

Optical and Microwave Remote Sensing in Monitoring Mangrove Phenology

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Abstract

Mangrove forests are critical coastal ecosystems that play an important role in the global carbon cycle, yet they are increasingly threatened by human disturbance and habitat loss. Effective phenology monitoring is therefore essential for conservation and restoration. This paper reviews recent progress in applying optical and microwave remote sensing to mangrove phenology monitoring, with a focus on Sentinel-2 optical imagery and Sentinel-1 SAR data. Optical remote sensing can effectively capture vegetation physiological changes through indices such as NDVI and EVI, but its performance is strongly limited by persistent cloud cover in mangrove regions. In contrast, microwave remote sensing enables all-weather observation and can compensate for optical data gaps, although both phenological and non-phenological factors influence its backscatter signals. The paper further discusses the complementarity of the two data types and summarises current fusion strategies at the data, feature, and decision levels. It concludes that integrating optical and microwave remote sensing, together with ground validation under a space-air-ground framework, offers strong potential for developing more reliable and continuous mangrove phenology monitoring systems.

Keywords

remote sensing, mangrove, optical sensing, microwave sensing

1. Introduction

Mangrove forests are important coastal ecosystems, but human activities have severely reduced their areas. This continuous loss leads to the degeneration of ecological functions. Under the circumstances, monitoring mangrove phenology is very crucial for effective ecological conservation and restoration.

Traditional mangrove phenology monitoring has relied mainly on manual ground observations. While this method provides precise data, its coverage is limited, and the cost is high. Therefore, there is a requirement for other methods that can offer more extensive coverage at a lower cost. Remote sensing technology presents an effective solution to this problem. In practical applications, Sentinel-2 optical images are widely used to extract phenological information. However, in mangrove areas, images are often affected by cloudy and rainy weather, leading to data gaps and undermining the sustainability of monitoring [1]. In comparison, Sentinel-1 SAR can operate in adverse weather, which is a great advantage for continuous monitoring in cloudy coastal areas. This satellite-monitoring platform is sensitive to vegetation, providing

a new method for mangrove phenology monitoring that complements optical methods. However, the ability of microwave remote sensing for phenology monitoring has not yet been systematically evaluated across different ecosystems or mangrove species. The similarities and differences between microwave and optical data for phenological characterisation, as well as effective fusion methods to integrate both sources, require further study and development. Furthermore, data derived from remote sensing phenology requires validation against ground observations. Litterfall dynamics directly reflect mangrove phenology. In this context, building a validation system that integrates space, air, and ground is critical to enhancing the reliability and accuracy of monitoring results [2].

This article offers a systematic review of relevant research progress in this field. The main aims focus on comparing what optical and microwave remote sensing can and cannot do for mangrove phenology monitoring, and on exploring the similarities, differences, and potential relationships between the two data types. The article also summarises the key methods used for ground validation of remote sensing phenology parameters. In practical terms, the general purpose is to offer a reference for developing an all-weather phenology monitoring approach that would actually work in the typical cloudy and rainy conditions of mangrove regions.

2. Relevant Operating Principle

2.1 Principle of Optical Remote Sensing

Optical remote sensing mainly uses electromagnetic waves, including visible light, near-infrared, and shortwave infrared bands. The principle is that it passively receives electromagnetic wave energy that comes from ground objects that reflect or emit it. Different ground objects, such as water, vegetation, and soil, exhibit different behaviours when sunlight reaches the ground [3]. They reflect and absorb light at various wavelengths in different ways, and this differential response essentially defines their spectral characteristics. Optical remote sensing sensors record the energy reflected and form an image. By analysing the brightness values across different image bands, the types and states of ground objects can be inferred.

2.2 Principle of Microwave Remote Sensing

Microwave remote sensing uses electromagnetic waves in the microwave band to detect. It operates actively or passively. Active sensors, namely radar, work by emitting microwave signals to the ground [3,4]. The sensor will capture the returning signal when the wave reflects off the ground surface. By analysing the returning signal's intensity, phase, and time delay, information about the ground surface can be obtained, including distance, degree of roughness, and dielectric constant. Meanwhile, passive sensors can detect the microwave emissions from objects. This mode is usually used to detect factors like temperature and moisture.

3. Application of Optical Remote Sensing in Mangrove Phenology Monitoring

Optical remote sensing is a key approach for monitoring mangrove phenology because it captures temporal changes in vegetation reflectance across the visible-to-near-infrared spectrum, where mangroves exhibit distinctive spectral characteristics. By constructing time-series vegetation indices, this method can quantify canopy dynamics and retrieve phenological stages. A representative study in the Sundarbans region of the Ganges Delta used Savitzky–Golay filtering on EVI and LSWI time-series data to extract 13 phenological features, achieving an overall accuracy of 91.02% with a Kappa coefficient of 0.892, outperforming methods based directly on spectral information [5].

In general, optical remote sensing for mangrove phenology monitoring involves three main steps: data acquisition, index construction, and phenology extraction. First, satellite sensors such as Landsat and Sentinel-2 periodically acquire multispectral imagery of target mangrove areas. Because healthy mangrove leaves strongly absorb red light and reflect near-infrared radiation, seasonal changes in pigment content, water content, and leaf structure lead to corresponding changes in spectral reflectance. Based on these spectral responses, researchers commonly construct vegetation indices such as NDVI and EVI to characterise canopy greenness, while red-edge indices such as REIP and NDVI_{re} are increasingly used to capture subtler biochemical changes [6]. Finally, to reduce noise and derive reliable phenological parameters, time-series fitting methods such as

the Double Logistic Function, asymmetric Gaussian functions, and Savitzky–Golay filtering are applied to identify critical seasonal transition points.

4. Potential of Microwave Remote Sensing in Mangrove Phenology Monitoring

Synthetic Aperture Radar (SAR) systems work by emitting microwave signals and receiving the backscattered echoes. These signals can go through clouds, rain, and fog. Therefore, SAR is particularly useful for compensating for optical remote sensing's limitations under poor weather conditions. The C-band SAR data from Sentinel-1 offer a stable revisit cycle, enabling continuous phenology monitoring over time.

Several factors influence microwave backscatter intensity. These factors include vegetation canopy structure, dielectric constant, and surface roughness. The dielectric constant itself is closely related to vegetation water content. In a mangrove environment, VH polarisation is more sensitive to volume scattering, mainly showing information from branches and leaves in the canopy. In comparison, VV polarisation is influenced by ground-surface and canopy interactions jointly [5]. Therefore, the time-series dynamics of the VH and VV backscatter coefficients can exhibit seasonal variations in theory. These changes mainly affect canopy biomass and water content, which together encode phenological information. For example, a clear increase in leaf density and water content in the canopy may enhance volume scattering, which, in turn, may lead to VH backscatter values rising.

5. Comparison of Optical and Microwave Remote Sensing and Combination

Optical and microwave remote sensing operate on completely different principles. They show clear complementarity in monitoring mangrove phenology. Optical remote sensing itself provides rich spectral information about vegetation characteristics. However, its effectiveness is constrained by persistent data loss in regions prone to cloudy and rainy conditions. Microwave remote sensing can monitor in all weather conditions, which is an advantage, but its sensitivity to specific phenological parameters still needs further testing. Most comparative studies focused on analysing the relationship between temporal characteristics and phenological parameters. However, these studies tend to be limited to uncommon cases. There is still a lack of expandable conclusions, and comprehensive research on data fusion methods has not been conducted [5,6]. Therefore, finding an effective approach to improve the accuracy of mangrove phenology monitoring is crucial. The approach is expected to combine the high signal-to-noise ratio of optical data with the all-weather monitoring capability of microwave data.

Existing research on combining optical and microwave data is mainly conducted at three levels: data-level fusion, feature-level fusion, and decision-level fusion. Data-level fusion combines raw remote sensing data directly to obtain a continuous time series. In contrast, spatio-temporal fusion algorithms, such as the STARFM model and its advanced versions, have been widely applied [7]. These approaches can effectively combine the high spatial resolution of Sentinel-2 and the high temporal resolution of Sentinel-1. They can make up for the lack of optical data during cloudy periods, significantly improving the quality of fitted phenology curves [8]. Moreover, machine learning methods such as Random Forest and support vector machines can be employed. They establish a nonlinear mapping between optical and microwave data, enabling the prediction of optical vegetation indices during cloudy and rainy periods.

In feature-level fusion, phenological parameters such as SOS, POS, and EOS are first extracted from each data source separately. After the initial extraction step, a fusion analysis is performed using weighted averaging or evidence theory to reduce uncertainty in the final results. Decision-level fusion involves making a comprehensive judgment based on professional knowledge or predefined rules, and this process is performed after phenological information has been separately extracted from each data source. There is a practical example that uses optical data during cloud-free periods and microwave data during cloudy periods. Although fusion methods show promising application prospects, they face great challenges in mangrove phenology monitoring. One of the challenges is that different sensors have different response mechanisms to vegetation's physical properties, which can lead to systematic bias in the fusion results. Future work should place greater emphasis on advancing studies of physics-driven fusion models, as this would help improve both the robustness and broader applicability of these methods.

6. Conclusion

Monitoring mangrove phenology is of great importance for environmental research because it enhances understanding of the global carbon cycle, supports ecosystem condition assessment, and provides a scientific basis for conservation and restoration. With the rapid development of remote sensing technology, the combined use of optical and microwave remote sensing has shown strong potential to improve mangrove phenology monitoring and to support broader studies of global environmental change.

However, significant challenges remain. Mangroves are evergreen forests, and their phenological signals are often weak and easily obscured by background noise. In addition, mangrove regions are typically cloudy and rainy, which makes it difficult for optical remote sensing to obtain continuous, high-quality time-series observations. Although microwave remote sensing can operate under all weather conditions, its signals are often affected by multiple sources of interference, which complicates interpretation. At the same time, the strong internal heterogeneity of mangrove ecosystems further complicates monitoring. Different mangrove species and habitats may exhibit distinct phenological patterns, making it difficult to infer ecosystem-level information from single-pixel observations accurately.

To address these limitations, future research should advance both methodology and technology. A major priority is to strengthen multi-source data fusion to integrate information from different sensors more effectively. In addition to making full use of existing satellite constellations, researchers should explore incorporating canopy structural information from emerging remote sensing technologies to reduce information gaps. Methodologically, research should move beyond purely data-driven approaches toward more physically based frameworks, especially by developing inversion algorithms that couple radiative transfer models with ecological process models. Meanwhile, machine learning and deep learning can serve as useful tools for analysing complex nonlinear relationships in multi-source data. Most importantly, long-term, multi-scale ground validation networks covering different mangrove types and climate zones are needed to ensure the reliability and practical applicability of remote sensing phenology products and to support the development of an operational space-air-ground collaborative monitoring system.

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Conflicts of Interest

The authors declare no conflict of interest.

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