滨海湿地遥感研究进展与展望

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摘 要：滨海湿地是连接海陆生态系统的交错过渡带，具有独特的结构和功能。它们不仅在固碳方面发挥重要作用，还为动植物种群提供关键栖息地，从而有效促进了生物多样性的维持和生态系统的健康。滨海湿地遥感作为重要的交叉学科方向，其历史可以追溯到20世纪70年代。在过去的50年中，滨海湿地遥感的热点主题从分布范围、生态参量反演逐步演进到生态系统功能以及碳水循环的研究。本文以Web of Science核心合集为数据库检索滨海湿地遥感的论文成果，基于VOCviewer识别了热点研究主题，并按时间顺序划分为1989年前、1990年—1999年、2000年—2009年、2010年—2019年和2020年至今5个历史阶段。通过将研究主题与新传感器的出现相结合，揭示了滨海湿地遥感的历史演变与研究现状。对于每个研究主题，详细分析了第一篇发表的文章以及被引次数较多的文章，深入解析了各个主题的发展脉络。最后，从空间大数据环境下的分类与范围制图、生态参量的精细反演、遥感与气候变化模型以及生态服务综合遥感4个方面进行未来研究趋势的展望。本研究将为了解滨海湿地遥感历史、热点和未来发展提供借鉴，并有助于指导相关领域的研究者制定更具前瞻性和针对性的研究策略，同时为政策制定者提供科学依据，以促进滨海湿地的有效保护和可持续管理。

关键词：滨海湿地，遥感，综述，热点研究，研究进展

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1 引 言

滨海湿地是陆地和海洋生态系统的交错过渡带，包括红树林、盐沼、滩涂、珊瑚礁和海草床等生态系统（Sun等，2015；赵焕庭和王丽荣，2000）。根据国际湿地公约的定义，滨海湿地的范围自海平面以下6 m（通常以大型海藻生长区外缘为限）至大潮高潮位之上，并延伸至与内河流域相连的淡水或半咸水湖沼以及海水上溯未能抵达的入海河的河段（李伟 等，2014；陆健健，1996）。狭义的滨海湿地主要指海岸附近的沼泽湿地，通常包括盐沼、红树林和其他潮间带湿地等，而不包括如湖泊、河流和水库等内陆的自然或人工水体（陈宜瑜和吕宪国，2003；毛德华 等，2023；杨永兴，2002）。作为最具生产力和生物多样性的生态系统之一，滨海湿地提供了多种生态服务功能，能够为动植物提供栖息地和食物资源，并在碳固存、水源涵养、生物多样性保护和气候调节

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等方面发挥着重要作用（Harrow-Lyle等，2023；Liu和Ma，2024；Ma等，2023；Sun等，2023a；Van Coppenolle和Temmerman，2020；Zhang等，2023a，2019）。鉴于滨海湿地在生态服务功能方面的重要性，采取综合措施保护和恢复滨海湿地，确保其生态功能得以持续发挥，是当前生态保护工作中的重要任务（刘润红 等，2017）。

近年来，由于人口增长、经济发展、城镇化进程加快以及基础设施建设的迅速推进，滨海湿地生态系统经历了显著变化，威胁到了其生态安全和服务功能的可持续发挥（Brown等，2021；Sun等，2015）。在联合国2030年可持续发展目标（SDGs）的近200个技术指标中，有75个与湿地相关，这充分体现了湿地保护在实现SDGs中的重要性（刘润红等，2023）。滨海湿地作为湿地生态系统的重要组成，其保护对于生态系统的健康和功能的持续发挥尤为关键。

滨海湿地可达性较差，遥感技术因具有节省人力、物力和财力的优势，已成为滨海湿地研究的有效手段（Villoslada等，2022；Wu等，2022）。随着遥感对地观测技术的不断提升，滨海湿地的遥感研究已经从简单的范围绘制和分类，扩展到包括生态系统过程表征和生物物理参数反演等复杂主题的研究（Song等，2021；Yin等，2024；邹乐 等，2023）。

基于上述背景，本文按研究主题和时间顺序进行阐述，旨在梳理和总结滨海湿地遥感研究的发展脉络。具体目标包括：（1）识别滨海湿地遥感的热点；（2）确定滨海湿地遥感研究的发展脉络，并提供时间顺序的历史演变；（3）预测滨海湿地遥感的未来研究方向。本研究能够为滨海湿地遥感研究与滨海湿地保护策略提供参考，促进滨海湿地学科的发展。

2 滨海湿地遥感热点研究

以滨海湿地遥感为对象，利用Web of Science核心合集数据库，通过关键词“coastal wetland remote sensing”检索相关论文，并利用VOSviewer对湿地遥感研究的热点关键词进行统计分析。根据图1，除与搜索关键词相同的3个关键词外，出现频次排名居前的关键词依次为“红树林”、“盐沼”、“分类”和“变化检测”等。红树林和盐沼是滨海湿地的两个重要研究对象，分类和变化监测是两种常见的分析手段。红树林和盐沼作为滨海湿地的重要组成部分，其生态功能和环境价值备受关注（Hang等，2024；Jia等，2018）。分类一直是滨海湿地的核心内容和重要基础，包括识别和区分不同类型的湿地及其群落等（刘瑞清 等，2021；肖锦成 等，2013）。变化检测包括滨海湿地的空间分布及其动态变化，主要关注由于城市化、工业化和基础设施建设等发展活动，导致滨海湿地被占用及其类型的转换。这包括滨海湿地内部不同类型的转变，以及湿地向其他土地利用类型（如农业、城市建设用地）的转变（Duan等，2024）。

从时间维度来看（图2），近年来出现的关键词包括“blue carbon”、“climate change”、“NDVI”和“biomass”等。这表明，滨海湿地的生物物理参数反演、健康状况分析、气候变化及碳循环等方面的研究已逐渐成为新的热点。在生物物理参数反演方面，主要涉及生物量、植被覆盖度、叶面积指数（LAI）和叶绿素含量等，这些参数对于了解湿地的生态状况和变化趋势至关重要（Klemas，2013）。对于滨海湿地的健康状况，遥感技术已广泛用于监测湿地的生态健康，包括植被健康状况、土壤湿度、盐度变化以及水质状况等（Lorrain-Soligon等，2023；Wu等，2024）。气候变化对滨海湿地的影响也逐渐成为当前研究的焦点。随着全球气候变化导致的海平面上升以及极端气候事件频率的增加，滨海湿地生态系统受到了巨大威胁（Chen等，2024）。因此，利用遥感技术进行长期监测和数据分析以探究气候变化对滨海湿地的多重影响变得尤为重要（宫宁 等，2016）。此外，滨海湿地在全球碳循环中扮演重要角色，尤其是其蓝碳储量近年来受到广泛关注（Duarte de Paula Costa等，2023）。遥感技术能够量化滨海湿地的碳储量和碳通量，评估湿地在碳吸存和碳排放方面的功能，为制定碳管理策略提供关键证据。

3 滨海湿地遥感的发展

本文以狭义的滨海湿地为研究对象，依据时间和技术手段对不同阶段的滨海湿地遥感研究主题进行总结，并系统梳理了其研究重点，为了解滨海湿地的历史发展和关键科学问题奠定了基础（图3）。图3不仅提供了滨海湿地遥感研究的宏观视角，也为后续小节深入探讨具体研究内容和成果提供了一个清晰的导向。

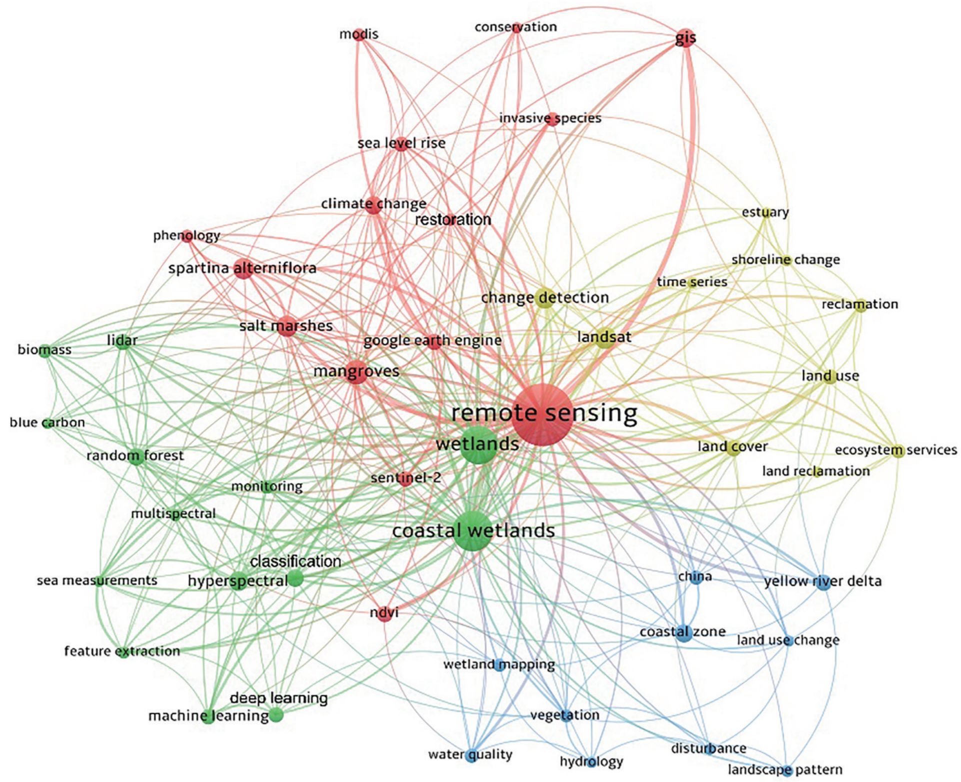

图1 滨海湿地遥感研究论文的关键词热点分析

Fig. 1 Keyword hotspot analysis of research papers on coastal wetland remote sensing

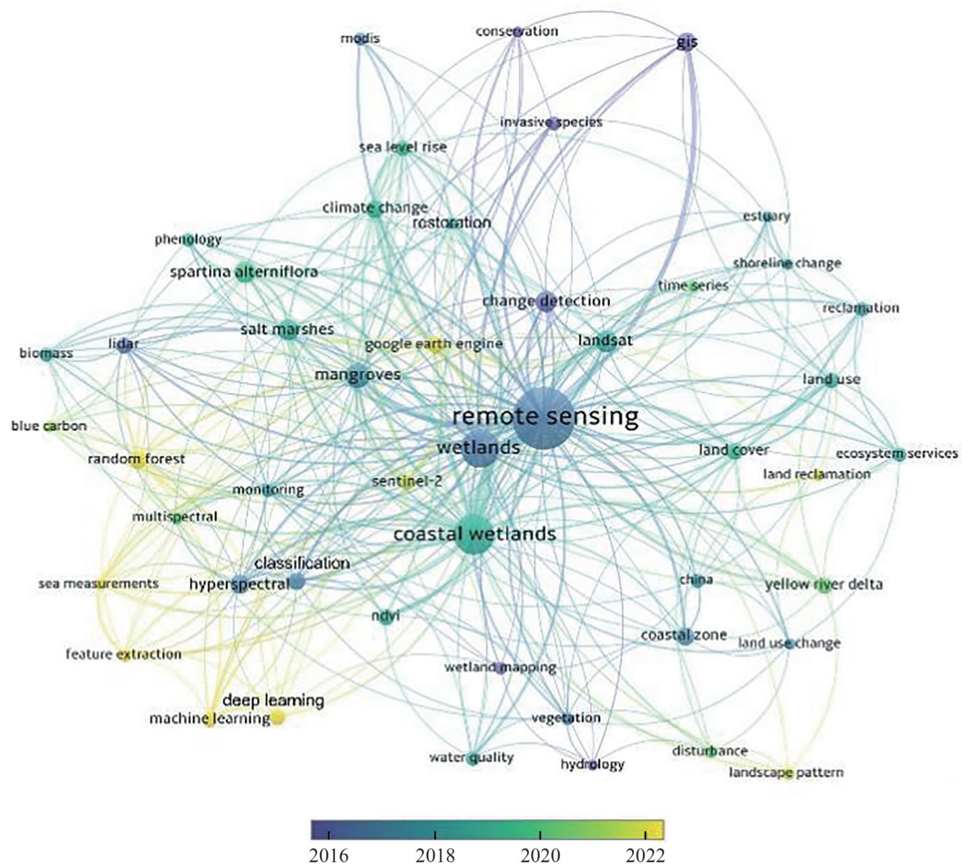

图2 时间维度上的滨海湿地遥感研究关键词热点分析

Fig. 2 Temporal keyword hotspot analysis of coastal wetland remote sensing research

图3　滨海湿地遥感研究发展

Fig. 3　Development of coastal wetland remote sensing research

3.1　1989年之前

滨海湿地生态系统具有高度的空间复杂性和时间变异性，精确描绘和追踪滨海湿地空间分布与动态变化的挑战在于其复杂的光谱特征和多样的时空变化模式。为了应对湿地植被、土壤和水体反射率的多样性，以及季节性和潮汐对数据解译和分析的复杂影响，需要采用高精度、实时且具有成本效益的测绘技术（Green等，1998）。

利用遥感数据绘制滨海湿地空间分布与动态变化的历史可以追溯到20世纪70年代。在初期阶段，研究主要依赖于航空摄影和地面调查。随着卫星遥感技术的发展，特别是自1990年代以来卫星数据的广泛应用，使更精确和全面地监测滨海湿地成为可能，为滨海湿地生态环境保护和可持续管理提供了关键的科学依据。在过去50年间，该领域论文数量呈现指数增长趋势（图4），相关研究主要关注3个方面：遥感数据源、分类方法以及空间/时间尺度。从遥感数据源方面来看，滨海湿地遥感研究起初依赖黑白航空照片、彩色照片和彩色红外相片来绘制滨海湿地的分布图（Alsid，1974）。这些传统的影像资料为湿地植被和地貌特征的初步绘制提供了重要依据。1972年，Landsat系列卫星的发射，开启了利用卫星数据绘制滨海湿地地图的新纪元，并显示出多光谱影像在沿海湿地规划和测绘项目中应用的巨大潜力（Kandus等，1999；Mumby等，1999；Ruiz-Luna和Berlanga-Robles，1999；Sader，1981）。随着技术的进步，印度遥感卫星（IRS-1A）（Sanjeevi，1996）、SPOT卫星（Gao，1999；Mumby，1997；Pasqualini等，1999）等光学遥感卫星，以及ERS-1 SAR数据（Dwivedi等，1999；Mougin等，1999；Rao等，1999）和AIRSAR数据（Dwivedi等，1999；Mougin等，1999；Rao等，1999）等多种数据源也相继用于滨海湿地的研究。总体来看，在20世纪后期，Landsat卫星成为该领域的主要数据源。进入21世纪，遥感技术得到了进一步的发展，卫星影像的分辨率显著提升。WorldView、Sentinel和高分等新卫星，为地球表面资源和环境变化监测提供了丰富而精确的数据支持。一些学者将来自不同平台和载荷的高分辨率数据应用于区域尺度的高精度滨海湿地测绘。这些数据源包括：激光雷达（LiDAR）数据（Chust等，2010；Collin等，2010；Jin等，2017）、WorldView（Heenkenda等，2014；Heumann，2011）、高分（Su等，2021；Zhang等，2021）、QuickBird卫星影像（Laba等，2008；Neukermans等，2008），以及无人机获取的高光

谱影像和多光谱影像等（Cao等，2018；闻馨 等，2020）。近年来，越来越多的学者关注多源数据融合，以提高滨海湿地监测精度（Chen等，2022a；谷玉双，2022；Wang等，2023）。

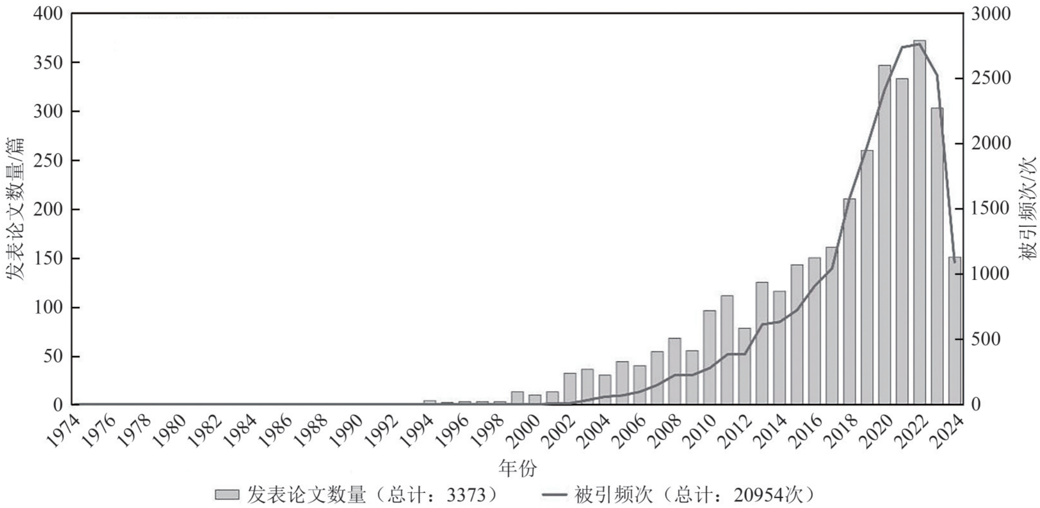

图4 自1970年以来滨海湿地空间分布与动态变化领域论文发表数量以及被引频次的变化趋势

Fig. 4 Trends in the number of publications and citation frequency in the field of coastal wetland spatial distribution and dynamic changes since 1970

从分类方法来看，相关研究通常采用基于像元或对象的机器学习分类方法或深度学习（刘家福等，2018；Murray等，2022b；Tian等，2020；Wang等，2019b；Zhang等，2012b）。近年，基于云平台的存储和计算能力显著提升，特别是在大尺度土地覆盖测绘方面展示了巨大潜力（王小娜 等，2022）。当前，越来越多的滨海湿地遥感领域相关研究关注于利用密集时序数据进行时序特征分析或统计分析（程丽娜等，2022；Jia等，2021；Wang等，2021；Yang等，2022；Zhang等，2022b；智超 等，2022）。

从研究的空间/时间尺度来看，滨海湿地空间分布与动态变化相关研究经历了从局部短期分析逐步扩展到大尺度、长时间序列的过程。早期研究主要聚焦于特定区域的湿地分布和变化，依赖较小空间尺度和短期数据。随着图像处理技术和计算能力的提升，研究范围扩展至国家、洲际乃至全球尺度，同时数据时间跨度延展至数十年，形成了长时间序列的数据集。在全球尺度上，目前已创建了一些重要的数据集，如1984年—2019年30 m分辨率的全球潮滩分布（Murray等，2022a，2019）、2020年10 m空间分辨率全球红树林空间分布等（Jia等，2023）。在国家尺度或洲际尺度，部分研究报告了1986年—2016年30 m空间分辨率的中国沿海滩涂分布（Wang等，2020）、2020年10 m空间分辨率中国潮滩分布（Jia等，2021）、1984年—2018年30 m空间分辨率中国沿海湿地分布（Wang等，2021）、2020年10 m空间分辨率东亚潮汐湿地分布（Zhang等，2022b）以及2020年中国主要红树林群落空间分布等（Zhao等，2024）。

3.2 1990年—1999年

1990年以后，滨海湿地的范围测绘已取得显著进展，研究重点逐渐转向对内部物种的结构与状态参数表征，尤其是叶面积指数、植被覆盖度以及植被健康状况等方面的遥感应用。此类研究的进展得益于遥感技术的不断提升，包括分辨率的提高和数据类型的丰富化。

3.2.1 LAI

叶面积指数LAI（Leaf Area Index）指的是单位地表面积上叶片面积的多少，是无量纲的量（Chen和Black，1992；Jonckheere等，2004；阎广建等，2016）。叶面积指数作为植被基础的生物物理变量，其与初级生产力、光合作用、蒸腾作用以及能量交换密切相关（Kamal等，2016；Zheng和Moskal，2009），同时也是将叶片尺度性状扩展到冠层尺度以及理解生物圈过程的重要中间输入变量（Asner，1998；Bréda，2003）。

滨海湿地植被LAI的相关研究最早可追溯到1984年，Bay（1984）基于野外实测数据探索了科西嘉岛Calvi海湾的海草生长动态和生产力。在

接下来的10年里，相关学者围绕着海草床和红树林这两种滨海湿地植被，基于野外实测LAI数据进行生产力估算以及探索种间种内性状变异研究（Amarasinghe 和 Balasubramaniam，1992；Mukai，1993）。野外实测采样方式虽然能够获取准确可靠的数据，然而该方法极其耗时耗力且难以获取长时序、大尺度的LAI变化，尤其对于生长在复杂地形上的滨海湿地植物，缺点更为突出（Green等，1997）。尽管在这段时期也有一些中空间分辨率的遥感影像（如Landsat TM），然而受限于遥感影像资料的未公开以及滨海湿地植物的生长环境，直到1996年，才出现第一篇利用遥感技术研究滨海湿地植被LAI的研究。Ramsey和Jensen（1996）首次探索了红树植物冠层反射率与LAI之间的关系，该研究也为后续基于遥感影像的滨海湿地植被LAI的相关研究提供了理论基础。随后，Green等（1997）建立归一化植被指数NDVI（Normalized Difference Vegetation Index）与实测LAI之间的关系，并基于该关系构建线性回归模型首次实现了红树植物LAI的遥感估测。这项研究也为后续滨海湿地植被LAI的遥感估测提供了方法指导。

截止到2024年7月，共计发表了197篇LAI相关文献（图5）。从遥感数据源来看，早期研究主要依赖于中、低分辨率影像，如MODIS、Landsat（Díaz和Blackburn，2003；Ramsey和Jensen，1996）、SPOT影像（陈永林 等，2017；Green等，1997），这些数据尽管分辨率不高，但为滨海湿地研究提供了基础。随着技术的进步，高分辨率影像逐渐成为研究热点，如IKONOS（Kovacs等，2005）、Worldview（Guo等，2021；Zhu等，2017）和无人机影像（Liu和Wang，2018）。从反演模型来看，线性回归模型（即经验模型）（Green等，1997；Guo等，2021；Tian等，2017）以及非参数回归模型（即机器学习模型）（Fu等，2022；王诗文等，2021；Zhu等，2017）是应用最为广泛的模型。然而，该类模型高度依赖于大量且具有代表性的实测验证数据（Verrelst等，2015，2019），使得该模型不具备通用性。近年来，物理机理模型因其能够在植被功能性状与冠层光谱反射率之间提供明确的物理联系，使得普遍认为该模型具有普适性和可转移性，也使得越来越多的研究开始关注该模型反演滨海湿地植被LAI（Binh等，2022，2024；Jia等，2024；Zhao等，2023a）。例如，Jia等（2024）基于物理机理模型模拟生成训练数据集，并利用机器学习算法训练反演模型，成功绘制漳江口红树林国家级自然保护区LAI分布图。

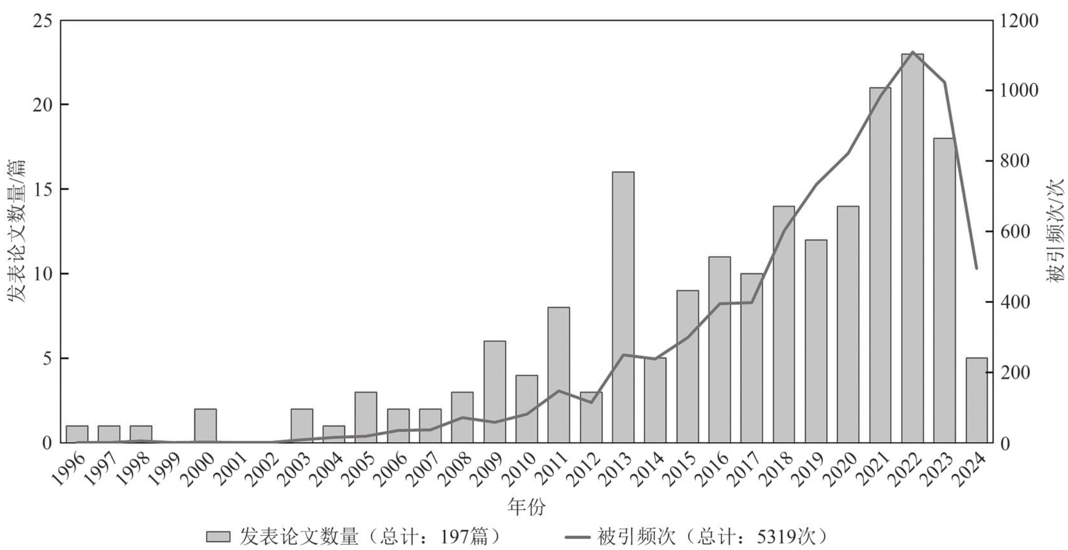

图5 自1990年以来滨海湿地植被LAI遥感反演领域论文发表数量以及被引频次的变化趋势

Fig. 5 Trends in the number of publications and citation frequency in the field of remote sensing inversion of coastal wetland vegetation LAI since 1990

3.2.2 植被覆盖度

植被覆盖度（FVC）为植被（包括叶、茎、枝）在地面上的垂直投影面积与植被总面积的比值（Jia等，2015），能够反映该区域内植被的生态特征、分布情况和密集程度，是衡量生态系统健康状况和土地利用类型的重要参数（Jing等，

2011；Wang等，2002）。迄今为止，FVC已广泛应用于农业、水土流失风险评估、干旱监测、环境评估等相关研究中（Gutman和Ignatov，1998；Matsui等，2005；Zhang等，2010）。近年来，沿海FVC受自然和人为因素的多重影响，在不同的时空尺度上发生了显著变化（Berlanga-Robles和Ruiz-Luna，2020；Maneas等，2019），尤其在滨海湿地中，气候、地形等自然因素和人类活动与FVC的变化密切相关（Coldren等，2019；Wu等，2018）。

早期的FVC研究主要通过传统的地面调查和样方分析方法来评估。归一化植被指数（NDVI）是植被密度和生长状况的指示因子，是评估FVC的重要指标，对监测区域和全球尺度的植被动态非常有效（Band等，1993；Lawley等，2016）。遥感技术的快速发展以及计算机及云计算平台等对卫星、无人机等地面监测数据的整合分析，为大规模植被动态监测提供了重要的数据支持和多维度的观测视角（Pettorelli等，2005）。谭清梅等（2013）对滨海湿地进行分类、改进的二元像素模型和归一化植被指数（NDVI），建立了植被覆盖度估计模型（VCEM），采用VCEM计算江苏省盐城研究区不同湿地类型植被覆盖度和等级水平，通过叠加覆盖分类图和湿地景观图，进一步分析了湿地植被覆盖度与其类型之间的关系。Hinkle和Mitsch（2005）利用地理参考遥感数据和地理信息系统（GIS）分析，确定了恢复地点的植被覆盖率以及自然恢复的参考沼泽。Jin等（2020）利用多源遥感影像提取黄河三角洲滨海湿地植被景观信息，对1984年—2018年Landsat TM/OLI遥感影像的植被覆盖度进行了长时间序列动态监测。LiDAR能够高效获取地表和植被的三维结构信息，包括湿地植被的垂直分布和立体结构，详细地分析湿地植被的空间格局和生长动态，汪煜等（2024）采用无人机多光谱激光雷达融合技术提取不同物候期互花米草冠层高度、植被指数、覆盖度和倒伏率，分析冠层高度与植被指数的时空变化特征，计算冠层高度与植被指数等参数的相关系数。

迄今为止，已经发表了约116篇滨海湿地植被覆盖度相关文献（图6），其中绝大多数文献以红树林、互花米草、海草为研究对象。相关研究主要集中在绘制和监测沿海湿地植被覆盖度，通常仅关注其分布范围和面积。动态监测长时间序列的植被覆盖率变化仍然较为缺乏。滨海湿地植被覆盖度研究为生态系统管理、生态恢复效果评估、全球变化研究以及实现生态系统可持续发展提供了重要的数据支持。

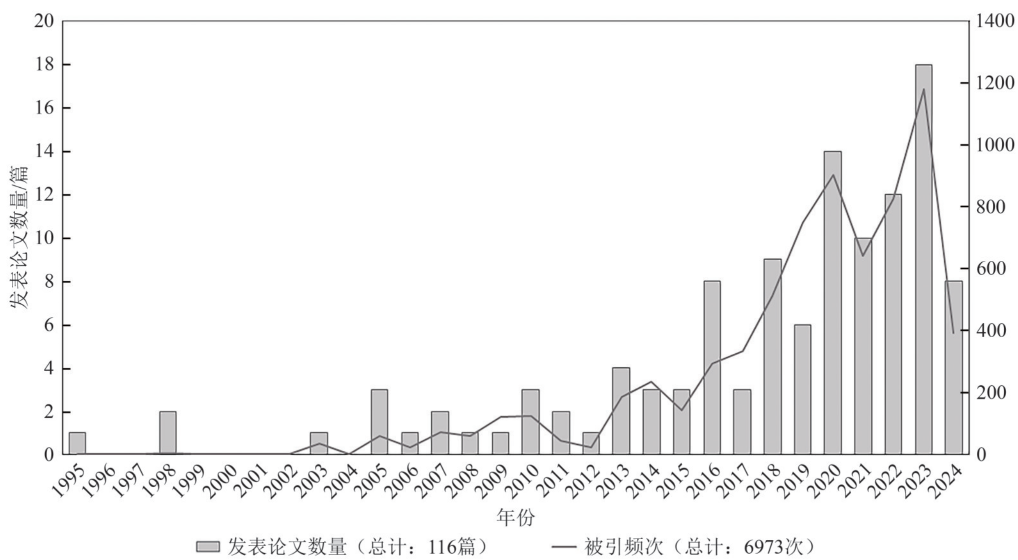

图6 自1990年以来滨海湿地植被覆盖度遥感领域论文发表数量以及被引频次的变化趋势

Fig. 6 Trends in the number of publications and citation frequency in the field of remote sensing of coastal wetland vegetation coverage since 1990

3.2.3 植被健康状况

植被健康状况通常是指植被的生长状况和生理状态，反映了植被在特定时间内的生态功能和健康水平。植物群落是森林健康的有效生态指标，林下植物可用作森林活力、健康和保护状态的依据（Ahmad等，2018；Haq等，2023）。

滨海湿地植被健康状况的相关研究最早可以追溯到1997年，由于沿海盐沼的范围和健康状况迅速下降，Zhang等（1997）使用恒定采样等非破坏性方法来评估盐沼生态系统功能和物种分布，通过野外测量获取植被冠层反射率、生物量和植被结构等参数。基于遥感卫星可以收集空间和光谱的植被健康状况信息，大多数研究人员使用Landsat系列（MSS，TM，ETM+和OLI）数据进行VHC分析（Erener，2011；Jiang等，2021；Lawley等，2016；Singh和Kogan，2002；Su等，2009）。Kumar和Das（2023）使用实地测量和Landsat 8 Operational Land Imager数据对红树林植被的健康状况进行估算。这些数据中应用了不同的植被指数进行植被健康指数（VHI）评估，使用不同类型的植被指标（NDVI、绿/红比和植被比指数（RVI））进行植被健康和生长监测，并显示植被受损的位置。Akumu等（2010）基于卫星影像使用最大似然标准算法进行监督分类，生成归一化差值植被指数，并对湿地植被的健康状况进行了评价。在许多研究中，基于多光谱卫星图像的VI与综合多标准分析一起用于植被或森林健康研究（Kayet等，2020；Phua和Minowa，2005；Sam，2022）。Ekumah等（2020）采用地理空间技术，利用结构、功能和恢复力指标，评估了Densu Delta、Sakumo II和Muni-Pomadze Ramsar遗址在32年期间的生态系统健康状况。遥感图像中地表植被状况的识别和监测取决于多光谱图像上植被的色调特征。因此，这些光谱变化有助于在监测植被状况和植被覆盖变化时提供相当精确的时空信息。

截止目前，共计发表了115篇滨海湿地植被健康状况相关文献（图7）。研究内容主要集中在植被类型和分布、植被生长状况及其生理特征、植被指数与健康评估，以及生态恢复与管理措施等方面。对滨海湿地植被健康状况的研究，在提升生态系统服务、缓解气候变化和保障湿地可持续性方面具有重要意义。

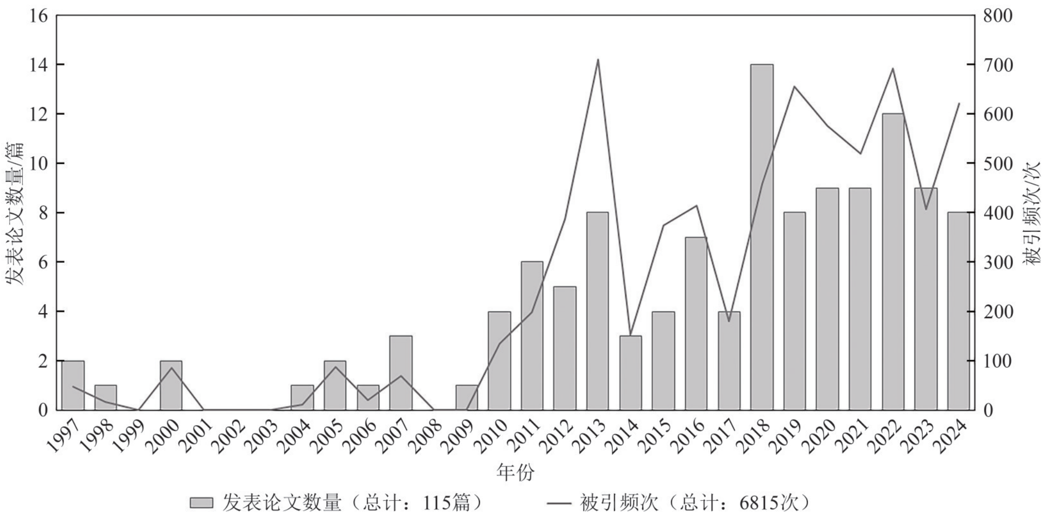

图7 自1990年以来滨海湿地植被健康状况遥感领域论文发表数量以及被引频次的变化趋势

Fig. 7 Trends in the number of publications and citation frequency in the field of remote sensing of coastal wetland vegetation health since 1990

3.3 2000年—2009年

过去的研究为后续更为精细的滨海湿地生态系统分析奠定了基础。2000年后，随着遥感技术的不断进步，以及对滨海湿地生态过程和机理的认知更加深入，滨海湿地遥感开启了对植物生理与个体水平参数的深入探索阶段，涵盖了叶绿素含量、生物量以及单木的精细测量。这一过渡标志着遥感研究从宏观的生态特征表征，逐步迈向了对滨海湿地生态系统内部动态的更深层次理解。

3.3.1 叶绿素

植被叶绿素含量（Chlorophyll content）指的是表层叶片中绿色光合色素的浓度，与植被的光合作用和生产力密切相关（Croft等，2017；Zhang等，2022a）。此外，叶绿素含量作为生态系统建模的重要参数，已成为表征植物健康状况、环境胁迫和干扰以及营养缺乏的有效指标（Houborg等，2011）。

滨海湿地植被叶绿素遥感研究最早可追溯到2003年，Joyce和Phinn（2003）基于高光谱数据分析了珊瑚礁底物叶绿素含量和光合能力。随后，Ustin等（2004）基于机载高光谱数据（AVIRIS）对能够表征植被色素含量的mNDVI（modified Normalized Difference Vegetation Index）进行计算和制图，并基于分布图探讨了污染对滨海盐沼植物的影响。在接下来的10年里，相关研究也主要围绕上述两方面开展工作：一是相关光谱波段或植被指数与叶绿素之间的关系（Ajithkumar等，2008；Ramsey和Rangoonwala，2005；Zhang等，2012）；二是以植被指数表征色素，并根据其分布图探索不同胁迫对植被的影响（Brun和Barros，2013）。直到2013年，Flores-de-Santiago等（2013）第一次利用便携式高光谱仪获取的高光谱数据进行了红树林叶片叶绿素a含量的估测。随后，随着遥感影像数据源的迅速发展，相关的遥感估测研究逐渐从高光谱数据拓展到高空间分辨率影像（如WorldView-2）（Heenkenda等，2015），并进一步向兼具光谱分辨率和空间分辨率均衡的影像（如Sentinel-2影像）转变（Jia等，2024）。

目前，滨海湿地植被叶绿素的相关文献（图8），绝大多数以红树林为研究对象。从研究内容来看，滨海湿地植被叶绿素遥感研究从早期探索光谱波段或植被指数与叶绿素之间的关系（Ajithkumar等，2008；Ramsey和Rangoonwala，2005）到基于两者关系进行遥感反演研究（Flores-de-Santiago等，2013；Gholizadeh等，2015；Heenkenda等，2015；Jia等，2024）。

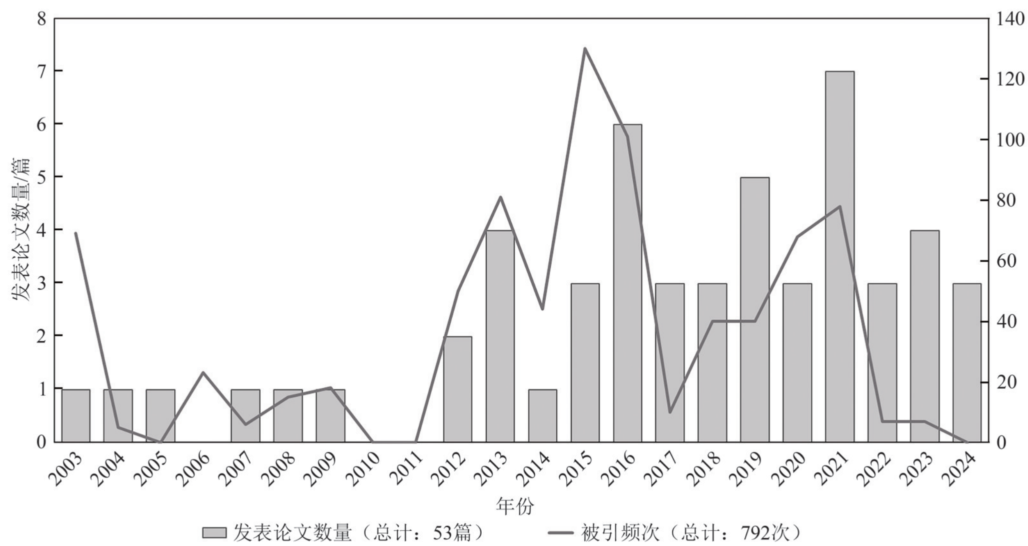

图8 自2000年以来滨海湿地植被叶绿素遥感反演领域论文发表数量以及被引频次的变化趋势

Fig. 8 Trends in the number of publications and citation frequency in the field of remote sensing inversion of coastal wetland vegetation chlorophyll since 2000

3.3.2 生物量

生物量是衡量生态系统生产力、碳储量的关键指标之一，且对碳循环和气候变化的理解具有重要意义（Cartus等，2012；Houghton，2005；Pan等，2011）。

滨海湿地生物量的研究最早可追溯到1962年，基于野外实测数据测量了盐沼中主要植物（如盐生草本植物）的生物量和初级生产力（Teal，1962），在接下来的二十年时间内，都是基于野外实测数据对生物量进行了一系列的研究（Houghton和Woodwell，1980；Nixon和Oviatt，1973），但这种方法难以对地形复杂的区域进行原位检测和测量，例如茂密的林下植被以及潮间带（Giri等，2011）。直到1993年，出现了第一篇利用遥感技术估算滨海湿地生物量的研究，Armstrong（1993）利用Landsat（TM）传感器的可见光波段对巴哈马附近浅滩海草进行了实证估算，该研究为后续基于遥感影像对滨海湿地植被生物量的研究提供了理论基础。然而，真正基于遥感大规模开展滨海湿地生物量研究是在2000年后，此后相关研究逐渐增多，标志着该领域进入快速发展阶段（图9）。尤其是高分辨率遥感和雷达卫星的快速发展，为

单木的清查提供了较为便利的手段（Hirata等，2010；Zhou等，2010）。近年来，基于单木尺度对滨海湿地生物量的研究逐渐增多，主要是利用高分辨率影像、无人机影像和无人机雷达数据进行分析（Qiu等，2019；Yin等，2024；Alejandro等，2020），以及部分研究将深度学习应用到单木尺度生物量的研究中，取得了较好的研究结果（Guillaume等，2022）。

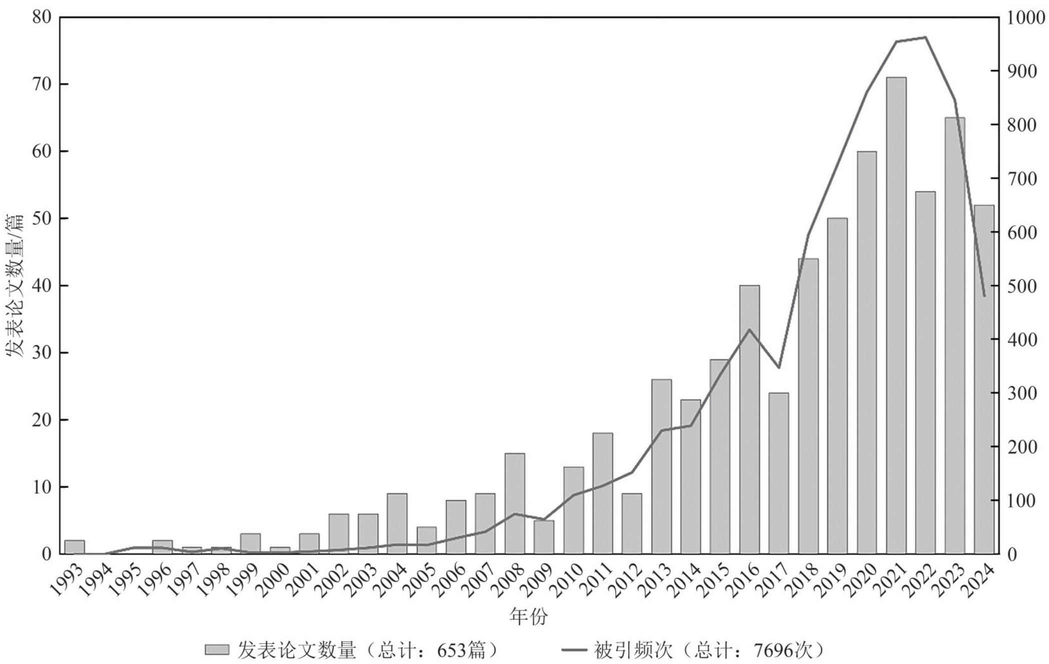

图9　自1900年以来滨海湿地植被生物量遥感反演领域论文发表数量以及被引频次的变化趋势

Fig. 9　Trends in the number of publications and citation frequency in the field of remote sensing inversion of coastal wetland vegetation biomass since 1900

迄今为止，已经发表了大约548篇关于滨海湿地生物量的研究。这些研究主要从不同类型的遥感数据和研究方法两个角度进行探索。从数据源的角度分析，主要包括高分辨率影像（Heenkenda等，2014；Roelfsema等，2014）、中分辨率影像（Armstrong，1993；Klemas，2001）（Blasco和Aizpuru，2002；Fromard等，2004）、雷达影像（Aja等，2022）、无人机多光谱影像（Doughty和Cavanaugh，2019）、无人机高光谱影像（Hill等，2014）和激光雷达数据（Chen等，2023；Ou等，2023）。从反演模型角度分析，主要包括线性回归模型（即经验模型）（Castillo等，2017；Koedsin等，2016）、非参数回归模型（即机器学习模型）（Pham等，2019；Zhu等，2015）以及近年来出现的高效益模型（Lemieux等，2023）。

3.4　2010年—2019年

随着基于遥感技术的滨海湿地制图和结构反演研究的广泛开展，滨海湿地的范围、分布和生态参数的准确性不断提升，为进一步深入研究其生态系统功能奠定了基础。滨海湿地生态系统功能是指诸如红树林、盐沼、滩涂、珊瑚礁和海草床等类型的滨海湿地生态系统内部及其与外部自然和社会联系而表现出的价值（欧阳志云 等，1999；Schulze和Mooney，1994）。

对于滨海湿地生态系统功能，学者们结合不同学科优化生态系统评估模型并结合恢复措施前后湿地情况验证评估有效性（Hauer和Smith，1998；Zedler和Callaway，2000）。此期间主要在小区域内基于实测数据和文献调查进行生态系统功能评价（Billen和Garnier，1997；Carletti等，2006；Rodrigo等，2003；Tuttle等，2008）。虽然实测数据可靠，但难以适用于大尺度长时序研究。2010年前，多数研究源于会议进行滨海湿地制图以及保护建议的探讨。伴随遥感发展，区域性和大尺度湿地生态系统的遥感研究开始广泛开展（Camacho-Valdez等，2013；Kaiser等，2013；Lao等，2013；Li等，2011；Ma等，2012）。其中滨海湿地生态系统服务、健康、安全及其与周边环境

响应机制类研究不断涌现（Camacho-Valdez等，2013；Nguyen等，2013）。但受限于遥感数据源有限性，评价单元过粗且时序较短，难以为湿地生态系统保护与恢复提供精确的决策建议（Camacho-Valdez等，2013）。2015年后开源免费的遥感数据日益丰富，基于长时序或多源遥感数据的滨海湿地生态系统功能评价研究逐渐增多，为滨海湿地保育恢复提供了数据支撑（Allen，2016；Xu等，2016；Yang等，2016）。而数据源也从早期中低分辨率影像逐渐转变为高分辨率无人机影像，并开始从生物功能多样性层面量化滨海湿地修复成效（Rahmania等，2020）。

目前，滨海湿地生态系统功能相关文献中，近40%的研究内容涉及滨海湿地生态系统固碳（图10）。随着学界对滨海湿地作为有效且长期碳汇的认知加深，遥感技术逐渐被应用于该生态系统的碳储量估算研究中（Benson等，2017；Bindu等，2020；Lagomasino等，2019）。包涵红树林、海草床和潮汐沼泽等在内的蓝碳生态系统BCEs（Blue carbon ecosystems）单位面积碳封存率最高（Hartig等，1997；Rogers等，2019）。近期研究发现气候变化和海平面上升将增加滨海湿地的有机碳埋藏率，但伴随湿地逐渐被淹没，其碳储量将减小（Kirwan和Mudd，2012）。为响应《联合国气候变化框架公约》减缓气候变化，基于遥感绘制滨海湿地地图以支持蓝碳恢复的研究兴起（Hang等，2024；Nuyts等，2024；Sun等，2023b）。其中红树林的固碳作用屡被提及（Almahasheer等，2017；Hamilton和Casey，2016；Nguyen等，2013）。Hamilton和Casey（2016）发布高时空分辨率全球红树林数据集对监测生长在海岸潮间带红树林的碳储存具有重要意义，引用量骤增（Hamilton和Casey，2016）。2010年后，滨海湿地遥感生态系统功能研究取得了显著进展，将滨海湿地视为一个耦合的生态系统，强调了其在全球碳循环、能量平衡以及应对气候变化方面的重要作用。

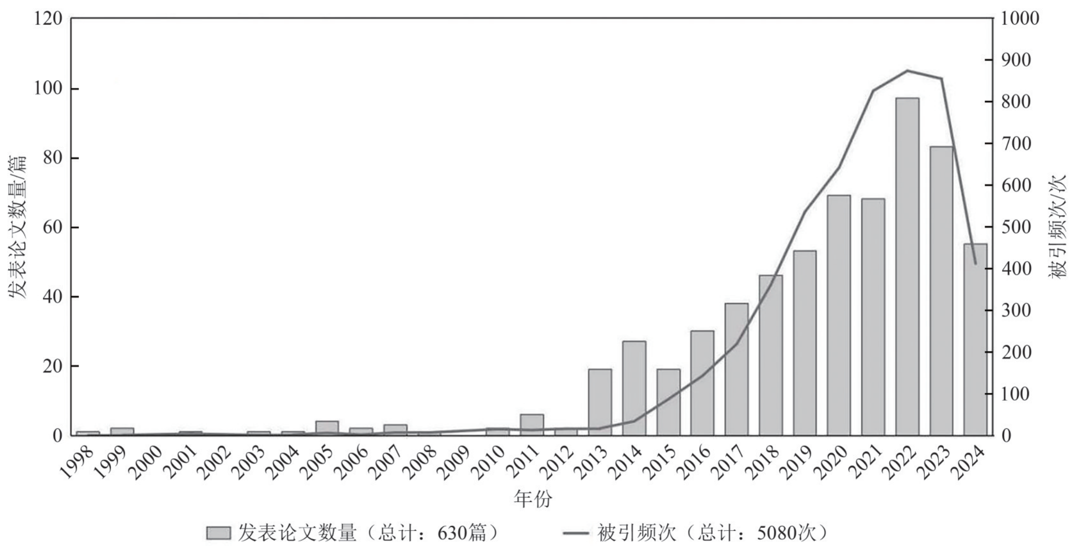

图10 自1900年以来基于遥感的滨海湿地生态系统功能领域论文发表数量以及被引频次的变化趋势

Fig. 10 Trends in the number of publications and citation frequency in the field of remote sensing of Coastal Wetland Ecosystem Functions Since 1900

3.5 2020年至今

生态系统的物质循环指组成生物体的元素在非生物环境和生物群落二者间的循环过程。碳循环与水循环在地球系统产生多过程关联，降水、蒸发和蒸腾影响碳移动和分布，大气圈的碳变化通过影响气候改变蒸发和降水模式（Fosberg，1989）。碳水循环整体对地球系统内部各圈层影响深远（Barron等，1989；Berner，1999）。

碳循环是指生产者以光合作用从大气获取碳，并合成有机物，后经消费者和分解者以呼吸作用和分解作用将碳返还大气的过程（Dioxide，1985；Olson等，1978）。基于遥感的滨海湿地固碳研究在3.4节已述。碳排放CE（Carbon Emission）指温室气体的排放。研究CE在减缓气候变化和提高生态系统弹性以支持可持续发展具有重要价值。Yan

等（2008）基于塔基测量和MODIS时间序列并去除潮汐和厌氧甲烷产生造成的碳损失影响来估算崇明岛河口湿地2005年碳预算（Yan等，2008）。近期的滨海湿地碳排放研究聚焦于分析人类活动与自然因素的影响。其中，人类活动包括土地开垦与恢复、塑料垃圾污染以及芦苇冬季收割等；自然因素则涉及海岸带底栖生物的扰动、潮汐动态以及泥炭地的转化等对湿地碳排放的影响（Huang等，2024；Lu等，2024；Tan等，2020；Xiao等，2024；Zhao等，2023b）。

水循环是指大气降水通过蒸发、蒸腾又进入大气的往返过程（Nebel和Wright，1993）。降水与遥感关联较浅，因此本节概述基于遥感进行水蒸散发的相关研究。蒸散量ET（Evapotranspiration）是地表水分蒸发与植物体内水分蒸腾的合称（Goyal和Harmsen，2013；Novák，2012）。研究ET可辅助生态系统模型建模以模拟碳水动态过程并预测气候。基于遥感计算滨海湿地ET的研究可回溯至2013年，Glenn利用Terra卫星上的MODIS传感器获取的气象数据和增强型植被指数来估算ET（Hartig等，1997）。同年基于通量站和微气象观测计算国家尺度ET的研究出现（Xiao等，2013）。早期ET研究或需要地面观测数据等辅助数据且计算复杂，或数据精度不高且存在一定的不确定性（Reio等，2023）。现今，基于遥感的全球滨海湿地ET估计研究仍在探索（图11）。Mokhtari等（2023）提出了一种不需要热量数据且简化计算的实际ET估算模型。为解决缺乏一致的土壤湿度数据ET模型受限问题，学者将美国国家航空航天局（NASA）土壤湿度主动被动任务（SMAP）中的卫星增强的表面和根区土壤湿度纳入ET估计模型中（Kim等，2023）。利用遥感模拟碳水循环的研究仍存在不确定性，综合多学科视野探索不同尺度和系统循环间效应或成为解决路径。

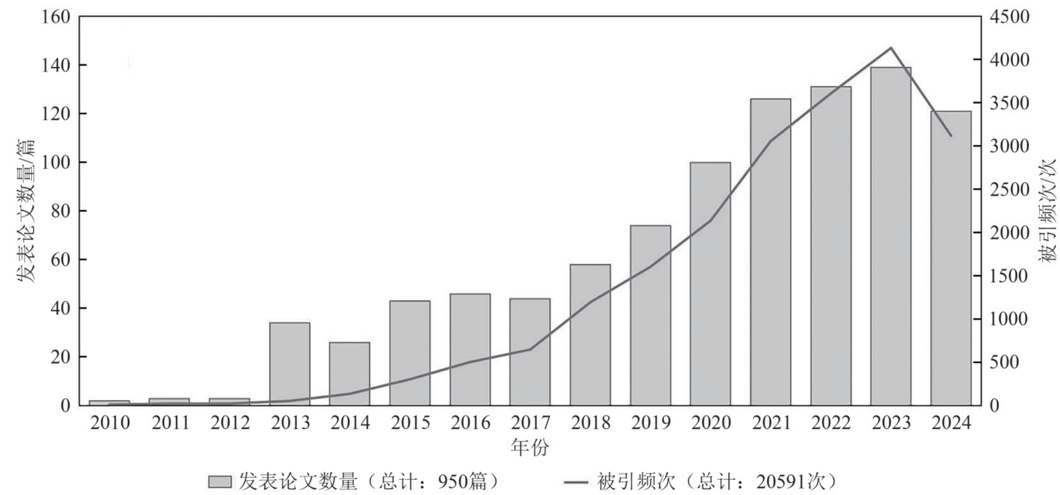

图11　自2010年以来基于遥感滨海湿地碳水循环领域论文发表数量以及被引频次的变化趋势

Fig. 11　Trends in the number of publications and citation frequency in the field of remote sensing of coastal wetland carbon and water cycles since 2010

4　未来发展方向

基于上文所述，随着传感器的进步，滨海湿地遥感研究迎来了许多关键突破。研究内容逐渐从空间范围的绘制，扩展到物种结构与状态参数的监测、生理与个体水平参数的分析，最终深入到生态系统功能和物质循环的探究。展望未来，我们将探讨几个重要的发展方向和趋势，包括新型传感器的应用、数据处理技术的进步以及遥感技术在湿地生态系统研究中的多样化应用，以展示滨海湿地遥感技术的巨大潜力和广阔应用前景。

4.1　分类与范围制图

滨海湿地的分类与范围制图是其他滨海湿地遥感研究的基础，但大尺度（大陆或全球尺度）的研究仍较为稀缺。2011年，Giri等（2011）基于Landsat使用混合监督和无监督数字图像分类技术完成了全球红树林湿地制图。随后Zhu和Gong（2014）建立了全球湿地适宜性分布数据集，Zheng等（2015）创建了全球湿地验证样本数据库（GWVS）。然而以往的湿地与沿海潮汐湿地产品因数据和技术的限制，存在低频次、低空间分辨率

等问题，难以准确反映湿地动态变化。传统的制图方法往往依赖于单一数据源，难以全面捕捉湿地的时空变化特征，这限制了对湿地生态系统的精确监测和保护。目前，随着遥感技术和计算能力的迅速提升，遥感数据在滨海湿地分类和制图的应用中已经展现出高分辨率和多源化的发展趋势（Yan和Niu，2024；Zhang等，2023b）。在未来大数据时代背景下，如何实现时间密集和高空间分辨率的大范围滨海湿地精细研究是一个巨大挑战。值得提到的是，随着对地观测系统的不断完善，高光谱、时间和空间分辨率的“三高”数据（H^3）的获取已经成为可能（Liu等，2022）。随着计算机技术的革新，面向遥感大数据的云存储和云计算技术也在快速发展。例如，GEE（Google Earth Engine）作为可视化计算和处理分析云平台，已经集成了Landsat、MODIS、Sentinel等遥感数据集并持续更新，使全球规模滨海湿地数据产品的高效开发成为可能（Wang等，2019a）。因此，开展高频、大尺度和长时序的滨海湿地分类与范围绘制研究成为滨海湿地遥感未来发展的关键方向之一。

此外，人工智能技术在未来滨海湿地遥感的分类和制图中前景广阔（Han等，2022）。滨海湿地类型丰富、形态多样且边界模糊，传统的解译工作通常依赖于丰富的经验（Schmidt和Skidmore，2003）。近年来，自动化遥感解译技术不断进步，已被证明对数据融合等关键任务有效（Shen等，2016；Zhang和Zhang，2022）。同时，以深度学习为代表的人工智能技术正在革新遥感数据处理和分析方法。虽然深度学习已经开始应用于滨海湿地遥感监测，但现有方法源于计算机视觉领域，未来的研究需开发针对滨海湿地遥感的深度学习模型，并建立大规模的湿地遥感解译数据集，以提高模型的准确性和鲁棒性（钟燕飞 等，2022）。尽管“数据驱动”的方法在处理海量多源遥感影像方面表现优异，但许多神经网络模型的可解释性仍不足（Hong等，2021）。为此，新一代的人工智能需要引入“知识引导”的新范式，通过融合地学知识图谱和专家先验信息，增强模型的可解释性和推理能力（Chen等，2022b）。通过人工智能技术，可以提高遥感图像的分类精度和自动化程度，为滨海湿地遥感研究提供更强大的工具和方法。

4.2 生态参量的精细反演

基于遥感的滨海湿地生态参量反演的主要障碍包括：（1）滨海湿地环境的高度动态性和复杂性；（2）地面实况数据收集困难；（3）生态参量不完善。我们认为该类研究可以在以下两个方面进行改进。

（1）滨海湿地环境的高度动态性和复杂性。滨海湿地环境具有高空间和时间异质性，其植被、水体和土壤的状态会因季节变化、潮汐影响和人类活动等因素而不断变化（Duan等，2024）。这种动态性和复杂性使得相关生态参量的精细反演变得更加困难。为了解决这一问题，未来的研究可以利用多时相、多源遥感数据捕捉湿地环境的动态变化，并采用先进的数据融合技术和机器学习算法，提高数据的时空一致性和精度，从而增强生态参量反演的准确性。

（2）野外调查数据收集困难。滨海湿地的现场数据收集受到地理位置、气候条件和人力资源的限制（毛德华 等，2023）。为克服这一障碍，研究可以通过无人机和自动化传感器网络等新技术，增强数据收集的灵活性和覆盖范围。此外，建立长期的湿地观测站和数据共享平台，可以有效整合和利用现有的地面观测数据，为遥感反演提供更为丰富和准确的参考数据。

（3）生态参量不完善。目前，关于滨海湿地生态参量反演的研究正在逐渐增多，包括碳储量、净初级生产量、蒸散量和生态系统健康状况等（Zhang等，2024；Zhao等，2024）。然而，当前滨海湿地生态参量体系尚不完善，部分关键参数缺乏统一的定义和标准，这限制了遥感反演的精度和可靠性（胡雪红 等，2020）。近年来，森林和草地等生态系统在关键生态参量的监测技术和产品研发方面取得了显著进展（Du等，2024；Suleymanov等，2024）。但针对滨海湿地生态系统生态参量的精确量化仍存在不足（Meng等，2019）。生态参量的不完善和不规范，使得不同研究之间的对比和对滨海湿地健康状况的综合分析变得困难。为应对这一问题，未来的研究需要制定和完善湿地生态参量的标准体系，确保各类参数的准确定义和统一度量。

4.3 遥感与气候变化模型

滨海湿地在应对全球气候变化中扮演着重要

角色，然而它们自身也受到气候变化的显著影响（Day等，2008）。滨海湿地作为“蓝碳”储存库，通过捕获和储存大量的大气二氧化碳，有效地缓解了气候变化（Lovelock等，2023）。此外，滨海湿地能够调节局地气候，减少洪水风险，并提供生态系统服务（Li等，2020）。然而，气候变化对滨海湿地本身也带来了显著影响。随着全球气温上升和海平面上升，滨海湿地面临着盐度变化、侵蚀加剧、栖息地丧失和生物多样性减少等挑战（Nevermann等，2023）。极端气候事件的频发，如飓风和暴雨，也加速了湿地的退化。因此，理解滨海湿地与气候变化之间的相互作用至关重要。气候变化模型作为模拟和预测气候系统变化的重要工具，通过求解大气、海洋、冰盖和陆地的物理和化学方程，能够模拟全球和区域气候变化的长期趋势和潜在影响（Pitman和Stouffer，2006）。在未来的滨海湿地遥感发展中，气候变化模型可以用于预测湿地面临的气候压力和变化趋势。同时，也能深入理解和预测不同气候情景下湿地生态系统的响应，为制定有效的保护和管理策略提供科学依据。

4.4 生态服务综合遥感

滨海湿地提供了诸多关键生态系统服务，包括防洪减灾、水资源供给、水质净化、野生动物栖息地保护以及水生生物的生存保障等（Jiang等，2015）。然而，近年来，由于滨海湿地的损失和退化，导致的生态环境问题日益凸显，严重影响了这些生态系统服务的稳定性和持续性（Jia等，2018）。因此，强化生态服务综合遥感可能成为滨海湿地遥感未来发展的热点方向之一。我们认为，通过集成多源遥感数据与生态模型，可以全面监测湿地的动态变化，评估生态服务功能的时空分布及其变化趋势。此外，利用遥感技术进行高精度的生态系统服务量化与评估，有助于制定有效的湿地保护与管理策略。同时，引入机器学习和大数据分析方法，可以进一步提升生态服务监测的精度和效率，为政策制定提供科学依据，确保滨海湿地的可持续发展。

5 结 语

滨海湿地遥感作为研究滨海湿地生态系统的重要手段，为其保护和可持续管理提供了坚实的科学支撑。因此，对滨海湿地遥感研究的系统综述能够为该领域的进一步发展提供重要的学术参考。在本文中，我们识别了滨海湿地遥感的热点研究主题，并按时间顺序划分为1989年前、1990年—1999年、2000年—2009年、2010年—2019年和2020年至今5个历史阶段。1989年前，研究主要集中在利用遥感技术绘制滨海湿地的范围。进入90年代后，范围测绘取得显著进展，研究重点逐渐转向湿地内部物种的结构与状态参数表征，主要包括LAI、植被覆盖度和植被健康状况。随着技术的进一步发展，21世纪的研究开始深入探讨植物的生理和个体水平参数，如叶绿素和生物量等。2010年后，范围和生态参数反演的精度不断提高，研究逐步扩展至滨海湿地的生态系统功能。进入2020年，研究进一步聚焦于滨海湿地的物质循环，开启了对这一关键生态系统更为全面的理解。未来，我们认为高频、大尺度和长时序的滨海湿地分类与范围是未来的关键方向之一，人工智能技术的应用能够为滨海湿地研究提供更强大的工具和方法。此外，对生态参量精细反演研究中的瓶颈突破，将为滨海湿地研究的深入推进奠定基础。考虑到滨海湿地与气候变化之间的相互作用，通过气候变化模型实现更精准的模拟和预测也将是未来的重要研究内容。最后，通过集成多源遥感数据与生态模型，并引入机器学习和大数据分析方法，能够进一步提高滨海湿地生态服务的综合遥感能力。

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Advances and perspectives in coastal wetland remote sensing research

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Abstract: Coastal wetlands are transitional zones connecting terrestrial and marine ecosystems, characterized by unique structures and functions, encompassing mangroves, salt marshes, tidal flats, coral reefs, seagrass beds, and so on. These ecosystems collectively represent one of Earth's most productive biogeochemical systems, where the interplay of tidal dynamics, vegetation zonation, and sediment transport creates distinct ecological niches. They play a crucial role in carbon sequestration and provide critical habitats for various plant and animal species, thereby effectively supporting biodiversity and ecosystem health. The complex feedback mechanisms and dynamic changes in these areas require monitoring approaches capable of capturing multi-scale dynamics. Remote sensing has the capacity to assist in the monitoring, conservation, and sustainable management of these vital ecosystems by providing spatially explicit, cost-effective, and temporally consistent observations. Coastal wetland remote sensing, as an interdisciplinary field, dates back to the 1970s. Over the past 50 years, the focus of coastal wetland remote sensing research has evolved from mapping distribution and retrieving ecological parameters to investigating ecosystem functions and material cycles. This trend indicates that the remote sensing of coastal wetlands has a promising future in supporting ecosystem-based management and global change research. In this study, we retrieved relevant publications on coastal wetland remote sensing from the Web of Science Core Collection and used VOSviewer to identify key research themes, which were then chronologically divided into five historical phases: before 1989, 1990—1999, 2000—2009, 2010—2019 and 2020 to the present. By linking research themes to the emergence of new sensors, we revealed the historical evolution and current status of coastal wetland remote sensing. This sensor-theme coupling analysis revealed pivotal technological transitions that facilitated novel insights into coastal wetland remote sensing processes. For each research theme, we analyzed the first published article and the most cited articles, providing an in-depth examination of the developmental trajectory of each theme. Importantly, our analysis demonstrates that coastal wetland remote sensing has evolved from early extent mapping to structural parameter retrieval, then physiological trait estimation, and ultimately ecosystem function assessment and biogeochemical cycle quantification, reflecting a paradigm shift from pattern observation to in-depth ecological process. Finally, we outlined future research directions from four aspects: large-scale classification and mapping, fine-scale inversion of ecological parameters, remote sensing and climate change model and comprehensive remote sensing of ecosystem services. These priorities emphasize the need for multi-sensor fusion, tighter integration with ecological process models, and transformative applications of artificial intelligence technologies. This study provides valuable insights into the history, key research areas and future directions of coastal wetland remote sensing, and reinforces the significance of coastal wetland remote sensing in ecosystem-based management, particularly in addressing emerging global and climate change challenges. Through a systematic review of multidisciplinary research progress over the past five decades, this study synthesizes the co-evolutionary dynamics between sensor technology advancements and wetland ecological research needs. It also outlines critical future development trajectories, offering guidance for researchers in developing forward-looking and targeted research strategies, and providing policymakers with scientific evidence to promote effective conservation and sustainable management of coastal wetlands under accelerating environmental pressures.

Key words: coastal wetlands, remote sensing, review, research hotspots, research progress

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