, 53.35°N)  
(b) Example of seasonal dynamics in the vegetation indices in savanna (115.16°E, 53.35°N)

— NDVI — EVI — NDGI --- SNOW

图4 北半球高纬度植被指数季节动态示例

Fig. 4 Example of seasonal dynamics in the vegetation indices in mid-high latitudes of the Northern Hemisphere

曲线特征法根据时序数据拟合曲线导数相关的特征点定义植被物候, 包括拟合曲线的曲率变化率及拟合曲线的各阶导数等。例如, Zhang 等 (2003) 使用曲率变化率定义物候指标; Gonsamo 等 (2013) 以拟合曲线的各阶导数定义了不同的物候期。曲线特征法可以避免阈值法存在的一些问题, 其获取的物候指标具有相对明确的植被生理含义。然而, 曲线特征法对遥感时序数据拟合曲线的形状要求较高, 其并不能保证每条拟合曲线都能得到曲线特征点, 导致在实际应用中物候指标提取率相对较低 (de Beurs 和 Henebry, 2010; Zeng 等, 2020)。

陆表植被物候遥感监测在过去几十年得到了快速发展, 但陆表植被物候中最为关键的 SOS 和 EOS 指标至今没有统一且明确的定义。不同物候提取方法得到的结果存在明显的差异 (图 5; NDVI 曲线为模拟的理想曲线, 30%  $\Delta$ NDVI 表示以 NDVI 季节性振幅的 30% 为阈值提取 SOS, 最大斜率值以曲线一阶导数的极值点提取 SOS, 拐点以曲线曲率变化率极值点提取 SOS), 这使得现有大多数的研究没可比性, 且现有的研究也没能就最佳物候指标提取方法达成统一。陆表植被物候没有明确定义的原因之一是广泛使用的 NDVI 等遥感指数在区分植被和非植被时没有明确的阈值。此外,

物候指标提取方法在地面物候指标提取 (基于通量和物候相机的参考物候) 中同样非常关键。因此, 物候指标提取 (或是指标定义) 仍然是陆表植被物候遥感监测亟待解决的核心问题。

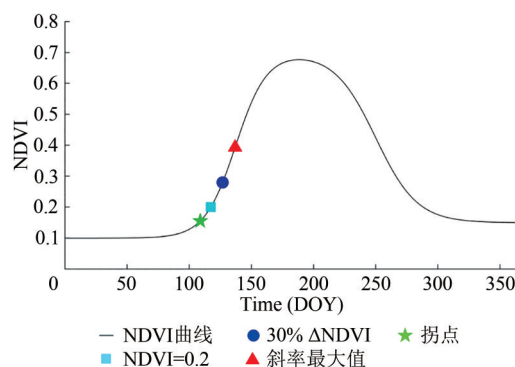


图5 不同物候指标提取方法获取的 SOS 对比示意图

Fig. 5 Comparison of SOSs obtained from different methods

### 3.3 真实性检验中的物候匹配问题

物候监测结果精度验证是陆表植被物候遥感监测流程的最后一个环节, 也是极其重要的一步。目前, 植被物候遥感监测精度验证存在的主要问题是参考物候指标与遥感物候指标间的匹配问题, 主要体现在观测尺度匹配和物候指标匹配两方面。

遥感物候监测结果验证存在的首要关键问题是遥感物候与地面参考物候之间的尺度匹配问题



(Peng等, 2017)。在基于通量数据的验证中, 遥感在景观尺度观测陆表植被冠层信息的变化, 而通量塔在景观尺度观测局地生态系统群落 $\text{CO}_2$ 变化。碳通量塔的覆盖范围 (footprint) 从几百米到几公里不等 (取决于塔的高度、风速和地形等诸多因素), 与几个主要卫星观测平台 (如MODIS、SPOT VGT) 的空间分辨率相当 (Xiao等, 2009; Chu等, 2021; Kong等, 2022)。但值得注意的是, 通量塔所观测的主要通量范围一般不在塔所在的周围, 而在其上风向区域 (Migliavacca等, 2011; 张慧等, 2012; Chu等, 2021; Kong等, 2022), 且其受风向和风速的影响具有明显的时空变异性。因此, 直接使用通量塔所在像元的遥感物候与通量物候进行比较会带来较大的误差, 这一问题在现有大多数研究中被忽略。物候相机观测范围与相机安装高度及观测角度密切相关, 大致观测范围为几平方米至几千平方米 (Migliavacca等, 2011; Browning等, 2017; Burke和Rundquist, 2021)。物候相机获取的植被物候是照片上感兴趣区“纯”植被信息, 而卫星遥感获取的陆表物候是像元内所有地物的综合信息, 导致两者在观测尺度上存在较大差异。这一问题在地表类型复杂或是区域内植被个体生长差异较大的地区更为突出。因此, 在验证站点筛选中需要选择植被类型单一且局地植被长势较为同步的站点, 以减少尺度匹配造成的影响。

遥感物候和参考物候间物候指标的匹配问题是遥感物候监测结果验证中的另一关键问题。不同手段获取的时序数据所表征的植被季节性变化特征存在差异, 例如, 在亚马逊热带雨林, 遥感指数 (EVI和LAI等) 很难捕捉到常绿林季节性动态, 而叶片更替导致植被光合作用能力具有季节性动态 (Wu等, 2016)。而具有明显季节性动态的草地, 不同手段获取的物候指标也存在明显差异 (图6; 引自Xie等 (2022))。基于碳通量和物候相机获取的地面参考物候是遥感物候精度验证的主要数据源。由于缺乏对陆表植被多维度特征之间关联性的深入认识 (如, 植被冠层绿度变化与GPP变化之间的关联性), 导致不同观测手段获取的物候指标之间的对应关系仍不清楚。虽然, Tian等 (2021) 等通过分析遥感物候与地面物候的关系, 探索了与地面物候对应关系最好的遥感物候指标提取阈值, 但这一阈值的普适性仍有待进一步验

证。另外, 基于通量塔和物候相机等获取的参考数据同样需要类似遥感物候监测的处理流程, 而现有大多数研究中参考物候指标提取所选用的方法存在较大的差异。

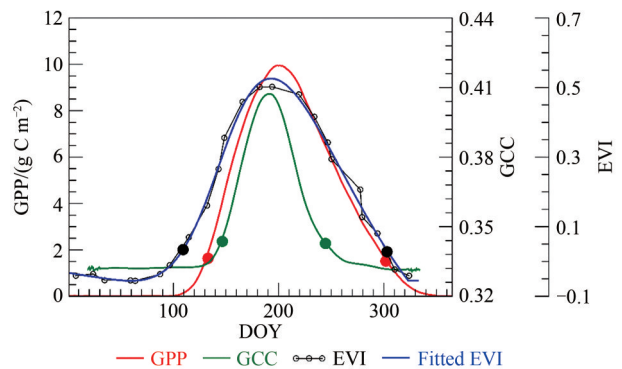


图6 EVI、GCC和GPP季节性变化及其监测物候指标对比示例(Xie等, 2022)

Fig. 6 Example of smoothed time series of the EVI, GCC, and GPP and phenometrics derived from these time series (Xie et al., 2022)

## 4 结 语

### 4.1 发展抗背景干扰的植被物候遥感监测方法

虽然研究者已发展了多种抗背景信息干扰的遥感物候指数, 并在部分典型植被物候监测中取得了较好的效果, 但是这些物候指数对于提升其他植被类型的物候监测精度仍非常有限 (Xie等, 2022; 孙莉昕等, 2023)。这些物候指数多致力于解决雪对植被物候监测的影响, 在克服土壤含水量变化以及植被枯枝落叶等地表背景干扰方面的表现仍然不足。因此, 亟需发展抗背景干扰的植被物候遥感监测方法, 以提高复杂地表背景条件下植被物候遥感监测精度和时空连续性。发展抗背景干扰的植被物候遥感监测方法的重要途径包括新型遥感指数的构建和方法集成。

新型遥感指数的构建需要从遥感机理出发, 探索构建抗复杂背景干扰的新型遥感指数, 提高遥感指数抗背景干扰的能力, 重点克服土壤和植被等地表背景对植被物候遥感监测的影响, 同时兼顾其他方面 (例如, 地形效应、观测几何及指数自身饱和问题等) 对遥感指数的影响。近些年发展的遥感指数 (例如, PPI、NDPI和NDGI等物候指数), 尤其是新发展的 $\text{NIR}_v$  (Badgley等, 2017)、FCVI (Fluorescence Correction Vegetation

Index) (Yang 等, 2020)、kNDVI (Camps-Valls 等, 2021) 和 NIRvP (Dechant 等, 2022) 等指数, 可为抗背景干扰的新型遥感指数构建提供新思路。

由于地表类型的复杂性和空间异质性, 单一遥感指数无法满足区域和全球尺度的植被物候遥感监测精度要求。因此, 有必要针对不同地表背景从现有诸多遥感指数中筛选最佳遥感指数, 并探索集成多种遥感指数优势的抗背景监测方法, 提高复杂背景条件下植被物候遥感监测精度和时空连续性。新近发展 NIRv、FCVI、kNDVI 和 NIRvP 等指数为筛选最佳遥感指数提供了新的选择, 后续的研究需充分验证这些指数在陆表物候遥感监测中的应用潜力。在集成方面, 需要深入探索基于多种最佳遥感指数的前端集成方法, 以及基于多种最佳遥感指数物候监测结果的后端集成方法。通过系统对比不同的集成方案, 筛选出最佳的监测集成方案, 形成最佳的抗背景监测方法。

## 4.2 联合观测

陆表植被物候联合观测包括地面多传感器的协同观测以及“天—空—地”多尺度一体化观测。基于地面多传感器协同观测网络, 可在同一时空尺度下获取表征植被生长发育的不同指标, 有利于明确具有不同含义物候指标之间的关联性, 为解决不同植被物候指标间的匹配问题提供有效手段。“个体物候—种群物候—群落物候”的尺度扩大方法是解决解决空间尺度问题的有效手段 (Liang 等, 2011)。因此, 针对不同观测手段的空间尺度匹配问题, 需构建“天—空—地”多尺度一体化观测。结合地面多传感器协同观测以及“天—空—地”多尺度一体化观测的联合观测是解决植被物候遥感监测结果验证中观测物候指标匹配以及空间尺度匹配问题的有效途径。此外, 联合观测也有利于筛选出最佳的植被物候指标提取方法, 或是筛选出与地面观测物候匹配最佳的遥感物候提取方法。

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## Key issues of remote sensing-based vegetation phenology monitoring

XIE Zhiying<sup>1</sup>, ZHU Wenquan<sup>2</sup>, FU Yongshuo<sup>1</sup>

*1.College of Water Sciences, Beijing Normal University, Beijing 100875, China;*

*2.State Key Laboratory of Remote Sensing Science, Faculty of Geographical Science, Beijing Normal University, Beijing 100875, China*

**Abstract:** Vegetation phenology is one of the most sensitive biological indicators of terrestrial ecosystem responses to global climate change and plays a crucial role in terrestrial ecological processes and functions. Changes in vegetation phenology have been strongly linked to climate change patterns and various ecological processes within terrestrial ecosystems, and may significantly impact land-atmosphere exchanges of carbon, water, and energy fluxes, and interactions between different species. Therefore, accurate monitoring of vegetation phenology is essential for simulating terrestrial ecological processes and understanding how terrestrial ecosystems respond to climate change. To date, various observation and monitoring methods for vegetation phenology have been developed, including ground-based observations (such as manual observation, phenocam observation / monitoring, and carbon flux-based monitoring) and remote sensing-based monitoring. Benefiting from the reliability of ground-based phenology observations and the spatial coverage and rapid repeatability of remotely sensed monitoring, a regional and global-scale vegetation phenology monitoring framework has been established, with satellite remote sensing as the primary method and ground observations for validation. A general technical workflow for remote sensing-based vegetation phenology monitoring has been formed, including remote sensing data acquisition, time series data construction (e.g., calculation of vegetation parameters such as various vegetation indices, leaf area index, fraction of absorbed photosynthetically active radiation, and gross primary production, etc.), time series data reconstruction (e.g., filtering, smoothing, and fitting), phenological metrics (phenometrics, e.g., start, peak, end, and length of the growing season) extraction, and phenometrics validation. However, each processing step in this workflow introduces uncertainty into the monitored phenometrics. This study focuses on three key aspects of remote sensing-based phenology monitoring: (1) remote sensing time series data (especially vegetation indices), (2) phenometrics extraction, and (3) phenometrics validation. Additionally, it discusses the effects of complex land surface backgrounds (e.g., snow, soil, and dry vegetation) on remote sensing time series data, the differences between various phenometrics extraction methods (i.e., threshold-based vs. derivative-based methods), and the matching issues between remote sensing phenometrics and reference phenometrics during validation (e.g., scale matching and phenometrics matching). Finally, two essential directions are proposed to address these key issues: (1) developing new remote sensing monitoring methods for vegetation phenology to counter background interference, such as constructing new remote sensing indices resistant to complex land surface backgrounds from the perspective of remote sensing mechanisms, and (2) establishing a comprehensive observation network that integrates ground-based multi-sensor coordinated observations and “space-air-ground” multi-scale integrated observations. Addressing these key issues will enhance the reliability of remote sensing phenology data, expand their applications, and deepen the understanding of land-atmosphere interactions.

**Keywords:** remote sensing, vegetation phenology, remote sensing time-series data, vegetation index, validation, scale effect

**Supported by** National Key Research and Development Program of China (No. 2020YFA0608504); National Science Foundation for Distinguished Young Scholars of China (No. 42025101)