EDITORIAL

Monitoring Vegetation Stress and Health Disturbances: A Remote Sensing Perspective

Plants form the foundation of terrestrial ecosystems and are essential for food security and sustaining the biodiversity that underpins resilient ecological and agricultural landscapes. Coordinated efforts to preserve their health while recognising their central contribution to agricultural production and ecological stability are essential. Yet, studies have shown that intensifying production often places considerable strain on natural ecosystems, contributing to soil degradation, biodiversity loss, and various forms of environmental contamination. Climate change adds further complexity. The growing occurrence and intensification of extreme weather events, such as droughts, heatwaves, severe storms, and extended wet and dry periods, affect not only cultivated crops but also rangelands, forests, and other types of natural and semi-natural vegetation. These disruptions hinder the capacity of landscapes to provide food, fibre, and ecosystem services essential for human well-being. As a result, achieving the Sustainable Development Goals, particularly SDG 2 and SDG 15, to achieve food security simultaneously while protecting the environment and sustainably managing and conserving natural resources, remains one of the most pressing challenges of our time.

Vegetation stressors

Across all vegetation types, plants are continually exposed to a wide range of stress factors, defined as any environmental condition or agent that adversely affects growth, physiological processes, or development. These stressors can be broadly categorised into two categories. Abiotic stressors include radiation extremes, salinity, prolonged flooding or waterlogging, lodging, drought, heat stress, elevated atmospheric CO_2, exposure to agrochemicals, chilling and freezing temperatures, nutrient imbalances, and heavy-metal contamination. Biotic stressors encompass pests, pathogens, and other biological agents, which are frequently intensified by primary abiotic stresses. Together, these pressures diminish vegetation function and productivity, leading to lower agricultural productivity, weakened ecosystem functioning, increased risks of species extinction, and wider threats to global food security. Symptoms such as lesions, chlorosis, premature senescence, and wilting reflect underlying physiological damage in vegetation, ultimately impairing productivity and ecosystem functioning, and, in agricultural systems, reducing both quality and quantity of yield. While the modernisation of land-management practices and crop intensification strategies aim to increase biomass production and resource efficiency, they often heighten vulnerability to biotic stressors such as pests and pathogens, particularly in landscapes dominated by monocultures or simplified vegetation structures. Moreover, global trade and climatic shifts further exacerbate these challenges by facilitating the introduction, redistribution, and adaptation of invasive pests and diseases across new geographic areas. These escalating pressures underscore the need for innovative, rapid, and scalable approaches to monitor vegetation health and manage stressors more effectively.

Role of Biophysical and Biochemical Characteristics

Assessing vegetation productivity, health, infection, or stress conditions is ultimately about tracking how plants capture light, turn that into chemical energy, allocate that energy for growth, and defend themselves under pressure. Biophysical (e.g., canopy height, leaf area index (LAI) and fraction of absorbed photosynthetically active radiation (fAPAR)) and biochemical characteristics (e.g., chlorophylls, carotenoids, anthocyanins, nitrogen, lignin) provide complementary, mechanistic windows into photosynthesis, growth, yield potential, and early warning of stress or disease by capturing the physiological disruptions.

Depending on the type of stress (caused by biotic or abiotic factors), the initial plant organs affected may vary (leaf, stem or bark, or roots). Yet, stress eventually leads to alterations in metabolic pathways, reduced photosynthetic efficiency, and disruptions in the transport of water and nutrients, which in turn limit the growth, development, and functioning of vegetation. For example, pathogens or insect infestations disrupt metabolic pathways, interfere with the stability of cellular components, and initiate defence reactions that leave measurable biochemical signatures. Early in the infection process, plants often exhibit shifts in chlorophyll and carotenoid concentrations, increased production of phenolic compounds, and elevated levels of reactive oxygen species, all of which reflect underlying stress responses. Biophysical characteristics add another dimension by revealing structural and functional changes that occur as stress is initiated and developed, changes that one may miss by merely considering biochemical characteristics alone. A concrete example is lodging in crops, where the stems weaken and begin to bend or fold. This process can be anticipated through biophysical changes such as modifications in canopy shape or reduced stem stiffness, well before the collapse becomes obvious in the field. Furthermore, alterations in stomatal behaviour or vascular impairment caused by stress factors often reduce transpiration, leading to measurable increases in leaf or canopy temperature. These changes usually emerge before visible symptoms appear, making them especially valuable as early indicators of plant health disturbances and the onset or progression of stress. Accordingly, systematic monitoring, assessment, and prediction of the dynamics of these characteristics on various scales are crucial for evaluating the functioning, productivity, and health of agricultural and natural ecosystems. Yet, measurements of these characteristics at high temporal and spatial scales are highly costly and, to some extent, impossible due to the rapid growth dynamics and phenological changes that can occur over short periods.

Vegetation Dynamics and Remote Sensing

Remote sensing is vital for addressing these challenges and serves as a powerful source for detecting changes in vegetation condition and their biochemical and biophysical characteristics as early indicators of stress, emerging threats, or disturbances in vegetation cover. The non-destructive, repeated, and large-scale data acquisition capabilities of satellite sensors provide a viable alternative solution to support systematic monitoring and analysis of these dynamics, enabling timely management actions and mitigation strategies. Remote sensing data span a broad range of spectral regions, including visible, near-infrared, shortwave-infrared, thermal, and microwave domains. By examining data from different spectral domains, as well as data obtained across multiple platforms (satellites, airborne platforms, unmanned aerial vehicles (UAVs), and field sensors), with varying spatial resolutions, remote sensing technologies hold a great potential for detailed assessment of vegetation responses to various biotic and abiotic stressors such as detection of drought-induced water stress, lodging, malnutrition due to soil salinity or acidity, poor management practice, nitrogen deficiency or excess and the heightened incidence of disease or pest infestations associated with prolonged heat or wet periods. While satellites and airborne data provide extensive coverage, enabling large-scale monitoring and comparison across sites, species, and environmental conditions, field sensors and UAVs offer detailed, localised information that allows a deeper understanding of the intrinsic responses of individual plants to various stressors at different and subsequent phenological stages.

A substantial body of research has focused on quantifying vegetation's biophysical and biochemical characteristics to assess plant stress and health disturbances using remote sensing. While the launch of new hyperspectral satellite missions has advanced the capacity to assess changes in plant biophysical and biochemical characteristics caused by a wide range of stressors, the difficulty in distinguishing among stressors that produce, to some extent, similar physiological or spectral responses in plants remains. Plant stressors frequently exhibit synergistic interactions, wherein the presence of one stressor exacerbates the vulnerability to others. For example, water deficit can weaken plants' physiological defense traits and internal functional responses, thereby increasing susceptibility to pathogens and herbivores, which in turn further impair their capacity to manage abiotic stress. The implications of such combined stressors on biophysical and biochemical characteristics, as well as corresponding remote sensing signatures, are complex and pose a constraint for current remote sensing approaches. While the use of field sensors and UAVs, owing to their high spatial and spectral resolutions, may allow, to some extent, the study of these overlapping signals at the field scale, technical challenges involved in their data acquisition and small-scale studies limit their applicability. This is mainly due to the fact that diagnostic models developed using remote sensing data for assessing a particular health disturbance or stress in a specific site may not be directly transferable to another site or season, as landscape heterogeneity and environmental conditions (neglecting the influence of the atmosphere) largely affect the dynamics of the remote sensing signals, restricting the generalizability of such models.

Future Directions

Addressing the shortcomings and complexities of using remote sensing data for monitoring plant health disturbances and stress requires further investigations to fully understand the influence of individual biotic and abiotic factors, and their multiplicative effects on the dynamics of vegetation's biophysical and biochemical characteristics, as well as their spectral signatures at the leaf and canopy levels. Such understanding is essential for improving the reliability of remotely sensed assessment of vegetation health disturbances and stressors. To enhance the generalizability and transferability of remote-sensing models for detecting plant stress, hybrid approaches that combine physical principles with data-driven learning are increasingly being adopted. These approaches integrate physical models, such as radiative transfer models that simulate how light interacts with vegetation, offering mechanistic insight into how stress-induced variation in biophysical and biochemical properties affects the remote-sensing signal, with machine learning models capable of capturing complex, nonlinear relationships within large datasets. Yet, selecting appropriate radiative transfer or machine-learning algorithms and supporting them with extensive, high-quality field observations are needed to enhance the reliability of stress detection at multiple scales and across varying environmental conditions. High-quality field observations must be collected through dedicated field and laboratory experiments to thoroughly examine plant physiological processes under single and multiple stress factors, as well as their associated biochemical, biophysical, and spectral dynamics.

Freely available Earth-observation data from platforms such as Sentinel-2, whose red-edge spectral bands are particularly sensitive to vegetation condition, and Sentinel-1 synthetic aperture radar (SAR), which provides weather-independent measurements, offer frequent revisit cycles and are highly valuable for analysing temporal variations in vegetation spectral responses and indicating plant stress. These, in addition to data from thermal missions (e.g., ECOSTRESS and Sentinel-3) and the upcoming FLEX (Fluorescence Explorer) mission, will further assist in characterising plant stress by capturing complementary information on canopy temperature, fluorescence, and physiological responses.

Hyperspectral satellite missions, including EnMAP, DESIS, and PRISMA, also offer great potential. Their fine spectral resolution, presented with many narrow spectral bands, enables the detection of subtle variations in biophysical and biochemical characteristics in the early stress stage, thereby improving the capacity to assess diverse stressors. The upcoming hyperspectral missions, such as CHIME(Copernicus Hyperspectral Imaging Mission for the Environment), are expected to significantly advance the field of remote sensing of vegetation and plant health. With an anticipated high revisit time (one to two weeks once the full constellation is deployed), CHIME will provide free and substantially richer temporal records than previous spaceborne hyperspectral instruments. This enhanced data availability will support the development of sophisticated, intelligent models to detect and monitor vegetation stress and disturbances across diverse terrestrial ecosystems.

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