Spectral Sensing for Plant Stress Assessment
– A Review –

Y. Kim, J. F. Reid

Abstract: Assessment of nitrogen and chlorophyll content from crop leaves can help growers adjust N fertilizer rates to meet the demands of the crop. Numerous researchers have presented their studies about spectral signature of plant leaves to characterize the plant features. However, interrelational review and summary were limited and a communication gap exists between the plant science and optical engineering. Understanding the mechanism of leaf interaction to electromagnetic radiation and factors affecting spectrophotometric measurements can enhance the foundation of optical remote sensing technologies. This paper provides extensive review of previous works in optical sensing and explains the basics of plant optics, spectral measurements for plant stress, factors that affect sensitivity to spectral analysis, and applications that deploy optical remote sensing technologies.
Keywords: Remote sensing, Spectroscopy, Multispectral sensors, Crop, Nitrogen, Precision agriculture

Introduction

Agricultural fields are variable and require site-specific crop management. Nitrogen (N) management is critical for crop production, because N is an essential nutrient required for plant growth and is a major component of the chlorophyll molecule that enhances photosynthesis (Tracy *et al.*, 1992). However, excessive N fertilizer leaches into the groundwater and creates serious environmental problems. These problems have been linked to hypoxia problems in the Gulf of Mexico. The U.S. Environmental Protection Agency (1998) reported that nutrients were one of the leading causes for contaminating the waterways. Nitrogen levels in drinking water in many regions are higher than the drinking water standards. Thus, there is a need for sensing technologies and that can assess plant N requirements throughout the growing season to allow producers to reach their production goals, while maintaining environmental quality through reductions in N fertilization.

Assessment of N and chlorophyll content from crop leaves can help growers adjust N fertilizer rates to meet the demands of the crop. Numerous researchers have published their studies about spectral signature of plant leaves to characterize the plant features. Each study contributes to a specified aspect of technology development but is limited to interrelate with other studies with limited review of previous works. The comprehensive review of spectral measurements for plant stress assessment will be of interest to many researchers in remote sensing.

Curran (1989) explored why and how remotely sensed data should be used to estimate foliar chemical content and recommended that the research be modeling in the long term to increase understanding of the interaction between radiation and foliar chemistry and experimentation in short-term to achieve unambiguous and accurate estimates of foliar chemical content. Understanding the mechanism of leaf interaction to electromagnetic radiation and factors affecting spectrophotometric measurements can enhance the foundation of optical remote sensing technologies. The objective of this paper is to provide extensive review of plant leaf optics, spectral measurements for plant N assessment, factors that affect sensitivity to spectral analysis, and applications using optical remote sensing technologies.

Theoretical Backgrounds

1. Plant Leaf Optics

Leaf characteristics have a major influence on the remote sensor responses. In the visible spectrum, leaf color was a sensitive non-destructive indicator of deficient nutrient levels (Blinn *et al.*, 1988). An intensive understanding about the optical characteristics of plant leaves and associated plant health effects is required to apply the principle of remote sensing.

The authors are **Yunseop Kim**, Research Associate, USDA-ARS, Northern Plains Agricultural Research Laboratory, Sidney, Montana, USA, **John F. Reid**, Manager, John Deer Technology Center, Moline, Illinois, USA. **Corresponding author:** Yunseop Kim, USDA-ARS, Northern Plains Agricultural Research Laboratory, 1500 North Central Avenue, Sidney, MT 59270, USA; phone: 406-433-9477; fax: 406-433-5038; e-mail: JKim@sidney.ars.usda.gov.

(1) Properties of Light

A classic definition of visible light is a portion of electromagnetic spectrum, having wavelengths from 380 nm to 700 nm (West, 1990). Wavelength is a distance between corresponding points of two consecutive waves (Figure 1). Wavelength is usually denoted by the Greek letter lambda (λ); it is equal to the speed (v) of light in a medium divided by its frequency (f): $\lambda = v / f$.

A more appropriate definition of light is energy with physical phenomena explained by the duality of wave and particles where the particles have the properties of photons (West, 1990). This extends light from gamma rays with wavelength of 3×10^{-14} cm to long radio waves measured in millions of kilometers as shown in Figure 2.

The spectrum of light in a particular waveband can be separated by a prism or an optical filter. For example, ultraviolet and visible wavebands can be filtered by a lead-containing flint glass and crystal, respectively. An instrument designed for visual observation of spectra is called a spectrometer.

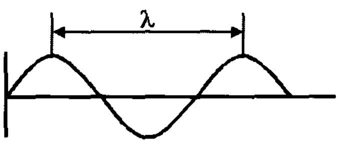


Fig. 1 Wavelength denoted by λ.

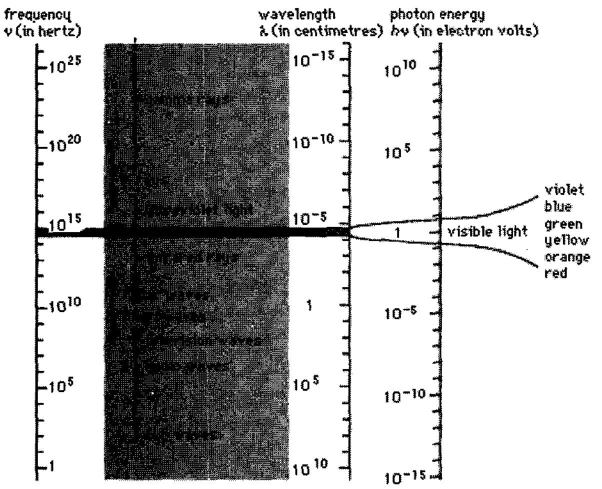


Fig. 2 Electromagnetic spectrum from gamma rays to radio waves. The small visible range (shaded) is shown enlarged at the right (Encyclopedia Britannica, Inc).

(2) Properties of Leaves

1) Leaf structure

Leaves of a plant are a primary photosynthesizing organ with photosynthesis occurring in chloroplasts where a chlorophyll pigment is located (Gates *et al.*, 1965). The cross-sectional leaf structure of a typical dicotyledonous plant such as cotton is shown in Figure 3. It generally consists of upper epidermises, lower epidermises, and mesophyll in the middle leaf. The mesophyll includes the major photosynthetic tissues: palisade parenchyma cells and the spongy parenchyma cells. The chloroplasts are readily seen located along the walls of the parenchyma cells.

The cellular structure of a leaf is large compared to the wavelengths of light. Gates *et al.* (1965) have presented an excellent discussion of the physical dimensions and relationships of leaf structure. Typically cell dimensions will be 15 μm×15 μm×60 μm for the palisade cells and 18 μm×15 μm×20 μm for the sponge parenchyma cells. The epidermal cells are of the same order of dimension as the spongy parenchyma cells, and these have a thin waxy cuticle overlay which is highly variable of thickness but often is only 3 μm to 5 μm thick. The chloroplasts suspended within the cellular protoplasm are generally 5 μm to 8 μm in diameter and approximately 1 μ m in width. Within the chloroplast are long slender strands called *grana* within which the chlorophyll is located. The *grana* may be 0.5 μm in length and 0.05 μm in diameter. Clearly, the *grana* is of the dimension of the wavelength of light and may produce a considerable scattering of light entering the chloroplast. The chloroplasts are generally more abundant towards the upper side of the leaf in the palisade cells and hence account for the darker appearance of the upper leaf

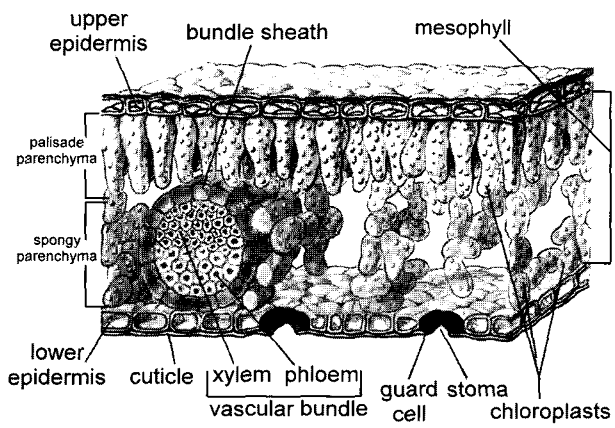


Fig. 3 Structure of a typical dicotyledonous leaf (http://www.lions.odu.edu/~kkilburn/bio109/plant_leaves.htm).

surface compared with the lower lighter surface. The pigments generally found in chloroplasts are chlorophyll (65%), carotenes (6%), and xanthophylls (29%), although the percentage distribution is highly variable (Gates *et al.*, 1965).

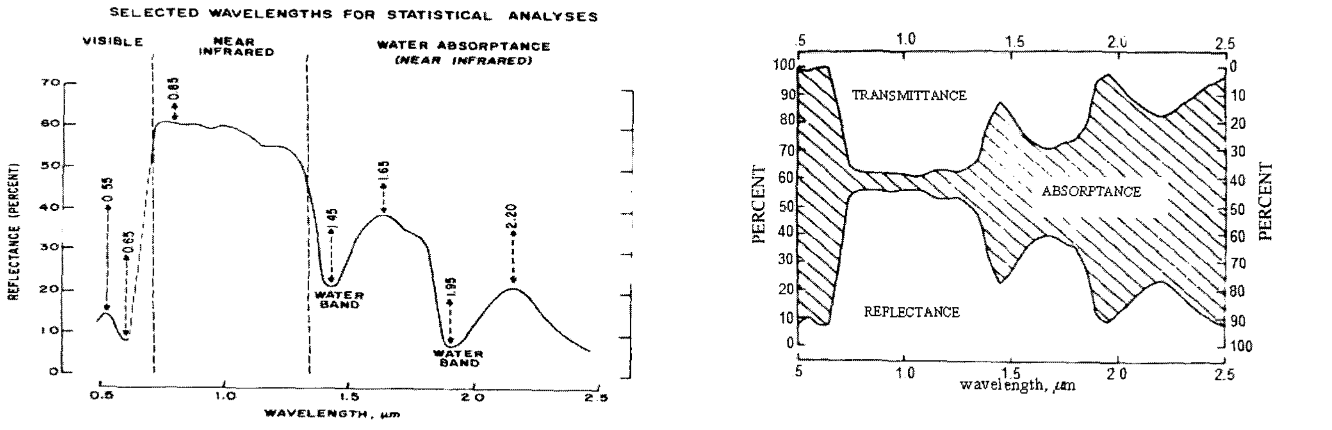
The structure of a monocotyledonous plant such as corn is different from the dicotyledonous leaf. The monocotyledonous leaf is more compact, because it has few air spaces due to the absence of palisade parenchyma cells. Structural difference between dicotyledonous and monocotyledonous-type leaves is generally responsible for a large difference in their near-infrared (NIR) light reflectance (Gausman, 1985). The upper layers of the leaves including the palisade layer are almost transparent to NIR radiation. However, in the mesophyll layer most of NIR radiation is scattered upward. At constant irradiance, the higher the chlorophyll exists the thicker the mesophyll layer becomes and therefore the higher amount of NIR radiation scatters upward (Tumbo *et al.*, 2000b).

2) Leaf optical properties

Most spectral measurements of plant leaves previously reported were made in 0.5 to 2.5 μm portion of the electromagnetic spectrum. The range of this waveband can be divided into three categories as depicted in Figure 4 (a): a visible waveband (0.4~0.70 μm), a NIR waveband (0.70~1.35 μm), and a water absorption waveband (1.35~2.5 μm). Most photons of solar radiation are in the visible waveband that is dominated primarily by pigment chlorophyll. Light in the visible band is mostly absorbed in plant leaves. An infrared band ranging from 0.7 μm to 2.5 μm is produced by a moderately heated surface and affected by internal plant leaf structure. Strong water absorption bands, which are influenced greatly by water concentration in leaf tissue, occur at around 1.45 μm and 1.95 μm (Figure 4 (a)).

Plant leaf responses to solar radiation are configured into three reactions: reflectance, absorptance, and transmittance. When a leaf intercepts incoming irradiation, a portion of the light is absorbed. When the incoming photons impinge on a leaf at a critical angle, another portion of photons are reflected. Light that is neither absorbed nor reflected is transmitted. Transmitted light interacts with subtended leaves or soil. All three reactions vary in electromagnetic wavelength as illustrated in Figure 4 (b). For example, most light is absorbed in the visible waveband (0.4~0.70 μm) and reflected in the NIR waveband (0.70~1.35 μm). Photons with short wavelength (visible light) are used for photosynthesis and photochemical reaction, whereas photons with long wavelength (NIR) are used for heating process evaporation and transpiration (Gausman, 1985). Spectral reflectance at the leaf cuticle is diffuse reflectance from light scattering mainly within the leaf mesophyll which contains water.

One of the earliest studies on leaf optics was done by Willstätter and Stoll (1918). They explained leaf light reflectance and transmittance on the basis of critical reflection of visible light at the cell wall-air interface of spongy mesophyll tissue. Kubelka and Munk (1931) derived differential equations for the treatment of reflection and transmission of diffused light. Their theory accounted for scattering and absorption and was the most satisfactory two-



(a) three regions of the visible, NIR, and water absorption wavebands

(b) three spectral reactions of reflectance, transmittance, and absorption.

Fig. 4 Leaf light response to irradiation over the 0.5 to 2.5 μm waveband of the upper surface of a citrus leaf (Gausman, 1985).

parameter representation of light interaction with a plant canopy. The theory was applied to an actual field plant canopy by Allen and Richardson (1968). They proved that the theory was sufficiently general to specify the interaction of light with a plant canopy and concluded that many reflectance techniques applied to powder, paper, cloth, and other commercial products could be adopted without modification to interpretation of reflectance from a plant canopy.

Gates *et al.* (1965) observed that the leaf materials that affect reflectance and emittance were common to all agricultural plants, and all foliage exhibited the same general pattern of reflectance and emittance. Reflectance, however, varies with plant species. Under field conditions, the reflectance is determined by foliage density, plant height, growth habit, vigor, and maturity. Environmental factors such as soil salinity, moisture availability, and nutrient toxicity or deficiency affect the optical properties of plants by modifying these and other plant characteristics. Therefore, remote sensing of the energy reflected and emitted offers a possible means for determining crop species, maturity, vigor, disease, and probable yield (Thomas *et al.*, 1967).

2. Leaf Spectral Measurements

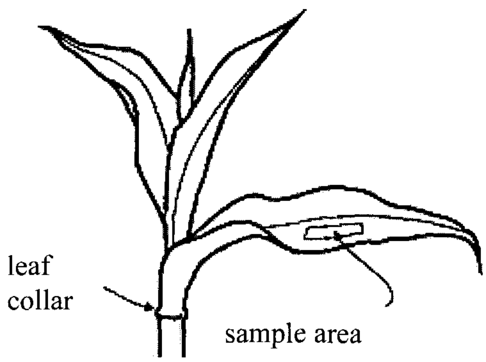
(1) Leaf Transmittance

Procedures have been developed to assess leaf chlorophyll content in a non-destructive mode using a chlorophyll meter (SPAD 502 Chlorophyll meter, Minolta Co., Japan) that measures light transmittance of two light emitting diodes through a canopy. The calculation of a ***SPAD value*** is based on optical density difference at two wavelengths of red at 650 nm and NIR at 940 nm as follows:

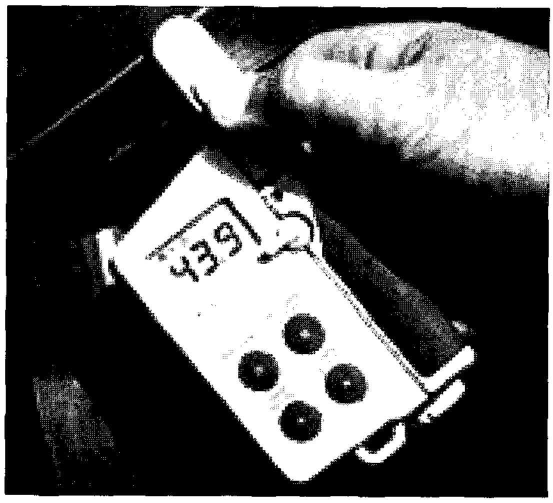
$$\textbf{\textit{SPAD value}} = K \cdot \log_{10}\left(\frac{IR_t \cdot IR_o}{R_t \cdot R_o}\right), \quad (1)$$

where K is a calibration constant, IR_t and R_t are the transmittance of NIR and red wavelength, and IR_o and R_o are the light power of NIR and red wavelength, respectively. The wavelength at 940 nm is not absorbed by chlorophyll, and is used for normalization. High absorption and low reflectance indicates a healthy plant.

The SPAD chlorophyll meter has been used to measure N concentration of corn plants by many researchers for many years (Ahmad *et al.*, 1999, Blackmer and Schepers, 1995, Piekielek *et al.*, 1995, Smeal and Zhang, 1994, Peterson *et al.*, 1993, Piekielek and Fox, 1992, and Schepers *et al.*, 1992). The studies have shown the feasibility of using a SPAD meter for indirectly assessing plant response to N based on chlorophyll response. However, SPAD chlorophyll measurement is a time-consuming process, because it needs careful location and measurement of the newest fully expanded leaf on one-half of the distance from the leaf tip to the collar and halfway between the leaf edge and midrib as illustrated in Figure 5 (a) (Peterson *et al.*, 1993). Such measurements are repeated several times on neighboring plants to derive an average value, which represents only a local spot. As shown in Figure 5 (b), moreover, only small sensing portion of leaf of 2 mm×3 mm (Spectrum Technologies Inc., 2000) is observed in each reading. Though the SPAD meter can be used for a quick reference of chlorophyll on local area, it is still labor intensive to characterize the local variations in entire crop fields.



(a)



(b)

Fig. 5 Measurement of chlorophyll content of a corn leaf using SPAD meter (Peterson *et al.*, 1993). (a) sample area for taking chlorophyll readings, (b) close-up of chlorophyll meter.

(2) Leaf Reflectance

Leaf reflectance is another useful source of plant health response. The use of reflected light has an advantage over transmitted light because light reflectance can be measured without attaching a meter or probe to a specific leaf. Additionally, reflectance measurements can substantially increase the number of plants being monitored and therefore potentially reduce variability. For N management, remotely sensing reflected light from a high-clearance vehicle allows the fertilization process to be automated, thus permitting variable fertilization rates for different parts of the field (Blackmer *et al.*, 1994).

Sinclair (1968) hypothesized that leaf reflectance responses result from the diffuse characteristics of plant cell walls. Lillesaeter (1982) reported that leaf-to-leaf variations in reflectance were approximately 2% for green leaves in the visible spectrum and up to 5% in parts of the NIR spectrum that was caused by variation in the leaf water content. He concluded that the reflecting signatures of plant predicted from single-leaf spectral data can be modeled to predict multiple-leaf reflectance with reasonable accuracy. Spectral reflectance in early stages has been widely measured by using a Beckman DK-2A spectrophotometer (Beckman Instruments, Inc., Fullerton, California) with a range of 500-2,500 nm wavelength. The spectrophotometer was used for spectral mapping of nutrient-deficient maize leaves (Al-Abbas *et al.*, 1974), effects of stacked cotton leaves (Allen and Richardson 1968), osmotic stress of cotton plants (Gausman *et al.*, 1969), effects of soil salinity on reflectance of cotton leaves (Thomas *et al.*, 1967), and water content (Thomas *et al.*, 1971).

Leaf color changes can be induced by stresses such as dehydration, flooding, insects, herbicides, disease, senescence, and insufficient N fertilization. Reflectance of leaves can provide an indication of plant health before any visible indication. Previous studies in the general area of leaf spectral reflectance include the effect of water content, soil properties, osmotic stress, physiological age, sunlight and shaded leaves, plant nutrients, and plant chlorophyll.

1) Water content

Reflectance in NIR waveband is primarily dependent on water content and internal structure of the leaves. The water content of leaves is inversely correlated to reflectance due to light scattering. Thomas *et al.* (1971) reported that reflectance of cotton leaves at 1,450 nm and 1,930 nm water absorption bands was significantly related to leaf relative turgidity or water content. The increased reflectance in NIR region as N deficiency became more severe suggests an increase in intercellular air spaces. Allen and Richardson (1968) showed the water absorption bands were greatly reduced in amplitude after the leaf was dried.

2) Soil properties

Thomas *et al.* (1967) examined the effects of soil salinity on reflectance and transmittance of radiation by cotton leaves and found that reflectance from cotton leaves increased as soil salinity increased. Besides affecting the water and nutrient balance of the plant, soil salinity reduces the leaf surface area and increases the amount of exposed soil. Salt deposits at the soil surface increase reflectance. Soil moisture and texture also affect reflectance.

Morra *et al.* (1991) explored a nondestructive method to determine total soil organic carbon (C) and N concentration. NIR spectroscopy was used to measure the total C and N concentrations in silt and coarse clay, separated from twelve surface soils. The diffused reflectance of NIR radiation was calibrated with constituent concentrations determined using combustion techniques. Their results indicated that NIR reflectance spectroscopy could be a nondestructive technique capable of predicting total C and N concentrations in soil size fractions.

3) Osmotic stress

Gausman *et al.* (1969) studied the effect of osmotic stress on reflectance and transmittance of cotton plants. Three different levels of osmotic stressed cotton plants of the same chronological age were examined over the wavelength interval 500 nm to 2,500 nm. High osmotic stresses reduced reflectance and increased transmittance of NIR as compared with leaves from plants grown with low osmotic stress.

4) Physiological age

Maturity of leaves is related to reflectance with increase due to the spongy effect in the matured leaf. Gausman *et al.* (1970) related the light reflectance of cotton leaves to histological and physical evaluation of leaf maturity. Cotton plants grown hydroponically with controlled environment were tagged on the day they became macroscopically visible. Measurement with a spectrophotometer made on the leaves showed that the largest increase in reflectance, approximately 5%, and decrease in transmittance, approximately 8%, occurred between average values for after-tagging-ages of 3.5 days and 8 days over 750-1,300 nm wavelength interval.

5) Plant nutrients

Al-Abbas *et al.* (1974) analyzed spectra at thirty selected wavelengths from 500 nm to 2,600 nm wavelength in response to N, phosphorus, potassium, sulfur, magnesium, and calcium deficiencies in maize leaves. Their results showed that nutrient-deficient leaves reflected more than those in the control in visible waveband whereas less in the NIR waveband. Nitrogen-deficient maize had the least amount of chlorophyll and was followed in order of increasing chlorophyll content by sulfur-, magnesium-, potassium-, calcium-, phosphorus-deficient, and normal maize plants.

6) Nitrogen and chlorophyll

An early symptom of N deficiency is the yellowing of leaves, called *chlorosis*, due to the loss of chlorophyll. Leaf greenness is affected by leaf chlorophyll content and is strongly related to leaf reflectance. Stressed yellowish leaves have a sharp increase in reflectance throughout the red and green portion of the visible spectrum. In the NIR waveband, yellow leaves have 2% to 3% lower reflectance than the green leaves (Gausman, 1985). Therefore, assessment of leaf reflectance has the high potential to detect N deficiency and promises opportunities for in-season N management.

A number of researchers have studied spectral reflectance of plant leaves correlated to N and chlorophyll concentration in agronomic crops including corn (Lee and Searcy, 2000, Bausch and Duke, 1996, Ma *et al.*, 1996, and Blackmer *et al.*, 1994), wheat (Solie *et al.*, 1996, Stone *et al.*, 1996, and Filella *et al.*, 1995), potatoes (Borhan and Panigrahi, 1999), sweet peppers (Thomas and Oerther, 1972), beans (Thai *et al.*, 1998 and Benedict and Swidler, 1961), cotton (Wilkerson *et al.*, 1999, Saranga *et al.*, 1998, Sui *et al.*, 1998, and Tracy *et al.*, 1992), and poinsettia plants (Meyer *et al.*, 1991). Primary studies observed that the spectral reflectance of the plants in visible region (400-750 nm) is primarily influenced by the leaf pigment chlorophyll and inversely correlated to leaf chlorophyll content.

The earliest study of N and chlorophyll assessment using leaf reflectance was published by Benedict and Swidler (1961). They introduced a non-destructive method to estimate chlorophyll content of soybean leaves by using leaf reflectance and quantified an inverse relationship between the chlorophyll content and percent reflectance of light at 625 nm as measured by a colorimeter with reflectance attachment.

Thomas and Oerther (1972) examined the feasibility of using diffuse light reflectance, measured by a spectrophotometer (Beckman DK-2A), from top leaf surfaces of sweet pepper leaves to quickly estimate their N status. Reflectance as a function of leaf N content of greenhouse-grown sweet pepper was used to estimate the N content of field-grown sweet peppers. They found that the difference between Kjeldahl-determined and reflectance-estimated N contents was less than 0.7% and reflectance measurement at 550 nm gave a better estimate of leaf N content than those at 675 nm.

Thomas and Gausman (1976) observed that spectral reflectance was inversely correlated to leaf total chlorophyll and carotenoid concentrations of eight crops including corn, cotton, cantaloupe, cucumber, head lettuce, grain sorghum, spinach, and tobacco. They found that chlorophyll was the most important independent factor affecting leaf reflectance. The best indication was observed at 550 nm, followed by 650 nm and 450 nm.

Blackmer *et al.* (1994) compared light reflectance (400-700 nm) as measured from corn leaves in the laboratory with a Hunter tristimulus colorimeter with Minolta SPAD chlorophyll meter readings, leaf N concentrations, and specific leaf N. They observed that both leaf N concentration and chlorophyll meter readings were similarly correlated with relative grain yield and 550 nm was the best wavelength to separate N treatment differences.

Bausch and Duke (1996) also compared ground-based canopy reflectance measured over irrigated corn with various N treatments to SPAD chlorophyll meter measurements and to plant tissue total N. Their data system consisted of an instrument platform with two Exotech 100BX four-channel radiometers: one pointed downward to measure target radiance and the other upward to measure solar irradiance. Nitrogen reflectance index was defined as the ratio of the NIR (760-900 nm)/green (520-600 nm) of a particular treatment to that of a reference area and gave a good representation of the N sufficiency index for corn growth stages between V11 and R4. Limitations remained due to soil background effects during early vegetative growth and invalid data under cloudy sky conditions.

Saranga *et al.* (1998) examined NIR analysis as a guide of N fertilization in irrigated cotton to monitor leaf N concentration. NIR reflectance data were collected using a NIR spectrophotometer (Model 6500, NIRSystems, Silver Spring, MD) equipped with a scanning grating monochromator and a spinning sample-cup module. The NIR data of leaf disks originating from field plots were calibrated against laboratory N measurements and required 30 sec for N determination of each sample. The NIR analysis-guided treatment with 60 kg/ha resulted in only 7.5% lower yield relative to the commercial predetermined N treatment with 150 kg/ha.

Lee *et al.* (1999) explored the feasibility of using spectral reflectance to predict N content in corn plant varieties with varying color. Their experiment was conducted in a laboratory equipped with a monochrometer (CM110, CVI Laser Corp., Albuquerque, New Mexico) with wavelength range of 400-1,100 nm, a detector (AD120, CVI Laser Corp.), and halogen-tungsten lamp (AS220, CVI Laser Corp.). They found that the reflectance at 552 nm was responsive to the N content of corn plants whereas variety effect to the reflectance at 552 nm was not significantly different. Their laboratory-based reflectance study was conveyed to in-field applications by Lee and Searcy (2000). The in-field N detecting system measured reflectance of corn leaves under an artificial lighting source inside a lighting chamber in 17.78 (H)×10.16 (L)×7.62 (W) cm dimension. Due to the variability of illumination, the sensor showed limited performance.

Applications

1. Factors in Spectral Analysis

(1) Sun and Shade Response of Leaves

Rao *et al.* (1979) reported that shadow effects were significant on the spectral signature of corn leaves and suggested the inclusion of shadow components in the study of directional effects of leaf spectral measurement. Gausman (1984) investigated the difference in reflectance between sun and shade responses of leaves over the visible waveband and found that the reflectance of sunlit leaves was negatively correlated with total chlorophyll concentration. Reflectance difference between sun and shade leaves over the visible waveband is shown in Figure 6.

(2) Variation of Illumination

In-field spectral measurements are made under natural ambient illumination and influenced by variable cloud cover and widely varying solar zenith angles. Solar radiation at the receiver varies over time and affects spectral measurements at all stages of plant growth. The fraction of solar radiation absorbed by plant leaves depends on the intensity and the spectral distribution of the incoming energy and the incident angle at which the solar energy strikes the plant surface (Gates *et al.*, 1965). Thus, knowing the intensity or amount of solar radiation reaching the crop canopy is one of the most critical aspects of in-field spectral measurements.

The variation of solar radiation is caused by several factors such as cloudy cover, atmospheric moisture, and solar azimuth (Figure 7). Total radiation reaching the ground depends mainly on solar azimuth, and cloud cover. The presence of certain types of clouds such as nimbostratus and fog can attenuate incident radiation by as much as 80% of the total radiation impacting the earth's upper atmosphere (Campbell and Norman, 1998).

The influences of solar radiation are more difficult to characterize under variable illumination conditions, independent of ground-based or airborne spectral image measurement. Data from most of previous studies to estimate

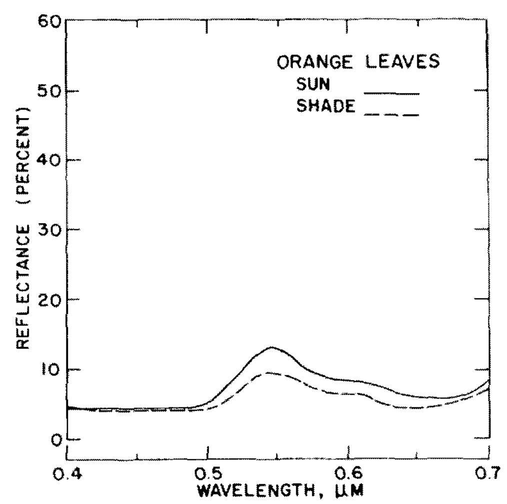


Fig. 6 Reflectance difference between sun and shade leaves of Valencia orange trees over the visible waveband (Gausman, 1984).

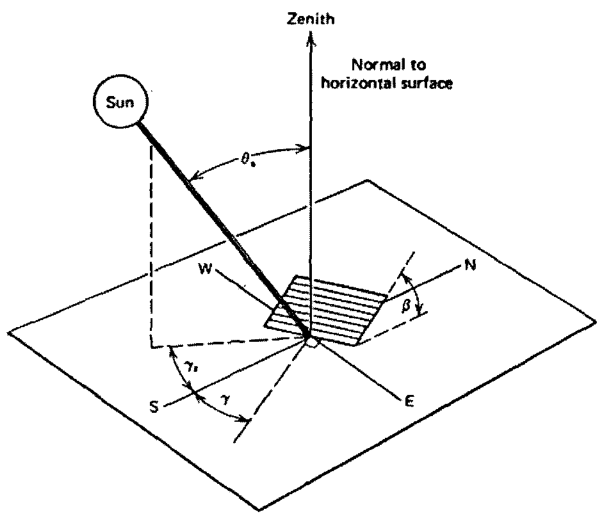


Fig. 7 Solar zenith angle (θ_z), slope (β), surface azimuth angle (γ), and solar azimuth angle (γ_s) for a tilted surface (Duffie and Beckman, 1974).

N and chlorophyll status were collected under clear sky conditions (Bausch and Duke, 1996, Filella *et al.*, 1995, Gates *et al.*, 1965, Ma *et al.*, 1996, Ranson *et al.*, 1985, and Yoder and Pettigrew-Crosby, 1995). Bausch and Duke (1996) excluded the data collected under cloudy sky conditions from the analysis. Yoder and Pettigrew-Crosby (1995) observed that cloudy spring weather limited their spectral measurements to only nine out of their intended 27 targets. As an alternative way to avoid the variations of natural ambient illumination, some research used artificial lighting sources (Lee and Searcy 2000, and Sui *et al.*, 1998).

Several field studies have documented the effects of changing sun angle on vegetation canopy reflectance. Ranson *et al.* (1985) explored that the effects of sun and view angles on reflectance factors from corn canopies at various stages of development. For nadir-view angles, the authors found a strong effect of solar zenith angle on leaf reflectance in all spectral regions and observed maximum reflectance when the sun and sensor directions coincided. In addition to effects of soil and shadows in the sensor field-of-view as major contributors to the changes of reflectance measured, they noticed a moderate increase in reflectance beyond solar zenith angle of approximately 30 degrees on either side of noon and attributed to the presence of specularly reflected light which was apparent to the naked eye as shiny spots on the surface of the leaves. Ranson *et al.* (1985) represented a step towards understanding the complex relationships between the sun, sensor, and scene for reflectance from crop canopies. However their studies were performed only under clear sky conditions.

Tumbo *et al.* (2000b) reported that the correlation between spectral reflectance and chlorophyll content of corn plants significantly decreased with variable solar irradiance. Tumbo *et al.* (2000a) used a neural network-based model to minimize the effect variation of solar radiation on spectral measurement. The training data were obtained at V6 growth stage between 0850 h and 1450 h solar time. The model improved chlorophyll prediction when trained 80% of the data; however, the limitation still remained due to the narrow range of input data. The validation of the model in other patterns of cloudy conditions could be included, because cloudy conditions have a variety of daily patterns of solar radiation. Kim *et al.* (2001) described ambient illumination effect on a spectral image sensor and compensated the non-linearity of the solar irradiation, resulting in consistent reflectance under varying solar zenith angles throughout the daytime.

(3) Bidirectional Reflectance Effect

Asner *et al.*, (1998) presented the phenomenon of bidirectional reflectance that is known as multi-view angle (MVA) reflectance and caused by the variation in reflectance depending on sun and sensor geometry. A bidirectional reflectance distribution function (BRDF) displays maximum reflectance at an antisolar point, often called the hot spot, where the sensor is in direct alignment between the sun and the ground target (Figure 8). Hapke *et al.* (1996) discussed the cause of the hot spot in the bidirectional reflectance of vegetation and soils with two different mechanisms, shadow-hiding and coherent backscatter. A specular reflection, often called sun glint, occurs at the position opposite the antisolar point.

The variation in the BRDF of vegetation results primarily from differences in landscape and canopy structural characteristics (Schaaf and Strahler, 1994 and Asner *et al.*, 1998). Models for bidirectional reflectance were presented by Schaaf and Strahler (1994) based on radiative properties of plants and Nilson and Kuusk (1989) based on geometric-optical considerations.

2. Applications of Optical Remote Sensing Technologies

(1) Multi-spectral Analysis

The spectrum of sun light varies widely over different wavelengths. Vegetation appears very different at visible and NIR wavelengths. Thus, when spectral signatures from more than one waveband are measured, the measurable indication can be amplified and more easily detected. The difference or ratio of multi-spectral responses can be used to maximize the signature of the measurement indication.

There were several indices used in previous studies to

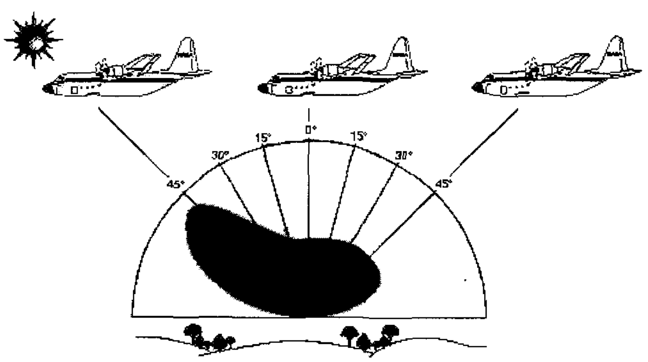


Fig. 8 Illustration of Bidirectional Reflectance Distribution Function (BDRF) for aerial spectral measurement in multiple-view angles (Ranson et al. 1994).

quantify the density of chlorophyll and N status of plant vegetation. A normalized difference vegetation index (NDVI) is widely used to estimate chlorophyll content and is a simple transformation at band reflectance and closely correlated with plant biophysical qualities as well as being less sensitive to external variables such as the solar zenith angle. The NDVI measures the abundance and health of green plants. It is calculated from the spectral response of visible wavebands (*VIS*) and NIR wavebands (*NIR*) reflected by vegetation as follows:

$$NDVI = \frac{NIR - VIS}{NIR + VIS} \quad (2)$$

Calculations of *NDVI* always result in a number that ranges from −1 to +1. Signatures having no green leaves gives a value close to zero. A zero means no vegetation, and approaching +1 indicates the highest density of healthy vegetation.

Figure 9 illustrates an example of the use of NDVI as a vegetation index. Healthy plants (left) reflect only a small portion of the visible light but reflect a large portion of the NIR light. On the other hand, unhealthy or stressed plants (right) reflects more visible light and less NIR light. Therefore, the ratio of the multi-spectral responses shown on the bottom of the Figure provides an amplified indication of difference between the healthy and unhealthy plants. The numbers on the Figure can be much more varied in real vegetation, but follows the same pattern (Figure 10). NDVI better differentiated N treatment effects than any single wavelength band (Ma *et al.*, 1996). Hansen and Schjoerring (2003) examined the selection of the optimal bandwidths in NDVI to improve the vegetation index and reported short bands (10 nm) performed better than broad bands using NDVI.

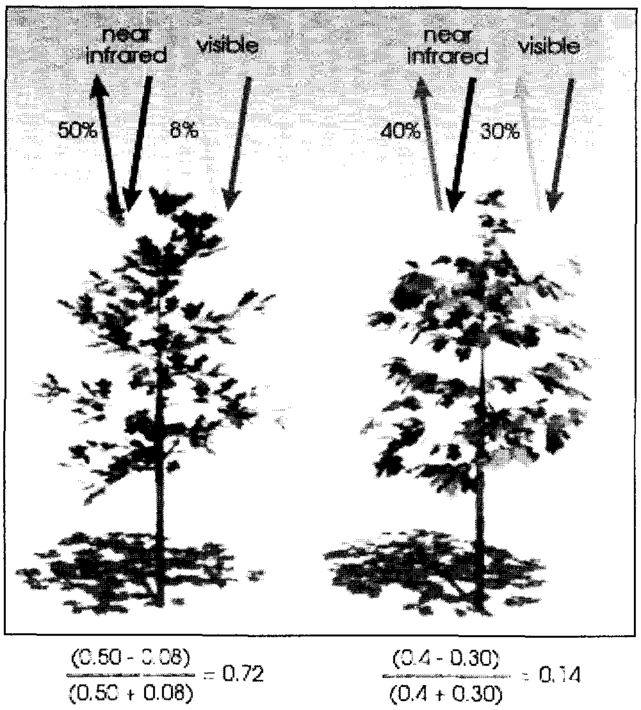


Fig. 9 NDVI as an indication of the density of chlorophyll and N status of plant vegetation (http://earthobservatory.nasa.gov/Library/MeasuringVegetation/measuring_vegetation_2.html).

The shift at the wavelength of red edge inflection point (REIP), i.e. point of maximum slope as shown in Figure 11, is also an often used measure (Horler *et al.*, 1983). Calculation of the *REIP* is as follows:

$$REIP = 700 + 40 \times \frac{(R_{670} + R_{780})/2 - R_{700}}{R_{740} - R_{700}} \quad (3)$$

The REIP value is a measurement of the chlorophyll productivity, so the higher the value, the healthier the plant. REIP is the wavelength location of the Red-NIR absorption line of a plant spectrum (Turner, 2001). As a plant matures, this absorption edge shifts to longer wavelengths (red shift). Geo-chemical or water stress has the reverse effect, causing a shift of the red edge towards shorter wavelengths (blue shift). For example, Rock *et al.* (1988) showed a 5 nm shift of REIP to shorter wavelengths in spruce and fir trees undergoing forest decline. It is noted, however, that the position of the REIP is defined by the shape of the red edge, which is basically an interpolation of reflectance values at a series of wavelengths. Boochs *et al.* (1990)

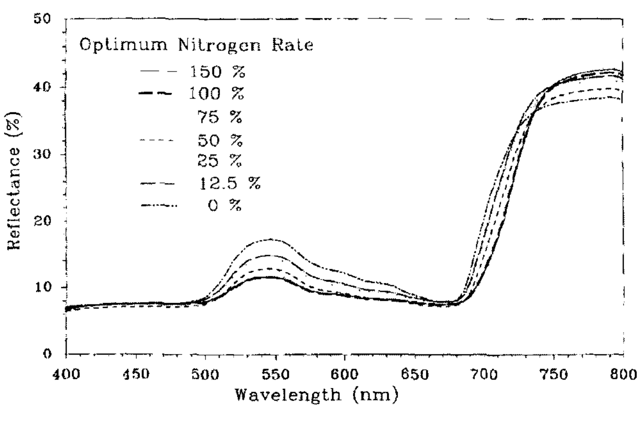


Fig. 10 Reflectance from 400 nm to 800 nm of filed grown corn subjected to different levels of nitrogen fertilization (McMurtrey *et al.*, 1994).

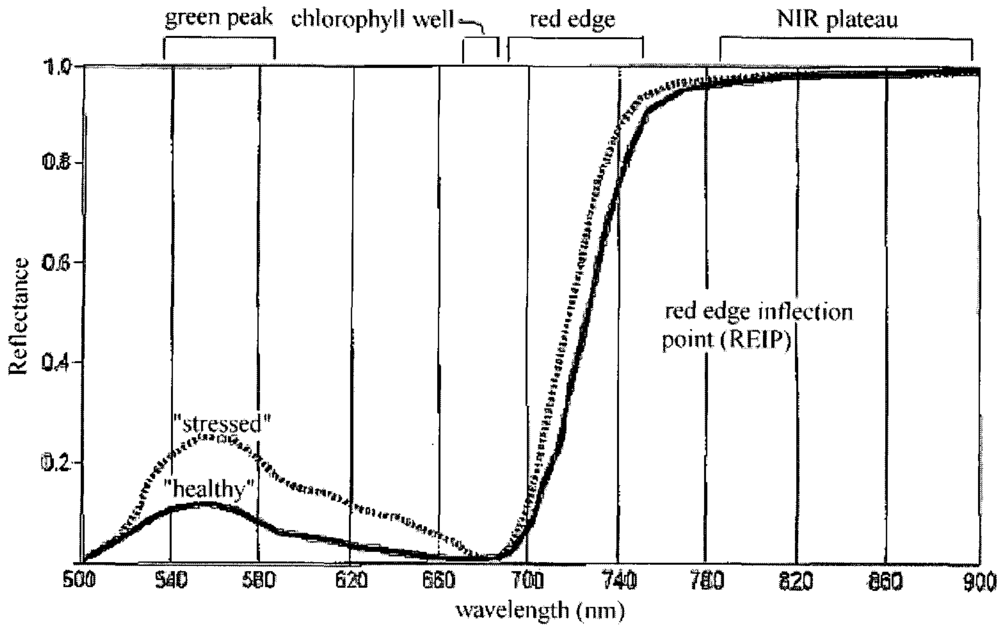


Fig. 11 Reflectance responses of healthy and stressed plant vegetation (Rock *et al.*, 1989).

reported that broader or fewer bands (i.e., fewer points) could lead to a less accurate curve and suggested that high spectral resolutions might be necessary for accurately detecting small differences in the physiological status of plants based on the red edge. The derivative of the spectrum has been extended to higher order derivatives for the analysis of spectral feature at leaf and canopy (Baret *et al.*, 1992) and for the elimination of low-frequency background signals (Butler and Hopkins, 1970 and Demetriades-Shah *et al.*, 1990)

Ratio-based indices are another common way to measure sensitivity of vegetation to stress. They typically combine reflectance from stress sensitive waveband (visible) and insensitive waveband (NIR). Such a normalized reflectance response is represented by the spectral response of a visible (***VIS***) waveband divided by that of a near-infrared (***NIR***) waveband as follows:

$$\text{normalized response} = \frac{VIP}{NIR} \quad (4)$$

The normalized responses with red and green wavebands are denoted by R_n and G_n, respectively. The advantage of using ratios is the capability to factor out extraneous variability. This is particularly useful with in-field remote sensing, because variations in reflectance response occur due to atmospheric conditions and the ratios tend to mask response by combining sensitive with insensitive wavebands.

Blackmer and Schepers (1995) derived an N sufficiency index (NSI) to estimate N status of the crop based on SPAD chlorophyll meter readings of the area with lower amounts of N fertilizer compared to those of the area with the highest amount of N as follow:

$$NSI = \frac{\text{average SPAD reading of N limited area}}{\text{average SPAD reading of N enriched area}} \times 100\% \quad (5)$$

Bausch and Duke (1996) presented another index using a radiometer called N reflectance index (***NRI***) as a ratio of NIR to G canopy reflectance to the same ratio for a well N-fertilized reference area. These indices resulted in a normalized ratios that amplified differences to detectable levels.

Fluorescence can also be an indicator of the plant stress. It is the energy absorbed from external energy source at a shorter wavelength and released by an object in visible or reflected infrared wavelengths at a somewhat longer one. Previous studies have indicated potentials to detect plant nutrients deficiency using laser induced fluorescence (LIF) (Buschmann *et al.*, 1989, Chappelle *et al.*, 1984, and McMurtrey *et al.*, 1994). The LIF technique uses fluorescence light interacted from plant leaf pigments and senses changes in plant physiology and metabolism.

There are many other vegetation indices such as soil adjusted vegetation index (Huete, 1986), photosynthetic reflectance index (Gammon and Serrano, 1997), and red-edge vegetation stress index (Merton, 1998). Differences in species, illumination, canopy architecture and other factors may potentially influence and decrease the correlation between the vegetation indices and the chlorophyll content. Thus, the relationship between canopy chlorophyll content and vegetation indices need to be examined further (Gitelson *et al.*, 1996).

(2) Image-based Spectral Sensing

The image-based spectral sensor minimizes soil background effects that are a major obstacle during early vegetative growth in standard spectroscopic techniques as addressed by Bausch and Duke (1996). One of the advantages with the use of an image-based spectral sensor is an ability to perform image processing to eliminate noisy portions of the sensor response (Figure 12). In-field application of the sensor can also support real-time N assessment as well as real-time fertilization. In any laboratory spectrophotometric setup, the geometric relationships between plant sample and incident radiation are at best a poor approximation to plant-light configurations in nature (Lillesaeter, 1982).

The recent development of technologies has increased the potential use of portable image-based multi-spectral sensors for in-field agricultural applications. The declining price of these technologies promises the cost effectiveness of portable multi-spectral imaging systems for agricultural applications. Perry et al. (2000) explored the impacts of spatial scale and measurement errors on crop stress indicators derived from narrow reflectance band using a hyper-spectral imagery. A multi-spectral imaging system was evaluated for assessment of N stress levels of corn (*Zea mays* L.) crops by Kim *et al.* (2000). The system was a ground-based remote sensor for measuring leaf reflectance from a nadir view over a crop under natural ambient illumination. Images of three spectral ranges (green with 550±50 nm, red with 650±50 nm, and near-infrared with 800±50 nm) were used to derive a reflectance index. The performance of the system was validated with reference measurements from a SPAD chlorophyll meter and stepped N treatments.

(3) Aerial Remote Sensing

Aerial remote sensing technologies provide potentials for mapping vegetation characteristics at large scales and has recently been of interest for assessing spatially-variable crop health in fields. Primary aerial remote sensing studies were conducted by researchers in forestry science. Thomas *et al.* (1967) took aerial photographs of field cotton using an infrared aero film to examine reflectance changes on saline and non-saline soils and showed greater reflectance from cotton not affected by salt. Hunter and Hoy (1983) used black and white aerial photography to assess the extent and variation of N deficiency in pine trees. Blinn *et al.* (1988) found the feasibility of color aerial photography for assessing the need for fertilizers in loblolly pine plantations.

Han *et al.*, (2001), Hendrickson and Han (2000), Moran *et al.* (1997), and Gopalapillai *et al.* (1998) showed the potential of aerial remote sensing to detect N stress using spectral images taken from satellite or aircraft. Images from those airborne sensors were used for monitoring seasonally variable crop conditions and for time-specific crop management. Moran *et al.* (1997) reviewed the prospect and limitations for image-based sensing in precision crop management from aircraft or satellite based platforms. They portrayed an infrastructure that may have promise for incorporating aircraft or satellite-based remote sensing technology into precision crop management system. The current limitations for satellite-based sensors are mainly due to sensor attributes such as restricted spectral range that may be inappropriate for a given application, coarse spatial resolution for within-field analysis, inadequate repeat coverage

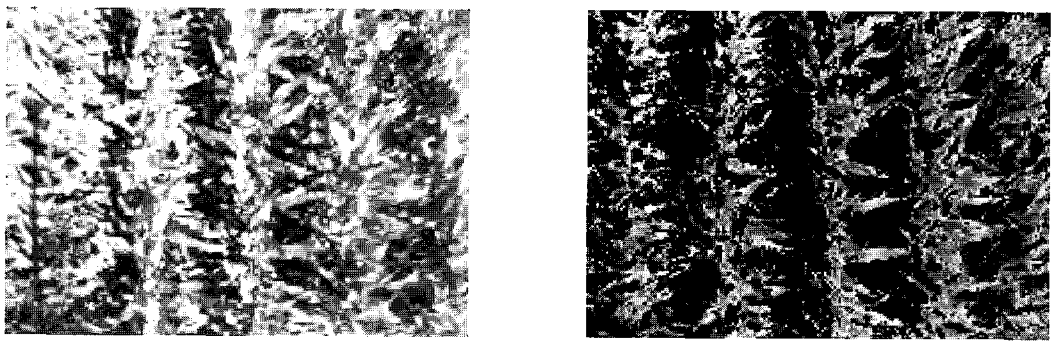


Fig. 12 Composite image of corn plants in three spectral channels where G, NIR, and R channels were displayed as red, green, and blue: (a) image before segmentation, (b) image after segmentation (Kim et al., 2000).

for intensive agricultural management, limited accessibility to the satellite images due to fixed cycling time, and long time period between image acquisition and delivery to user. Aircraft-based sensors avoid these limitations, but are difficult to calibrate and the frame-based output is difficult to register for mapping coordinates for large area coverage (Moran *et al.*, 1997).

Satellite-based remote sensing technologies became widely available for mapping of vegetation and has the potential to revolutionize regional and global-scale spectral measurements of ecological variables (Asner *et al.*, 1998). Reflectance measured at satellites can be simply related to the target reflectance at ground when the surrounding optical properties are similar. However, the atmospheric effects are significant in both incident solar energy and reflected light. Accurate knowledge of spectral instruments and careful radiometric calibration are required (Conel *et al.*, 1998 and Vane et al., 1984).

Conclusions

Assessment of plant nitrogen (N) has been of interest worldwide to provide growers with site-specific N fertilizer and minimize environmental impact. Plant leaf interaction with radiation is a major influence on the remote sensing signals. It is important to understand the optical characteristics of plant leaves to apply the principle of remote sensing. Most spectral measurements of plant leaves previously reported were made in 500 to 2500 nm portion of the electromagnetic spectrum. It was generally observed that N stressed plant leaves have a reflectance higher in visible and lower in near-infrared waveband than non-stressed leaves. Spectral signature of plant leaves have great potential to characterize the plant features and the spectral reflectance of the plants in visible region (400 - 750 nm) is primarily influenced by the leaf pigment chlorophyll and inversely correlated to leaf chlorophyll content. Several studies indicated a good estimation of leaf N content at 550 nm wavelength. This paper described remote sensing technologies, applications, and factors to be considered. With the progress of remote sensing technology and understanding plant optics, remote sensing is a promising tool to lead precision agriculture in the future.

References

Ahmad, I. S., J. F. Reid, N. Noguchi and A. C. Hansen. 1999. Nitrogen sensing for precision agriculture using chlorophyll maps. ASAE paper No. 99-3035. St. Joseph, MI: ASAE.

Al-Abbas, A. H., R. Barr, J. D. Hall, F. L. Crane and M. F. Baumgardner. 1974. Spectra of normal and nutrient-deficient maize leaves. Agronomy Journal 66(1): 16-20.

Allen, W. A. and A. J. Richardson. 1968. Interaction of light with a plant canopy. Journal of Optical Society of America 58(8):1023-1028.

Asner, G.P., B.H. Braswell, D.S. Schimel and C.A. Wessman. 1998. Ecological research needs from multi-angle remote sensing data. Remote Sensing of Environment 63:155-165.

Baret, F., S. Jacquemoud and G. Guyot. 1992. Modeled analysis of the biophysical nature of spectral shifts and comparison with information content of broad bands. Remote Sensing of Environment 41:133-142.

Bausch, W. C. and H. R. Duke. 1996. Remote sensing of plant nitrogen status in corn. Transactions of the ASAE 39(5):1869-1875.

Benedict, H. M. and R. Swidler. 1961. Nondestructive method for estimating chlorophyll content of leaves. Science 133: 2015-2016.

Blackmer, T. M. and J. S. Schepers. 1995. Use of a chlorophyll meter to monitor nitrogen status and schedule fertigation for corn. Journal of Production Agriculture 8(1):56-60.

Blackmer, T. M., J. S. Schepers and G. E. Varvel. 1994. Light reflectance compared with other nitrogen stress measurements in corn leaves. Agronomy Journal 86(6): 934-938.

Blinn, C. R., A. Lyons, and E. R. Buckner. 1988. Color aerial photography for assessing the need for fertilizers in loblolly pine plantations. Southern Journal of Applied Forestry 12(4): 270-273.

Boochs, F., F. Kupfer, K. Dockter and W. Kuhbauch. 1990. Shape of the red edge as vitality indicator for plants. International Journal of Remote Sensing 11: 1741-1753.

Borhan, M. S. and S. Panigrahi. 1999. Multi-spectral imaging techniques for nitrogen determination in potato leaf. ASAE paper No. 99-5005. St. Joseph, MI: ASAE.

Buschmann, C., U. Rinderle and H.K. Lichtenthaler. 1989. Detection of stress of coniferous forest trees with the VIRAF spectrometer. Proc. Int. Geosci. and Remote Sens. Symp. (IGARSS'89), pp. 2641-2644.

Butler, W. L. and D. W. Hopkins. 1970. Higher derivative analysis of complex absorption spectra. Photochemistry and Photobiology 12:439-450.

Campbell, G. S. and J. M. Norman. 1998. *An Introduction of Environmental Biophysics*. 2^{nd} Edition. (Springer-Verlag, New York, USA), p. 173-175.

Chappelle, E.W., J.E. McMurtrey III, F.M. Wood and W.W. Newcomb. 1984. Laser induced fluorescence (LIF) of green plants. II: LIF changes due to nutrient deficiencies in corn. Applied Optics 23:139-142.

Conel, J.E., S. Adams, R.E. Alley, G. Hoover and S. Schultz. 1988. AIS radiometry and the problem of contamination from mixed spectral orders. Remote Sensing of Environment 24:179-200.

Curran, P.J. 1989. Remote sensing of foliar chemistry. Remote Sensing of Environment 30:271-278.

Demetriades-Shah, T.H., M.D. Steven and J.A. Clark. High resolution derivative spectra in remote sensing. Remote Sensing of Environment 33:55-64.

Duffie, J. A. and W. A. Beckman. 1974. *Solar Energy of Thermal Processes*, (John Wiley & Sons, New York, USA), p. 10-20.

Filella, I., L. Serrano, J. Serra and J. Penuelas. 1995. Evaluating wheat nitrogen status with canopy reflectance indices and discriminant analysis. Crop Science 35: 1400-1405.

Gammon J.A. and L. Serrano. 1997. The photochemical reflectance index: an optical indicator of photosynthetic radiation use efficiency across species, functional types, and nutrient levels. Oecologica 112:492-501.

Gates, D. M., H. J. Kegan, J. C. Schleter and V. R. Weidner. 1965. Spectral properties of plants. Applied Optics 4(1):11-20.

Gausman, H. W. 1984. Evaluation of factors causing reflectance differences between sun and shade leaves. Remote Sensing of Environment 15:177-181.

Gausman, H. W. 1985. *Plant Leaf Optical Properties*. (Texas Tech Press, Lubbock, USA), p. 9-39.

Gausman, H. W., W. A. Allen, R. Cardenas and A. J. Richardson. 1970. Relation of light reflectance to histological and physical evaluations of cotton leaf maturity. Applied Optics 9(3):545-552.

Gausman, H. W., W. A. Allen, V. I. Myers and R. Cardenas. 1969. Reflectance and internal structure of cotton leaves. Agronomy Journal 61:374-376.

Gitelson, A.A., M.N. Merzlyak and H.K. Lichtenthaler. 1996. Detection of red edge position and chlorophyll content by reflectance measurements near 700 nm. Journal of Plant Physiology 148:501-508.

Gopalapillai, S., L. Tian and J. Beal. 1998. Detection of nitrogen stress in corn using aerial imaging. ASAE Paper No. 98-3030. St. Jospeph, MI: ASAE.

Han, S., L. Hendrickson and B. Ni. 2001. Comparison of satellite remote sensing and aerial photography for ability to detect in-season nitrogen stress in corn. ASAE Paper No. 01-1142. St. Jospeph, MI: ASAE.

Hansen, P. M. and J. K. Schjoerring, 2003. Reflectance measurement of canopy biomass and nitrogen status in wheat crops using normalized difference vegetation indices and partial least squares regression. Remote Sensing of Environment 86:542-553.

Hapke, B., D. DiMucci, R. Nelson and W. Smythe 1996. The cause of the hot spot in vegetation canopies and soils: Shadow-hiding versus coherent backscatter. Remote Sensing of Environment 58:63-68.

Hendrickson, L. and S. Han. 2000. A reactive nitrogen management system. Proc. 5th International Conference on Precision Agriculture. ASA Misc. Publ., ASA, CSSA, and SSSA, Madison, WI.

Horler, D. N. H., M. Dockray and J. Barber. 1983. The red edge of plant leaf reflectance. International Journal of Remote Sensing 4:273-288.

Huete, A.R. 1986. A soil-adjusted vegetation index (SAVI). Remote Sensing of Environment 25:295-309.

Hunter, I. R. and F. F. Hoy. 1983. Growth and nutrition of Pinus radiata on a recent coastal sand as affected by nitrogen fertiliser. New Zealand Journal of Forestry Science 13:3-13.

Kim, Y., J. F. Reid, A. Hansen and M. Dickson. 2000. Evaluation of a multi-spectral imaging system to detect nitrogen stress of corn crops. ASAE Paper No. 00-3128. St. Joseph, MI: ASAE.

Kim, Y., J. F. Reid, A. Hansen, Q. Zhang and M. Dickson. 2001. Ambient illumination effect on a multi-spectral image sensor for detecting crop nitrogen stress. ASAE Paper No. 01-1178. St. Joseph, MI: ASAE.

Kubelka, P. and F. Munk. 1931. Ein beitrag zur optik der farbanstriche (A contribution to optic of color paint). Zeitschr. Techn. Physik 11:593-601.

Lee, W. and S. W. Searcy. 2000. Multispectral sensor for detecting nitrogen in corn plants. ASAE Paper No. 00-1010. St. Joseph, MI: ASAE.

Lee, W., S. W. Searcy and T. Kataoka. 1999. Assessing nitrogen stress in corn varieties of varying color. ASAE Paper No. 99-3034. St. Joseph, MI: ASAE.

Lillesaeter, O. 1982. Spectral reflectance of partly transmitting leaves: laboratory measurements and mathematical modeling. Remote Sensing of Environment 12: 247-254.

Ma, B. L., M. J. Morrison and L. M. Dwyer. 1996. Canopy light reflectance and field greenness to assess nitrogen fertilization and yield of maize. Agronomy Journal 88: 915-920.

McMurtrey III, J.E., E.W. Chappelle, M.S. Kim, J.J. Meisinger and L.A. Corp. 1994. Distinguishing nitrogen fertilization levels in field corn (Zea mays L.) with actively induced fluorescence and passive reflectance measurements. Remote Sensing of Environment 47:36-44.

Merton, R. 1998. Monitoring community hysteresis using spectral shift analysis and the red-edge vegetation stress index. Proceedings of the 7th Annual JPL Airborne Earth Science Workshop.

Meyer, G. E., W. W. Troyer and J. B. Fitzerald. 1991. Vision methods for inspection of green house poinsettia plants. Proceedings of International Society of Optical Engineering 1379:99-105.

Moran, M. S., S. Inoue and E. M. Barnes. 1997. Opportunities and limitations for image-based remote sensing in precision crop management. Remote Sensing of Environment 61:319-346.

Morra, M. J., M. H.Hall and L. L. Freebom. 1991. Carbon and nitrogen analysis of soil fractions using near-infrared reflectance spectroscopy. Soil Science Society of America Journal 55(1):288-291.

Nilson, T. and A. Kuusk. 1989. A reflectance model for the homogeneous plant canopy and its inversion. Remote Sensing of Environment 27:157-167.

Perry, E. M., M. Gardner, J. Tagestad, D. Roberts, P. Cassady, J. Smith and D. Nichols. 2000. Effects of image resolution and uncertainties on reflectance-derived drop stress indicators. Proceedings of AVIRIS Airborne Geoscience Workshop. <ftp://popo.jpl.nasa.gov/pub/docs/workshops/ aviris.proceedings.html>

Peterson, T. A., T. M. Blackmer, D. D. Francis and J. S. Schepers. 1993. Using a chlorophyll meter to improve N management. University of Nebraska-Lincoln Cooperative Extension NebGuide G93-1171-A. July 1993.

Piekielek, W. P. and R. H. Fox. 1992. Use of a chlorophyll meter to predict sidedress nitrogen requirements for maize. Agronomy Journal 84:59-65.

Piekielek, W. P., R. H. Fox, J. D. Toth and K. E. Macneal. 1995. Use of a chlorophyll meter at the early dent stage of corn to evaluate nitrogen sufficiency. Agronomy Journal 87:403-408.

Ranson, K. J., C. S. T. Daughtry, L. L. Biehl and M. E. Bauer. 1985. Sun-view angle effects on reflectance factors of corn canopies. Remote Sensing of Environment 18: 147-161.

Ranson, K.J., J.R. Irons and D.L. Williams. 1994. Multispectral bidirectional reflectance of northern forest canopies with the Advanced Solid-State Array Spectroradiometer (ASAS). Remote Sensing of Environment 47:276-289.

Rao, V. R., E. J. Brach and A. R. Mack. 1979. Bidirectional reflectance of crops and the soil contribution. Remote Sensing of Environment 8:115-125.

Rock, B. N., T. Hoshizaki and J. R. Miller. 1988. Comparison of in situ and airborne spectral measurements of the blue shift associated with forest decline. Remote Sensing of Environment 24:109-127.

Saranga, Y., A. Landa, Y. Shekel, A. Bosak and U. Kafkafi. 1998. Near-infrared analysis of cotton leaves as a guide for nitrogen fertilization. Agronomy Journal 90: 16-21.

Schaaf, C.B. and A.H. Strahler. 1994. Validation of bidirectional and hemispherical reflectances from a geometric-optical model using ASAS imagery and pyranometer measurements of a spruce forest. Remote Sensing of Environment 49:138-144.

Schepers, J. S., D. D. Francis, M. Vigil and F. E. Below. 1992. Comparison of corn leaf nitrogen concentration and chlorophyll meter readings. Communications in Soil Science and Plant Analysis 23(17-20):2173-2187.

Sinclair, T. R. 1968. Pathway of solar radiation through leaves. M.S. thesis. Purdue University, Lafayette, Indiana.

Smeal, D. and H. Zhang. 1994. Chlorophyll meter evaluation for nitrogen management in corn. Communications in Soil Science and Plant Analysis 25(9-12):1495-1503.

Solie, J. B., W. R. Raun, R. W. Whitney, M. L. Stone and J. D. Ringer. 1996. Optical sensor based field element size and sensing strategy for nitrogen application. Transactions of the ASAE 39(6):1983-1992.

Spectrum Technologies, Inc. 2000. Nutrient Management. <http://www.specmeters.com/nutrientmgmt2.htm>. Accessed 3 May 2000.

Stone, M. L., J. B. Solie, R. W. Whitney, W. R. Raun and H. L. Lees. 1996. Sensors for detection of nitrogen in winter wheat. SAE Paper No. 96-1757. Warrendale, PA: SAE.

Sui, R., J. B. Wilkerson, W. E. Hart and D. D. Howard. 1998. Integration of neural networks with a spectral reflectance sensor to detect nitrogen deficiency in cotton. ASAE Paper No. 98-3104. St. Joseph, MI: ASAE.

Thai, C. N, M. D. Evans, X. Deng and A. F. Theisen. 1998. Visible & NIR imaging of bush beans grown under different nitrogen treatments. ASAE Paper No. 98-3074. St. Joseph, MI: ASAE.

Thomas, J. R. and H. W. Gausman. 1976. Leaf reflectance vs. leaf chlorophyll and carotenoid concentrations for eight crops. Agronomy Journal 69:799-802.

Thomas, J. R., L. N. Namken, G. F. Oerther and R. G. Brown. 1971. Estimating leaf water content by reflectance measurement. Agronomy Journal 63:845-847.

Thomas, J. R. and G. F. Oerther. 1972. Estimating nitrogen content of sweet pepper leaves by reflectance measurements. Agronomy Journal 64: 11-13.

Thomas, J. R., C. L. Wiegand and V. I. Myers. 1967. Reflectance of cotton leaves and its relation to yield. Agronomy Journal 59:551-554.

Tracy, P. W., S. G. Hefner, C. W. Wood and K. L. Edmisten. 1992. Theory behind the use of instantaneous leaf chlorophyll measurement for determining mid-season cotton nitrogen recommendations. Beltwide Cotton Conference. pp. 439-443.

Tumbo, S. D., D. G. Wagner and P. H. Heinemann. 2000a. Hyperspectral input-based neural network model for predicting chlorophyll status in corn. ASAE Paper No. 00-1009. St. Joseph, MI: ASAE.

Tumbo, S. D., D. G. Wagner and P. H. Heinemann. 2000b. Real-world hyperspectral characteristics of corn plants under different chlorophyll levels. ASAE Paper No. 00-1093. St. Joseph, MI: ASAE.

Turner, K. 2001. Integrating remote sensing data with a GIS application for precision agriculture customers. The 21st Annual ESRI International User Conference, July 9-13,2001. <http://www.esri.com/library/userconf/proc01/professional/papers/pap402/p402.htm>

U.S. Environmental Protection Agency. 1998. The quality of our nation's water: 1996. EPA841-S-97-001. April 1998. Washington, D.C.: United States Environmental Protection Agency. pp. 9.

Vane, G., A.F.H. Goetz and J.B. Wellman. 1984. Airborne Imaging Spectrometer: A new tool for remote sensing. IEEE Trans. Geosci. Remote Sens. GE-22 6, pp. 546-549.

West, P. C. 1990. *Optical Physics for Machine Vision: A Tutorial*. (Automated Vision Systems, Inc., Los Gatos, USA), p. 1.

Wilkerson, J. B., R. Sui, W. E. Hart, L. R. Wilhelm and D. D. Howard. 1999. Artificial neural networks for determining nitrogen status in cotton. ASAE Paper No. 99-3042. St. Joseph, MI: ASAE.

Willstatter, R. and A. Stoll. 1918. Untersuchungen uber die asimilation der kohlensaure (Analysis of the assimilation of carbonic acid). Springer-Verlag, Berlin. pp. 122-127.

Yoder, B. J. and R. E. Pettigrew-Crosby,. 1995. Predicting nitrogen and chlorophyll content and concentrations from reflectance spectra (400-2500 nm) at leaf and canopy scales. Remote Sensing of Environment 53:199-211.