
APPLICATION OF SPECTRAL REMOTE SENSING FOR CROP PHENOLOGY ESTIMATION

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Introduction

In the context of a changing climate, phenological studies have become increasingly important. Crop phenology examines the sequence of plant growth phases and their development in response to various abiotic and biotic factors, with particular emphasis on meteorological elements such as temperature, rainfall, humidity, radiation, and light exposure. Understanding the timing of phenological events and their variability can support the effective management of agricultural practices that require advanced knowledge of specific crop development stages. With insights from phenology, optimal cultivars can be selected, and practices like irrigation, fertilization, and harvesting can be scheduled appropriately. In addition to helping to identify the current effects of climate change on natural systems, phenological data are essential inputs for models that predict growth and yield, ecosystem productivity, and land surface processes. Climate warming significantly affects cereal production by accelerating crop phenology, which reduces the period available for plants to assimilate CO₂, ultimately leading to yield declines (Fatima *et al.* 2020). Higher temperatures have been shown to advance the anthesis and maturity stages of both rice and wheat in the Lower Gangetic Plains (Chandran *et al.* 2021).

To quantify the growth stages of cereals in a standardized manner, various cereal growth scales have been developed, with the Zadok's scale being the most widely used. Traditional methods for monitoring phenology, known as ground phenology, involve repeated visual observations of phenological events by trained personnel. While these methods provide high precision and frequent data, they are often expensive, labour-intensive, and time-consuming, yielding point values from specific locations. Although ground observations offer high accuracy, they are limited in capturing continuous phenological information over large areas. For evaluating the temporal and geographical dynamics of phenology at regional or global scales, remote sensing technology provides a potent substitute. This technology enables the monitoring of vegetation's biophysical properties, such as pigment concentration and leaf structure, and provides continuous surface observations across space and time. Based on the sensor platform used, phenology monitoring methods can be grouped into three categories: satellite platforms with low-frequency time-series data, unmanned aerial vehicle (UAV) platforms equipped with digital and multispectral cameras for high-frequency data, and near-surface platforms with digital and thermal infrared cameras that capture ultra-high-resolution images continuously (hourly). Vegetation remote sensing mainly relies on passive sensors or active sensors to collect electromagnetic reflectance information from plant canopies.



The daily revisit capability of MODIS, which produces 8–16 day composite products, has made it a popular choice for large-scale crop phenology studies and monitoring. For the same area, Sentinel-2 can capture about ten times more pixels than Landsat-8, thanks to its superior spatial resolution and higher revisit frequency. Optical sensor data for phenology monitoring primarily comes from MODIS, NOAA-AVHRR, Landsat, IRS, SPOT, and HJ-1A/B satellites, while Sentinel-1 provides microwave data, which is invaluable as it can capture data under day-night, foggy, and cloudy conditions, making it effective in any weather. Phenological information is extracted from satellite data using time-series vegetation indices, which are spectral transformations of multiple bands designed to highlight vegetation properties. These indices require continuous remote sensing imagery over large crop areas to accurately distinguish phenological differences. Common vegetation indices used in phenology studies include the Normalized Difference Vegetation Index (NDVI), Enhanced Vegetation Index (EVI), and the two-band Enhanced Vegetation Index (EVI2). NDVI is sensitive to chlorophyll levels, while EVI is more responsive to variations in canopy structure, like canopy architecture and leaf area index (LAI). The choice of vegetation index depends on the application, but they all utilize similar optical bands differentiated by color. Globally, NDVI and EVI are generated with 16-day compositing intervals at resolutions of 1 km and 500 m. MODIS-EVI time series have shown better alignment with in situ observations of green-up dates compared to MODIS-NDVI (Peng *et al.* 2017). Upadhyay *et al.* (2015) observed that EVI more distinctly reflects index value variations than other indices, with peak values occurring around the Dough stage and high values during Flowering, Milking, and Dough stages. Vegetation indices for winter wheat show a rapid increase at emergence and tillering stages and a rapid decline at maturity. Additionally, indices like NDGI and NDPI can remove the influence of snow cover or soil background, providing a clearer view of vegetation greenness under these conditions (Huang *et al.* 2022).

Paddy rice fields are typically prepared by flooding a few days before transplanting seedlings, maintaining at least one wet growing season in shallow floodwater. This intermittent flooding creates a distinct signature, making the identification of flooding and transplanting periods essential for accurately extracting rice planting areas. Monitoring these changes in surface water and vegetation in paddy fields requires spectral bands or indices that are sensitive to both water and vegetation. Studies indicate that a pixel is classified as water-covered when $LSWI > NDVI$, $LSWI > EVI$, and $LSWI > 0.2$ (Paul *et al.* 2020; Dong *et al.* 2015; Shi *et al.* 2013). RADARSAT-2, TerraSAR-X, and SCATSAT-1 scatterometer datasets have proven effective in tracking rice phenology (Palakuru *et al.* 2019).

Despite advancements in using remote sensing imagery in order to map crop phenology at field scales, several challenges remain, particularly for smallholder systems. These include the limited spatial resolution of publicly available satellite data, heterogeneous cropping patterns, small fields and frequent cloud cover during crop growing seasons. Near-surface remote sensing provides detailed, high-resolution field data, enabling precise identification of winter wheat developmental stages and disturbances in agricultural growth that are frequently overlooked by national crop surveys or conventional satellite-based vegetation indexes. In the end, this strengthens resilience to production risks and improves food security in smallholder farming systems by demonstrating the potential of near-surface remote sensing as a scalable platform for collecting plot-specific data that can support crop modeling, extension services, and insurance programs. Earth observation systems thus hold significant promise for phenology detection.



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