



气候变化背景下橡胶树物候研究进展

赖虹燕, 陈帮乾, 云挺, 尹雄, 陈岳, 吴志祥, 寇卫利

引用本文:

赖虹燕,陈帮乾,云挺,尹雄,陈岳,吴志祥,寇卫利. 气候变化背景下橡胶树物候研究进展[J]. 热带亚热带植物学报, 2023, 31(6): 886–896.

在线阅读 View online: <https://doi.org/10.11926/jtsb.4743>

您可能感兴趣的其他文章

Articles you may be interested in

巴西橡胶树栽培种质基因组C值测定和变异分析

Genome C Value and Variation Analysis of Cultivated Rubber Tree (*Hevea brasiliensis*) Germplasms by Flow Cytometry
热带亚热带植物学报. 2018, 26(5): 523–528 <https://doi.org/10.11926/jtsb.3857>

澳门5种植物叶变色盛期对气候因子的响应

Effects of Climatic Factors on Leaf Discoloration Peak Period of 5 Species in Macao
热带亚热带植物学报. 2020, 28(6): 574–582 <https://doi.org/10.11926/jtsb.4232>

基于植物功能性状的生态学研究进展:从个体水平到全球尺度

Plant Functional Traits: From Individual Plant to Global Scale
热带亚热带植物学报. 2019, 27(5): 523–533 <https://doi.org/10.11926/jtsb.4108>

全球气候变暖胁迫下的雅鲁藏布江流域植被覆盖度变化驱动机制探讨

Driving Mechanism of Vegetation Coverage Change in the Yarlung Zangbo River Basin under the Stress of Global Warming
热带亚热带植物学报. 2017, 25(3): 209–217 <https://doi.org/10.11926/jtsb.3685>

未来气候变化对孑遗植物鹅掌楸地理分布的影响

Potential Impacts of Climate Change in Future on the Geographical Distributions of Relic *Liriodendron chinense*
热带亚热带植物学报. 2021, 29(2): 151–161 <https://doi.org/10.11926/jtsb.4322>

向下翻页，浏览PDF全文

气候变化背景下橡胶树物候研究进展

赖虹燕^{1,2}, 陈帮乾², 云挺³, 尹雄^{1,2}, 陈岳¹, 吴志祥², 寇卫利^{1*}

(1. 西南林业大学林学院, 大数据与智能工程学院, 昆明 650224; 2. 中国热带农业科学院橡胶研究所, 海南省热带作物栽培生理学重点实验室, 海口 571101; 3. 南京林业大学林学院, 南京 210037)

摘要: 橡胶树(*Hevea brasiliensis*)是广布于热带地区的经济林木, 是战略物资天然橡胶的主要来源, 其物候学的研究对胶园生产管理和评估热带地区植被对全球气候变化的响应方面具有重要意义。早期的物候研究主要服务于苗木繁育、割胶规划和抗逆栽培等生产应用; 利用遥感监测植被物候日趋成熟, 已广泛应用于橡胶树并成为主流的物候监测方法; 橡胶树物候具有明显的时空异质性, 对气候变化的响应较为复杂, 其中温度和降水是关键影响因素, 同时内因(品系、基因和树龄等)和外因(种植密度、地理位置和农业措施等)也共同影响了其物候。为更好服务天然橡胶产业的可持续发展和热区气候变化科学研究, 未来的橡胶树物候研究应重点关注多源遥感数据的协同重建、物候指标提取算法的普适化和遥感预测模型的精准化。该文系统梳理了橡胶树物候的监测方法、服务价值、时空格局, 提出了存在问题及未来研究方向。

关键词: 橡胶树; 物候; 时空特征; 气候变化

doi: 10.11926/jtsb.4743

Research Progress on Phenology of *Hevea brasiliensis* Under Climate Change

LAI Hongyan^{1,2}, CHEN Bangqian², YUN Ting³, YIN Xiong^{1,2}, CHEN Yue¹, WU Zhixiang², KOU Weili^{1*}

(1. College of Forestry, College of Big Data and Intelligence Engineering, Southwest Forestry University, Kunming 650233, China; 2. Rubber Research Institute (RRI), Chinese Academy of Tropical Agricultural Sciences (CATAS), State Key Laboratory Incubation Base for Cultivation & Physiology of Tropical Crops, Haikou 571101, China; 3. College of Forestry, Nanjing Forestry University, Nanjing 210037, China)

Abstract: Rubber trees (*Hevea brasiliensis*) are widespread in the tropics and are a major source of natural rubber for strategic materials. The study of their phenology is of great importance for the production management of rubber plantations and for assessing the response of tropical vegetation to global climate change. The early phenological research mainly served the production application, such as seedling breeding, rubber tapping planning, and stress-resistant cultivation. The use of remote sensing to monitor vegetation phenology has become increasingly mature and has been widely applied to rubber trees, becoming the mainstream method for phenological monitoring. Rubber tree phenology has obvious spatio-temporal heterogeneity and its response to climate change is complex, which temperature and precipitation are key influencing factors, and both internal factors (strain, gene, and tree age, etc.) and external factors (planting density, geographic location, and agricultural practices, etc.) also affect its phenology. In order to better serve the sustainable development of natural rubber

收稿日期: 2022-11-01 接受日期: 2023-01-10

基金项目: 云南省教育厅科学研究项目(2022Y580); 国家自然科学基金项目(42071418); 海南省自然科学基金项目(422CXTD527); 国家天然橡胶产业技术体系(CARS-33); 中央级公益性科研院所基本科研业务费专项(1630022023007, RRIKLOF202301)资助

This work was supported by the Project for Science Research in Education Department of Yunnan (Grant No. 2022Y580), the National Natural Science Foundation of China (Grant No. 42071418), the Project for Natural Science in Hainan (Grant No. 422CXTD527), the Project for National Nature Rubber Industry Technology System (Grant No. CARS-33), and the Project for Central Public-interest Scientific Institution Basal Research Fund (Grant No. 1630022023007, RRIKLOF202301).

作者简介: 赖虹燕(1993年生), 女, 博士研究生, 从事林业遥感与信息技术研究。E-mail: lhy19931006@163.com

* 通讯作者 Corresponding author. E-mail: kwl_eric@163.com

industry and scientific research on climate change in tropics, future research on rubber tree phenology should focus on the collaborative reconstruction of multi-source remote sensing data, universalization of phenological index extraction algorithms, and precision of remote sensing prediction models. The monitoring methods, service values, spatio-temporal patterns of rubber tree phenology were systematic reviewed, and put forward the existing problems and future research directions.

Key words: Rubber tree; Phenology; Spatio-temporal characteristics; Climate change

植被物候是反映气候变化的综合环境指标^[1]。研究植被物候的变化规律及其对气象因子的响应程度,有助于更好地理解植被和气候因素之间的相互影响作用^[2-3]。气候变化对非热带地区的植被物候影响显著,包括广泛报道的春季提前和秋季延迟^[4-7]。然而,由于热带地区季节变化不明显,植被物候变化关注较少,关于全球气候变化对热带地区植被物候影响的认识还非常有限^[8-9]。但是,随着遥感等多源监测技术的不断发展,在全球气候变化大背景下探讨热带植被物候变化规律,分析气候因子与其耦合关系,已成为物候学研究的新兴热点。

橡胶树(*Hevea brasiliensis*)广泛种植于 10° S~24° N 地区,属于典型的热带落叶乔木,是国防和经济建设不可或缺的战略物资天然橡胶的主要来源^[10-12]。橡胶树/林具有明显的物候特征,物候研究备受国内外学者的关注^[13-15]。传统地面物候观测研究如叶蓬物候变化是苗木繁育、抗逆栽培和割胶规划等生产管理重要参考依据^[3,16-22]。随着遥感观测技术迅猛发展,以覆盖范围广、时间序列长和受干扰较小等优势,已成为橡胶树物候监测的主要手段(图 1)。目前,橡胶树物候指标遥感提取、空间特征分布及其动态分析方面已取得一定研究进展^[11,23-27],但研究集中分布在中国的西双版纳^[28-32]

和海南岛^[10,33-37],时间尺度多在 15 a 左右^[23]。橡胶林物候空间异质性与纬度^[16,38]、海拔^[39]、树龄^[40-41]等因子有关,且不同驱动因子对物候影响差异较大。然而,由于现有橡胶林物候指标来自不同的数据源或物候算法^[42-43],大尺度物候对气候变化的响应模式可能与区域尺度上的模式不同^[44]。不同尺度差异条件下,很难表达区域空间和大尺度物候年际变化的细节,橡胶林空间异质性和区域特异性研究尚显不足^[14,30]。

橡胶树横跨热带地区,探索橡胶林物候对气候变化的响应有利于揭示全球气候变化对热带植被物候的响应规律,也可以加强橡胶林物候动态预测,对橡胶生产和管理有重要意义^[9,45]。比如,展叶期延迟对后期复育、疾病防御和乳胶产量等有显著影响^[30,46]。现有橡胶树物候监测因研究区、数据源和动态阈值不同^[42,47],造成监测结果存在较大差异,包括生长季始期、生长季末期和生长季长度存在提前、延迟、没有明显变化和在波动中提前 4 种观点^[24,48-49]。此外,热带地区环境气候复杂严重影响遥感物候监测^[29,47,50],橡胶树物候的时滞效应和尺度效应未深入探索,增加监测结果的不确定性^[30,51]。鉴于此,本文对当前橡胶树物候研究进行梳理和展望,以期增强生产工作的预见性和应对全球气候变化提供新见解。

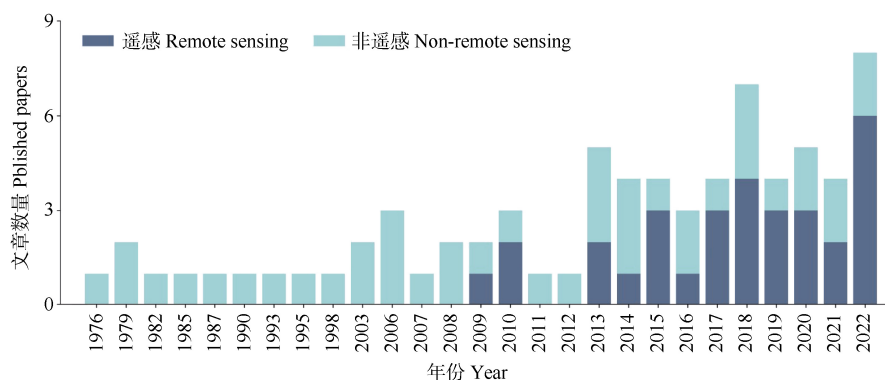


图1 橡胶物候研究文章数量年度分布

Fig. 1 Annual distribution of number of articles on *Hevea brasiliensis* phenology

1 橡胶树物候研究方法

1.1 橡胶树物候指标简介

橡胶树物候是叶片随着环境、季节而变化的生长节律，主要包括萌芽、展叶(铜棕色)、开花、变色(浅绿色)、结果、黄叶、落叶和休眠等现象^[52]。不同物候期，橡胶树的生理结构和形态特征有较大差异^[3]。生长季始期(又称展叶期, start of growing season, SOS)

表示橡胶树顶芽由铜棕色变为浅绿色的时间；生长季末期(又称落叶期, end of growing season, EOS)表示冠层上部叶片由浅黄色变为几乎完全黄色的时间；生长季长度(length of growing season, LOS)表示 SOS 与 EOS 之间的持续时间(图 2)。落叶前叶片由深绿色变为浅黄色约需 2~4 周^[42,53]，落叶到展叶约需 6~8 周^[30]。北半球橡胶树一般在 2 月中旬左右集中快速落叶，除落叶期或受自然灾害影响外，全年林冠较茂盛^[54]。

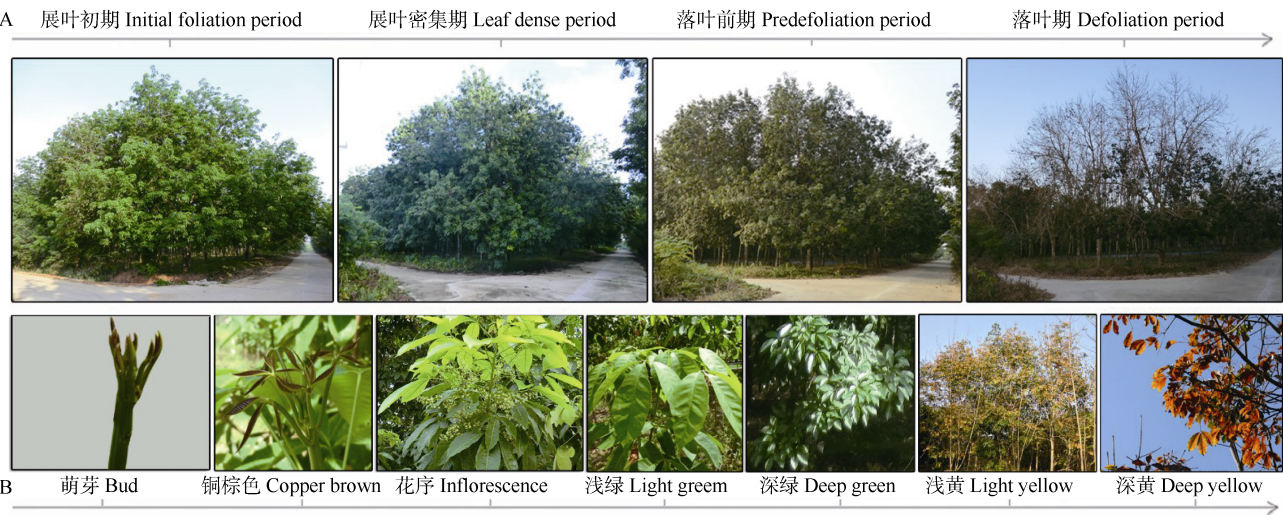


图 2 橡胶树的典型物候特征。A: 冠层水平; B: 叶片水平。

Fig. 2 General phenological characteristics of *Hevea brasiliensis*. A: Canopy level; B: Leaf level.

1.2 橡胶树物候人工观测

人工物候观测常在固定样地展开(表 1), 观测员按照“定时、定点、定株”的原则和统一观测标准记录橡胶树的落叶和展叶日期^[3,55]，最早可追溯到 1960 年^[21]。国内报道的物候观测站点主要位于海南省儋州市南丰镇的那王村、儋州两院试验农场、琼中阳江农场和保亭热作所^[14,36]。由于缺乏长期稳定

的经费支持，观测员专业培训度较低，导致观测标准受主观经验影响较大，高质量、长时间跨度的橡胶树物候观测数据一直匮乏。人工观测积累数据是物候监测结果验证必不可少的数据资源，后续可按照“定点、定人、常年性、标准化”的原则，增强橡胶树物候长期数据的收集和同步，并提高人工观测的精度^[37]。

表 1 橡胶树物候研究方法的优缺点

Table 1 Advantages and disadvantages of rubber tree phenology research methods

方法 Method	观测信息 Observation information	适用尺度 Applicable scale	优点 Advantage	缺点 Disadvantage
人工观测 ^[3,14,21,55]	叶片物候记录	植株	时间分辨率高	站点少、主观性、尺度小
遥感监测 ^[36,42,58]	NDVI	区域、大尺度	覆盖空间广	数据源、动态阈值存在主观性
模型预测 ^[30,37,42]	特定温度	植株、群落、区域	灵活可控	模型结果不确定性大

1.3 橡胶树物候遥感监测

卫星遥感数据可获取性强、覆盖范围广、时间序列长，可快速重复监测且受人为干扰较小，弥补了传统植被物候观测的局限，实现了物候监测由

“点”向“面”的转换，使大尺度研究橡胶树物候时空特征及其气候响应成为可能^[56]。同时，多源遥感数据协同监测，可以最大限度地发挥各自优势，获得更高精度和更多数据信息，从而有效提高橡胶树物

候对气候变化响应模式的可靠性^[42]。

1.3.1 遥感数据源

光学卫星是植被物候监测的主流数据源, 常用数据源包括中分辨率成像光谱仪(MODIS)^[10]、Landsat^[23,57]和 Sentinel-2^[42]。250 m 的 MODIS 具时间分辨率高, 能够缓解热区多云雨天气对监测的影响, 但斑块破碎化会有较明显的混合像元现象, 监测结果偏差较大; 中分辨率的 Landsat 和 Sentinel-2 虽能较好地解决混合像元问题, 但多云雨天气和长重访周期使得观测结果不连续^[58]。因此, 导致遥感监测和地面观测的橡胶树物候结果容易出现不一致的情况^[4]。虽然可通过多源数据融合和时空插值的方式来解决观测不连续问题, 获得更精细的橡胶树物候特征信息^[42], 但尺度效应仍是难题, 需根据研究目的在影像时间和空间分辨率之间进行取舍^[59]。

1.3.2 遥感时序数据预处理方法

除了数据源优选之外, 由于遥感数据存在噪声(如云、气溶胶等), 季节生长曲线常常存在异常值和缺失值等问题, 时序重构质量对准确提取物候指标有着决定性的影响。学者们致力于丰富遥感时序重构和空值插补方法^[56]。“时序重构”是利用多种统计和数值分析方法, 模拟季节变化规律, 从而插补缺失值, 增加数据连续性, 突显季节变化趋势, 提高时序数据重构质量, 如使用 Savitzky-Golay 滤波法^[60]、非对称高斯滤波法^[61]和双 Logistic 函数法^[62]来拟合植被指数曲线, 过度拟合和欠拟合都会影响物候提取的准确度。选择时序重构方法时, 需考虑植被生长的特点和数据源质量选择最合适的拟合方法。

1.3.3 物候指标提取方法

基于植被指数时序数据的季节生长曲线形态特征, 通过设定阈值或者寻找曲率变化速率的极值点来确定关键物候指标^[56]。物候指标提取主要有阈值法或拐点^[42]、求导数^[63]、移动平均法^[64]等方法。为了提高工作的效率, Jönsson 等^[61]开发了遥感影像时间序列滤波处理 TIMESAT 软件包来提取物候指标, 在业界得到广泛应用。目前, 对于 SOS 和 EOS 的动态阈值、平滑窗口大小、迭代次数、适应强度等设定存在较大差异。胡盈盈等^[36]将 SOS 和 EOS 的动态阈值分别设定为 30%和 60%, 但 Azizan 等^[42]分别设定为 20%和 20%。不同遥感数据源重构时序曲线与主观提取物候指标会导致监测精度降低。因此, 遥感提取物候指标是否准确仍具有较大的不确定性。

1.4 橡胶树物候模型预测

通过物候模型可以预测未来气候变化的响应, 同时有利于探索区域到全球尺度的碳、水循环和能量通量^[65]。目前大多数橡胶树物候模型都是基于遥感植被指数, 如归一化植被指数、地表水分指数和归一化燃烧指数^[25,32,42]。许多学者利用时序数据来模拟橡胶树生长, 研究橡胶树物候指标的时空动态规律。Zhai 等^[30]建立了橡胶树白粉病预测模型, 表明通过日最高温度、日最低温度和日温差能够调控白粉病的发生率。李宁等^[37]结合作物生长模型, 建立了海南岛橡胶树春季物候期预测模型, 春季物候期的年际变化呈现提前趋势, 产胶量会进一步提高。Azizan 等^[42]使用混合线性模型, 随温度升高导致 SOS 和 EOS 进一步提前。目前, 橡胶树物候预测模型总体表现欠佳, 模型通常基于特定温度, 对于光照、降水、光周期或低温持续天数等气候因子鲜有考虑, 各气候因子协同效应对物候也有重要影响^[66]。物候模型适用于某一时期的温度总和而忽略温度的时间变化, 因此, 难以预测极端气候条件下的橡胶物候的响应规律^[15]。基于此, 未来模型发展可向长势监测模型、产量预测模型、物候对气候变化的响应模型等方向发展。

2 橡胶树物候与服务生产价值

传统的物候研究主要是为橡胶树的苗木繁育(嫁接)、抗逆栽培和割胶规划等生产提供决策参考^[67]。栽培苗木通过无性繁殖(嫁接)来实现扩繁, 而不同叶蓬物候与芽接成活率、根接成活率有关, 萌发前的侧芽、古铜期和展叶期的砧木适宜芽接, 顶蓬叶片稳定期根接成活率高^[68-70], 而不同物候期砧木的抗逆性(抗旱、抗寒、抗病害等)存在显著的差异^[48,50]。长期干旱明显抑制生长, 叶片深绿期抗旱优于浅绿期^[71-72]。稳定期抗寒能力最强, 冬季萌发期受寒害尤为严重^[73]。古铜期和浅绿期易发生白粉病和炭疽病^[50,74-77]。落叶期到抽芽期主张“停割管养”, 调节割胶深度、转换割线和高割胶来解决产胶与生长之间的矛盾^[78-80]。因此, 精细化的物候信息有助于提高生产工作的预见性, 从而确保橡胶树长期稳产和高产^[22,30,66]。

3 橡胶树物候时空特征

3.1 橡胶树物候年际变化特征

橡胶树物候年际变化特征受生长环境影响差

异显著^[26,42]。以中国第二大植胶区海南岛为例, SOS 年际变化总体上呈波动提前趋势, LOS 呈普遍延长趋势, EOS 延迟成为橡胶林较显著的物候年际变化特征^[36]。苏门答腊岛和西双版纳橡胶树 SOS 和 EOS 在特定年份存在大幅波动, LOS 无显著变化^[30,42]。此外, 树龄或无性系繁殖后代因环境的不同, 从而影响物候年际变化的重复性及稳定性^[81]。橡胶树年际变化存在波动现象, 一方面与极端天气和环境气候异常等因素有关^[42], 另一方面橡胶树物候年际变化还与施肥有关, 施肥量越大, 当年气候对物候期的影响越小^[52]。但截至目前, 大尺度、长时序量化橡胶树物候时空异质的研究仍然很少, 以及预测橡胶树物候对气候变化的响应模式尚不明确。

3.2 橡胶树物候空间变化特征

橡胶树物候与树龄^[13]、海拔^[39]、品系^[83]和种植密度^[41]等有关。斯里兰卡境内 PB86 幼树的 SOS 和 EOS 均早于成龄大树, 低海拔地区的 SOS 和 EOS 均显著早于高海拔地区^[84], 但西双版纳较高海拔的 SOS 和 EOS 显著提前^[39]。马来西亚 RRIM 600、印

度尼西亚 GT1 比云研 277-5、云研 34-4 和印度尼西亚 PR107 的 SOS 和 EOS 提前 1~2 周, 且越冬期更短^[83]。橡胶树每行种植间隔 2 m, 混合间距为 4~12 m, 种植密度加剧对土壤水分、养分和光照的竞争, 种植密度增加显著抑制物候^[41]。总的来看, 小尺度范围内树龄、海拔、品系和种植密度对橡胶树物候空间特征均有明显规律, 但研究尺度较小, 连续性不足, 有必要进一步探讨大尺度下橡胶树物候空间特征。

4 橡胶树物候与气候变化

植被物候是反映气候变化响应的高度敏感指标^[85]。整理文献阐明橡胶树物候对温度、降水、冷胁迫、水分胁迫和日照时数的响应机制(表 2)^[30,86], 有助于提高对橡胶树如何应对未来气候变化的认识, 预测不同气候条件下的产胶量和病虫害的严重程度, 可为制定橡胶树物候适应气候变化的管理策略提供科学依据。

表 2 影响橡胶树物候指标的气候因素

Table 2 Climatic factors affecting rubber tree phenological indicators

气候因子 Climatic factor	研究区 Research area	展叶期 SOS	落叶期 EOS
温度	西双版纳 ^[30] 、海南岛 ^[37]	12 月相对较低温度	2 月较高温度
降水	西双版纳 ^[30]	2 月高降水量	2 月高降水量
温度+降水	苏门答腊岛 ^[42]	高降水和高温度	
冷胁迫	西双版纳 ^[88]		冷胁迫(<10 °C)
水分胁迫	东南亚 ^[89]		旱季需水量
日照时数	西双版纳 ^[83] 、苏门答腊岛 ^[42]	雨季日照时数	旱季日照时数

4.1 温度对橡胶树物候的影响

温度是影响橡胶树物候期的关键因子之一^[30,42,90-92]。橡胶树作为典型的热带作物, 在适应阈值内, 平均温度升高, 促使橡胶树 SOS 提前^[52]。同样, 冬季日温差对 SOS 有显著的推进作用^[30]。橡胶树物候与温度呈显著负相关, 其中温度每增加 1 °C, SOS 提前约 25 d、EOS 提前约 14 d^[42]。然而, 西双版纳的 SOS 和 EOS 与温度呈显著的正相关, 在其他气候变量不变的情况下, 温度对橡胶树物候的影响具有显著的滞后效应, 每年 12 月相对较低温度是次年 SOS 提前的关键因子, 2 月的较高温度延迟 EOS^[30,49]。冬季变暖趋势下, 可能会导致 SOS 提前和 EOS 延迟^[31,74,92]。橡胶树物候对温度变化表现出

复杂的响应机制, 全面的实验量化分析橡胶树物候与温度之间的关系, 充分考虑滞后效应, 明晰区域空间上物候对温度变化响应机制的理解。

4.2 降水对橡胶树物候的影响

降水对橡胶树物候期具有重要的调节作用^[12,83,93-94]。2 月降水量增加, 导致温度急剧下降, 间接延迟 SOS 和 EOS^[30]。1 月和 3 月降水量增加, 土壤湿度大, 不利于橡胶树萌芽, 5 月降水增加促进第二蓬叶淡绿盛期提前^[52]。此外, 苏门答腊岛季前 90 d 降水量减少导致 SOS 延迟^[42], 西双版纳高降水量延迟 EOS^[30]。在全球气候变暖的背景下, 极端干旱愈发频繁, 非常有必要研究降水与橡胶树物候之间的关系, 系统分析降水对橡胶树物候变化的潜

在影响^[87]。

4.3 其他气候因子对橡胶树物候的影响

西双版纳橡胶树严重落叶主要归因于冷胁迫的影响, 严重落叶导致光合速率显著降低, 进而限制碳水化合物储备的产生和积累, 导致较短的时间内落叶^[88]。在东南亚旱季明显的地区受水分胁迫的影响, EOS 较短, 相反, 如果旱季不明显, EOS 延长, 新叶生长缓慢^[89]。雨季日照时数和旱季日照时数是橡胶树物候变化的重要决定因素^[83], 雨量累积较多, 导致天气潮湿, 日照时数的较少延迟 EOS^[42]。目前, 已有研究多集中于物候与温度、降水的关系, 影响物候期的关键气候变量, 对气候因子的协同效应和大尺度气候变化对橡胶树物候响应机制研究较少^[2,41,95]。因此系统分析物候时空异质性的主要原因和年际变化潜在因素, 有利于加强未来橡胶林物候动态预测, 为揭示热带地区植被对气候变化的响应提供新见解。

5 挑战和展望

橡胶树物候对橡胶园生产管理和评估热带地区植被对全球气候变化的响应均有重要的科学意义。长远来看, 随着全球气候的变化橡胶树物候可能会呈现提前或延迟的趋势, 因此, 一些关键的挑战需在未来的研究中解决。

1) 多源遥感数据的协同重建。热区多云雨天气严重影响光学遥感影像获取, 影像质量是监测物候指标的关键。多源数据源融合算法是产业发展和科学研究的迫切需要, 提高不同数据源监测结果的可比性, 满足橡胶树物候实际应用中, 对高时空一致性和长时间序列的迫切需求。Landsat 和 Sentinel-2 影像以 30 m 的空间分辨率代替传统 250 m 单一的 MODIS 和叶绿素荧光影像数据, 以提高插值和时间平滑过程的数据可用性, 尽管 Sentinel-2 自 2015 年以来才开始使用, 可有效避免单一融合算法构建的时间序列数据不连续问题。遥感数据选择需要权衡时间和空间分辨率, 以便更好地描述橡胶树物候特征。未来研究需要更加关注多源遥感数据融合和人工智能算法相结合提高橡胶树物候监测精度。

2) 提取算法普适化。橡胶树物候指标提取算法普适性较低, 利用地面观测数据来验证遥感提取物候的方法已被广泛采用, 但橡胶树物候监测动态阈值设置存在较大差异。未来有必要明确 SOS 与 EOS

的动态阈值、平滑窗口大小、迭代次数、适应强度等的设定, 提高物候遥感监测准确性。人工观测方法按“定点、定人、定责、定标准、常年性”的原则, 详细描述橡胶树不同物候期的形态特征, 增加热带橡胶树物候数据长期收集和同步。减少动态阈值设置的经验性和主观性; 此外, 拓展物候相机、通量测量和无人机等新型观测手段, 从不同角度对遥感物候监测结果进行验证, 进一步提高橡胶树物候遥感提取的精确性。

3) 物候预测模型精准化。气候因子对区域尺度的物候响应可能不一样, 多种驱动因素之间的相互作用使橡胶树物候建模和预测复杂化, 改进橡胶树物候模型仍然具有挑战性。未来研究应考虑橡胶树物候对气候变化响应机制的尺度效应、时滞效应和协同效应, 结合物候生理指标综合性探讨橡胶树物候变化的潜在机制, 从单因素分析过渡到大尺度、多因素融合分析, 建立多源立体橡胶树物候预测体系, 以提高遥感预测模型在不同尺度和复杂气候条件下的适用性与有效性。

参考文献

- [1] REICH P B. Phenology of tropical forests: patterns, causes, and consequences [J]. Can J Bot, 1995, 73(2): 164–174. doi: 10.1139/b95-020.
- [2] WU D H, ZHAO X, LIANG S L, et al. Time-lag effects of global vegetation responses to climate change [J]. Glob Change Biol, 2015, 21(9): 3520–3531. doi: 10.1111/gcb.12945.
- [3] LI W X, HE J J, ZHANG H L, et al. Research progress in the phenology of *Heava brasiliensis* leaf [J]. Guangdong Agric Sci, 2019, 46(11): 37–44. [李文秀, 贺军军, 张华林, 等. 橡胶树叶蓬物候研究进展 [J]. 广东农业科学, 2019, 46(11): 37–44. doi: 10.16768/j.issn.1004-874X.2019.11.006.]
- [4] FU Y H, PIAO S L, DE BEECK M O, et al. Recent spring phenology shifts in western Central Europe based on multiscale observations [J]. Glob Ecol Biogeogr, 2014, 23(11): 1255–1263. doi: 10.1111/geb.12210.
- [5] MININ A A, VOSKOVA A V. Homeostatic responses of plants to modern climate change: Spatial and phenological aspects [J]. Ontogenez, 2014, 45(3): 162–169.
- [6] FU Y S, ZHANG J, WU Z F, et al. Vegetation phenology response to climate change in China [J]. J Beijing Norm Univ (Nat Sci), 2022, 58(3): 424–433. [付永硕, 张晶, 吴兆飞, 等. 中国植被物候研究进展及展望 [J]. 北京师范大学学报(自然科学版), 2022, 58(3): 424–433.]

- doi: 10.12202/j.0476-0301.2022170.]
- [7] XU B. Effects of global warming on plant phenology [J]. Popular Sci Technol, 2018, 20(9): 22–25. [徐波. 全球变暖对植物物候的影响 [J]. 大众科技, 2018, 20(9): 22–25. doi: 10.3969/j.issn.1008-1151.2018.09.007.]
- [8] ABERNETHY K, BUSH E R, FORGET P M, et al. Current issues in tropical phenology: A synthesis [J]. Biotropica, 2018, 50(3): 477–482. doi: 10.1111/btp.12558.
- [9] CAO M, ZOU X M, WARREN M, et al. Tropical forests of Xishuangbanna, China [J]. Biotropica, 2006, 38(3): 306–309. doi: 10.1111/j.1744-7429.2006.00146.x
- [10] CHEN H L, CHEN X M, CHEN Z L, et al. A primary study on rubber acreage estimation from MODIS-based information in Hainan [J]. Chin J Trop Crops, 2010, 31(7): 1181–1185. [陈汇林, 陈小敏, 陈珍丽, 等. 基于 MODIS 遥感数据提取海南橡胶信息初步研究 [J]. 热带作物学报, 2010, 31(7): 1181–1185. doi: 10.3969/j.issn.1000-2561.2010.07.025.]
- [11] LI Y C, ZHANG J, XUE Y F, et al. Remote sensing image extraction for rubber forest distribution in the border regions of China, Laos and Myanmar based on Google Earth Engine platform [J]. Trans Chin Soc Agric Eng, 2020, 36(8): 174–181. [李宇宸, 张军, 薛宇飞, 等. 基于 Google Earth Engine 的中老缅交界区橡胶林分布遥感提取 [J]. 农业工程学报, 2020, 36(8): 174–181. doi: 10.11975/j.issn.1002-6819.2020.08.021.]
- [12] ZHANG M J, ZHANG J H, LIU S J, et al. Research progress of rubber meteorology [J]. Chin Agric Sci Bull, 2015, 31(29): 191–197. [张明洁, 张京红, 刘少军, 等. 中国橡胶气象研究进展概述 [J]. 中国农学通报, 2015, 31(29): 191–197. doi: 10.11924/j.issn.1000-6850.casb15050181.]
- [13] ZAPATA-GALLEGO N T, ÁLVAREZ-LÁINEZ M L. Effect of the phenological stage in the natural rubber latex properties [J]. J Polym Environ, 2019, 27(2): 364–371. doi: 10.1007/s10924-018-1337-x.
- [14] CHEN X M, CHEN H L, LI W G, et al. Remote sensing monitoring of spring phenophase of natural rubber forest in Hainan Province [J]. Chin J Agrometeorol, 2016, 37(1): 111–116. [陈小敏, 陈汇林, 李伟光, 等. 海南岛天然橡胶林春季物候期的遥感监测 [J]. 中国农业气象, 2016, 37(1): 111–116. doi: 10.3969/j.issn.1000-6362.2016.01.014.]
- [15] LIU S J, ZHANG J H, LI W G, et al. Characteristics of rubber potential productivity in Chinese main rubber plantation areas [J]. J Northwest For Univ, 2018, 33(3): 137–143. [刘少军, 张京红, 李伟光, 等. 中国橡胶树主产区产胶能力分布特征研究 [J]. 西北林学院学报, 2018, 33(3): 137–143. doi: 10.3969/j.issn.1001-7461.2018.03.21.]
- [16] LAN G Y, CHEN B Q, YANG C, et al. Main drivers of plant diversity patterns of rubber plantations in the Greater Mekong Subregion [J]. Biogeosciences, 2022, 19(7): 1995–2005. doi: 10.5194/bg-19-1995-2022.
- [17] CHEN H J, XIE G S, YAO Q Q. Study of photosynthesis characteristics of grafted mini-seedling of *Hevea brasiliensis* at different phenophases [J]. Chin J Trop Crops, 2006, 27(3): 30–35. [陈海坚, 谢贵水, 姚庆群. 橡胶树籽苗芽接苗不同物候期的光合特性 [J]. 热带作物学报, 2006, 27(3): 30–35. doi: 10.3969/j.issn.1000-2561.2006.03.006.]
- [18] HE K, HUANG Z D. Rubber Culture in the Northern Part of Tropical Area [M]. Guangzhou: Guangdong Science and Technology Press, 1987: 19–23. [何康, 黄宗道. 热带北缘橡胶树栽培 [M]. 广州: 广东科技出版社, 1987: 19–23.]
- [19] LIN W F, HUANG S F. Study on sugar content of rubber seedlings at different leaf extraction phenological stages [J]. Chin J Trop Crops, 1993(2): 8–11. [林位夫, 黄守锋. 橡胶实生苗不同抽叶物候期的糖分研究 [J]. 热带作物研究, 1993(2): 8–11.]
- [20] LIN Y X, ZHANG Y P, ZHAO W, et al. Comparison of transpiration characteristics in different aged rubber plantations [J]. Chin J Ecol, 2016, 35(4): 855–863. [林友兴, 张一平, 赵玮, 等. 不同林龄橡胶林蒸腾特征的比较 [J]. 生态学杂志, 2016, 35(4): 855–863. doi: 10.13292/j.1000-4890.201604.006.]
- [21] MO S W. Phenology and tapping [J]. World Trop Agric Inform, 1979 (4): 9–13. [莫善文. 物候与割胶(国外文献综述) [J]. 世界热带农业信息, 1979(4): 9–13.]
- [22] YIN S S, CHUAN X X, WANG C M, et al. Occurrence of powdery mildew on *Hevea brasiliensis* in Southwest Yunnan [J]. Chin J Trop Agric, 2022, 42(3): 57–61. [殷山山, 钊钊仙, 王春梅, 等. 滇西南植胶区橡胶树白粉病发生规律 [J]. 热带农业科学, 2022, 42(3): 57–61. doi: 10.12008/j.issn.1009-2196.2022.03.011.]
- [23] RAZAK J A B A, SHARIFF A R B M, AHMAD N B, et al. Mapping rubber trees based on phenological analysis of Landsat time series data-sets [J]. Geocarto Int, 2018, 33(6): 627–650. doi: 10.1080/10106049.2017.1289559.
- [24] CHE X F, ZHANG J H, LIU S J, et al. System construction of rubber tree growth monitoring in Hainan Island [J]. J Meteor Res Appl, 2014, 35(1): 46–49. [车秀芬, 张京红, 刘少军, 等. 海南岛橡胶长势监测系统建设 [J]. 气象研究与应用, 2014, 35(1): 46–49.]
- [25] KOU W L. Spatio-temporal changes of rubber plantations based on multi-source remote sensing [D]. Kunming: Kunming University of Science and Technology, 2015. [寇卫利. 基于多源遥感的橡胶林时空演变研究 [D]. 昆明: 昆明理工大学, 2015.]
- [26] LI Y Y, ZHANG J, LIU C L, et al. Research on extraction and spatial-temporal expansion of rubber forest in five provinces of northern Laos

- based on multi-source remote sensing [J]. *For Res*, 2017, 30(5): 709–717. [李阳阳, 张军, 刘陈立, 等. 老挝北部5省橡胶林提取及时空扩张研究 [J]. *林业科学研究*, 2017, 30(5): 709–717. doi: 10.13275/j.cnki.lykxyj.2017.05.002.]
- [27] LIU Y Y, XIAO C W, LI P, et al. Extraction of mature rubber plantations based on the CR_{NBR} algorithm and spatio-temporal variations in Xishuangbanna [J]. *J Geo-Inform Sci*, 2019, 21(3): 467–474. [刘怡媛, 肖池伟, 李鹏, 等. 基于 CR_{NBR} 物候算法的西双版纳橡胶成林提取及时空变化研究 [J]. *地球信息科学学报*, 2019, 21(3): 467–474. doi: 10.12082/dqxxkx.2019.180431.]
- [28] LIU W J, LI J T, LU H J, et al. Vertical patterns of soil water acquisition by non-native rubber trees (*Hevea brasiliensis*) in Xishuangbanna, southwest China [J]. *Ecohydrology*, 2013, 7(4): 1234–1244. doi: 10.1002/eco.1456.
- [29] YANG J B, XU J C, ZHAI D L. Integrating Phenological and geographical information with artificial intelligence algorithm to map rubber plantations in Xishuangbanna [J]. *Remote Sens*, 2021, 13(14): 2793. doi: 10.3390/rs13142793.
- [30] ZHAI D L, YU H Y, CHEN S C, et al. Responses of rubber leaf phenology to climatic variations in Southwest China [J]. *Int J Biometeorol*, 2019, 63(5): 607–616. doi: 10.1007/s00484-017-1448-4.
- [31] ZHAI D L, WANG J, THALER P, et al. Contrasted effects of temperature during defoliation vs. refoliation periods on the infection of rubber powdery mildew (*Oidium heveae*) in Xishuangbanna, China [J]. *Int J Biometeorol*, 2020, 64(11): 1835–1845. doi: 10.1007/s00484-020-01969-y.
- [32] ZHAI D L, DONG J W, CADISCH G, et al. Comparison of pixel- and object-based approaches in phenology-based rubber plantation mapping in fragmented landscapes [J]. *Remote Sens*, 2018, 10(2): 44. doi: 10.3390/rs10010044
- [33] TIAN G H, LI H L, CHEN H L. Research on remote sensing extraction of planting information for rubber trees based on phenological characteristic parameters [J]. *Chin Agric Sci Bull*, 2013, 29(28): 46–52. [田光辉, 李海亮, 陈汇林. 基于物候特征参数的橡胶树种植信息遥感提取研究 [J]. *中国农学通报*, 2013, 29(28): 46–52. doi: 10.3969/j.issn.1000-6850.2013.28.010.]
- [34] YANG S Q, YANG C, GONG Y, et al. Phenological characteristics of net ecosystem carbon exchange in Hainan rubber forest ecosystem [J]. *Chin J Trop Crops*, 2022, 43(6): 1288–1296. [杨思琪, 杨川, 龚元, 等. 海南橡胶林生态系统净碳交换物候特征 [J]. *热带作物学报*, 2022, 43(6): 1288–1296. doi: 10.3969/j.issn.1000-2561.2022.06.022.]
- [35] TONG J H, LIU S J, CHEN X M, et al. Study on the variation characteristics of rubber trees climate suitability in China [J]. *Ecol Sci*, 2021, 40(1): 162–168. [佟金鹤, 刘少军, 陈小敏, 等. 中国橡胶树气候适宜度分布特征研究 [J]. *生态科学*, 2021, 40(1): 162–168. doi: 10.14108/j.cnki.1008-8873.2021.01.021.]
- [36] HU Y Y, DAI S P, LUO H X, et al. Spatio-temporal change characteristics of rubber forest phenology in Hainan Island during 2001–2015 [J]. *Remote Sens Nat Resour*, 2022, 34(1): 210–217. [胡盈盈, 戴声佩, 罗红霞, 等. 2001–2015 年海南岛橡胶林物候时空变化特征分析 [J]. *自然资源遥感*, 2022, 34(1): 210–217. doi: 10.6046/zrzyyg.2021110.]
- [37] LI N, BAI R, WU L, et al. Impacts of future climate change on spring phenology stages of rubber tree in Hainan, China [J]. *Chin J Appl Ecol*, 2020, 31(4): 1241–1249. [李宁, 白蓁, 伍露, 等. 未来气候变化对海南橡胶树春季物候期的影响 [J]. *应用生态学报*, 2020, 31(4): 1241–1249. doi: 10.13287/j.1001-9332.202004.002.]
- [38] LIU X N, FENG Z M, JIANG L G, et al. Rubber plantation and its relationship with topographical factors in the border region of China, Laos and Myanmar [J]. *J Geogr Sci*, 2013, 23(6): 1019–1040. doi: 10.1007/s11442-013-1060-4.
- [39] JIA K X. Study on growth change of the rubber plantation along an altitudinal gradient in Xishuangbanna, Southwest China [D]. Xishuangbanna: Xishuangbanna Tropical Botanical Garden, Chinese Academy of Sciences, 2006. [贾开心. 西双版纳三叶橡胶林生长随海拔高度变化研究 [D]. 西双版纳: 中国科学院西双版纳热带植物园, 2006.]
- [40] LI Y W, LAN G Y, XIA Y J. Rubber trees demonstrate a clear retranslocation under seasonal drought and cold stresses [J]. *Front Plant Sci*, 2016, 7: 1907. doi: 10.3389/fpls.2016.01907.
- [41] LIN Y X, ZHANG Y P, ZHOU L G, et al. Phenology-related water-use efficiency and its responses to site heterogeneity in rubber plantations in Southwest China [J]. *Eur J Agron*, 2022, 137: 126519. doi: 10.1016/J.EJA.2022.126519.
- [42] AZIZAN F A, ASTUTI I S, ADITYA M I, et al. Using multi-temporal satellite data to analyse phenological responses of rubber (*Hevea brasiliensis*) to climatic variations in South Sumatra, Indonesia [J]. *Remote Sens*, 2021, 13(15): 2932. doi: 10.3390/rs13152932.
- [43] OKUNEYE P A, AROMOLARAN A B, ADETUNJI M T, et al. Environmental impacts of cocoa and rubber cultivation in Nigeria [J]. *Outlook Agric*, 2003, 32(1): 43–49. doi: 10.5367/000000003101294253.
- [44] DOI H, GORDO O, MORI T, et al. A macroecological perspective for phenological research under climate change [J]. *Ecol Res*, 2017, 32(5): 633–641. doi: 10.1007/s11284-017-1480-1.
- [45] GOLBON R, COTTER M, SAUERBORN J. Climate change impact assessment on the potential rubber cultivating area in the Greater Mekong Subregion [J]. *Environ Res Lett*, 2018, 13(8): 084002. doi: 10.1088/1748-9326/aad1d1.

- [46] RIVANO F, VERA J, CEVALLOS V, et al. Performance of 10 *Hevea brasiliensis* clones in Ecuador, under South American Leaf Blight escape conditions [J]. Ind Crops Prod, 2016, 94: 762–773. doi: 10.1016/j.indcrop.2016.09.035.
- [47] OKUNEYE P A, AROMOLARAN A B, ADETUNJI M T, et al. Environmental impacts of cocoa and rubber cultivation in Nigeria [J]. Outlook Agric, 2003, 32(1): 43–49. doi: 10.5367/000000003101294253.
- [48] SABU T K, VINOD K V. Population dynamics of the rubber plantation litter beetle *Luprops tristis*, in relation to annual cycle of foliage phenology of its host, the para rubber tree, *Hevea brasiliensis* [J]. J Insect Sci, 2009, 9: 56. doi: 10.1673/031.009.5601.
- [49] ZHAI D L, XU J C. The legacy effects of rubber defoliation period on the refoliation phenology, leaf disease, and latex yield [J]. Plant Diversity, 2023, 45(1): 98–103. doi: 10.1016/j.pld.2022.01.003.
- [50] GUYOT J, LE GUEN V. A review of a century of studies on South American Leaf Blight of the rubber tree [J]. Plant Dis, 2018, 102(6): 1052–1065. doi: 10.1094/PDIS-04-17-0592-FE.
- [51] QIAN S W, CHEN X Q, LANG W G, et al. Examining spring phenological responses to temperature variations during different periods in subtropical and tropical China [J]. Int J Climatol, 2021, 41 (S1): E3208–E3218. doi: 10.1002/JOC.6918.
- [52] LIANG S P, CHEN B G. The phenological change law of rubber tree canopy in Gaozhou area [J]. Chin J Trop Crops, 1985(4): 19–25. [梁尚朴, 陈炳国. 高州地区橡胶树叶蓬物候变化规律 [J]. 热带作物研究, 1985(4): 19–25.]
- [53] TIAN G H, LI H L, CHEN H L. Research on remote sensing extraction of planting information for rubber trees based on phenological characteristic parameters [J]. Chin Agric Sci Bull, 2013, 29(28): 46–52. [田光辉, 李海亮, 陈汇林. 基于物候特征参数的橡胶树种植信息遥感提取研究 [J]. 中国农学通报, 2013, 29(28): 46–52. doi: 10.3969/j.issn.1000-6850.2013.28.010.]
- [54] RAO P S, SARASWATHYAMMA C K, SETHURAJ M R. Studies on the relationship between yield and meteorological parameters of para rubber tree (*Hevea brasiliensis*) [J]. Agric For Meteorol, 1998, 90(3): 235–245. doi: 10.1016/S0168-1923(98)00051-3.
- [55] WAN M W, LIU X Z. Chinese Phenology Observation Method [M]. Beijing: Science Press, 1979: 19–27. [宛敏渭, 刘秀珍. 中国物候观测方法 [M]. 北京: 科学出版社, 1979: 19–27.]
- [56] WANG M Y, LUO Y, ZHANG Z Y, et al. Recent advances in remote sensing of vegetation phenology: Retrieval algorithm and validation strategy [J]. Nat Remote Sens Bull, 2022, 26(3): 431–455. [王敏钰, 罗毅, 张正阳, 等. 植被物候参数遥感提取与验证方法研究进展 [J]. 遥感学报, 2022, 26(3): 431–455. doi: 10.11834/jrs.20211601.]
- [57] FAN H, FU X H, ZHANG Z, et al. Phenology-based vegetation index differencing for mapping of rubber plantations using Landsat OLI data [J]. Remote Sens, 2015, 7(5): 6041–6058. doi: 10.3390/rs70506041.
- [58] LEINENKUGEL P, KUENZER C, OPPELT N, et al. Characterisation of land surface phenology and land cover based on moderate resolution satellite data in cloud prone areas: A novel product for the Mekong Basin [J]. Remote Sens Environ, 2013, 136: 180–198. doi: 10.1016/j.rse.2013.05.004.
- [59] LUAN H J, TIAN Q J, ZHANG X X, et al. Trends on scaling research for land surface parameters in quantitative remote sensing [J]. Adv Earth Sci, 2018, 33(5): 483–492. [栾海军, 田庆久, 章欣欣, 等. 定量遥感地表参数尺度转换研究趋势探讨 [J]. 地球科学进展, 2018, 33(5): 483–492. doi: 10.11867/j.issn.1001-8166.2018.05.0483.]
- [60] SAVITZKY A, GOLAY M J E. Smoothing and differentiation of data by simplified least squares procedures [J]. Anal Chem, 1964, 36(8): 1627–1639. doi: 10.1021/ac60214a047.
- [61] JÖNSSON P, EKLUNDH L. Seasonality extraction by function fitting to time-series of satellite sensor data [J]. IEEE Trans Geosci Remote Sens, 2002, 40(8): 1824–1832. doi: 10.1109/TGRS.2002.802519.
- [62] BECK P S A, ATZBERGER C, HØGDA K A, et al. Improved monitoring of vegetation dynamics at very high latitudes: A new method using MODIS NDVI [J]. Remote Sens Environ, 2006, 100(3): 321–334. doi: 10.1016/j.rse.2005.10.021.
- [63] PIAO S L, FANG J Y, ZHOU L M, et al. Variations in satellite-derived phenology in China's temperate vegetation [J]. Glob Change Biol, 2006, 12(4): 672–685. doi: 10.1111/j.1365-2486.2006.01123.x.
- [64] BADHWAR G D. Automatic corn-soybean classification using landsat MSS data: I. Near-harvest crop proportion estimation [J]. Remote Sens Environ, 1984, 14(1/2/3): 15–29. doi: 10.1016/0034-4257(84)90004-X.
- [65] CLELAND E E, CHUINE I, MENZEL A, et al. Shifting plant phenology in response to global change [J]. Trends Ecol Evol, 2007, 22(7): 357–365. doi: 10.1016/j.tree.2007.04.003.
- [66] CHEN Y, ZHU Y, ZHANG J Y, et al. Study on dynamic forecast of the suitability degree of rubber powdery mildew weather condition in Yunnan Province [J]. J Catastrophol, 2019, 34(4): 148–152. [陈瑶, 朱勇, 张加云, 等. 云南省橡胶树白粉病流行天气适宜度预报研究 [J]. 灾害学, 2019, 34(4): 148–152. doi: 10.3969/j.issn.1000-811X.2019.04.025.]
- [67] CHEN X T. The mini-juvenile-type bud stick were cultured *in vitro* and the method of seed seedling bud grafting of *Hevea brasiliensis* [D]. Haikou: South China University of Tropical Agriculture, 2008. [陈雄庭. 橡胶幼态微型芽条的离体培育及其籽苗芽接法的研究 [D]. 海口: 华南热带农业大学, 2008.]

- [68] LI Q, WANG J, ZHOU J, et al. Effect of grafting factors on the success rate of root-graftings of rubber tree [J]. *J Trop Biol*, 2014, 5(4): 320–325. [李庆, 王军, 周琨, 等. 影响橡胶树根系嫁接成活的因素 [J]. *热带生物学报*, 2014, 5(4): 320–325. doi: 10.3969/j.issn.1674-7054.2014.04.003.]
- [69] TAO Z H, LUO W, LIN Z M, et al. Study on macro-element contents of leaves in new high-yield varieties of *Hevea brasiliensis* at different phenophases [J]. *Chin J Soil Sci*, 2009, 40(5): 1127–1130. [陶仲华, 罗微, 林钊沐, 等. 高产新品种橡胶树不同物候期叶片大量元素含量研究 [J]. *土壤通报*, 2009, 40(5): 1127–1130. doi: 10.19336/j.cnki.trtb.2009.05.032.]
- [70] South China Institute of Tropical Crops. Rubber Cultivation Science [M]. Beijing: Agricultural Press, 1979: 71–77. [华南热带作物学院. 橡胶栽培学 [M]. 北京: 农业出版社, 1979: 71–77.]
- [71] WANG J K, WANG L F. Study on drought response mechanisms in bag seedlings of GT1 of *Hevea brasiliensis* Muell Arg. [J]. *SW China J Agric Sci*, 2013, 26(6): 2271–2275. [王纪坤, 王立丰. 巴西橡胶树 GT1 袋装实生苗旱害响应机制研究 [J]. *西南农业学报*, 2013, 26(6): 2271–2275. doi: 10.16213/j.cnki.scjas.2013.06.083.]
- [72] WANG S M, LI Q, WANG J, et al. The effect of three-season drought on rubber plantations in Southeast Yunnan in the year of 2009 to 2010 [J]. *Trop Agric Sci Technol*, 2010, 33(4): 7–9. [王树明, 李芹, 王涓, 等. 2009/2010 年秋冬春连旱对滇东南植胶区橡胶树的影响 [J]. *热带农业科技*, 2010, 33(4): 7–9. doi: 10.3969/j.issn.1672-450X.2010.04.002.]
- [73] XU Q X. The relationship between some internal factors and cold resistance of rubber tree [J]. *Yunnan Hot Work Technol*, 1982(4): 7–10. [徐其兴. 橡胶树某些内在因素与抗寒力的关系 [J]. *云南热作科技*, 1982(4): 7–10. doi: 10.16005/j.cnki.tast.1982.04.003.]
- [74] ZHAI D L, THALER P, LUO Y Q, et al. The powdery mildew disease of rubber (*Oidium heveae*) is jointly controlled by the winter temperature and host phenology [J]. *Int J Biometeorol*, 2021, 65(10): 1707–1718. doi: 10.1007/s00484-021-02125-w.
- [75] CAI Z Y, SHI Y P, JIANG G Z, et al. Investigation and causes analysis of rubber powdery mildew and its controlling suggestions in Xishuangbanna region in 2017 [J]. *China Plant Prot*, 2018, 38(1): 29–33. [蔡志英, 施玉萍, 蒋桂芝, 等. 2017 年西双版纳地区橡胶树白粉病灾情调查与原因分析 [J]. *中国植保导刊*, 2018, 38(1): 29–33. doi: 10.3969/j.issn.1672-6820.2018.01.005.]
- [76] LIU S Q. Differences in inhibitory effects of tributanine aerosol on powdery mildew in different phenological stages of rubber trees [J]. *Yunnan Hot Works Technol*, 1996, 19(2): 21–22. [刘素青. 粉锈宁烟雾剂在橡胶树不同物候期对白粉菌抑制作用的差异 [J]. *云南热作科技*, 1996, 19(2): 21–22.]
- [77] WANG L, XIONG Y L, HE H N, et al. Investigation on pests and diseases of *Hevea brasiliensis* at Jiangbei in Jinghong City in 2017 [J]. *Trop Agric Sci Technol*, 2019, 42(2): 16–20. [王愣, 熊延林, 何海宁, 等. 2017 年景洪市江北橡胶树主要病虫害危害调查 [J]. *热带农业科技*, 2019, 42(2): 16–20. doi: 10.16005/j.cnki.tast.2019.02.004.]
- [78] RIGHI C A, BERNARDES M S. The potential for increasing rubber production by matching tapping intensity to leaf area index [J]. *Agroforest Syst*, 2008, 72(1): 1–13. doi: 10.1007/s10457-007-9092-3.
- [79] RU S F, LI Z H, LIANG D, et al. Progress in the research of tapping technology of natural rubber tree [J]. *J Chin Agric Mech*, 2018, 39(2): 27–31. [汝绍锋, 李梓豪, 梁栋, 等. 天然橡胶树割胶技术的研究及进展 [J]. *中国农机化学报*, 2018, 39(2): 27–31. doi: 10.13733/j.jcam.issn.2095-5553.2018.02.006.]
- [80] FEI M. How to raise trees to cut gum to prevent dead skin [J]. *Pract Rural Technol*, 2013(2): 16. [费墨. 如何养树割胶防死皮 [J]. *农村实用技术*, 2013(2): 16.]
- [81] OMOKHAFE K O, ALIKA J E. Phenetic relationship of rubber tree clones [J]. *Biol Plant*, 2003, 46(2): 217–222. doi: 10.1023/A:1022898510317.
- [82] GHOSH S, MISHRA D R. Analyzing the long-term phenological trends of salt marsh ecosystem across coastal LOUISIANA [J]. *Remote Sens*, 2017, 9(12): 1340. doi: 10.3390/rs9121340.
- [83] LIYANAGE K K, KHAN S, RANJITKAR S, et al. Evaluation of key meteorological determinants of wintering and flowering patterns of five rubber clones in Xishuangbanna, Yunnan, China [J]. *Int J Biometeorol*, 2019, 63(5): 617–625. doi: 10.1007/s00484-018-1598-z.
- [84] DE S LIYANAGE A. Influence of some factors on the pattern of wintering and on the incidence of oidium leaf fall in clone PB 86 [J]. *J Rubber Res Inst Sri Lanka*, 1976, 53: 31–38.
- [85] XU G X, LUO S X, GUO Q S, et al. Responses of leaf unfolding and flowering to climate change in 12 tropical evergreen broadleaf tree species in Jianfengling, Hainan Island [J]. *Chin J Plant Ecol*, 2014, 38(6): 585–598. [许格希, 罗水兴, 郭泉水, 等. 海南岛尖峰岭 12 种热带常绿阔叶乔木展叶期与开花期对气候变化的响应 [J]. *植物生态学报*, 2014, 38(6): 585–598. doi: 10.3724/SPJ.1258.2014.00054.]
- [86] LIU Q, FU Y H, ZHU Z C, et al. Delayed autumn phenology in the Northern Hemisphere is related to change in both climate and spring phenology [J]. *Glob Change Biol*, 2016, 22(11): 3702–3711. doi: 10.1111/gcb.13311.
- [87] GUARDIOLA-CLARAMONTE M, TROCH P A, ZIEGLER A D, et al. Local hydrologic effects of introducing non-native vegetation in a tropical catchment [J]. *Ecohydrology*, 2008, 1(1): 13–22. doi: 10.1002/

- eco.3.
- [88] LIN Y X, ZHANG Y P, ZHAO W, et al. Pattern and driving factor of intense defoliation of rubber plantations in SW China [J]. *Ecol Ind*, 2018, 94: 104–116. doi: 10.1016/j.ecolind.2018.06.050.
- [89] CARR M K V. The water relations of rubber (*Hevea brasiliensis*): A review [J]. *Exp Agric*, 2012, 48(2): 176–193. doi: 10.1017/S0014479711000901.
- [90] PRIYADARSHAN P M. *Biology of Hevea Rubber* [M]. Switzerland: Springer, 2017: 17–32. doi: 10.1007/978-3-319-54506-6.
- [91] XUE X X, REN C Q, XU Z W, et al. Characteristic of defoliation of rubber plantations (*Hevea brasiliensis*) in Hainan, China [J]. *Chin J Trop Crops*, 2022, 43(2): 377–384. [薛欣欣, 任常琦, 徐正伟, 等. 海南橡胶林落叶特征研究 [J]. *热带作物学报*, 2022, 43(2): 377–384. doi: 10.3969/j.issn.1000-2561.2022.02.019.]
- [92] YU H Y, HAMMOND J, LING S H, et al. Greater diurnal temperature difference, an overlooked but important climatic driver of rubber yield [J]. *Ind Crops Prod*, 2014, 62: 14–21. doi: 10.1016/j.indcrop.2014.08.001.
- [93] GUARDIOLA-CLARAMONTE M, TROCH P A, ZIEGLER A D, et al. Hydrologic effects of the expansion of rubber (*Hevea brasiliensis*) in a tropical catchment [J]. *Ecohydrology*, 2010, 3(3): 306–314. doi: 10.1002/eco.110.
- [94] TAN Z H, ZHANG Y P, SONG Q H, et al. Leaf shedding as an adaptive strategy for water deficit: A case study in Xishuangbanna's rainforest [J]. *J Yunnan Univ (Nat Sci)*, 2014, 36(2): 273–280. [谭正洪, 张一平, 宋清海, 等. 落叶作为热带雨林水分亏缺适应对策的研究: 以西双版纳热带雨林为例 [J]. *云南大学学报(自然科学版)*, 2014, 36(2): 273–280. doi: 10.7540/j.ynu.20130318.]
- [95] YEANG H. Synchronous flowering of the rubber tree (*Hevea brasiliensis*) induced by high solar radiation intensity [J]. *New Phytol*, 2007, 175(2): 283–289. doi: 10.1111/j.1469-8137.2007.02089.x.