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Global crop monitoring: an integrated approach

Russell A. Ambroziak

Climate Impact Assessment Division/AISC/NESDIS/NOAA, 3300 Whitehaven St. NW, Washington, DC 20235

Abstract

An integrated climate impact monitoring system was designed using all available data sources, including satellite data. Rather than attempt to use the complex processes that have been developed, the project began with the basic premises of image interpretation and introduced the simplest and most widely accepted procedures into an existing operational process. The intent was to improve the accuracy and timeliness of the impact assessment reports without a large increase in resources. To do this the human mind was used to do what it does best and the computer to do what it does best. The human mind is used to look at color images for pattern recognition and to do all of the final analysis. The computer does all of the computation and presentation but does none of the analysis.

Introduction

The project was designed to do drought assessment of subsistence crops in the tropics. In many ways this is easier than working in the temperate latitudes, where temperature and short term frontal weather greatly complicate the assessment process. In the tropics it is rainfall that controls the food supply. Satellite rainfall estimates have been done operationally by hand in Africa for the past five years and not a single drought has been overlooked. In addition, there has not been a drought anywhere that wasn't reported by the system. There are a great many difficulties involved in instantaneous, point specific rainfall estimation, but what is needed to estimate subsistence agriculture in the tropics is large area monthly rainfall. Actually it is not even rainfall, but the lack of it that is the important parameter. You may not know for sure how much rain fell from a cloud on any given day, but if there hasn't been a cloud over a crop region for the past six months, it doesn't take a lot of analysis to correctly assess a dry spell.

The total climate impact assessment system involves regional agricultural analysis, synoptic weather analysis, and satellite analysis (table 1). The procedure is to combine agricultural analysis with rainfall analysis to determine the status of the crop. Satellite vegetation condition analysis is then compared with the results of more traditional analysis and inconsistencies are resolved. The satellite subsystem is the only one of the three subsystems that requires development work.

The satellite subsystem is used to measure both precipitation and crop condition. A first pass of the data looks at the cloud images on the visible and thermal IR data sets to estimate rainfall over each region, each day. The satellite rainfall estimates are then combined with surface precipitation reports to obtain monthly total precipitation for each of 300 agricultural regions. A second pass uses visible and near IR to estimate crop vigor and general surface conditions between clouds. In this way all pixels are examined. Parts of the satellite subsystem have been operational for several years, but some parts were only recently added to the system (table 1). The purpose of this paper is to describe the total integrated system with emphasis on the unique parts of the satellite subsystem that are undergoing operational test and evaluation.

Subsystem Status and Platforms

	Platform			Status		
Subsystem	Geostationary	Landsat	NOAA AVHRR	Development	T & E	Operational
Satellite						
rainfall estimate						
single channel	X		X			X
multichannel	X		X	X		
surface monitoring						
time series index			X		X	
color images		X	X		X	
Synoptic Weather Analysis						X
Agricultural Analysis						X

Table 1

The satellite suosystem was designed to accentuate the useful information contained in the satellite data and to avoid problems, such as look angle and atmospheric moisture and particulates, which are difficult, if not impossible, to solve. The interface of the human mind with the computer using an IHS (Intensity Hue Saturation) color coordinate system for visual qualitative and spatial interpretation and the computer for mensuration and index calculation is the key element of the project.

Since 1973 satellite data have been used to monitor vegetation. Landsat data were the cornerstone of the LACIE (Large Area Crop Inventory Experiment) and later AgRISTARS (Agriculture and Resource Inventory Through Aerospace Remote Sensing) Programs. The main thrust of these multimillion dollar programs was crop identification and area measurement using remote sensing as a stand alone system. The task was beyond the capabilities of the data, and, although a great many breakthroughs in remote sensing were made and many techniques were invented and perfected, useful, operational products were few.

Attention has now changed from an ideal solution to finding a practical use for the information that is obviously contained in the satellite data. Rather than build a satellite assessment system, a satellite assessment subsystem was designed and combined with other subsystems now in operation. Although Landsat was the first satellite to show potential for crop monitoring, the NOAA AVHRR (National Oceanic and Atmospheric Administration Advanced Very High Resolution Radiometer) data from the polar orbiting satellites have the same basic spectral response. The Landsat data have better spatial resolution (80m vs. 1.1km), but the AVHRR data have better temporal resolution (1 per day vs. every 18 days).

Each platform and sensor is used to emphasize its various strengths. Channels III through V of the AVHRR are thermal IR channels which can be used for cloud screening and precipitation estimation. By using all five AVHRR channels in various combinations, a great deal of information can be inferred about both the atmosphere and the earth's surface. Rainfall estimation requires low resolution, high frequency coverage of cloud patterns. Geostationary and polar orbiting weather satellites are the obvious choices for this application. Surface imaging and vegetation analysis require both visible and reflected IR measurements, which are found on Landsat and the NOAA polar orbiters. For global monitoring, a sampled subset of the AVHRR data is used. For closer looks, full resolution AVHRR or Landsat data is used. Because of the variety of platforms available, no part of the project is designed for a single satellite. NOAA AVHRR does, however, offer the best single compromise between temporal and spatial resolution, and it has the correct spectral data for the various tasks of the project. It is, therefore, the backbone of the satellite subsystem.

AVHRR as a crop monitor

Channels I and II of the AVHRR data are ideal for monitoring the health and status of vegetation. Channel I responds to reflected sunlight in the long wavelength, visible region and is similar to looking at the earth through an orange filter (figure 1a). Channel II records near infrared (IR) reflected sunlight, which is invisible to the human eye but which can easily be photographed using normal IR film and an appropriate filter.

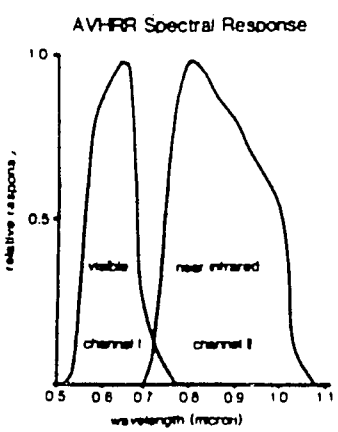

Figure 1a

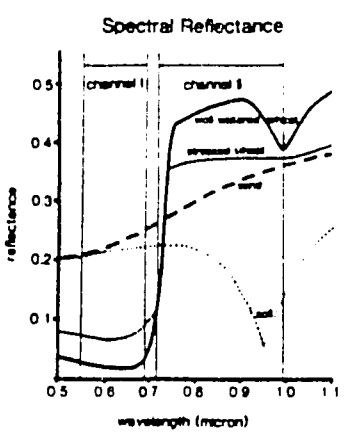

Figure 1b

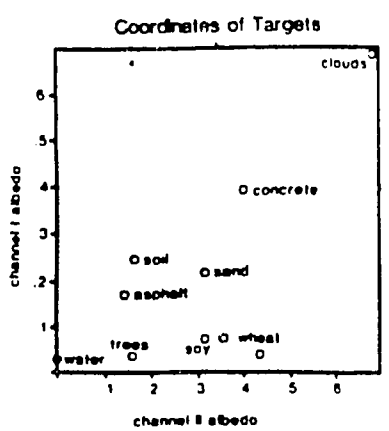

Figure 1c

These two channels are useful for watching plants because healthy plants absorb visible light, which is their source of energy or food. More importantly, plants are unique in that they reflect nearly all incident near-IR radiation. Turgid plant cells (swelled by internal fluid pressure) provide air/water boundaries that are highly reflec-

index value of 1, red to 0, and blue to -1, a fairly natural scene results that avoids cyan completely (figure 4b). On this coordinate system healthy vegetation is green, stressed vegetation is yellow, bare soils are red or brown, and water is black or blue. Changes in index values are easily detected and their meaning is quickly learned. Cyan is avoided so CRT presentations maintain maximum perceptual resolution. The image is superior in all ways to false color IR.

Image analysis: This subsystem does not depend on absolute measures, but rather, works with the relative information contained in the images. The human mind is the logical analyzer because of its phenomenal ability to detect relative change and, at the same time, ignore absolute values. It is the mind, not the eye, that perceives the world around us, and it does it in a way that has not yet been duplicated by computer. The mind senses an entire multidimensional data field as a single entity, and it does so in relative measures only.

The human mind can combine synoptic pattern recognition and relative difference detection which is most useful to crop monitoring from a satellite. There are a multitude of serious problems with satellite data that work to confuse the analyst, but most of these problems can be reduced to mere nuisances by the mind's perception. Look angle, sun angle, cloud cover, atmospheric moisture, and atmospheric particulates all affect the spectral returns used to evaluate the crop condition. As yet, there is no way to remove any of these sources of noise and for only a few of these problems are there any methods of reducing the noise, but the human mind can see through these problems.

Fortunately, these sources of interference are not randomly distributed over an image. Sun angle is nearly constant for any single image. Look angle changes slowly across the orbital path and is constant for equal distances from the nadir point of the satellite. Atmospheric effects are organized by weather systems which have unique, structured patterns. This is as it is in nature for the mind. The mind recognizes familiar objects and patterns, sees normal color, and identifies objects and entire scenes amazingly well under a wide variety of viewing conditions. For example, a white house appears to be white even at sunset when the incident radiation is orange. The mind adjusts to the shift in color coordinates as a natural thing. It perceives all other colors relative to the known white house, thereby seeing normally under abnormal lighting conditions.

Another reason for using the mind to analyze images is its ability to present a synoptic view. Digital computers process one word at a time, and no matter how rapidly they do it, it is still a collection or stream of separate points. Clever software can be designed to do simple pattern recognition, but it cannot be done with a degree of skill that approaches that of the mind. On an image of cropland, the rivers and stream beds are easily visible. Because they are near the water table, it is here that the native vegetation is most drought resistant. If, during a severe drought, this vegetation becomes stressed the crops can usually be assumed to be dead. Almost anyone with normal color vision can be trained to view any image, check the stream beds, and see if the vegetation is healthy or stressed. As yet, no computer can even find the stream beds, let alone evaluate the condition of the native vegetation in them.

The human mind as an analyzer. The human mind and computers are very different in the way in which they analyze images. Just as people do not carry descriptions of their families in their wallets, the Department of Motor Vehicles does not keep digital image files of drivers' faces. People can analyze images much better than computers, and computers work best with quantitative facts in large quantity. The satellite subsystem was therefore divided into two parts to use both the computer and the analyst to their fullest.

For synoptic vegetation analysis, two indicators or "tags" are needed at every point (pixel) on an image of the earth's surface, one for each of the two channels. The meteorologist is faced with an analogous problem, representing two wind properties, speed and direction at many points on the earth's surface. They solve the problem by using directional arrows with a varying number of barbs for magnitude. We solve it by using two properties of color, hue and intensity.

If the mind is to be the analyzer of the image, then the color coordinate system chosen must be one that is natural to the mind. With all of its power to analyze, there is a severe limitation to the mind's ability -- it cannot quantify. Without theorizing why this is and actually must be so, we must accept it as true. The mind can always tell which point is to the left or right of any other point, but it cannot tell where either point is on some absolute scale. Likewise with color, very subtle shade or brightness differences can be detected in adjacent areas, but only within very wide limits can a color be quantified. This phenomenon of relative comparison only is the basis for all optical illusions. The assumption is always that the mind can quantify and a situation is presented where using relative measurement fails to give the correct answer.

tive to near-IR radiation. As soon as the internal pressure of the cells decreases, this high reflectance falls rapidly. The loss of near-IR reflectance can be seen before the plant shows any sign of wilting. After a day or so the wilting may affect the chlorophyll, and the visible reflectance can increase as the chlorophyll dies (figure 1b). Reflectance varies considerably among different types of plants and their stages of development, yet when a full cover of healthy plants is viewed through a clear atmosphere there is no doubt about the target's identity.

The product of the sensor response and the reflectance at each frequency is integrated by the sensor for each channel. These two values can be plotted on a two-dimensional Cartesian coordinate system. If y is chosen to represent channel I and x is chosen to represent channel II, field crops end up in the lower right hand corner of the graph, water is in the lower left, clouds are in the extreme upper right, etc. (figure 1c). Healthy plants, especially field crops, are the only objects in the lower right hand corner of this graph.

Problem. With all of its unique abilities the satellite platform does not provide a stand-alone monitoring system, due mainly to its inability to quantify. The unknowable atmosphere through which the satellite must view the earth will always work against quantification. Without some help, two numbers taken from a satellite which is looking through a "dirty" atmosphere cannot give much information about what is on the ground. Healthy plants will give the only response with a low channel I and a high channel II value, but identifying the plant is difficult. Drought can completely kill a young crop and late rains can produce a green cover of weeds over the dead fields. To a satellite, weeds can look like wheat, and, unless the interpretation is done by someone who is knowledgeable of both the farming practices and the recent climate history, mistakes are easily made.

One might think that two channels of information, each containing a value of 0 to 255, would be more than enough to classify agriculture and several other types of surface. After all, this represents 65,536 different classes, which could serve as quite a catalog system. Three problems reduce the information content by several orders of magnitude. First, the spectral responses of various surfaces are not quantitatively unique, but rather represent fairly large and nebulous regions on the two dimensional coordinate system plot, and these regions can overlap with other regions. Secondly, the atmosphere shifts the axes from scene to scene in unpredictable ways. These shifts are neither constant from day to day nor from pixel to pixel on the same image, and no objective method has been found to completely correct for these errors. Finally, the useful dynamic range of the sensors is much less than 256 for surface objects. Other than snow, clouds, or bright sand, the dynamic range is more like 40. The net result of all of these factors is a quantitative classification scheme of from 6 to 20 classes, depending on the geographic location and the time of year of the image.

Solution. The solution to the problem is to first divide the subsystem into two parts and then combine it with the other subsystems. The two parts are human image interpretation and computer generated crop index time series. The interference problems can be reduced if surface observations and knowledge of the local farming practices are combined with satellite data and careful analysis. The satellite data in image form give a synoptic view of the relative situation at any one time. Time series plots of index values over a specific region provide temporal comparisons. Surface reports of precipitation and crop model output at specific points provide quantitative information that can calibrate the qualitative satellite data and measure the entire world's crop vigor.

Only two dimensions are needed to represent all of the information from AVHRR data, but the channel I and II values are not necessarily the best choice of axes. By using one of several crop indexes as the primary coordinate the status of crops can be best seen. Hue is the obvious choice for the crop index axis because of its high perceptual resolution. Hue is best represented as an angle on a color chart, and the normalized difference index is an angle on the Cartesian plot. The distance from the origin should be represented by intensity for two reasons. First, it is the axis of next highest perceptual resolution, and, secondly, it makes a natural looking scene as it does in false color IR. Saturation is not necessary for data mapping but it does have a purpose for improving analysis. Saturation reduction causes colors to appear as they would under thin cloud cover. By reducing saturation in the region of the coordinate system where clouds are most likely to be located, a more natural looking cloud display is achieved. This display could be further enhanced by using one or more of the thermal channels to distinguish clouds from the surface and then putting saturation onto this cloud axis.

The final step is to choose the hues for each of the index values. If possible, the cyan region, which lies between green and blue, should be avoided because of the low saturation produced on CRT displays. The green phosphor on a CRT has too much red in it to produce a cyan that has a saturation value of more than 0.5. By assigning green to an

Choosing a color coordinate system. An accepted measure of crop vigor is one or both of the two types of indexes which are computed from the visible and near-IR values. The two types of indexes are the simple difference and the normalized ratio. Both indexes give zero values when the two channels are equal, negative if the visible is greater, and positive if the near-IR is greater (figure 2). Both have advantages and disadvantages, but basically they show that to get a single number that represents crop vigor the first step is to rotate the Cartesian coordinate system by 45°.

The first, and most obvious solution to the problem, is to take one of these index based coordinate systems and give each index value a different color. If the normalized difference index is used, the result is a series of multicolored wedges on the Cartesian coordinate plot (figure 3). Adjacent colors could be chosen to be complementary to aid in quantification of the index values. The resultant image would then resemble a false color density slice image or a contour map of index values.

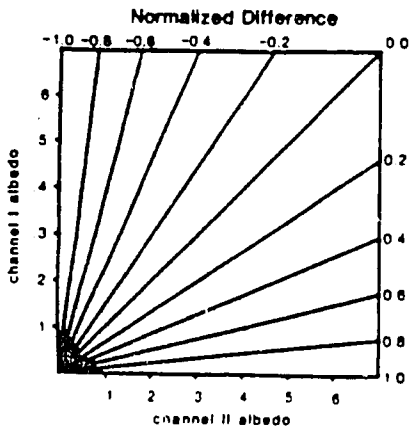

Figure 2a

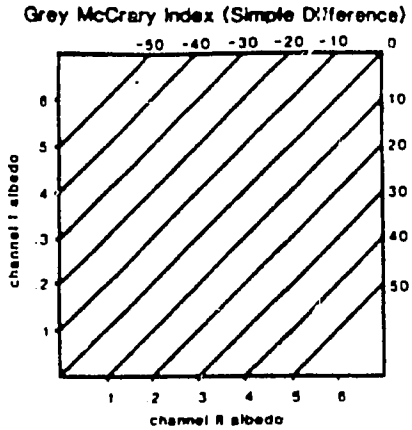

Figure 2b

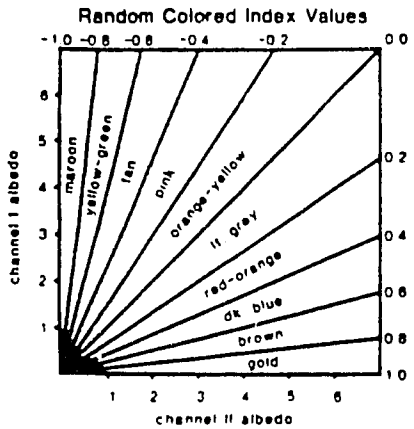

Figure 3a

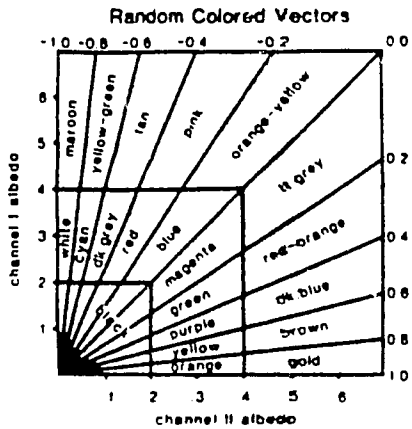

Figure 3b

There are two basic problems with this type of display. First, there has been a needless loss of information by using only the index value. Granted the index value is the single best number for measuring crop vigor, but it does not contain all of the spectral information. If the index value is high the target is a healthy crop, but if it is near zero the target could be polluted water, bare soil, sand, snow, or clouds. The distance from the origin is different for all of these targets, but the index does not contain this information. This problem can be fixed by simply dividing the wedges into randomly colored trapezoids (Figure 3b).

Although the trapezoids cure the vector-versus-scalar locational problem, they do not address the most serious problem, that of absolute versus relative measure. This randomly colored coordinate system subsumes that each trapezoid on the plot has some unique set of quantifiable characteristics that separates it from adjacent trapeziods. Moreover, it assumes that relative measure is of less importance than absolute measure. For example, an index value of 0.70 would be recognizable as such everywhere on an image, because it is the only value colored brown. However, a lowering of 0.20 in the index value is not identifiable as such, because the color change depends on the initial value. Going from 0.70 to 0.90 is displayed as a change from brown to gold, while going from 0.50 to 0.70 is a change from dark blue to brown. Although both of these changes on an image could be iden-

tified as being 0.20 by referring to the Cartesian coordinate plot, there is no perceptual consistency between them. The change in color does not relate in any natural way to either the direction or the size of the change, only that there is a change.

If we could completely remove the effects of look angle and atmospheric interference, the randomly colored trapezoid coordinate system would be the logical choice, but we can't remove this noise completely and must, therefore, develop a color coordinate system that does not depend on the solution to these problems.

As long as the colors are not scrambled, the mind does not have any problem adjusting, therefore, the colors used in the coordinate system must have a perceptually linear and logical gradient in all directions. If worsening crop conditions are shown by a move from green to yellow over ten shades of color, then a move from shade 1 to shade 2 must have the same perception of change in all ways as a change from shade 2 to shade 3. Because the mind has a difficult time quantifying color in the absolute, shade 1 could not be distinguished from shade 2 if they were on different images or not adjacent on the same image. If some form of interference between two consecutive images changes the healthy crops which should be shade 1 (green) to shade 2 (slightly yellow green), the change to the less healthy crop would be to shade 3, and would appear identical to a change to shade 2 in the first image.

The IHS color system is perceptually orthogonal and linear and has a logical gradiant. Except in the low ranges of saturation and intensity, each color axis can be seen to change totally independently of the other two. Turning the color intensity, color balance, and the brightness and contrast knobs on a TV can convince anyone of this. The color intensity control changes saturation, and for small changes the mind sees a change in saturation alone. From a pastel picture just short of a black and white picture to brilliant carnival colors, all hues and intensities remain the same, and only saturation changes. The same is true of the brightness control (intensity) and the color balance control (hue).

RGB axes are not perceptually orthogonal. An experienced observer can estimate the amount of red, green, and blue light in any color at a point on an image, but patterns of these primary colors are invisible to the mind. The mind can only see RGB patterns by viewing through a filter which removes all but one color. Changing one axis can affect colors in unrelated ways, depending on the original color and the primary color changed. For example, adding blue to various colors can produce changes in hue, saturation, and intensity or any combination of the IHS axes.

False color IR images from either Landsat, metsat, or even aereal photography are IHS representations of the normalized difference vegetative index (Figure 4a). Since color IR film, on which the coordinate system is based, predates our knowledge of crop reflectance spectra, it is safe to assume that the relationship is fortuitous rather than designed. As far as crop vigor investigation is concerned, almost all of the information is contained in the difference between the visible and the near-IR, and very little if any information is found in differences between the various visible channels. The net result of this is that if colors from a false color IR image are plotted on a chromaticity diagram, their saturation values are found to equal the normalized index at every point. If the index is positive the hue is red, and if the index is negative the hue is cyan. An index value of 0.5 is displayed as a pink color which is a red with a saturation of 0.5, etc. If the index is zero the saturation is zero and the color must, by definition, be white or grey. Intensity is zero at the origin and increases outward in normal fashion. Objects that reflect more radiation appear brighter than those that reflect less.

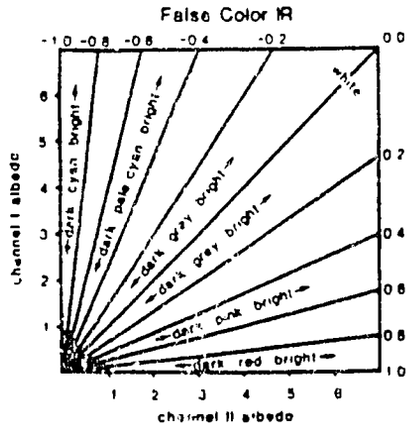

Figure 4a

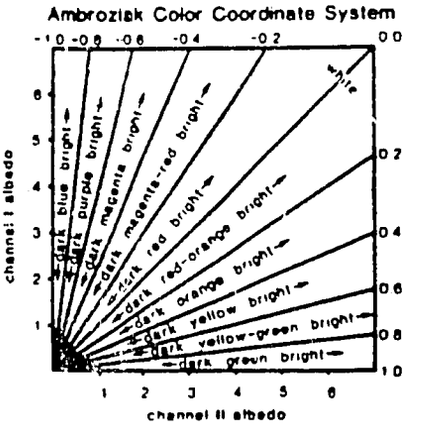

Figure 4

This may seem like the answer to the problem, but perceptual resolution of color is not the same for each axis of the IHS system. The mind perceives about an order of magnitude more hues than it does saturation, with intensity somewhere in between. Perception of derivatives is, to some extent, a function of color, but in general, the mind distinguishes hues better than either saturations or intensities. The axis of hue should, therefore, be used to represent the most useful data component. For crop vigor this axis is the vegetative index. False color IR imagery has the axis of maximum information (normalized index) displayed on the channel of minimum perception (saturation). If one were trying to design a coordinate system which met our criteria but minimized the chance of success, a good case could be made that the false color IR system is that system.

The choice of hue for the index and intensity for the scene brightness corrects the saturation resolution problem of the false color IR while keeping its natural brightness attribute. The scenes look more natural in some ways, but clouds tend to become red and do not look natural. Work is underway to correct this problem, but the results are not ready for operational testing.

The computer as the data processor. The computer works with fields of numbers much better than the human mind, and it should be used to summarize the digital information that is contained in the satellite data. The index values are digital representations of the condition of the crop, and it is important to use this information to the maximum degree possible. The index value of one pixel on one image does not contain much useful information, but many pixels averaged together and examined over time do contain useful information. The shape of the time series can give emergence, flowering, and harvest dates. In some cases it can identify the predominate crop types. The height of the curve can give an indication of yield. Comparisons to previous years can quantify the crop status. On any given day the atmosphere will introduce noise, but the clear days will be seen as peaks. An envelope encompassing the highest points serves as a crude cloud filter to measure crop vigor. Any cloud filter that works will show up immediately as reduced noise in the time series, making it an ideal cloud filter tester.

The Grey, McCrary Index (GMI), which is the simple difference between channels I and II, was chosen for the time series analysis, because it most effectively cuts off the bottom right hand corner of the Cartesian plot which is where the healthy crops are located. It effectively removes trees, which have the same or greater normalized difference index value, but, because of geometry, reflect less light and have a lower GMI. This is especially true of coniferous forests.

A great deal of care must be exercised in using the index values. As previously stated, a high index is a healthy plant, and a low index is something else. If a weekly composite index drops it may be water stress, but could also be cloud cover or standing water in the fields. Used in conjunction with the vector (four dimensional) images, the index plots are extremely useful, but used alone they can be misleading.

CONCLUSIONS

If properly displayed, meteorological satellite data can be operationally combined with more traditional methods of crop assessment to improve the total assessment process. Without the basic assessment capability in place and producing operational products, it is very difficult to determine the worth of a new satellite assessment tool. Moreover, it is extremely difficult to develop products that are easy to use, have operational value, and answer the questions that the users are asking. Even to the trained image interpreter the image alone is of very limited use regardless of the scale and platform. To be of value there must be some idea of what it is that should or shouldn't be there. If you know what you're looking for and what might be there to confuse you, there is a good chance that you will learn something from an image. If, however, you depend on the image to do your analysis for you, it is just a matter of time before you are wrong, and that time is usually very short.