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Remote Sensing of Vegetation Characteristics for Farm Management

Ray D. Jackson

U. S. Department of Agriculture, Agricultural Research Service,
U. S. Water Conservation Laboratory, 4331 East Broadway Road, Phoenix, Arizona 85040

Abstract

The potential for remotely sensed data being used by farmers in making day-to-day management decisions has not been fully realized because the data have generally not been available in real-time. Furthermore, the relationships between spectral data and crop and soil properties have yet to be incorporated into the expert systems necessary for rapid data analysis and interpretation. This review details some major requirements for a farm oriented remote sensing system, and evaluates the state-of-the-art concerning relationships between spectral data and crop and soil properties. Current and proposed remote sensing systems geared toward farm management are discussed.

Introduction

Remote sensing, as we know it today, is generally considered to date from about 1960. From the start, agriculture was promoted as a prime user of remotely sensed data. Early flights with multispectral scanners frequently chose agricultural targets. These experiments clearly showed that emitted thermal infrared radiation was an indicator of the water content of soil and several visible and near-infrared bands could readily distinguish vegetation. The agricultural potential of remote sensing was obvious. Farmers were to have readily available data to assist them in making management decisions concerning such factors as irrigation, fertilization, plant diseases, and insect infestations. This message was implicit in a number of publications,[1,2,3] and was the theme of an article in the 4 March 1984 Los Angeles Times.

The launch of the first satellite of the Landsat series in 1972 spurred remote sensing research in the agricultural arena. During that year, large grain sales to Russia upset the commodity market. As a consequence, efforts were begun to monitor agricultural crops on a worldwide basis. Agricultural remote sensing research was focused on acreage estimations, crop identification, and yield prediction. With scanty historical data, some reasonably current meteorological data, and Landsat imagery, crop production forecasts were made for a number of countries. It was obvious that most information must come from satellite data, since many targets of interest could not be visited by ground crews. Classification techniques were developed to circumvent the lack of ground data and to handle the large areas covered by the imagery. Strong efforts were made to convert image interpretation from a human art to a machine printout.

The benefits of these efforts have been considerable. Remotely sensed data are routinely used by crop production forecasters. Resource surveys have been invaluable. Yet the promise to the farmer has not been kept. The Los Angeles Times article of 4 March 1984, after headlining "New Satellite Will Keep an Eye on Crops," stated that "The findings of Landsat-5 ... are expected to be of great benefit to commodity market traders, large agricultural interests, oil, gas and mineral explorers and the U.S. and foreign governments." Farmers were not mentioned. The benefits of Landsat-5 will undoubtedly be enormous. However, it was not designed to provide real-time information to farmers. Remotely sensed data that can be used by farmers to make day-to-day management decisions are available in only a rudimentary form. No operational satellite remote sensing system exists that can provide farmers with near real-time information, frequent coverage, and high spatial resolution.

If the hardware for such a system were available now, another problem would be immediately evident. Because agricultural remote sensing has, by necessity, concentrated on satellite imagery, insufficient ground-based data are available to develop the necessary expert systems that would allow a farmer to, with the touch of a computer key, determine what nutrient was deficient from a field and whether it would be economically feasible to add the optimum amount of fertilizer. What is needed is a detailed examination of what remotely sensed data can tell us about soils and crops. The ground rules are different, a farmer knows what crops are planted and the field areas. What is not known is the day-by-day soil and crop conditions. Does the south 40 need irrigating? How widespread is the Pythium aphanidermatum infection in the sugar beets? To provide such information, a remote sensing system must be specifically designed to accommodate these unique requirements. The development of such a system will be considerably different than the previous efforts in agricultural remote sensing. The groundwork will be done, and then a dedicated system will be designed specifically for farm management remote sensing.

This report outlines the requirements for a remote sensing system whose specific purpose would be to assist farmers in making day-to-day management decisions, reviews the recent reports concerning the remote detection of soil and crop conditions and evaluates them as to how well they meet the needs of a highly automated remote sensing system, and discusses some current and future systems.

System requirements

A remote sensing system for farm management has a number of unique requirements. Timeliness, frequency of coverage, and spatial resolution are three important factors. The fusing of remotely sensed data with meteorological and agronomic data bases is necessary in order to run appropriate models. Recent developments in expert systems (a subset of artificial intelligence) have enhanced the feasibility of highly automated data analysis.

The remote sensing system

Timeliness. Timeliness is perhaps the most important requirement for a farm management remote sensing system. Figure 1 is a hypothetical relation that shows how the usefulness of remotely sensed data decays with time. To obtain maximum usefulness, the data must be available within minutes. This may appear extreme, but farm operations must be carried out when crop conditions demand. A remote sensing system that required, say, five days for data delivery after initial acquisition would be essentially useless for indicating when to irrigate, because yield reducing damage would have occurred by the time water could be applied. A remote sensing system for farm management would have an optimum data delivery time of minutes, and a maximum time of a few hours.

Frequency of coverage. Frequency of coverage is another important aspect. Figure 2 shows a hypothetical relationship between usefulness and frequency. For farm management, the maximum usefulness would obtain if continuous coverage were available. Features related to canopy architecture, leaf area index, dry matter, and other plant properties are best assessed in the morning, whereas stress related features are optimally obtained within an hour after solar noon. During the growing season crop conditions continously change. In arid areas, irrigation may be required every 7 to 20 days. A system with a 16 day repeat time would provide little useful information. Also, cloud conditions may increase the time period between acquistions. Continuous coverage would be the optimum, with once a day coverage as a minimum.

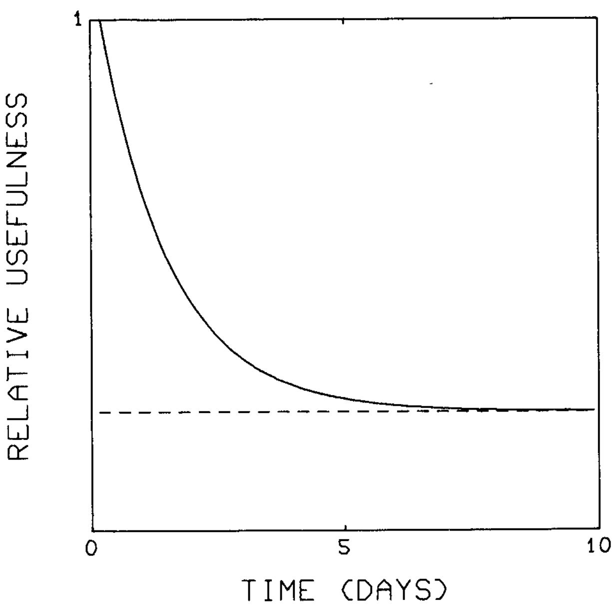

Figure 1. Relative usefulness of remotely sensed data to farmers in relation to time from acquisition to delivery in usable form.

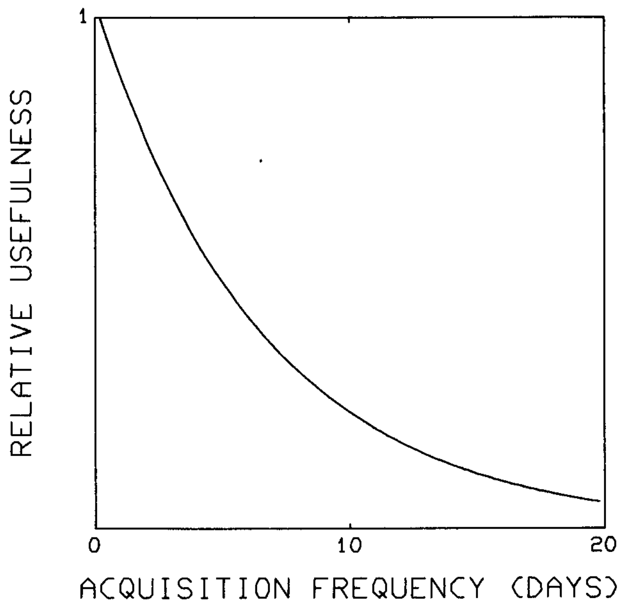

Figure 2. Relative usefulness of remotely sensed data to farmers in relation to frequency of coverage.

Resolution. The spatial resolution requirements for a farm management system are dependent upon the particular application for the data. For a farm with relatively uniform soils and a minimum field size of about 40 acres the 30 x 30 m resolution of a sensor such as the Thematic Mapper may be adequate. This is usually not the case. Many fields are considerably smaller than 40 acres and soil heterogeneity across fields causes plant growth differences. As an example, during irrigation, areas with low water infiltration may not have the root zone replenished with water, whereas areas of high intake would. The irrigation program for that field would probably be decided on the basis of availability and cost of water and the current crop. A farmer may decide to over-irrigate the high intake areas to assure good crop development over the entire field. Under limited water conditions the high intake areas may be used as the indicator of when to irrigate with the lower yields on the other areas accepted. Considering a number of factors, it appears that a resolution of 5 x 5 m would be optimum, with 20 x 20 m acceptable, if sensor design constraints will not allow a smaller figure.

Meteorological and agronomic data bases

Remote sensing cannot provide all necessary data for a farm management system. Meteorological data (air temperature, vapor pressure, windspeed, solar irradiance, etc.) are inputs into models that predict plant development and the amount of evapotranspiration. These models should run continuously throughout a growing season. Remote sensing inputs should be used whenever available to correct the models to actual conditions. Agronomic inputs such as plant varieties, plant and row spacing, and row orientation, are also required by the models.

These data bases would be parts of an expert system. Such a system would include economic inputs, and could predict the economic consequence of a farm management decision. For example, if the remote sensing system indicates that a particular field is deficient in fertilizer, the expert system could predict what the yield would be with and without the additional fertilizer and compute whether the management practice was economically feasible.

Spectral indicators of crop and soil parameters

By the mid-1970's small, lightweight radiometers that could be hand-held or boom mounted were being used to obtain ground data for the main purpose of aiding the interpretaton of satellite imagery. The long needed process of collecting intensive data sets concerning the interactions of electromagnetic radiation with soils and crops had begun. The elucidation of these complex interactions was approached by frequently collecting data over numerous small plots in which crops were carefully monitored, cultural variables such as soil water, nutrients, row spacing, and row orientation, conveniently manipulated, and the aerial environment of the crop adequately specified. The detailed laboratory work carried out during the previous decade provided necessary guidance for the interpretation of the field data.[4,5,6,7,8]

The number of locations conducting field investigations of this type have steadily increased during the past decade. Several groups used radiometers that measured emitted radiation in the 8-14 µm waveband to infer the temperatures of plants and soils, while others used radiometers that measure in the visible and the near-infrared wavelengths. A radiometer that contains three visible, two near-IR, two mid-IR, and one thermal-IR band was developed,[9] and reports containing data in these wavebands have recently appeared.[10]

The objectives of many ground-based investigations have been to assess the amount of vegetation present in a field and to evaluate the health of the plants. In general, thermal-IR techniques have been used to detect the onset of plant stress, whereas techniques that use reflected solar radiation have been most useful for assessing plant properties such as biomass (phytomass is a more accurate term) and the leaf area index (the area of green leaves per unit area of soil), which can be used to evaluate the result of stress and serve as inputs to plant growth and evapotranspiration models.

Vegetation indices

A spectral vegetation index is obtained by ratioing, differencing, or otherwise combining or transforming spectral data to represent plant canopy characteristics such as leaf area index, phytomass, green weight, dry weight, percent cover, etc.[11] Its purpose is to differentiate vegetation from the soil background, and to provide a numerical value that can be related to the various plant parameters. At least four dozen vegetation indices have been proposed, but most are functionally related.[12]

Perhaps the most popular vegetation index is the ratio of radiance or reflectance of a near-IR band to that in a visible red band. This ratio is sensitive to vegetation because red light (0.63 - 0.67 μm) is absorbed by chlorophyll with little being transmitted or reflected, whereas in the near-IR (0.7 - 1.3 μm) absorption is nearly zero and reflectance and transmittance are high.[7] Thus, the near-IR band increases, the red band decreases, and the ratio increases, as the amount of vegetation increases. Jordan[13] first reported the use of the near-IR/red ratio as a measure of vegetation. It has been used by a number of authors since then. Tucker[14] reviewed vegetation indices formed by various combinations of the near-IR and red bands and showed that they are useful for monitoring the photosynthetically active biomass of plant canopies.

In the analysis of Landsat imagery over western rangelands, the near-IR/red ratio was found to be relatively insensitive to sparse vegetation.[15] The difference-sum ratio of the two bands (near-IR - red)/(near-IR + red), now known as the normalized difference (ND) was found to be more sensitive to low vegetation amounts than the simple near-IR/red ratio. Under certain conditions the ND may become negative, because for very low vegetation densities the composite reflectance is nearly that of soil (the red reflectance from soil may be greater than the near-IR reflectance). To avoid negative values and to circumvent other perceived problems, the transformed normalized difference (TND) was formulated. This index is merely the square root of (ND + 0.5). Its utility over the other two indices has not been adequately demonstrated.

Richardson and Wiegand[16] showed that a plot of near-IR versus red band radiances for soils would fall on a straight line. As vegetation grows on the soil, the red radiance decreases and the near-IR radiance increases. A vegetation point would lie away from the soil line with the perpendicular distance from the point to the soil line being a measure of the amount of vegetation present. This distance is called the perpendicular vegetation index (PVI). Figure 3 shows a soil line with two soil and three vegetation points. Points A and B represent dry and wet soil respectively. Points C and D represent points with vegetation covering only part of the soil. The same amount of vegetation is present, but the soil surface is dry (highly reflecting) for point C and wet (less reflecting) for point D. Since both points have the same perpendicular distance from the soil line, they have the same PVI value. Point E represents full vegetative cover and is essentially unaffected by soil background changes. (Soil background may affect vegetation indices because of differences in transmission of near-IR and red radiation through vegetation).[17] In Figure 3, the distances from point F to the intersection of the lines from points C, D, and E and the soil line are called the soil line index (SLI).[18]

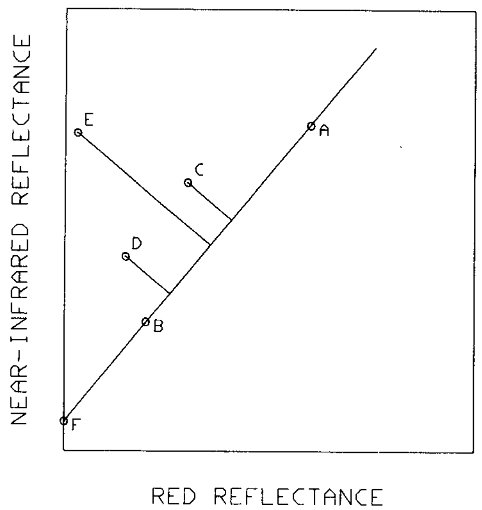

Figure 3. Relationship between near-infrared and red reflectance for soils (AB), and vegetation (C, D, E).

The four-dimensional tasseled cap transformation of Kauth and Thomas[19] is based on principles similar to those underlying the PVI. The soil line becomes a soil brightness index and the orthogonal distance from the line to a vegetation point is the greenness. The third dimension (yellowness) is orthogonal to both greenness and brightness, and the fourth dimension (called nonsuch because no features were evident) is orthogonal to the first three. The coefficients of brightness, greenness, etc., are unit vectors that indicate direction.

Kauth and Thomas[19] showed that brightness and greenness contained almost all of the variation within a sample segment, and suggested that shifts in yellowness and nonsuch were diagnostic of a physical state of the atmosphere. The average yellowness over a segment forms the basis of the XSTAR haze correction algorithm of Lambeck et al.[20] Kauth et al.[21] stated that nonsuch primarily contains noise. Jackson et al.[17] showed that yellowness was sensitive to haze conditions and nonsuch was sensitive to water vapor absorption. Jackson et al.[22] suggested that yellowness and nonsuch could be used to correct for atmospheric path radiance and vapor absorption. Brightness and greenness have proved useful for evaluating soil and vegetation features in Landsat data.[21,23] Brightness and greenness can be calculated using any number of spectral bands.[24]

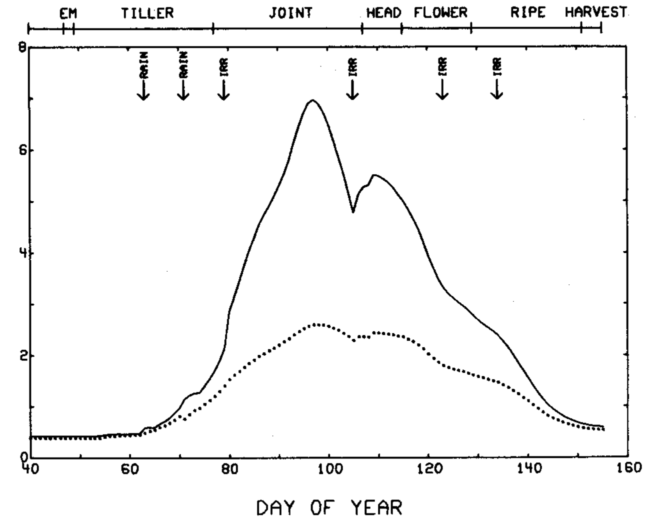

Figure 4. The near-infrared/red ratio for wheat over a growing season; top line represents a clear atmosphere, and the lower line represents a turbid atmosphere.

Atmospheric path radiance and water vapor absorption can adversely affect vegetation indices calculated from satellite data. Slater and Jackson[25] showed that path radiance affected the soil line of the tasseled cap transformation (and by implication, the PVI) especially when soil reflectance was low. Dave's[26] results indicated that atmospheric effects have considerable influence on the tasseled cap transformation, and on the brightness-greenness relationship for wheat at several stages of growth. Jackson et al.[17] compared nine vegetation indices over a wheat growing season. They showed that the near-IR/red ratio is reduced by 50% by going from a clear to a turbid atmosphere (Figure 4). Other indices were less sensitive to atmospheric effects, but were also less sensitive to vegetation.

Although vegetation indices were developed to discriminate vegetation from soils, soil background can affect the indices. Huete et al.[27] showed that up to 26% error can be incurred by using a global soil line when calculating the four dimensional greenness. Although their data were obtained using a ground-based radiometer, similar results were noted for Landsat data.[28] Elvidge and Lyon[29] demonstrated the effect of background substrate on vegetation indices obtained from airborne sensors.

It appears that no one index can optimally assess vegetation over a growing season, and that two or more indices may be required.[17] Using several indices may help to decide whether an index value changed because of vegetation changes, soil background changes, or atmospheric changes.

Relationships between spectral indices and two plant parameters are presented as in the following sections. Only a few of the numerous reports describing these relations are cited.

Leaf area index. Leaf area index (LAI) is the area of leaf surface per unit area of soil surface. Its measurement is straightforward but tedious, time-consuming, and beset with sampling problems caused by plant variability. Values of LAI are used as inputs in evapotranspiration and photosynthesis models to partition energy between plants and the soil and to estimate light interception.[30,31] Plant growth models typically include evapotranspiration and photosynthesis subroutines and attempt to mimic the plant's response to its environment by predicting LAI increases and biomass accumulation.[31] Spectral estimates of LAI and biomass can aid in extending the models to large areas, and can provide an independent check on model calculations, allowing them to be reset to actual conditions periodically throughout the growing season.

There is little consensus in the literature concerning which vegetation index is the best predictor of LAI for any particular crop. LAI of soybean and corn was shown to be a quadratic function of greenness.[32,33] For values of LAI ranging from 5 to 7, greenness values were about 40 for soybean and about 25 for corn, indicating that the LAI-greenness relation is crop specific.

The near-IR/red ratio was linearly related to the LAI of corn,[34,35] to chickpea,[36] and to wheat.[37] For the three studies, the slopes obtained by linearly relating LAI to the near-IR /red ratio were 0.296, 0.161, and 0.285, with intercepts of 0.263, -0.24, and -0.36, respectively. The slope and intercept values for wheat were the average for five different planting dates. Consideration of individual planting dates revealed that the slopes ranged from 0.199 to 0.326, encompassing the slope for corn, and nearly that for chickpea. The differences in the intercepts may be due to crop specific factors and to soil spectral differences.[38]

Pinter et al.[39] showed that the time of day (sun angles) at which the spectral measurements were made had a significant effect on the slope and intercept values for the LAI, near-IR/red relationship. When spectral data were taken near solar noon, the intercept was 0.28, whereas when data were obtained in the late afternoon, the intercept was -0.49. The slopes for these two times were 0.23 and 0.18, respectively.

Dry matter accumulation. The measurement of dry matter accumulation is less tedious than the measurement of LAI and provides useful information for estimating yields, wind and water erosion control measures,[40] and for evaluating the amount of carbon stored in plant communities.[41]

Tucker et al.[41] measured dry matter accumulation in winter wheat at 21 sample times during a growing season. They formed near-IR/red ratios and normalized differences from the spectral data at each sampling period and correlated these values with final dry matter production. They found the best correlation for the time of peak green phytomass accumulation was the period just before heading. Aase and Siddoway[40] found a relationship between dry-matter accumulation in winter wheat and the near-IR/red vegetation indices as long as green leafy material dominated the phytomass (through the end of tillering). Aldrich and Bauer[42] stated that, during the early part of the growing season, dry matter was highly correlated with reflectance because the amount of green leaf area increased proportionally to the increase in biomass. After the plants reached their maximum leaf area (at anthesis), the amount of green vegetation decreased while the total dry matter continued to increase. When plants began to senesce, the relation between final dry matter production and spectral data becomes ill-defined.[40]

Plant stress

The word "stress" has become a catchall term to signify a detrimental effect on plant growth. It is without precise physiological meaning but is useful for communication among scientific disciplines because of its implication of adversity. The term will be used here without further definition.

Thermal-IR techniques can be used to detect and, in some cases, quantify plant stress. Although temperatures can indicate the occurrence of stress, they cannot identify its cause. Temperatures of plants are determined by the environmental conditions, the availability of water, and the health of the plants. If transpiration is restricted because of a deficit of water (water stress), or by the reduction of the number of conducting vessels by disease or insects (biological stress), or by high salinity in the soil water (salinity stress), the net result is an increase in plant temperature.

When plants are stressed, physiolgical changes take place within leaves that may alter their light absorption and transmittance properties. This, along with plant geometry changes such as wilting and leaf curl, can affect the amount of radiation that reaches a remote sensor. In general, by the time stress can be ascertained by measurements of reflected solar radiation, visual signs are evident, and yield reducing damage has occurred. Thus, plant temperatures indicate the onset and degree of stress at a particular time, whereas reflected solar measurements integrate the effects of stress over time.

Water stress. In arid areas where supplemental water must be applied to crops, plant temperature has proven useful as an indicator of plant water stress.[43] The potential of using infrared thermometers to measure canopy temperatures was suggested over two decades ago.[44,45] Airborne thermal-IR scanner data conclusively demonstrated the feasibility of using remote sensing to evaluate crop water stress. Wiegand et al.[46] conducted experiments that included extensive ground measurements along with imagery from an airborne scanner. They showed that freshly irrigated crops were up to 20 °C cooler than nonirrigated portions of the same fields. Myers and Allen[47] presented similar data and stated that remotely sensed plant canopy temperatures appeared to be a feasible means of assessing irrigation needs, or the extent and severity of drought. Later, Myers and Heilman[48] demonstrated the effect of plant cover on remotely sensed temperatures. They showed that soil background greatly influences aircraft obtained thermal images.

Bartholic et al.[49] were among the first to use an airborne thermal scanner specifically to determine the temperature of soils and of crop canopies differing in water stress. They observed up to 6 °C differences between the least and most stressed plots planted to cotton. From airborne data taken over Kansas, Heilman et al.[50] observed that soybean was 2.6 °C cooler than sorghum. Blad and Rosenberg[51] used an airborne scanner to compare surface temperatures of wheat, alfalfa, and pasture. The wheat and alfalfa were cooler than pasture. They also used portable radiation thermometers to measure surface temperatures. Alfalfa was found to be 5 to 7 °C cooler than air (measured at 2 m) during mid and late afternoon. Irrigated corn, on the other hand, was always warmer than alfalfa and was usually warmer than air (except for short periods in the late afternoon).

Millard et al.[52] presented thermal imagery for six differently irrigated wheat plots. The stressed plot was 8 °C above the air temperature measured at 1.5 m. The well-watered plots were as much as 6 °C below air temperature. The pseudo-colored thermal imagery clearly showed the temperature differences and the temperature variations within plots. Their data show that, when full ground cover is achieved, airborne thermal imagery can readily distinguish irrigation treatments, and that it could be used as an irrigation scheduling tool.

When lightweight hand-held infrared radiometers became available research efforts turned toward quantifying water stress measurements. Four indices, based on infrared temperature measurements, have been proposed: the stress-degree-day (SDD),[53,54] which is the canopy-air temperature difference measured post-noon near the time of maximum heating; the canopy temperature variability (CTV),[55] which is the variability of temperatures encountered in a field during a particular measurement period; the temperature-stress-day (TSD),[56,57] which is the difference in canopy temperatures between stressed and a non-stressed reference; and the crop water stress index (CWSI),[58,59] which includes the vapor pressure deficit of the air in relating the canopy and air temperature difference to water stress. Although these indices were developed to quantify water stress, they are useful with any type of stress that causes a rise of plant temperature.

In the development of the stress-degree-day, it was assumed that environmental factors (such as vapor pressure, net radiation, and wind) would be largely manifested in the canopy temperature, and that the difference between the canopy temperature (T_A) and the air temperature (T_c) would be an indicator of plant water stress. Gardner et al.[56] demonstrated that the stress-degree-day (SDD) was insufficient to assess water stress in corn. They showed that stressed corn plants were below air temperature much of the time, and suggested that corn may be more sensitive to water stress than wheat. They also suggested that canopy-air temperature differences may be soil, crop, and climate specific.

Aston and van Bavel[60] proposed that soil water depletion could be remotely detected by determining the increase in visible and thermal radiant heat loads upon plant leaves as the underlying soil dried. They suggested that, for full canopies, because of the inherent heterogeneity of soils, various locations in a field would become stressed before others, and the canopy temperature would show a greater variability than under well-watered conditions. They proposed that the varibility of temperatures within a field be used to signal the onset of water deficits.

Gardner et al.[56] built on the suggestion of Aston and van Bavel[60] and tested the deviation of mid-day canopy temperature as to its usefulness as an irrigation scheduling tool. They found standard deviations of 0.3 °C in fully irrigated plots of corn. In non-irrigated plots, the standard deviation was as great as 4.2 °C. They concluded that plots which exhibited a standard deviation above 0.3 °C were in need of irrigation. Clawson and Blad[55] presented daily values of corn canopy temperature variability (CTV), defined as the range (maximum minus minimum) of all IR thermometer sensed temperatures within a plot during a particular measurement period. For this work, irrigations were given when the CTV reached a value of 0.8.

Clawson and Blad[55] also discussed the difference in temperature between a stressed plot and a well-watered plot (called the temperature stress day TSD by Gardner et al.[57]) as to its usefulness as a water stress indicator. Use of the well-watered plot as a reference compensates for environmental effects such as air temperature and vapor pressure deficit. The corn plots were irrigated when the average of all canopy temperatures measured in the stressed plot during a particular time period were 1 °C warmer than the average canopy temperatures of the well-watered plot. These experiments indicate that both methods, the CTV and the TSD, could be used as viable irrigation scheduling techniques.

Ehrler[61] measured cotton leaf temperatures and suggested that the leaf-air temperature difference was linearly related to the air vapor pressure deficit (VPD). Idso et al.[58] used thermal-IR radiometers to obtain canopy temperatures and demonstrated that a linear relation indeed existed between the canopy-air temperature difference ($T_c - T_A$) and the VPD, for plants transpiring at their potential rate. The relation was further demonstrated by obtaining data for alfalfa at several locations in the western U.S.[62]

Monteith and Szeicz[45] developed an equation that related ($T_c - T_A$) and VPD from energy balance considerations. Jackson et al.[59] used a similar approach and presented the equation

$$T_c - T_A = \frac{r_a R_n}{\rho c_p} \cdot \frac{\gamma (1 + r_c/r_a)}{\Delta + \gamma (1 + r_c/r_a)} - \frac{VPD}{\Delta + \gamma (1 + r_c/r_a)} \qquad (1)$$

where r_a and r_c are the aerodynamic and canopy resistances (sm^{-1}), R_n is the net radiation (Wm^{-2}), ρc_p the volumetric heat capacity of air ($Jm^{-3}\ C^{-1}$), γ is the psychrometric constant (PaC^{-1}), and Δ is the slope of the temperature-saturated vapor pressure relation (PaC^{-1}).

For well-watered plants the canopy resistance (r_c) is low but usually not zero.[63] Assuming that r_c = 5 sm^{-1} represents r_c at potential evapotranspiration, $T_c - T_A$ was calculated as a function of VPD. Results of these calculations are given in Figure 5. Also shown are lines for r_c = 50, 500, and ∞, which correspond to moderate, severe, and infinite stress, respectively. When $r_c = \infty$, equation (1) reduces to

$$T_c - T_A - \frac{r_a R_n}{\rho c_p} \qquad (2)$$

which shows that the upper limit of plant temperature is dependent on the aerodynamic resistance and the net radiation, and independent of the VPD.

The point B in Figure 5 represents a measured value of $T_c - T_A$. The points A and C represent the values of $T_c - T_A$ that would occur if the plants were under maximum and minimum stress, at a particular value of VPD. A crop water stress index (CWSI) was defined as the ratio of the distances BC/AC.[58,59] The mathematical equivalent,

$$CWSI = \frac{\gamma\ (1 + r_c/r_a) - \gamma^*}{\Delta + \gamma\ (1 + r_c/r_a)} \qquad (3)$$

can also be written.[59] The term $\gamma^* = \gamma(1 + r_{cp}/r_a)$ where r_{cp} is the canopy resistance at potential evapotranspiration. Equation (3) and the graphical calculation shown in Figure 5 have been used by a number of authors to evaluate plant water stress in the field.[64,65,66,67]

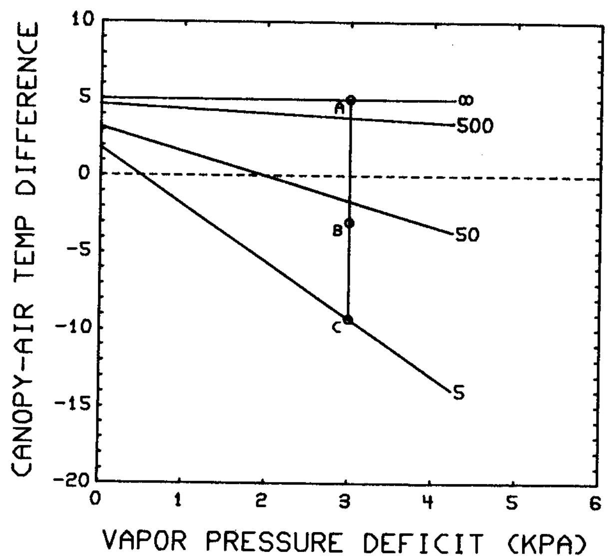

Figure 5. Theoretical relationship between the canopy-air temperature differential and the vapor pressure deficit. Numbers at the end of lines indicate the value of the canopy resistance (r_c) used for the calculations.

A novel use for equation (1) was recently reported.[68] In the development of a meteorologically based rice growth model, it was found that model parameters had to be changed for different climatic regions if air temperatures were assumed to be equal to plant canopy temperatures. Since remotely sensed canopy temperatures were not available over the large rice growing regions of Texas and California, equation (1) was used to calculate canopy temperatures from the weather station derived air temperatures and vapor pressures. When the derived canopy temperatures were used in the model the same parameters were applicable for the different climates.

Salinity stress. In arid areas, increased soil salinity is a frequent consequence of irrigating. Early detection of saline areas may permit preventative measures before the crop is significantly damaged. Myers et al.[69] using ground based canopy temperature measurements, determined that the canopy-air temperature difference increased about 11 °C with an increase of salinity corresponding to 16 dS/m. Recently, Howell et al.[65] found that canopy temperatures were as sensitive to osmotic stress as were traditional measures, but that temperatures provided a better spatial resolution.

Howell et al.[65] determined the VPD at which cotton could maintain "unstressed" transpiration rates as related to the soil electrical conductivity in the rootzone

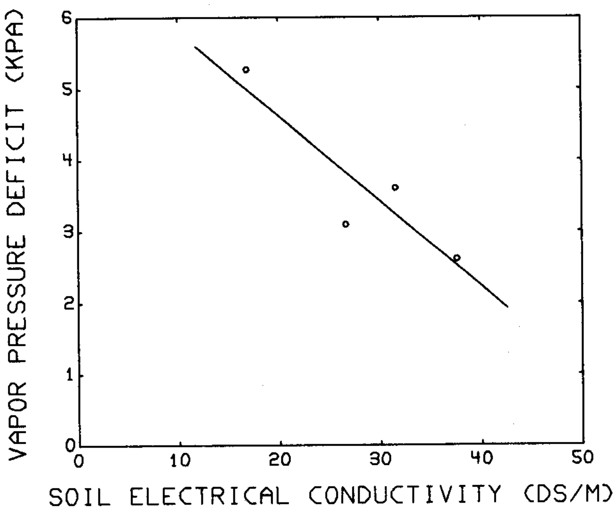

Figure 6. The vapor pressure deficit at which cotton can transpire at an "unstressed" rate versus the mean root zone soil water electrical conductivity.

(Figure 6). The data show that cotton could maintain "unstressed" transpiration only until the VPD exceeded 3.5 kPa. Figure 6 shows the interaction between the aerial environment and soil salinity in determining whether transpiration is adequate to maintain healthy plants. For this soil, salinity would be detrimental to yield at electrical conductivities exceeding 14 dS/m. These results suggest that a specific value of soil salinity will be less detrimental to cotton yields in more humid climates that in dry regions.

Biological stress. Insects and disease organisms can affect the temperature of plants by disrupting the transpiration stream. Disrupting transpiration vessels has the effect of increasing the canopy resistance, and thus increasing the canopy-air temperature difference (Figure 5). Pinter et al.[70] used a thermal-IR radiometer to measure leaf temperatures of sugar beets infected with Pythium aphanidermatum. They found that leaf temperatures of diseased plants averaged 2.6 to 3.6 °C warmer than leaves of healthy plants, yet the disease could not be ascertained visually without examining the roots. Temperatures of diseased plants remained higher than healthy plants even under conditions of water stress. Results with cotton infected with Phymatotrichum omnivorum were similar. Sunlit leaves of moderately diseased plants averaged 3.3 to 5.3 °C warmer than those on plants with no sign of fungal infection. The temperature difference between diseased and healthy plants was evident one day after an irrigation. As soil moisture was depleted, the diseased plants invariably wilted first.

Nutrient stress. Laboratory studies of nutrient stress showed that mineral deficiencies increased the reflectance of radiation in the visible wavelengths, whereas effects on near and middle infrared reflectance varied according to the specific mineral deficiency.[71] Field measurements of corn canopies that received four nitrogen treatment levels showed that visible red reflectance increased and the near infrared reflectance decreased with decreasing nitrogen.[35] The ratio of near infrared to the visible red radiances was related directly to the amount of nitrogen applied. Similar results have been reported for nitrogen-deficient sugarcane.[72]

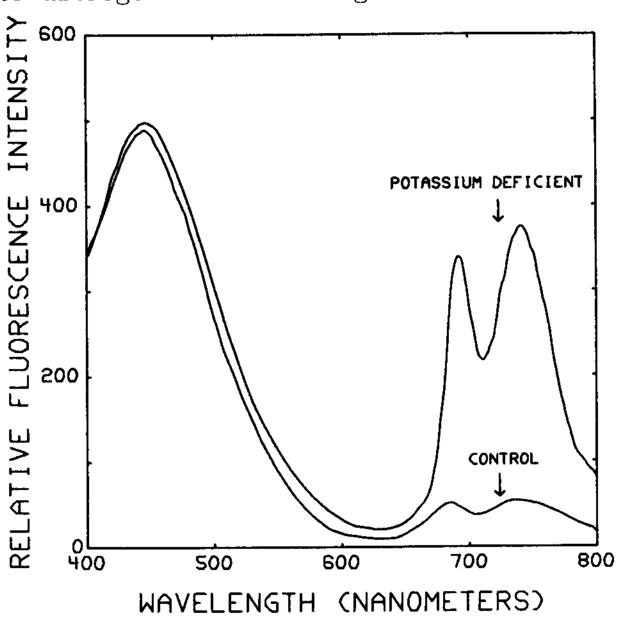

Figure 7. Effect of potassium deficiency on fluorescence spectra of corn.

Laser-induced fluorescense (LIF) shows promise of becoming a remote sensing tool for the detection of nutrient deficiencies.[73,74] With a pulsed nitrogen laser emitting at 0.337 µm as the excitation source, fluorescence maxima in corn were found at 0.44, 0.69, and 0.74 µm. Plants deficient in phosphorus, nitrogen, and iron showed a decrease in fluorescence at 0.69 and 0.74 µm. The lack of potassium caused a threefold increase in fluorescence at 0.69 and 0.74 µm (Figure 7). An airborne laser-based fluorosensor has been tested,[75] lending support to the concept of LIF as a remote sensing tool.[76]

Evaluative summary

A considerable number of papers have reported relationships between plant parameters such as leaf area index and spectral vegetation indices. There is little consensus about which indices are best for a particular parameter or a particular crop. Futhermore, the derived relationships may be sun angle dependent, and therefore may be a function of canopy architectural properties and row orientation. Soil background can also affect the relationships. When these factors are considered there is little wonder why no "best" relationship has surfaced. To date, ground-based spectral measurements have been statistically related to plant parameters. It is time to proceed from the statistical phase to developing theoretical concepts and models that allow generalization and the development of expert systems.

Methods for detecting and quantifying crop stress are reasonably well developed. The identification of the cause of stress remains a problem. Water stress, being the most ubiquitous, has received considerable attention. However, spectral detection of nutrient deficiencies have been demonstrated only when they were known to exist. Little, if any, work has been reported that specifically identified a nutrient deficient crop when the cause of the stress was not known beforehand. Similar statements could be made for biological stress detection. It is time to initiate research projects that address the identification of the cause of stress. New methods such as laser induced fluorescence may help provide an answer.

The soil background exposed by incomplete canopies poses a difficult problem for determining plant canopy temperatures from aircraft and spacecraft derived thermal data.[77] A remote sensor above an incomplete canopy would see sunlit and shaded soil and sunlit and shaded vegetation. These four surfaces would probably have somewhat different temperatures, and a composite of the various temperatures would be detected by the sensor. The problem is more serious for crops with wide rows than for crops that are broadcast planted or drilled in narrow rows. Hatfield[78] measured vertical and angular temperatures of wheat drilled in 0.18 m rows, using a 20° field of view portable radiation thermometer. The angular-vertical temperature difference was near 0° for low and full cover conditions, and reached a minimum of -2 °C at about 40% plant cover. Pinter[79] combined a temperature based crop water stress index with spectral reflectance data to evaluate plant growth and water stress in alfalfa shortly after a harvest when the soil background was exposed. His approach indicates that a combination of spectral bands may reduce the magnitude of the problem. Because the ultimate use of canopy temperature techniques for agricultural management decisions such as irrigation scheduling will be from aircraft or spacecraft platforms, a solution to this problem is urgently needed.

Since a remote sensing system for farm management will include ground-based data, parameters such as air temperature, windspeed, and vapor pressure which are measured at the site, can be combined with remotely sensed data for use in stress indices. The total solar radiation absorbed by a crop can be estimated from a ground based solar spectral irradiance measurement and remotely sensed radiances. Combining ground and remote measurements should allow images representing various features of importance to farm managers to be displayed in near-real time.

Current and future systems

Current and future remote sensing systems that can provide information to farm managers fall into 4 categories; current, imminent, possible within 10 years, and possible within 20 years. Current systems use airborne sensors and send reports to clients by mail, or by telephone if a critical factor is noticed. Imminent systems will telemeter video data from low altitude aircraft in real time. A system that is possible within 10 years will use a long endurance solar powered airplane to patrol an agricultural area for an entire growing season. A system that may take 20 years to develop will use artificial intelligence and expert systems with a fleet of satellites to provide real time data with repeat cycles of 2 days.

The following discussion of the four systems is taken largely from the original papers and company brochures.

Operational airborne systems. Aerial photography has been a useful farm management tool for many years. In the Western U.S., several commercial companies offer periodic farm coverage using color and color-IR film. At least one commercial company offers multispectral monitoring in the visible, near-IR, and the thermal-IR. Their system is comprised of airborne video cameras and a thermal imaging device, general crop models, and multiparameter data bases, and monitors (according to the company's brochure) agricultural crop status, irrigation water requirements, pest infestations, and potential yield. Farmers and farm consultants contract with the company to have their land monitored at intervals ranging from once a year to frequent coverage during a crop growing season, depending on their needs. The remotely sensed data are recorded on magnetic tape and later downloaded to a computer by telephone link. The data are processed, reviewed by an agronomist, and a report generated and mailed to the client. If a critical factor is detected the client is contacted by telephone.

That commercial companies are beginning to use remote sensing techniques elucidates two important points: (1) remote sensing equipment and expertise that can provide farm management information are available now (albeit at a rudimentary level), and (2) some farmers recognize the usefulness of remotely sensed data and are willing to pay for it.

Airborne video systems. Several research groups are using aircraft mounted video cameras to monitor agricultural features.[80,81,82] The spatial resolution of video cameras depends on a number of camera characteristics in addition to aircraft altitude.[83] Generally, aircraft are flown at altitudes of less than 5 km in order to obtain adequate resolution. Recently developed charged couple device (CCD) cameras can be filtered to yield data in any bandwidth between 0.4 and 1.1 µm. A common array dimension in use today is 380-by-488 pixels. In the near future, 1000-by-1000 pixel CCD's should be available, which will improve resolution, allow higher altitudes to increase coverage, or both. Video cameras produce an analog image that can be interpreted visually or digitized. The image can be computer enhanced and interpreted using programs originally developed for Landsat image analysis. Data can be recorded on magnetic tape, or telemetered directly to a ground station. Storage could be on laser disks. With the addition of a TV-compatible imaging thermal radiometer (9.5 - 13.5 µm),[84] a relatively inexpensive, real-time, remote sensing system could be operational within months. Used in conjunction with statewide computer networks that provide timely weather data for agricultural interests such as the University of Nebraska's Automated Weather Data Network (AWDN),[85] this system could be a valuable tool for farmers.

Remotely piloted airplanes. The feasibility of heavier than air remotely piloted vehicles for use as long-endurance observation or communications platforms has been studied for some time.[86,87] Until recently, an airplane capable of flying continuously at high altitude for even 2 or 3 days appeared impracticable owing to technological limitations. With recent advances, a high-altitude powered platform (HAPP) is within the realm of possibility. A HAPP could provide, on a continuous basis over a specified area, the services which orbiting satellites now provide on an intermittent basis, and manned airplanes for only a few hours.

A solar powered HAPP offers the unique advantage of months-long flight endurance at altitudes of 18 to 30 km, over much of the Earth's surface. A conceptual solar powered HAPP is shown in Figure 8. The upper wing and and horizontal tail surfaces are covered with solar cells. They collect enough energy during daylight to drive the payload and two 6-horsepower electric propulsion motors. Near midday, an excess of solar energy is available for storage in a regenerative fuel cell to power the motors and payload at night. This design would carry a 45 kg payload at an altitude of 18 km from March to September at latitudes up to 40 degrees north.[86]

Consider a solar powered HAPP carrying a state-of-the-art sensor with the appropriate bands for crop condition assessment, an instantaneous field of view of 0.5 mr, and a total scan angle of 45 degrees. With the HAPP at 20 km, the ground resolution would be 10 m and the sensor scan width 16.6 km. Flying at 100 km/hr, coverage could be obtained over approximately 5000 km^2 in about 8 hours with a flight pattern shown in Figure 9. The pattern is such that each target area would be sensed twice (at different look angles) within

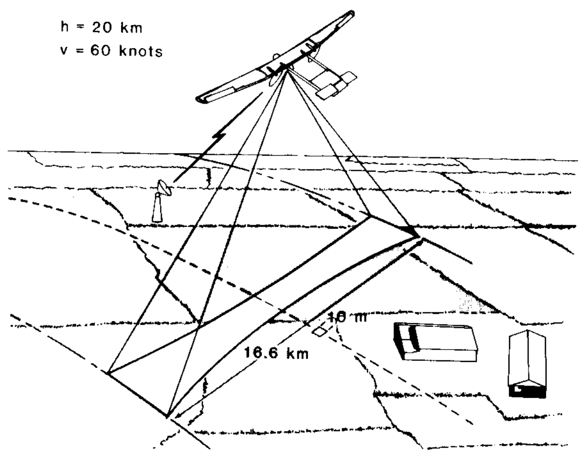

Figure 8. Proposed configuration for a solar powered plane.

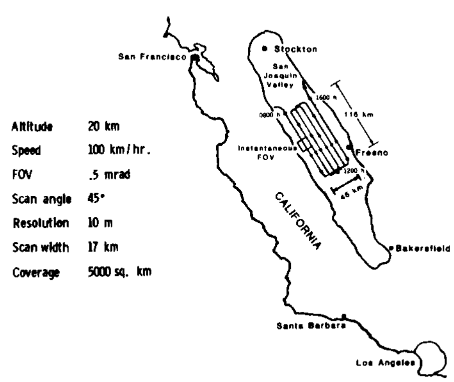

Figure 9. Possible flight path for a solar powered airplane over a large agricultural area.

3 hours. The first leg would start at about 0800 hours and the final leg at about 1430 hours, finishing at about 1600 h. The pattern is flown repetitively over the same area on successive days to measure day-to-day variations in plant properties. Alternatively, the pattern may be flown in reverse to obtain site-specific data at other times of the day under different lighting conditions. Also, "standard" patterns can be linked together on successive days to enlarge the area covered.

The onboard sensor package would be capable of some preprocessing of data, which subsequently would be telemetered to a ground station for further processing. The data would be immediately available to farm operators by direct link to their personal computers. Files would be kept on laser disks to insure that data taken at an earlier date could be recalled for comparison with current information. It is conceivable that the sensor package could be directly interrogated with a home computer.

An Earth sensing system. An advanced concept for a user oriented remote Earth sensing system was proposed by Fay et al.[88] The proposed system consists of six cooperative autonomous satellites in low Earth orbit communicating with two geostationary satellites, which in turn are in communication with ground processing facilities. The ground facilities provide a direct user interface for scheduling, acquisition, and processing of data.

The heart of the system is a World Model: a representation of predictable spatial and temporal characteristics of the Earth together with algorithms for implementing the representation. The World Model describes the topography and environment of the Earth and is used to predict features of what the satellites will observe, as well as to assist in the transmission of redundant data by ignoring the expected and identifying significant departures from the norm.

The World Model has two components, a data base that defines the state of the world to a predetermined accuracy, and a set of interacting expert systems that abstract useful information from imagery. The expert systems achieve large-scale data reduction by use of feature extraction and data compression, and provide experience by which to judge new knowledge.

The Earth monitoring system proposed by Fay et al.[88] covers most of the issues that must be resolved during the development of a remote sensing system for farm management. In fact, they suggest that farm interests would be a prime user of the system. In any case, artificial intelligence and expert systems will be essential features for any future operational remote sensing systems.

Concluding remarks

Remote sensing for farm management has not been a part of the present large scale remote sensing systems. Although agriculture is frequently promoted as a prime beneficiary of the data, what is seldom mentioned is that data flow from the sensor to the user may take at least 4 to 6 weeks.[88] This delay essentially negates the usefulness of the data for identifying an adverse crop condition in time to alleviate it.

Interest in farm management oriented remote sensing systems is starting to increase. A few commercial companies are providing rudimentary remotely sensed information to farmers. New developments in video technology should lead to real time systems in the near future. High altitude powered platforms, dedicated to agricultural remote sensing, are possible within 10 years. New satellite systems that may prove useful for farm management are in the planning stage. AGSAT, a complete agriculturally oriented satellite system, was recently designed by a class in Space Systems Engineering at Stanford University.[89] A number of research locations have active programs that should lead to rapid interpretation of remotely sensed imagery with the aid of artificial intelligence and expert systems to provide essentially instantaneous analysis to farm managers.

What will comprise a farm management remote sensing system of the future has not been entirely determined. It must, however, provide real-time data in a format that will allow farm managers to quickly make decisions concerning farm operations. The need is obvious, the potential benefits are enormous. It is time to fulfill the promises of the past quarter century.

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