Remote Detection of Crop Stress: Application to Plant Pathology

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Remote sensing carries many different connotations to different individuals, ranging from photography to large satellite platforms. Each day we are provided many frames of remote sensing information through our eyes, which we use to make visual assessments of an object. These scenes provide an information source about objects from which we judge certain characteristics, e.g., size, condition, or change. The local TV weather report uses remote sensing of clouds to show the passage of storms. Plant pathologists have used remote sensing tools for a number of years and were among the first to use color infrared photography to assess the presence of disease in trees. The application of remote sensing via airborne cameras provided an answer to a question that would not have been possible through ground surveys. In many aspects we have progressed rapidly to our current state of knowledge about the utility of remote sensing. The intent of this address is to arouse the interest of individuals in discovering how remote sensing could be applied to plant pathological problems of today and tomorrow.

REGIONS OF THE SPECTRUM

The spectrum of electromagnetic radiation ranges from the short, high energy wavelengths to the long radio waves. As a receptor, the human eye only measures a relatively small portion of the spectrum in the visible wavelengths from 0.4 to 0.7 μm. Remote sensing instruments, on the other hand, have utilized wavelengths extending in the microwave region for a variety of applications. For this discussion, we will confine the wavelengths to the region from 0.4 to 14 μm. The region from 0.4 to 5 μm can be represented as the reflected wavelengths. Reflection is that phenomenon in which an impinging beam of radiation of a particular wavelength is reflected back away from the object without any change. This can be contrasted to emittance, which is the emitting of radiant energy at a particular wavelength due to the temperature of an object. Surfaces at the temperature of the earth (300° K) emit mostly in 10–12 μm waveband, while the sun at 6000° K emits in the 0.5 μm region. Both reflectance and emittance provide information that can be utilized in applying remote sensing to agricultural problems.

REFLECTION FROM LEAVES

Reflection from individual leaves is not constant across the wavelengths from 0.4 to 2.5 μm. Leaves have a low reflectance in the visible (0.4–0.7 μm), a high reflectance in the near-infrared (0.7–1.2 μm), and a low reflectance in the middle and far infrared (1.2 μm) wavebands. This variation in leaf reflectance has allowed for the differentiation of leaves from soil, which tends to show little variation in reflectance across these wavelengths.

Reflectance from leaves is species dependent and sometimes cultivar dependent. The primary variation among species is in the visible reflectance and is due to species or leaf age. Reflectance tends to increase in individual leaves as the leaf matures; however, the changes are wavelength dependent. These changes are due to changes in intracellular water content and chlorophyll content. Lesions and reduction in chlorophyll content created by a disease also cause an increase in reflectance. Water stress by reducing the internal water content increases the reflectance from an individual leaf. Information gathered from individual leaves provides a basic set of information about the mechanism of the changes occurring within a plant; however, to be of practical application it must be extended to a canopy or field level.

REFLECTION FROM CANOPIES AND FIELDS

Composites of leaves or canopies exhibit the same reflective properties of individual leaves; however, there are a series of variables that now must be considered. Leaf orientation, i.e., the arrangement of leaves on the stem and orientation to the sun, provides a source of variation when viewing a canopy compared with an individual leaf. Also, all leaves are not exposed to the same level of incoming radiant energy and often do not reflect back to the sky due to distortions in the leaf surface. Leaf surfaces often act as polarizing filters and reflect back to portions of the sky that are not always detected by viewing the canopy only from the vertical direction. However, the information contained in bidirectional and polarized reflectance has yet to be fully exploited in the evaluation of canopy response to stress. Leaf fluorescence is another attribute that has been observed in all plants and can be related to the efficiency of the photosynthetic process. It is possible that leaf fluorescence could be used to assess the impact of diseases on the physiological status of a plant. This technique has only been used on individual leaves; however, it could be extended to canopies through the use of laser-induced fluorescence. This procedure will have to be adapted to plant canopies but may become a powerful and useful research tool.

Canopies of plants are grown in fields with varying soil, and soil also has some unique reflective properties. The variation across wavelengths is less for soil than for leaves; however, the reflectance changes in response to modifications in the surface. The addition of organic matter as residue on the surface reduces the reflectance. Soils vary in reflectance due to mineral composition and weathering of the minerals. However, across the visible and near-infrared wavelengths the reflectance from soil remains relatively constant within a given soil type. Changes in water content in the upper 2 mm cause the largest variation in reflectance. Water has a low reflectance and the addition of a water film around the soil aggregate causes an increased absorption of the incident radiation. As a soil is wetted there is a darkening in the color, which lightens as the soil dries. This variation in the reflectance from soils due to changing soil water adds complexity to the reflectance from canopies, particularly when there is less than complete ground cover by the plant, i.e., exposed soils when viewed from above the plant. Since there is a changing amount of plant material both in the adding of new leaves or the senescence of the older leaves, there is a continually changing scene to be viewed. This challenge must be faced and understood if we are to develop the tools that allow us to assess the effect of a disease or any other stress on the plant.

Instruments available for the measurement of reflected radiation adaptable to remote sensing range from the portable spectroradiometer, which measures all wavelengths between 0.4 and 1.1

μm to radiometers with multiple channels set for discrete wavebands. Instruments with individual channels mimic the wavebands available on the current satellites. A rapidly emerging technology that has yet to be applied is the use of multiple waveband video cameras. This system offers a capability not possible with other radiometers, in that the data are readily available for viewing without intense signal processing and manipulation. Video camera systems may provide a practical tool for disease assessment.

VEGETATIVE INDICES

To use the information contained in the reflectance across wavelengths, several vegetative indices have been proposed and evaluated. These indices are based primarily on the ratio or difference between the reflectance in the near-infrared and red wavelengths. The approaches range from simple ratios of near-infrared/red reflectance to a calculation of the matrix coefficients for the use of four wavebands. Each index provides a description of the canopy response throughout a growing season. The ratio vegetative index (near-infrared/red ratio) is related to the change in leaf area index, while the normalized difference [(near-infrared − red)/(near-infrared + red)] is more appropriately related to the interception of photosynthetically active radiation. To account for the soil background the perpendicular vegetative index was developed to account for a changing soil background due to surface soil water content changes. There have been several other indices developed to describe how the changing reflective properties change with growth of the plant.

Observed changes in the vegetative index, in particular, the ratio vegetative index and the normalized vegetative index have shown unique seasonal patterns. The patterns of both indices show an increase with the developing canopy and a hysteresis effect during senescence because plant material remains standing in the field, which has different reflective properties than the soil in the background. Over fields of seemingly uniform conditions there is considerable variation in the observed signal whether the data are collected with hand-held, boom-mounted, or aircraft-mounted systems. The variation is typically 10% of the field mean. However, the change in spatial variability may be one of the methods that could be effectively used to monitor the changes that occur within fields as a result of disease. Most diseases do not infect a whole field uniformly and thus could induce a change in the field pattern. Even on a single sample event this method could provide valuable information given a priori knowledge about the expected level of field variability.

EMITTED RADIATION

All objects that have a temperature emit radiation according to Planck's Law. Soil and plant canopies emit energy, and given the temperatures found on the earth's surface, range in the 10–14 μm waveband. Temperature of a plant canopy can be described by either the temperature of individual leaves, the temperature of foliage, or the temperature of the canopy that includes the soil. Leaf temperatures that have been measured relative to the occurrence of Verticillum wilt or brown rot of soybeans (*Phialophora gregata* Gams) have been measured with attached leaf thermocouples. Other measurements of Verticillum wilt have been made with infrared thermometers. Each method has provided a unique relationship of describing the change in leaf temperature relative to the presence of a disease.

ENERGY EXCHANGE PROCESSES

Temperatures of the leaf, foliage, or canopy are a result of the energy exchange process. The observed temperatures are a result of the partitioning between the sensible and latent heat exchanges and therefore are a balance between the energy impinging on the leaf or foliage and the water available for evaporation. Simply stated then, a surface with a free water surface will be as cool as possible given the meteorological conditions while one without water will be the warmest possible under a given set of conditions. It is this relationship that has allowed foliage temperature to be effectively used in the estimation of transpiration from canopies. Also, any factor that disrupts this water flow to the leaf, e.g., vascular diseases, root diseases, or diseases that disrupt the stomatal action, will cause the foliage temperature to be higher than that observed in healthy foliage. We have been successful in using foliage and canopy temperature in evapotranspiration models for a variety of crops. In well-irrigated crop canopies, the variation across a field is relatively uniform and the variation increases with increasing soil water deficits. As with the reflected radiation, the change in field variability may be useful in defining the characteristics of a given field.

CROP STRESS INDICES

To improve the efficiency of using foliage temperatures, several crop water stress indices have been proposed and evaluated since the middle 1970s. These became possible at this time due to the development of the accurate, portable, hand-held infrared thermometer. At first, the comparison was made between the foliage and air temperature ($T_f - T_a$), since this form was the integral part of the energy exchange process. It was found that although the $T_f - T_a$ differences were related to crop yield induced by water stress, the relationships were site dependent. Further development and study revealed that other environmental variables were needed to fully interpret foliage temperatures and develop less site-specific relationships. The primary variables were net radiation, wind speed, and vapor pressure deficit. These stress indices have been based on the energy exchange principles between the foliage and the surrounding atmosphere. Any factor that affects the rate of water movement to the leaf has an impact on the foliage temperature. For example, the addition of high salt content irrigation even in large amounts causes the foliage temperatures to be warmer than those plants irrigated with the same volume of salt-free water.

Recent research has identified that plants have biochemical temperature optima that define the optima temperature for plant growth. Combining foliage temperature with these predetermined optima temperatures provides another description of plant stress. It has been found that plants with maximum growth in a particular environment have the minimum amount of time outside of this predetermined thermal range. For cotton, this range was determined to be 23–30 C and for wheat 18–25 C. This range has been defined as the thermal kinetic window and is based on the biochemical efficiency of a particular plant. The utility of this stress index has yet to be fully evaluated; however, it offers a method of linking the plant response to an observed parameter, e.g., foliage temperature.

Other methods that can be used are to calculate the canopy resistance to water vapor exchange. It is known that many diseases affect the stomatal resistance and the combination energy balance and observed foliage temperature provide a method of estimating canopy resistance. These techniques, however, are yet to be applied to any measure of disease. They may offer the potential of quantifying the degree of stress or level of infection in ways that have not been possible before.

The instruments available for measuring the foliage temperature range from hand-held portable units, to fixed, battery-powered systems to airborne or satellite thermal scanners systems. The latter are relatively expensive and can view large areas if repeated coverage is obtained, e.g., NOAA or GOES satellites. Smaller areas are covered with systems that provide less frequent coverage, e.g., LANDSAT or SPOT. The variation within a scene of data obtained with an airborne or satellite system will not permit the reliable detection of the onset of a disease. The handheld or fixed units on the ground may be useful in a research setting to determine the casual relationships and the development of a monitoring program where a problem is suspected. Each of these instruments require some training to most properly collect and interpret the data.

TEMPORAL AND SPATIAL VARIATION

Both the temporal and spatial attributes of remote sensing techniques detect unique features about the surface being observed. Satellites that provide repeated coverage of the earth have allowed assessments to be made of the changes that have occurred over a period of months or years. The same factors apply when applying remote sensing to the monitoring of agricultural fields, forests, and native or managed grasslands. The value of repeated coverage has provided for a unique glimpse at the ecosystem that we are trying to monitor.

Temporal variations can be large because the system to which we are applying may be changing due to the normal progression of growth. However, we know what patterns to expect and deviations away from that pattern provide an investigative tool. Likewise, changes in the spatial patterns may signal a potential problem within a given field or ecosystem. The interpretation of the temporal and spatial pattern will require some experience but may provide an indication of a problem not possible before this information was made available.

INTEGRATING REMOTE SENSING INTO PLANT PATHOLOGY

There are two avenues in which remote sensing information, either reflected or emitted radiation, can be incorporated into disease monitoring. The two approaches involve either direct or indirect methods of evaluating the disease occurrence and extent. Given the number of factors that cause variation in both the reflected and emitted radiation signals it is unlikely that the direct monitoring method will be useful. Both the indirect and direct methods require a priori knowledge that a condition may exist. Given this knowledge then, one may use a direct monitoring program to measure the extent of a disease, e.g., *Phytophthora* spp. on soybeans or *Fusarium* spp. on beans, which cause a reduction in leaf area. The spatial sampling capability provides an assessment not possible with ground monitoring.

The indirect method would involve interpretation of deviations from the expected case either in temporal or spatial patterns. For example, an increase in foliage temperature in a field with an adequate soil water supply would signal a potential problem that could invoke a monitoring effort. An unexplained change in leaf area or wilting resulting in a change in reflectance could signal a problem before complete infestation. The utilization of both indirect and direct methods will require imagination and dedication to the problem by a number of researchers.

THE CHALLENGE FOR THE FUTURE

Remote sensing is a technology and not the complete answer. As a tool it provides information about the particular system in a way not possible through other avenues. The use of remote sensing, crop models, and meteorological data may be most efficiently used to predict the conditions in which a particular disease may occur and forecast the occurrence, rather than the monitoring, of possible infestations. The advantage of remote sensing information lies in its combination with other available information. If we are to fully use that information then individuals with varied disciplinary backgrounds interested in solving a problem will have to develop those answers. We have the capability, the tools, and the scientists with imagination—all that is required is to bring all of the ingredients together. This is our greatest challenge and from it will emerge the largest rewards.