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Advances in Remote Sensing with Image Analytics for Crop Disease Monitoring

Divyadarshan R[1], Sridhar Reddy B[2], Rahul Kumar Meher[3], Jatoth Uday Bhargav[4] and Nikkondi Chandra Prabha[5]

Abstract: -

Remote sensing of vegetation and plant stress involves a range of nondestructive spectral analysis techniques conducted from platforms such as satellites, drones, and ground-based systems. Multispectral imaging allows for detailed, nondestructive examination of plants, including the detection of plant diseases and pathogens, at scales ranging from macroscopic to ultramicroscopic. This paper reviews various methods such as multispectral radiometry, photography, videography, infrared (IR) thermography, multispectral image analysis, and nuclear magnetic resonance (NMR) along with their applications in plant pathology and disease assessment. While remote sensing currently cannot diagnose specific diseases, it effectively detects and measures the severity of plant stress and disease. These capabilities enhance the precision and efficiency of phytopathological research, adding significant value and insight to studies in plant health monitoring.

Introduction:

Remote sensing and digital image analysis are techniques used to measure and interpret the characteristics of an object without making physical contact. These methods are both nondestructive and noninvasive, allowing repeated analysis of the same object without causing any harm. The specific condition of vegetation, whether healthy or diseased, affects the type and amount of radiation it reflects or emits. This makes remote sensing a valuable tool in phytopathological research, including disease

Divyadarshan R[1], Sridhar Reddy B[2], Rahul Kumar Meher[3], Jatoth Uday Bhargav[4] and Nikkondi Chandra Prabha[5]

[1]B.Sc Scholar, Kerala Agricultural University, Kerala

[2]M.Sc Scholar, Department of Plant Pathology, College of Agriculture, CAU, Pasighat, Arunachal Pradesh

[3]System Manager, Geo-Spatial Lab, LRI-REWARD, OUAT, Chiplima

[4]Assistant professor, Department of Agronomy, Loyola academy, Hyderabad, Telangana

[5]M.Sc Scholar, Department of Genetics and Plant Breeding, Orrisa University of Agriculture and Technology, Bhubaneswar

assessment or phytopathometry. Plants experience stress when their growth and development are negatively affected by biotic or abiotic factors. This stress can be short term or long lasting and may trigger physiological changes similar to natural aging (senescence). Plant stress or disease may manifest in various forms, such as water imbalance leading to stomatal closure, reduced photosynthesis, lower evapotranspiration, and higher leaf surface temperatures. Other visible symptoms include leaf curling, wilting, stunted growth, yellowing (chlorosis), tissue death (necrosis), or shedding of leaves and other parts. While some symptoms are visible, early stage stress is often difficult to detect and quantify accurately and quickly. Remote sensing offers a reliable way to identify and evaluate these physiological and structural changes in plants and crop canopies. This paper focuses on the application of remote sensing in plant pathology and disease assessment. However, before detecting diseased plants through these methods, it is essential to first establish accurate measurements of healthy plants. Understanding external factors that might influence measurements is critical. Only by comparing data from healthy plants to stressed or diseased ones can remote sensing be effectively utilized for plant health monitoring.

Application of instrumental remote sensing

Several key instruments and techniques are used to gather information through remote sensing, including cameras with film and filters, radiometers, video systems, sonar, and radar. These devices can be positioned on a wide range of platforms from satellites and space shuttles to high altitude manned or unmanned aircraft, regular airplanes, balloons, helicopters, remote controlled aircraft, truck mounted hydraulic arms, or other platforms, including ground based and hand held systems. Additionally, close-range photogrammetry and fibre optic based macro and microscopes represent other forms of remote or non-contact sensing. A common measurement in remote sensing is the reflectance factor, which is the proportion of light reflected by an object relative to the incoming sunlight. When measuring a healthy leaf with an appropriate radiometer, reflectance is typically low in the blue (around 450-480 nm) and red (600–700 nm) ranges, slightly higher in the green (500–550 nm), and significantly higher in the near-infrared (NIR, 750–1100 nm). The low reflectance in the visible spectrum is due to the absorption of light by pigments like chlorophyll and xanthophyll. However, when a plant experiences physiological stress, disease, or a reduction in photosynthetic pigments, reflectance increases in the red and blue regions and sometimes in the yellow spectrum, while often showing a marked decrease in NIR reflectance.

Sometimes, analyzing the decrease in NIR reflectance alone is sufficient, but combining data from multiple spectral ranges provides better insights. For example, the ratio IR/R or the normalized difference vegetation index (NDVI) [(IR - R)/(IR + R)] is commonly used. NDVI is typically strongly correlated with green biomass, while IR/R often corresponds to the leaf area index (LAI). Comparing these values across different plots or sections of a field helps assess stress levels, even if the exact cause of stress isn't immediately apparent. Numerous other vegetation indices have been developed to simplify multispectral data into single values representing characteristics like leaf area, biomass, and stress. Examples include the transformed vegetation index (TVI), perpendicular vegetation index (PVI), soil-adjusted vegetation index (SAVI), transformed SAVI (TSAVI), brightness index, yellowness (YN), greenness (GN), green vegetation index (GVI), and physiological reflectance index (PRI). Special attention has also been given to changes in spectral reflectance near 700 nm, known as the "red edge," for narrow band multispectral radiometry. More recently, researchers have shown growing interest in narrow spectral bands within the yellow region. With the advent of more sophisticated narrow band radiometers, studies have increasingly demonstrated the value of vegetation indices incorporating bands from the mid infrared (MIR) alongside NIR and red wavelengths. MIR reflectance is notably influenced by the biochemical composition of leaves, including the content of elements and compounds like carbon, hydrogen, nitrogen, oxygen, starch, cellulose, lignin, and water.

A key factor in radiometric analysis of crop canopies is how variations in the sun's angle throughout the day affect canopy reflectance, especially in relation to the orientation of crop rows. Reflectance patterns are also influenced by factors such as the plant's growth stage, canopy structure, and soil cover. Lord et al. (1988) observed that solar angle impacted red reflectance more than near-infrared (NIR) reflectance across four crops with varying row orientations and spacings. Interestingly, in their study, cereal rows were spaced 18–35 cm apart, whereas in Sweden 12 cm spacing is more typical. Changes in reflectance over the course of the day can also result from shifts in moisture stress, and these fluctuations can be quite significant. Furthermore, crop varieties often vary in their tolerance to water stress, and this stress may interact with other factors like fertilizer use, disease presence, and general growing conditions.

Satellite based vegetation reflectance measurements typically rely on broad spectral bands about 100 nm wide. While this resolution is generally suitable for parts of the spectrum where reflectance changes gradually, it does not capture sharp transitions in reflectance that plants can exhibit. One such feature is the "red edge," a steep rise in reflectance between 680 and 750 nm. This feature becomes particularly apparent when analyzing the first or second derivative of narrow band reflectance curves. The red edge is characteristic of healthy green vegetation and arises from two key properties of plant tissues strong chlorophyll absorption in the red spectrum and high internal scattering of light in the NIR spectrum. Horler et al. (1983) emphasized that measuring the red edge is particularly useful for evaluating chlorophyll content and leaf area index (LAI), independent of ground cover variation, making it especially valuable for early detection of plant stress.

These complexities highlight the challenges involved in interpreting the relationships between crop reflectance and stress. Adding to the difficulty is the diversity of possible stress factors ranging from environmental stresses like heat, cold, light intensity, water availability, and nutrient deficiencies to air pollutants such as ozone and sulfur or nitrogen compounds. Biological stresses, including infectious diseases or pest infestations, further complicate analysis. Stress from diseases may thin out the canopy, increasing soil reflectance and potentially obscuring disease specific signals. Weeds growing in such areas also influence overall canopy reflectance, making detection more challenging.

Currently, remote sensing technology cannot reliably identify specific diseases, but it can detect plant stress earlier than many conventional approaches, offering a nondestructive and objective means of assessment. As it stands, remote sensing of disease or stress is mainly about comparing reflectance data from stressed areas with that of surrounding healthy vegetation. Looking ahead, advancements in instrumentation, data analysis techniques, and Geographic Information Systems (GIS) hold promise for improving disease identification accuracy. However, it’s important to recognize that multiple stresses can produce similar reflectance patterns, making it difficult to isolate specific causes, especially when multiple stressors are present simultaneously.

Photography, aerial photography and photogrammetry

Neblette (1927) and Taubenhaus et al. (1929) were among the first to use aerial photography for detecting cotton root rot (Phymatotrichum omnivorum) in Texas. Later, Bawden (1933) employed infrared film to study virus infections in potato and tobacco plants. During World War II, aerial photography especially using infrared films became widely used for camouflage detection. After the war, this expertise was adapted for identifying vegetation stress and diseases in agriculture and forestry. Colwell (1956) demonstrated the effectiveness of aerial photography using panchromatic and infrared films for detecting diseases like cereal rusts and viral infections in crops. His contributions, along with the work of Manzer and Cooper (1967) on potato late blight, inspired extensive agricultural and forestry research using these methods. Early pioneers in this field also included researchers such as C.H. Blazquez, G.H. Brenchley, A. Hooper, H.R. Jackson, and V.R. Wallen.

Infrared aerial photography has since been widely used across the world to monitor various agricultural and horticultural problems, including plant diseases, pollution damage, and nutrient or water stress. For example, Blazquez and Edwards (1983) studied tomato and potato diseases using IR color photography and spectral reflectance, while their 1984 study applied densitometric techniques to assess color infrared images of diseased cucumber leaves. Similarly, Blazquez (1993) used these methods to study citrus diseases. Blazquez et al. (1988) and Greaves et al. (1983) also used aerial photography to investigate barley yellow dwarf virus and aphid infestations in winter wheat. Interestingly, aerial photography appears to have been used more extensively in forestry, likely because fewer alternative assessment methods exist for large-scale forest health monitoring.

Aerial photography has also proven useful for selecting optimal areas for experimental field plots, as it allows photogrammetric measurements of plant size and canopy structure. Techniques like retro-reflection photography have been used to detect dew on leaves important in phytopathology studies (Mattsson 1974; Mattsson & Cavallin 1972). While large-format cameras were initially popular for aerial photography, 70 mm and 35 mm films like Kodak's Ektachrome infrared film 2443 became standard tools. Zsilinsky et al. (1985) proposed using negative processing of color infrared (CIR) films to improve color contrast in these images. Although early analysis relied on densitometry, later advances in image processing and spectral enhancement have made evaluations more detailed and reliable.

Personally, I began using 35 mm black-and-white infrared films in the 1950s to study take-all disease and herbicide damage in Swedish cereal crops. By 1971, I was using Kodak Ektachrome infrared film 2443 for research in Tanzania, focusing on wheat diseases, copper deficiency, and water stress. Using a conventional Leicaflex camera with yellow and polarizing filters, I achieved excellent image quality, particularly with access to advanced digital image processing at Ernst Leitz-Wetzlar laboratories. Most of my early photographs were taken from the elevated platforms of tractors or Land Rover vehicles. More recently, there have been successful trials using small, radio-controlled aircraft for low-altitude aerial photography to survey crop diseases. Similar initiatives have been started at the Department of Agricultural Engineering at Uppsala, where model aircraft with a wingspan of 3.5 meters designed by Professor Sven-Olof Ridder have been used for slow, low-altitude flights over research plots. Equipped with wide-angle navigation cameras and infrared sensors, these aircraft transmit real-time video and IR images to ground-based monitors, further advancing the precision and practicality of remote sensing in agriculture.

Active and passive remote sensing

Up to this point, the focus has been on passive remote sensing, which involves using photographic or electronic equipment to measure solar electromagnetic energy reflected by vegetation. A critical requirement for accurately detecting stress or disease through these methods is a uniform plant canopy, as previously discussed. However, there has been a growing need for remote sensing systems capable of directly assessing the physiological condition of vegetation. These systems are intended to complement passive methods and help reduce uncertainty in interpreting results.

In response to this demand, active remote sensing techniques have been developed over the past 15 years. These methods involve directing controlled energy pulses of specific wavelengths at vegetation and analyzing their interaction with plant tissues. One prominent example is LIDAR (Light Detection and Ranging), which utilizes laser light in a manner similar to how RADAR (Radio Detection and Ranging) works with radio waves.

Technologies involving laser light, such as laser-induced fluorescence, are increasingly being explored for their potential in remote sensing and image analysis. These techniques hold significant promise for applications in plant pathology and phytopathometry. Another emerging technique at the microscopic scale is multidimensional spectral confocal microscopy, a non-destructive "remote sensing" approach applied to living cells or organelles.

Additionally, radar and microwave radiometry are gaining attention in the remote sensing of soils and vegetation, mainly because they are less affected by cloud cover. These techniques show particular potential in monitoring soil moisture and water content in plant canopies. Since water stress in plants can be detected using these methods, they are of considerable interest for plant pathologists. However, despite their potential, research and applications of these technologies specifically in phytopathometry remain relatively limited.

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