Operational Interpretation of AVHRR Vegetation Indices for World Crop Information

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ABSTRACT: The Foreign Crop Condition Assessment Division of the U.S. Department of Agriculture analyzes satellite images and supporting information to monitor and assess crop condition in selected countries. Available to the analysts is a potentially useful database, containing a continually supplemented archive of vegetation index numbers (VINs) derived from the AVHRR satellite data. Each VIN is calculated as the average vegetation index of a geographically referenced cell of AVHRR pixels. This study has found that, despite the preponderance of mixed pixels, useful crop information can be reliably and efficiently derived from the database, and that its operational use will improve crop assessment.

INTRODUCTION

THE FOREIGN CROP CONDITION ASSESSMENT DIVISION (FCCAD) of the U. S. Department of Agriculture's Foreign Agricultural Service is the operational outgrowth of LACIE, the Large Area Crop Inventory Experiment (Colwell, 1983). Formed in 1978, the FCCAD is responsible for assessing and monitoring crop condition in selected areas of the world, with the ultimate goal of quantifying the assessment. This responsibility is carried out through analysis of satellite images, drawing upon all available crop, meteorological, soils, and other supporting information.

The principal image data used by the FCCAD analysts are those acquired by the Multispectral Scanners (MSS) on the Landsat satellites and the Advanced Very High Resolution Radiometers (AVHRR) on the polar-orbiting meteorological satellites. Computer-compatible tapes of the four channels of MSS data and the first two channels of AVHRR data are received respectively from the Earth Observation Satellite Company (EOSAT) and the National Oceanic and Atmospheric Administration (NOAA), within one week of acquisition. During peak periods, some analysts receive as many as 20 images per day.

Before the satellite images are viewed by the analysts, each scene is processed to calculate vegetation indices which are averaged over pixels in geographically referenced grid cells. The cell averages are entered into a database. In performing their task, however, most analysts make little use of the database, relying instead on visual interpretation of computer-displayed images, weather data, and any supporting crop and soil information. This is because visual analysis has been found adequate for assessing general crop condition and time is normally limited. The FCCAD's operational demands for obtaining timely information on a worldwide basis, with a limited staff, often preclude the adoption of image processing or analysis techniques which might otherwise be useful.

Despite the difficulties of modifying a proven operational procedure, it is felt that the database is too valuable to omit from analysis. Its inclusion should provide an important source of information for improved crop assessments and, possibly, for production forecasting.

In the context of interpreting database values, the AVHRR portion of the database poses the more difficult problem. Because cropping in most agricultural areas of the world is neither monocultural nor in fields larger than 1.1 kilometre on a side—the size of an AVHRR ground resolution element at nadir—vegetation indices of nearly all cells of AVHRR pixels are derived from a preponderance of mixed pixels (i.e., pixels filled by more than one class of land cover). The question, then, is whether useful crop information can be reliably and efficiently derived from a time series of vegetation indices, when each index is the average vegetation index of a geographically referenced group of mixed AVHRR pixels. A procedure for interpreting and incorporating the AVHRR cell data should be transferable to the MSS cell data.

This study was undertaken to evaluate the operational utility of the AVHRR database; that is, to determine if the AVHRR cell data convey useful crop information, if they can be used efficiently, and if their use improves crop interpretations.

BACKGROUND

Although the subject of mixed pixels is not new in remote sensing (e.g., Horwitz *et al.*, 1971; Detchmendy and Pace, 1972; Nalepka *et al.*, 1972; Chhikara and Odell, 1973; Marsh *et al.*, 1980; Metzler and Cicone, 1983), the focus has not been on AVHRR data, vegetation indices, or interpreting averaged vegetation indices of groups of mixed pixels. This being the case, the problem will be reviewed in greater detail than would normally be necessary. In keeping with FCCAD terminology, numerical values of vegetation indices will be referred to as vegetation index numbers or VINs, with the average VIN for a grid cell of pixels being labeled a cell VIN.

A VIN AVERAGE

The FCCAD calculates two VINs for the AVHRR data: an Environmental Vegetation Index (EVI), defined as channel 2 (0.725 to 1.10 μm) minus channel 1 (0.58 to 0.68 μm), and a Normalized Vegetation Index (NVI), defined as the EVI divided by the sum of the two channels. These indices have been described by Yates *et al.* (1984).

When calculated as the average of the VINs of a group of pixels, the EVI is largely independent of whether the pixels are pure or mixed. As long as the respective areas of the land covers imaged by the pure pixels are the same, or proportionally the same, as the respective areas of the land covers imaged by the mixed pixels, the average of the pure-pixel EVIs will be nominally the same as the average of the mixed-pixel EVIs. While this is not strictly true for the NVIs, any difference is generally small.

It should be noted that, whether dealing with mixed or pure pixels, a VIN average derived from a group of pixels of different land covers cannot be apportioned to the land covers based solely on areas. The land-cover VINs as well as their respective areas must be taken into account. To determine VINs for different

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land covers, the image must first be classified for those land covers of interest. The VINs can then be calculated separately for the classified pixels.

With pure pixels, classification of individual land covers (e.g., different crops) may be difficult, but it is possible. Consequently, "crop VINs" can be determined. With mixed pixels, direct classification of individual land covers is generally impossible, and crop VINs cannot be determined. Exceptional cases are those where (1) the classification process can use pure pixels in the scene (see all previously cited references on mixed pixels) or (2) temporal differences are sufficient to allow crop separation (e.g., the area covered by a single pixel is shared by temporally overlapping spring and summer crops). The former exception is inapplicable with AVHRR data, which may have no pure pixels, and the latter exception, if applicable, could not be relied on to determine crop areas.

Grid Cell VINs

When considering geographically defined grid cells, each of which is composed of a group of pixels, the concepts of mixed and pure *pixel* VINs can be transferred to mixed and pure *cell* VINs (Figure 1).

An average cell VIN can be viewed in two ways: (1) the average of all pixel VINs within the cell or (2) the area-weighted average of all cover-type VINs within the cell. These may be written

$$V_{ijt} = (\Sigma V_{pt})/n$$

or

$$V_{ijt} = [\Sigma(V_{ct}A_{ct})]/A_{ij}$$

where

V_{ijt} = average VIN for cell i, j at time t;
V_{pt} = VIN of each pixel in cell i, j at time t;
n = number of pixels in cell i, j;
V_{ct} = VIN of each cover type in cell i, j at time t;
A_{ct} = corresponding area of each cover type in cell i, j at time t; and
A_{ij} = total area of cell i, j.

While these equations are correct for the general case, the variables must be modified when dealing with grid cell VINs in the FCCAD database.

In the present FCCAD system for processing AVHRR data, input data values for channels 1 and 2 are converted to percent albedo using NOAA-supplied coefficients (Kidwell, 1985); multiplied by ten to stretch for display; and truncated, whereby values above 255 are set to 255 and values below 0 are set to 0. The pixels are then screened for cloud cover, based on cut-off values in both channels. Those pixels that pass—the "*good*" pixels—are accumulated in a geographically referenced grid, whose cells are nominally 25 n.mi. on a side. Also accumulated in each cell are "*green*" pixels, defined as good pixels for which channel 2 minus channel 1 (i.e., the EVI) is greater than a defined minimum value, 25.0.

It is significant that, in the present FCCAD system, *cell VINs are calculated only from green pixels*. In addition, although images can only be rejected by the analysts, VINs *are not retained in the database unless they are derived from cells with at least 80 percent good pixels*. Limiting the record of cell VINs in this way is intended to maximize the value of the database for crop investigations by minimizing the contribution of non-vegetative pixels.

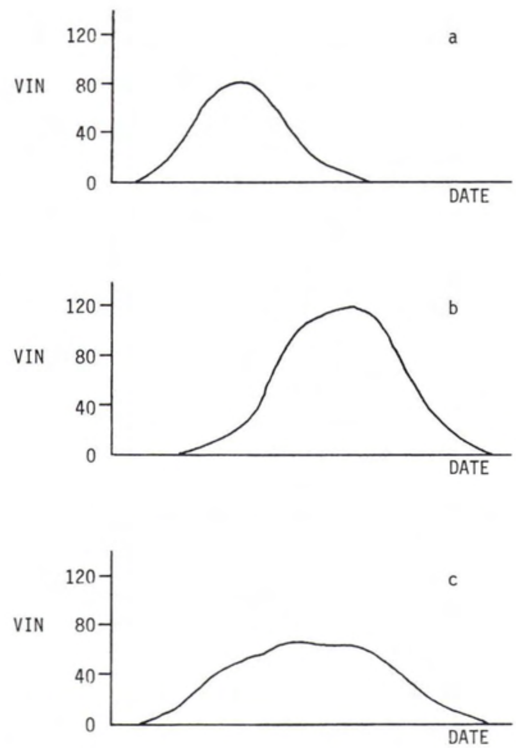

FIG. 1. Hypothesized seasonal change in vegetation index numbers (VINs) of two crops in pure and mixed pixels or cells. (*a*) Pure pixel or cell of crop A, (*b*) pure pixel or cell of crop B, and (*c*) mixed pixel or cell shared equally by crops A and B.

Footnote to figure: Values of VINs are relative, and it is assumed that all plants of each crop are temporally identical—all plants emerge, mature, and senesce simultaneously.

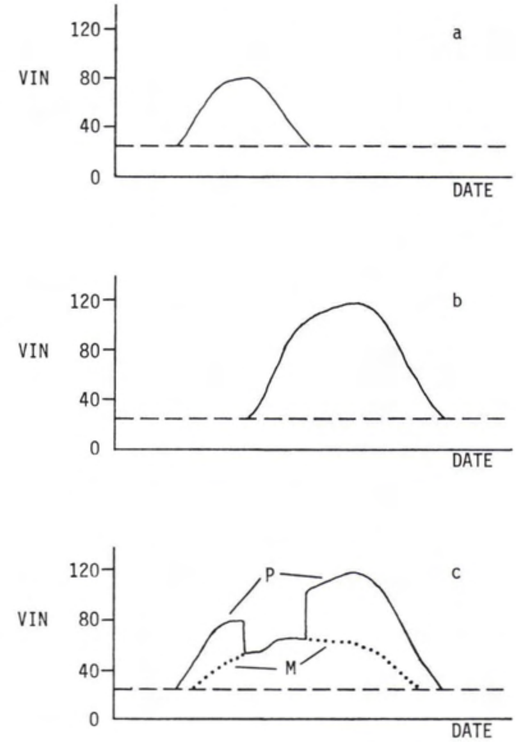

FIG. 2. Hypothesized seasonal change in vegetation index numbers (VINs) of two crops in pure and mixed cells in FCCAD's AVHRR database. (*a*) Pure cell of crop A, (*b*) pure cell of crop B, and (*c*) mixed cell shared equally by crops A and B in pure (P) or mixed (M) pixels.

Footnote to figure: VINs are assumed to be Environmental Vegetation Indices (EVIs). Because VINs are calculated only for green pixels, values of 25 or less would not be recorded. Also, see footnote to Figure 1.

An interesting side effect of limiting VINs to green pixels is to enhance the difference between mixed cells composed of pure pixels and mixed cells composed of mixed pixels (Figure 2, P vs. M). The curve of pure pixels in Figure 2 is explained as follows. Consider a mixed cell which is divided evenly between pure pixels of crop A and pure pixels of crop B. Crop A emerges and matures earlier than crop B, and consequently, the early-season cell VIN (assume EVI) is derived entirely from "green" pixels of crop A. These pixels must be green because in the FCCAD system, cell VINs are calculated only from green pixels (i.e., pixels with EVIs exceeding 25.0). Assuming that crop A grows and matures uniformly, the VIN is thereby derived from one-half of the cell. The other half of the cell, occupied by crop B, will not contribute to the cell VIN until the crop B pixels become green. When crop B does, in fact, reach the growth stage that the EVIs of the crop B pixels just exceed 25.0, the cell VIN drops sharply. At that point, the cell VIN is derived from the average of crop A and crop B pixels. Assuming uniform growth of crop B, this means that half of the cell will contribute the VIN associated with crop B (just over 25.0), while half of the cell will contribute the VIN associated with crop A (a relatively high number in Figure 2). Both crops contribute as long as their pixels are green. The sharp increase in the cell VIN occurs when the pixel VINs of crop A fall below 25.0. From that moment to the end of the season, the cell VIN is derived entirely from green pixels of crop B.

Given the manner in which AVHRR cell VINs are calculated in the FCCAD system, the variables in the equations must be redefined as follows:

V_{ijt} = average VIN of green pixels observed in cell i, j at time t;
V_{pt} = VIN of each green pixel observed in cell i, j at time t;
n = number of green pixels observed in cell i, j at time t;
V_{ct} = VIN of each green cover type observed in cell i, j at time t;
A_{ct} = corresponding area of each green cover type observed in cell i, j at time t; and
A_{ij} = total area of green cover types observed in cell i, j at time t.

VALUE OF AVHRR DATABASE

Within certain fundamental limits, a pixel VIN relates to the cover, biomass, vigor, and, potentially, yield of vegetation in the pixel (Perry and Lautenschlager, 1984). This should also be true for a cell VIN. Further, the number of green pixels in a cell should relate to the area over which the cell VIN, indicative of vegetation, has been calculated. Together, a cell's VIN and number of green pixels should relate to vegetative production, which usually correlates with the marketable portion of the vegetation. Temporal changes in cell VINs and in the number of green pixels should thus provide useful measures of vegetative change and a basis for estimating change in production—even when the cell contains different vegetative cover types.

At any one time, the VINs of different crops in a cell will likely differ because of their respective planting dates and phenology, if not because of their inherent reflectance differences (Figure 1). By itself, however, this should not prevent valid comparisons of temporal cell VINs as long as four conditions are met:

- The mix and respective areas of the different vegetative cover types in each cell are constant or nearly constant;
- Cell VINs are examined at comparable growing periods from the different years, as judged from weather and planting records;
- Green pixels are statistically representative of the vegetative cover in the cell, in terms of types, relative areas, and status; and
- Atmospheric effects are negligible or are taken into account.

The ideal case for comparisons is when the planting dates of different crops within a cell are uniform, relative to one another, and the effects of weather on the different crops are similar.

Probably, the most useful information that can be derived from the AVHRR data base is the profile of a cell's VINs and green pixels over a growing season, and a comparison of this profile with profiles of different years or the norm (assuming data are sufficient to establish the norm) (Figure 3). Such objective, quantified measures of growth or production trends cannot be derived through visual analysis of single or paired images. The information should therefore assist monitoring and qualitative forecasting (*cf.*, Crist, 1984; Odenweller and Johnson, 1984), as well as provide a basis for quantitative yield modeling.

Selection of images for temporal comparisons will be governed by the quality of the images and the dates at which the cell VINs will be most informative for the particular crop or crops grown in the region. Although the optimum dates will vary with crop and weather, comparison of images from different years must be based on comparable stages of growth, the second condition.

With reference to the third condition, it must be recognized that, because the AVHRR database contains data from cells from which as many as 20 percent of the pixels may have been removed, the cell VINs cannot be accepted blindly. Insofar as the

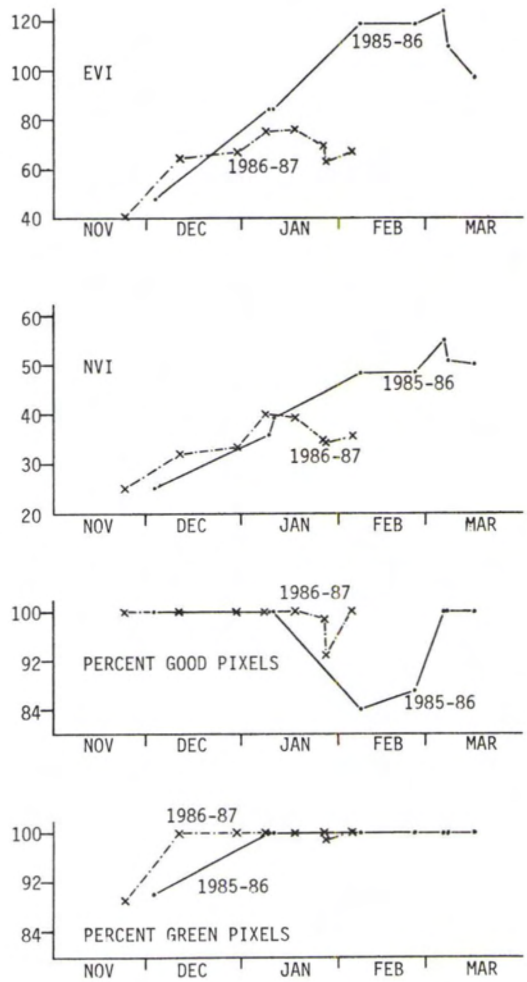

FIG. 3. Values of Environmental Vegetation Index (EVI), Normalized Vegetation Index (NVI), percent good pixels, and percent green pixels for sample cell during 1985-86 and 1986-87 (in-progress). (From NOAA-9 AVHRR data of Argentina.)

80 percent criterion provides a representative sample of all cover types, and insofar as atmospheric differences do not affect pixel values, error in cell VINs should be minimal. The more serious effect will likely be a reduction in the number of green pixels. If the number of green pixels is "reduced" by cloud cover rather than by actual crop production, direct comparison of year-to-year values for estimating changes in production could be deceiving. Indirect comparison (i.e., inference) must either presume the number of green pixels is constant or rely on visual observations in other parts of the cell. The latter option, while reasonable with pure cells, may be unacceptable with mixed cells.

Before comparing year-to-year cell VINs, then, the analyst must first consider the good and green pixels. If the numbers and distributions of good pixels cannot provide reliable and representative cell VINs, or if all green pixels cannot be accounted for through direct or indirect observation, the cell VIN should normally be disregarded. On the other hand, if the good and green pixels are found to be reliable and representative, the matrix in Table 1 provides a guide for interpreting year-to-year changes.

The matrix presumes that a change in VIN is indicative of a change in vigor and, possibly, of a change in yield; and that a change in the number of green pixels is indicative of a change in the area of production. If true, where the cell VIN and number of green pixels both increase, production should increase; where both decrease, production should decrease; and other combinations are possible (Table 1). Question marks in the table relate to those situations where changes in production are not readily interpretable—crop area declines but vigor increases, or crop area increases but vigor declines.

AN OUTLINE FOR AVHRR DATABASE INTERPRETATIONS

Having concluded that the AVHRR database contains useful crop information that would improve crop assessments if interpreted correctly, the authors prepared a procedural guide for incorporating the database values into the analysis process. The guide is outlined here for completeness.

I. Preliminary Steps
   A. Collect and analyze supporting information (e.g., crop calendars; crop area, yield, and production data).
   B. Visually screen computer-displayed images for clouds and image quality.
   C. Review images to document crop activities and effect of any episodic weather events.

II. Evaluate Cell VINs
   A. Obtain VINs from database.
   B. Visually check areas affected by cloud or haze.
      1. If any crop production area is affected, reject VIN.
      2. If no crop production area is affected, accept VIN.
   C. Record date, cell number, cell VIN, total number of pixels, percent good pixels, and percent green pixels for all cells or, if sufficient for analysis, for selected key cells.

III. Crop Monitoring and Qualitative Forecasting (for all or selected cells)
   A. Monitoring
      1. Follow VIN-versus-date curve progression through the growing season.
      2. Compare current year's VIN curves with curves and crop calendars of previous years.

TABLE 1. EXPECTED CHANGE IN PRODUCTION GIVEN OBSERVED YEAR-TO-YEAR CHANGES IN CELL VIN AND GREEN PIXELS.

		CELL VIN		
		decrease	no change	increase
GREEN PIXELS	decrease	major decr.	decrease	?
	no change	decrease	no change	increase
	increase	?	increase	major incr.

      a. Record overall vegetative development or, if possible, specific crop development.
      b. If current year's VIN curves do not follow "normal" progression, record the deviations and reason(s) (e.g., due to weather).
   B. Forecasting
      1. Choose dates that are most informative for forecasting overall vegetative production or specific crop production, allowing for deviations from crop calendars due to weather and other factors.
      2. Considering the cell VINs and number of green pixels from the current and previous years, and using Table 1, qualitatively forecast any change in production.

IV. Modeling for Quantitative Production Forecasts
   A. If a sufficient number of years of observations is available, assemble crop data (area, yield, production), VINs, and numbers of green pixels.
   B. Combine the cell VINs and green pixels to correspond to the geographic unit for which production statistics are compiled (e.g., the state).
   C. Develop quantitative estimators of production or change in production (either graphically or analytically). Consider a regression approach based on (1) values of VINs and green pixels, (2) observed changes in VINs and green pixels, or (3) area under the VIN curves and green pixels, or consider some other approach.

V. Possible Problems
   A. VINs and green pixels may represent or be affected by non-crop vegetation which may respond differently than crops of interest.
   B. Crop VINs do not necessarily correlate with crop yields.
   C. Atmospheric effects (e.g., haze) have a major effect on VINs.
   D. Sensor degradation may affect data values, particularly over different years.
   E. Episodic or extreme weather events may have a controlling effect on crop conditions.
   F. VIN curves may be misinterpreted due to missing data points.

EXAMPLE OF AVHRR DATABASE INTERPRETATION*

The value of the database and outline can be illustrated with reference to Figure 3. Note the importance of weather data and supporting crop information. The data are from a single grid cell in a part of Argentina where approximately 80 percent of the area is cropped. Soybeans and corn are dominant, and they are found in approximately a 3-to-2 ratio. Corn is generally planted prior to the first crop of soybeans, and these are followed by a second soybean crop.

Examination of VINs from 1985-86 and 1986-87 suggests that planting began a week or two later in 1985-86. This would prevent a year-to-year comparison of VINs for any one date but not an interpretation of overall differences. A difference in planting dates is in line with weather records which show that October and November were wetter than average in 1985. Of greater significance is that, in 1986-87, VINs of the maturing crops leveled off earlier and at lower values than those in 1985-86.

This difference could be partly attributed to the timing of corn senescence. Because of the delayed planting in 1985, corn senescence may have been masked by the second crop of soybeans; VINs continued to rise in December 1985 and January 1986. In contrast, corn senescence in 1986-87 could have occurred when the second crop of soybeans was in an early vegetative stage; VINs leveled off in December 1986, prior to increasing in January 1987 with the second soybean crop. But the decrease in 1986-87 VINs is too large to be attributed solely to corn senescence.

A more likely cause is the weather: records show that the

*The authors are indebted to Tamara L. Warner and Kenneth R. Hylton, FCCAD analysts, for providing the example and assistance in its interpretation.

1986-87 crop was subjected to unusually high temperatures and below average rainfall. Heat and moisture stress would have adversely affected the first soybean crop and accelerated the senescence of corn. The effect on yields could be substantial, though estimates of the magnitude should await later data. Improved weather would cause a partial recovery of soybeans, a trend suggested by the last point in 1986-87.

The logic of these interpretations may be clear; however, as outlined, VINs cannot be properly interpreted without considering the percentages of good and green pixels. On checking these values for both cropping years, one finds that VINs for several dates were derived from cells with fewer than 100 percent good pixels (Figure 3). The reliability of these points should be checked by examining the images. (Considering the remaining points, the overall interpretation of a crop decline in 1986-87 should not change.)

CONCLUSIONS

An evaluation of the FCCAD database has shown that useful crop information can be derived from vegetation indices which have been averaged over geographically referenced cells of mixed AVHRR pixels. Additionally, the evaluation has shown that information from the database can be incorporated efficiently into the operational procedure for assessing crop condition.

Finally, as the FCCAD analysts who previously had made little use of the database begin to interpret the AVHRR cell data in concert with imagery, weather data, and supporting crop and soil information, they report an improved capacity for crop assessment. The principal gain is the capacity to examine objective measures and trends of vegetative growth from numerous dates in a single table or graph.

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