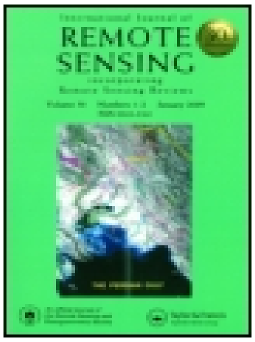

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Uses of satellite data for famine early warning in sub-Saharan Africa

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Abstract. Since 1984, national and international agencies have sought to improve their ability to forecast famine in sub-Saharan Africa. A number of early warning systems have been implemented for this purpose that monitor physical and social variables that may indicate the likelihood and magnitude of famine. Several famine early warning systems use satellite remote sensing data to supplement ground-based observations. These systems have demonstrated the advantages in timeliness and consistency of remote sensing data. Although user needs have not been clearly defined, experience gained in the operation of early warning systems and the results of related research suggest that: (*a*) at the continental scale AVHRR GAC data offer many advantages over traditional, ground data sources; (*b*) quantitative crop yield estimates might be improved through consideration of both photosynthetic activity of the vegetation and length of growing season; (*c*) qualitative comparisons of crop years have provided useful inputs to current early warning needs; and (*d*) stratification of the region into coherent geographical areas would improve all estimates.

1. Introduction

The need for timely and accurate information on the status of agricultural crops and rangelands in Africa has received high priority since the onset of the current series of droughts in 1968. International relief responses to the famines that frequently accompanied drought often were late or poorly coordinated because famine could not be anticipated. Moreover, when famine occurred, information describing its extent and magnitude was often lacking, unreliable, or contradictory. This was due in part to the variable quality and long lag time in 'conventional' reporting, such as meteorological observations or crop bulletins, that are compiled from incomplete or poorly managed ground observation networks.

The advent of global meteorological satellite systems made available another source of comprehensive observations that, when combined with ground samples, could provide consistent descriptions of meteorological conditions for the entire continent of Africa; however, while these combined datasets could be used to describe more accurately weather patterns for large areas (of the order of $100\,km^2$), they were and are inadequate to assess directly the general status of crops for relatively small areas.

The advanced very high resolution radiometer (AVHRR) instrument carried on the current NOAA (National Oceanic and Atmospheric Administration) series of satellites is capable of yielding data for relatively small areas in two formats: local area coverage (LAC) at maximum of $1\,km^2$ resolution, or global area coverage (GAC) resampled onboard the satellite to about $16\,km^2$. Because the AVHRR observes in both the red and infrared parts of the spectrum, the data are also suitable for assessing vegetation condition (Tucker 1979). This capability has prompted considerable research in the development of techniques for monitoring vegetation condition over large areas (Justice 1986). The practical need for current data on the condition of crops and rangelands in Africa—the emergence of a new class of satellite remote sensing instruments capable of providing almost continuous data, and a heightened political interest in taking positive action to combat famine—all combined to produce a number of early warning systems (EWSs) related to food security, especially in the period since 1985.

The purposes of this paper are to examine the nature of the early warning activity in general and the data that are commonly used, to review the status of the major early warning systems that employ satellite data, and to identify some of the methodological issues related to remote sensing and suggest future lines of development.

2. The nature of early warning systems

With the notable exception of war, no single factor causes famine. Some observers would have it that modern famines, especially in Africa, are the direct result of demand outstripping food production, largely as a consequence of drought (Arnold 1988). However, it is also argued that famine often is as much a product of political or economic troubles as it is a product of imbalances between demand and production (Garcia 1981). The agricultural year of 1988 illustrates the complexity of the argument. 1988 was a year in which the United States experienced a significant drought without famine, food shortages, or even a noticeable increase in food prices. In contrast, Sudan had no drought, but famine was widespread as a result of a civil war in which both sides kept farmers from their fields and intercepted food assistance.

There is little doubt that a host of social, political and economic considerations may create a vulnerability to famine at either local or national scales; however, drought remains the single largest controlling factor in determining crop variability in the region (LeComte *et al.* 1988). Hence, drought may often play a critical role in dictating the onset of famine events, particularly in the Sahel region of Africa.

Because of the complex nature of famine, much effort has been devoted to identifying indicators that might be monitored to predict impending famine. These commonly include physical indicators, such as precipitation patterns, as well as social indicators, such as market prices and migrations (Reining 1978, Currey 1981, Cutler 1984, Eldridge *et al.* 1986). To date, however, no individual or set of reliable indicators has emerged and, because of famine's geographic variability and inadequate understanding of coping strategies across the region, it is unlikely that such indicators will emerge soon.

In the absence of a reliable set of indicators, a conservative approach is usually taken that considers several types of independent data to identify populations that might be at risk. This 'convergence of evidence' approach is a tool regularly applied by air-photo interpreters (Estes *et al.* 1983). The approach is sound only if the indicators are relevant, reliable, and gathered from independent sources. Because physical data, such as precipitation, cannot gauge the human impact of famine, social data, for example, market prices, that describe the response of populations to stress must also be considered. In using this approach, the EWSs may become unwieldy and subjective in that they must weigh data that vary widely in format, scale, coverage and reliability.

2.1. *Ground data*

Some EWSs gather primary data; however, owing to the expense of field operations and/or the assumption that appropriate data are routinely gathered by various agencies, most ground data are derived from secondary sources, including international agencies, host country ministries, assistance project personnel, or non-governmental organizations (NGOs) (Hervio 1987).

2.1.1. *Rainfall and temperature*

Because drought leads to declines in food production, rainfall observations are fundamental to most EWSs. These are commonly gathered and distributed by national networks, regional organizations such as the AGRHYMET Centre in Niamey, or the World Meteorologial Organization's Global Telecommunications System (WMO/GTS) (EDC 1988b). These data may be evaluated qualitatively (Eldridge *et al.* 1986) or incorporated in quantitative models (§ 2.3). The spatial variability of rainfall in the region and the sparse recording network, though, often make it difficult to pinpoint areas that might be experiencing drought.

2.1.2. *Crop yields*

Crop projections are developed by national agricultural ministries based largely on meteorological data and ground surveys. Crop projections are used in EWSs where and when they are available; however, owing to the inherent variability of production systems, the shortcomings of estimation techniques employed, and the limitations of local operating budgets, crop projections are of highly variable quality. They may, however, be used to confirm the direction of trends suggested by other data.

Actual crop statistics are used to verify and improve predictions, and to validate crop production models (§ 2.3). While potentially among the most valuable data for developing a sound methodology, crop statistics for many countries must be used with caution. Reports tend to be highly variable in accuracy owing, in part, to the limitations of the reporting systems suggested above, but also because of political and economic incentives to over- or under-report production.

2.1.3. *Food stocks*

The amount of food available at the farm and village level is a critical variable in the food security equation; however, because they cannot be directly observed, food stocks are difficult to estimate systematically. In general, estimates of stocks are generated by field teams despatched when trouble spots have already been identified (Pons 1986). More commonly, qualitative assessments are made about food availability based on the previous year's crop.

2.1.4. *Food and animal prices*

Ideally, all factors relating to the availability of food, such as food stocks, imports, production outlook, should be reflected either in the relative prices of commodities, or in the volume of sales of assets, such as animals (Eldridge *et al.* 1986). For instance, a decline in the price of cattle and an increase in the price of grain sometimes reflect early reactions to drought stress as farmers dispose of assets to buy scarce grain. However, these relationships appear to be highly variable in both time and space (Cutler 1984, Reardon *et al.* 1988). As a result, they are not yet well understood and not systematically incorporated in most systems. Ultimately, though, market prices may prove more sensitive than most other indicators for gauging the magnitude of famine.

2.1.5. *Health and nutritional status*

Health data have sometimes been suggested to be the most fundamental measure of stress a population is experiencing (Reining 1978). Records of infant mortality, incidences of disease, and children's height and weight in different age classes are the most commonly considered (Eldridge *et al.* 1986). While often useful in documenting the severity of famine after it has occurred, health and nutritional indicators are 'lagging' rather than 'leading' indicators, having little predictive value. In fact, precipitation and other measures describing crop production have been used to predict malnutrition some months in advance (Mason *et al.* 1987).

2.1.6. *Aerial photography*

Although not gathered on the ground, aerial photographs can be used to observe and map ground features, such as agricultural fields, crops, water resources, animals, migration, etc. Unfortunately, current aerial photography is in limited supply for most areas, and expensive to acquire for large areas; however, sampling methods have been developed for acquiring large-scale aerial photography using 35 mm cameras and light aircraft over very large areas in relatively short time frames (ILCA 1981, Prince *et al.* 1988).

2.1.7. *Other observations*

Even though no EWSs generate primary data routinely, some dispatch special teams to areas in which difficulties are suspected. Where in-country staff are available, they are used to observe population movements and pest infestations, and to get a general impression of local conditions. Assistance personnel participating in other in-country projects can provide information and insight to problems in their own areas; furthermore, travellers can be queried about their impressions of conditions in areas that cannot be visited.

2.2. *Satellite-derived data*

In addition to vital information describing social, health and economic conditions, all EWSs require current, synoptic data describing local environmental conditions that affect crop growth or that reflect their current status. Many of these data are important, particularly precipitation data; however, even such common observations are seldom available for an entire country on a regular or timely basis. Others, such as yield forecasts, may be available but describe only one or a handful of points and thus lack a comprehensive geographic dimension.

Repetitive satellite images that cover the entire continent hold a distinct promise for EWSs in Africa and elsewhere. Aside from temporal and geographic dimensions, their performance characteristics are relatively well known, so that the opportunity exists for establishing a broad, long-term record for reference purposes.

AVHRR and Meteosat instruments have been widely used in both experimental and operational modes for monitoring conditions in the Sahel (Justice 1986, Prince and Justice 1991). In EWS applications, the two instruments have been used to provide three types of data that are used for many different purposes.

2.2.1. *Rainfall estimates*

Networks that provide meteorological data are sparse and, in some places, inaccurate or non-existent. Where stations exist, data may not be delivered for 2–3 weeks after the observation period (LeComte *et al.* 1988). To cope with these shortcomings, thermal images from the geostationary Meteosat satellite are acquired and interpreted to produce simple maps of cloud distribution over large areas, to monitor cloud cover duration, and to estimate cloud-top temperatures to identify clouds that might be precipitating. This information, combined with measurement of actual precipitation at scattered recording stations, can be used to develop precipitation estimates for large areas (Kalensky *et al.* 1985, Milford and Dugdale 1986, Snijders 1991). In addition, because wet soil is cooler than dry, estimates of outgoing long-wave radiation derived from NOAA data are sometimes compared with historical means to corroborate rainfall estimates (LeComte 1988, Hervio 1987).

2.2.2. *Vegetation condition*

AVHRR data have been extensively used to monitor vegetation condition and estimate biomass (see Justice, 1986, Prince and Justice 1991). Briefly stated, healthy green plants absorb radiant energy in the red part of the spectrum and reflect or scatter energy in the near-infrared part. Vegetation condition and amount can be estimated by combining observations from these two spectral regions in a normalized difference vegetation index (NDVI). Index values vary, principally, as a function of photosynthetic activity of the vegetation (Tucker 1979, Prince 1991a).

It is possible to monitor plant conditions throughout the growing season over large areas and, assuming that crops and natural vegetation respond to rainfall in similar ways, to assess general crop and rangeland conditions (see Justice 1986, Prince and Justice 1991). These data are increasingly used to make qualitative comparisons of the growing season with previous ones (Malingreau 1986), and with some reservations, to make statements about forage production and crop yields by comparing integrated AVHRR NDVI values for the current season with previous years (LeComte *et al.* 1989).

2.2.3. *Cropped area*

To derive a quantitative relationship between NDVI data and crop production it is necessary to estimate the area devoted to crops. The coarse resolution of AVHRR images makes them unsuitable for this task. Higher resolution image data from the Landsat and SPOT land remote sensing satellites can be used to map directly the areas devoted to crops, or they may be used to develop an area sampling frame from which a more accurate estimate of cropped area and crop types can be made (RCSSMRS 1987).

While higher resolution satellite data are also suitable for monitoring vegetation production, their high cost and infrequent imaging of the same target preclude their regular use. Often, arbitrary delineations of agricultural regions are made from integrated AVHRR NDVI images, and topographic or other maps.

2.3. *Forage production and crop yield models*

Relationships among the factors that control crop growth and yield have been formalized in a number of models. Generally, these relationships have been developed for specific crops in other geographic regions, but have been applied in the African setting, sometimes in combination with satellite data.

2.3.1. *Water balance*

Rainfall and temperature data are of relatively little value alone; however, they can be combined in models to estimate soil moisture that might be available for plant use and thus suggest crop or rangeland status (Doorenbos and Pruitt 1977).

2.3.2. *Crop yield and production*

In more complex analyses, plant water requirements at various stages of crop development are compared with estimated soil moisture throughout the growing season to estimate crop condition. Based on known relationships of crop yields and water balance patterns through the growing season, a crop yield forecast for the current season can be developed by monitoring predicted water balance (Frère and Popov 1979).

If an estimate of the area devoted to individual crops is made (§ 2.2.3), crop production predictions can be made based on crop yield estimates.

3. Status of early warning systems in Africa

The past four years have seen a surprising increase in the number of organizations involved in early warning (Hervio 1987). In part, this is due to increased attention paid to the Sahel as a result of the 1984 drought and subsequent resolutions for increased monitoring that came from the Bonn summit of 1985. This interest has been complemented by heightened activity within the scientific community in the use of satellite data as an inexpensive tool for monitoring large areas.

For our purposes, EWSs employing satellite data fall into two categories: operational systems with assured institutional support that regularly produce and distribute a product, and experimental systems of uncertain lifespans that are being evaluated for possible operational use. The brief descriptions that follow show both the scope of applications and the types of agencies involved.

3.1. *Operational systems*

3.1.1. *Regional AGRHYMET Centre*

The Regional AGRHYMET (agriculture, hydrology, meteorology) Centre in Niger issues reports every ten days that can be used for early warning, with monthly and annual summaries. The reports describe the current growing season in terms of rainfall, water balance, stream flows, crop conditions, pest infestations, and range conditions, based primarily on meteorological data and field reports supplemented with Meteosat, local market data, and NDVI images from AVHRR. Reports are distributed to the European Community, member countries of the Comité Permanent Inter-États de Lutte contre la Sécheresse dans le Sahel (CILSS), and the US (Soares 1989).

The Regional AGRHYMET Centre is moving into its third phase of development. In the future, rather than issuing reports alone, AGRHYMET will develop and distribute a range of data products describing rainfall probability and actual precipitation derived from Meteosat. Using its new AVHRR receiving station, AGRHYMET will also report biomass development, crop phenological development and potential locust infestations produced from AVHRR NDVI data (EROS Data Centre 1988 b).

3.1.2. *Famine early warning system (FEWS)*

FEWS is operated by the US Agency for International Development (USAID) in Washington, D.C. At present, this system incorporates more diverse types of data than any other EWS, almost all of which come from secondary sources (Hervio 1987). It considers rainfall, yield estimates, production estimates, market prices, other social indicators (when available), and AVHRR NDVI data. In the past, bulletins were issued as needed, and reports were issued monthly and distributed to USAID offices and missions, US government agencies and regional and international assistance organizations. Although FEWS has only been officially functioning for three years, prototype EWSs have been under development within USAID since 1979 (Johnson *et al.* 1987).

Confronted with such a wide array of different data types, FEWS analysts have come to rely more heavily on AVHRR GAC NDVI data than any other single type of information (Gary Eilerts, personal communication). In particular, decadal (10-day composite) NDVI images for large regions help to reveal regional patterns that might not be readily observed in precipitation station data alone (see figure 1). Similarly, AVHRR NDVI time series for administrative units are compared to historical means and extremes (for instance, the 1984 drought) to gauge the current conditions (figure 2).

3.1.3. *Global information and early warning system (GIEWS)*

In 1973, the United Nations created GIEWS within FAO and gave it prime responsibility for early warning within the UN family. It has been in production since 1975.

The food balance approach adopted by GIEWS is different than FEWS. Generally, GIEWS seeks to establish measures of food security (food production, stocks, and imports compared to food demands) on a country-by-country basis (Hervio 1987). It incorporates field data provided by host country ministries, FAO field personnel, special missions dispatched to suspected problem areas, and meteorological data. Bulletins on crop and climate status are issued bimonthly, a food outlook is published monthly, and special reports on food shortages are issued as needed.

The FAO Remote Sensing Centre in Rome has established a satellite-based adjunct to GIEWS with support from the Netherlands, called Africa Real-Time Environmental Monitoring using Imaging Satellites (ARTEMIS). It provides timely information to GIEWS, as well as other programmes in FAO, UN sister organizations, national and international EWSs. There are also cooperative arrangements between FAO and NASA Goddard Space Flight Center (NASA/GFSC; see § 3.2.4), the University of Reading (U.K.), and the National Aerospace Laboratory of the Netherlands. The programme uses automated databases of geographic features, agroclimatology, METEOSAT rainfall estimates, AVHRR NDVI values and the Desert Locust Habitat (Hielkema *et al.* 1986). Two FAO field projects, in Nairobi and Harare respectively have been established to provide subregional components of the early warning system in the IGADD (Horn of Africa) and SADCC (Southern Africa) countries.

3.1.4. *Other systems*

Beyond those discussed above, there is another class of operational system for monitoring world agriculture patterns that uses similar technology but does not focus on the Sahel. The USDA/NOAA Joint Agricultural Weather Facility (JAWF) develops crop yield potential forecasts for the world's major agricultural areas based primarily on conventional meteorological data, supplemented by satellite data. It produces critical descriptions of world-wide crop conditions for crop-commodity specialists within USDA (Motha and Heddinghaus 1986).

In addition to yield-potential forecasts made by JAWF, crop production forecasts are made for major grain-producing countries by the Foreign Crop Condition

Assessment Division (FCCAD) of the Foreign Agriculture Service (FAS) in USDA. The FCCAD differs significantly from other systems in that it produces crop production estimates by using high-resolution satellite data, for example, Landsat, to develop cropped area estimates and combining these data with JAWF data and ground samples. AVHRR data are used to corroborate other observations (Johnson *et al.* 1987).

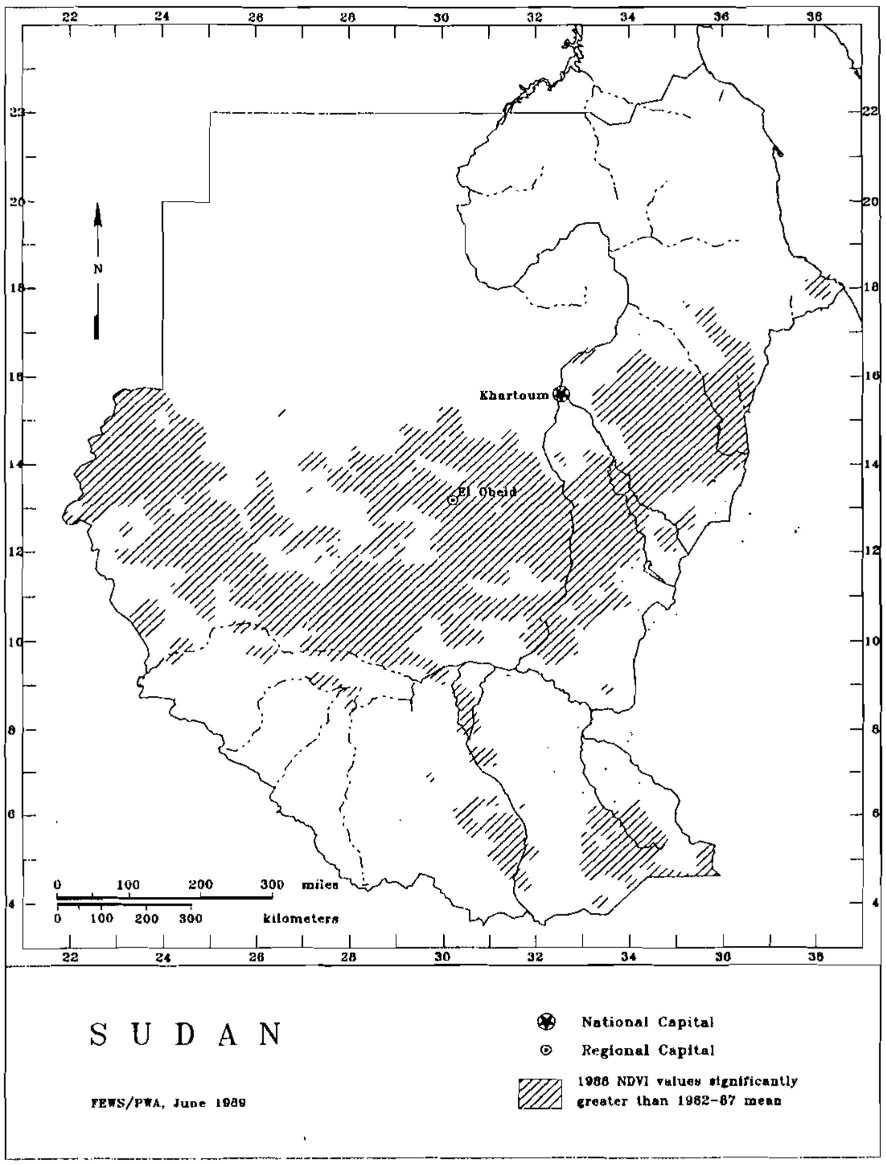

Figure 1. The distribution of higher-than-average NDVI values for Sudan in 1988. This was a good crop year, but marked by famine as the result of civil war and local flooding. USAID/FEWS project; Price, Williams and Associates.

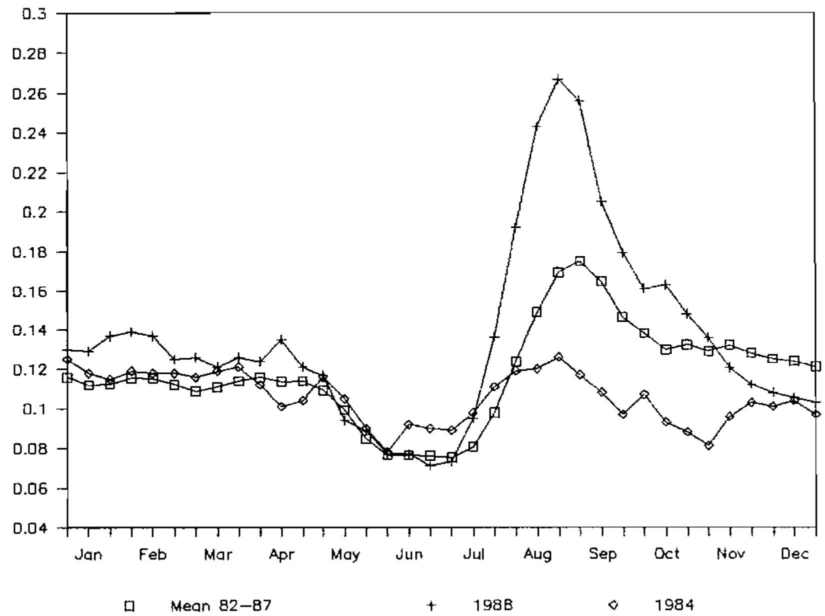

Figure 2. NDVI decadal (10-day) time series for the region around El Obeid, Sudan. The 1988 growing season was perhaps the best in 20 years. It is compared with the 1981–1987 mean, and the extreme drought of 1984. USAID/FEWS project; Price, Williams and Associates.

3.2. *Experimental systems*

3.2.1. *Centre de Suivi Ecologique (CSE)*

The CSE was established in 1986 within the Senegalese Ministry of Water and Forests with support provided by Denmark through the UN Sudano-Sahelian Office of the UN Development Programme (UNSO, UNDP). It was intended to serve as the first in a proposed network of ecological monitoring units in the Sahel.

The CSE has used AVHRR data to monitor rangeland biomass in Senegal since 1987. They also have used field surveys and the systematic reconnaissance flight (SRF) technique (see § 2.1.7) to monitor the distribution of livestock and rangeland condition in relation to the development of bore-hole wells in Senegalese rangelands (Diallo *et al.* 1991).

In addition to its rangeland monitoring programme, CSE is expanding its efforts to include such activities as the monitoring of rainfed and recession agriculture along the Senegal River, using a combination of field observations, SRF, airborne integrated camera and radiometer (ICAR), SPOT, Landsat, AVHRR, and Meteosat data.

3.2.2. *Earth Resources Observation Systems (EROS) Data Center*

The EROS Data Center (EDC) is operated by the US Geological Survey. Recently, in support of the FEWS project, EDC has worked to adapt techniques developed by FAO (Hielkema 1980; Tucker *et al.* 1985) for integrating AVHRR NDVI with geographic data, for example provincial boundaries and road networks to predict locations of possible grasshopper outbreaks in West Africa (EROS Data

Center 1988 a). In addition, EDC provides primary geographic information systems support to the new phase of the FEWS project. As a first step in this project, EDC is developing standards for the FEWS data base, including both satellite and geographic data, which will be maintained at EDC.

3.2.3. *Evaluation et suivi de la production agricole en fonction du climat et de l'environment (ESPACE)*

ESPACE is a French experiment begun in 1986 that deals with Senegal and Mali. It incorporates water indices derived from meteorological data, supplemented by AVHRR and Meteosat models. Working in collaboration with AGRHYMET, ESPACE seeks to provide identification of drought areas, an estimate of crop (spectral) emergence, and estimates of soil moisture that can be used in crop yield models (Hervio 1987).

3.2.4. *Global Inventory Monitoring and Modelling Studies (GIMMS)*

GIMMS is a research unit of NASA/GSFC that has promoted the development of AVHRR tools for use in a wide range of monitoring problems. A primary thrust of their research has been to explore the use of AVHRR NDVI to monitor regional vegetation patterns in the arid and semi-arid regions of sub-Saharan Africa (see Justice 1986, Prince and Justice 1991). As part of this research, GIMMS has developed an AVHRR archive for Africa from 1981 onwards. It also provides AVHRR NDVI products to virtually all of the major EWSs, such as FEWS, ARTEMIS, EDC. Additionally, GIMMS has provided informal technical support to most groups interested in applying AVHRR to monitoring problems in the Sahel.

3.2.5. *Integrated livestock production project (ILPP)*

Since 1984, Tufts University, in collaboration with New Mexico State University, has evaluated several techniques for early warning with the Ministry of Animal and Water Resources in central Niger (Maidagi *et al.* 1987). It differs from most others in its focus on livestock, specifically in the prediction of pasture deficits. The project combines AVHRR NDVI with ground sampling to make range production estimates.

3.2.6. *Surveillance de resource naturelle (SRN)*

SRN is an experimental programme attached to the Regional AGRHYMET Centre and sponsored by the European Development Fund. A primary focus of their current work is in the development of a spatial stratification scheme using SPOT and Landsat to improve the generation of agriculture statistics. Its involvement in early warning is marginal (Hervio 1987).

4. Methodological issues

The large number of systems that have come into existence during the past four years and the methodological differences among them has led to a discussion about the limitations of the technology (Pons 1986, EDI 1987, Hervio 1987, NRC 1987). The following section focuses on some of the issues that have emerged from these discussions regarding the effective use of satellite data in early warning.

4.1. *Audience and objectives*

Much informal debate about the use of satellite data in EWSs has revolved around issues of scale, timeliness, accuracy and the suitability of AVHRR—particularly GAC—for monitoring (NRC 1987). Much, if not most, of this debate could be resolved if user needs were clearly defined by the agencies involved. As yet, however, no such guidance has been forthcoming.

Based on experience to date, users can be divided first according to the size of area with which they are concerned. One group includes relief agencies that work bilaterally for the most part, considering each country individually, such as CARE, the Red Cross, OXFAM, in addition to national agricultural and planning ministries. The second group would include major international agencies, such as FAO, EEC, USAID, or regional coordinating and support agencies, such as AGRHYMET, CILSS, who, generally, consider regions consisting of several countries. Others have made this broad distinction between local or 'micro' systems, and 'macro' or regional systems (Hervio 1987). Obviously, for any agency information needs and hence the scale of data considered will differ depending on their scope of interest.

For those systems that have used satellite data—both micro and macro—the AVHRR GAC NDVI dataset has worked reasonably well. It provides a dataset that is comprehensive for the region and covers the past eight years. While the higher resolution of LAC data might argue in its favour, especially for smaller areas, no studies have been forthcoming to demonstrate any improvement in performance at either local or regional levels that might justify consequent increases in data storage and processing costs at the present time. Moreover, because there is no region-wide historical archive of LAC data comparable to the GAC dataset, the primary analytical tool of temporal comparison is not available at present.

In addition to considerations of scale, a more fundamental difference has emerged between systems based on the ultimate use of the data. For example, early warning data may be used simply to identify areas that are experiencing a poor cropping season so that, in the case of GIEWS, field teams can be dispatched to establish the severity of the hazard. In such applications, a 'simple' monitoring programme based on a qualitative analysis of AVHRR GAC data might suffice, for example current conditions better, the same, or worse than last year or the historical mean. In contrast, some potential users, such as the proposed early warning and food information system (EWFIS) that will be launched by the Inter-Governmental Agency for Drought and Development (IGADD) for the Horn of Africa, apparently see the early warning system as an extension of or supplement to conventional crop statistical services (FAO 1988). The approach proposed for EWFIS would be based on an area sampling frame and would produce crop production estimates. Such a system should require larger staffs, more expensive higher-resolution data, such as Landsat or SPOT, and more analysis time, resulting in longer delivery lags and higher costs.

To date, most systems have chosen to view early warning as distinct from crop forecasting. Thus, they have tended to adopt 'simple' monitoring strategies based on a comparison of current AVHRR GAC with the historical data set, and have accepted levels of accuracy that are perhaps lower in exchange for shorter reporting times, lower costs, and smaller volumes of data.

Finally, a legitimate question that might be asked is how 'early' must an early warning system deliver warning to be of value. In the past, some users complained that reports reach them 'too late' to be of maximum utility or much interest (NRC 1987, Hervio 1987). Again, there are two levels of decision that must be made for the

EWS, and each has a different time threshold. One is the decision to acquire more detailed information to determine if a problem exists. The second is the decision to act on a problem once it is recognized; however, from the recent reviews cited, it is not possible to identify to which threshold users are reacting.

Even though there is some complaint about the timeliness of satellite data, weather and vegetation information derived from satellite data (3–10 days) appears to offer advantages over conventional ground-based sources (2–4 weeks) that are often overlooked (Johnson *et al.* 1987, LeComte *et al.* 1988); however, if the demands for accuracy are high, they may outweigh considerations of timeliness.

Ultimately, however, the issues of timeliness, accuracy, scale, and the suitability of LAC versus GAC cannot be resolved until the EWS audience(s) is identified and its needs more specifically defined.

4.2. *Crop assessment*

Reliable quantitative relationships between NDVI and crop yield or rangeland production in Africa do not yet exist. Relationships between NDVI and forage production are promising, but are not yet well enough developed to be used with confidence everywhere (see Justice 1986, Maidagi *et al.* 1987, Beck *et al.* 1990, Prince 1991 b). Similarly, although the technique of using Landsat data to determine cropped area combined with temporal AVHRR NDVI data to estimate yield has been used with some success in predicting crop production in the U.S., see Barnett and Thompson (1982), its applicability in the African context has been questioned (NRC 1987, Sakamoto 1988).

Several lines of research have been pursued to improve our ability to assess crops and rangelands (Prince and Justice 1991). One approach has been to understand better those factors that affect the quality of the data, such as sensor calibration (Holm *et al.* 1989), the atmosphere (Jackson *et al.* 1983) and the view angle (Holben and Fraser 1984). Others have examined spectral reflectance and relationships between biomass, green leaf area, dry matter, and the amount of photosynthetically active radiation (Tucker 1979, Tucker *et al.* 1985 a, Sellers 1985). Still others have explored the complex spectral interaction between plants and soil (Huete and Jackson 1987), and the mixed pixel problem (Hanan *et al.* 1991).

Many estimates of yield are based on the general correlation between primary production and NDVI values integrated over the growing season. Physical models have been proposed that relate integrated NDVI and total biomass production, and these can be used with caution in estimating rangeland production (Prince 1991 a, b); however, when applied to crops, this approach may not work well if there is not a linear relationship between total biomass production and grain yield (see Gallagher and Biscoe 1978).

Another set of approaches for dealing with this inherent weakness has focused on assessing plant conditions at critical points in the growing season. Crop yield is determined, in large part, by soil water conditions during the reproductive stage of crop growth. Generally, maximum leaf area is achieved at the onset of reproductive growth in grain crops, and thus there is good correlation with this point and the maximum NDVI value (Hatfield 1983, LeComte *et al.* 1988, Gallo and Flesch 1989). As the crop ripens, NDVI values decline, reaching a minimum value near harvest. The maximum NDVI value (Barnett and Thompson 1982), the rate of NDVI decline (Idso *et al.* 1980) and, indirectly, the length of time between heading and harvest (Idso *et al.* 1980, Malingreau 1986) have all been used to estimate yield for cereal crops.

The nature of the decadal NDVI composite dataset may make it difficult to identify some critical points in the growing season with any precision, especially during the later parts of the growing season. For example, the NDVI decline between heading and harvest is swift, often as short as 20 days (Idso *et al.* 1980). However, because the NDVI database is a composite of the 'greenest' pixel occurring during a decade, it is possible that critical declines in NDVI might be missed by at least one decade.

Most early warning efforts have focused on the period from spectral emergence (green-up threshold) to the reproductive phase (maximum green). Recent research has shown that NDVI values at seven weeks after emergence for millet (Johnson *et al.* 1987) and nine weeks for both sorghum and millet (Sakamoto 1988) in some cases are more effective than models that consider changes in NDVI throughout the early growth period. Other research has shown generally favourable relationships between crop yields and the length of the growing season determined by similar NDVI thresholds (Malingreau 1986, Henricksen and Durkin 1986). These results suggest that additional improvements might be achieved by combining nine-week NDVI values with NDVI-defined estimates of growing season duration.

The search for improved techniques for estimating production will undoubtedly progress; however, there are several facts that argue that qualitative assessments are more appropriate for early warning. First, the performance of the 'simple' qualitative approach, that is better/worse/same as last year, meets the demand for speed. Second, the general reliance on 'staged' approaches that seek more information when trouble is identified satisfies demands for both efficiency and accuracy. Third, it may be argued that the qualitative information conveyed by existing techniques is all that might be expected given the inherent limitations of the data. Finally, a qualitative assessment may be entirely adequate for the current demands of early warning (Malingreau 1986, NRC 1987). This might change, however, if accuracy standards are established (see §4.1).

4.3. *Regionalization*

A fundamental problem in monitoring food security in Africa is understanding the complexity of land use and cropping patterns found there. Some of this is apparent at the field level with intercropping of several crops in small, irregular plots and variability in the use of inputs. At the provincial level, it encompasses the range of responses to differences in agroclimatic environment, the availability of labour and crop inputs, land tenure patterns, crop preferences and changes in season. As already noted, this heterogeneity limits our ability to estimate crop yields or even to make general assessments regarding food security. For instance, an apparently significant change in vegetation cover may signal a catastrophic event in an intensively cropped area, but something less disastrous in a rangeland area.

As noted, all techniques used to assess crop condition or predict crop yield are highly sensitive to differences in agricultural practices and thus tend to be region-specific. Stratification of large areas has been widely suggested, but not yet employed systematically (Hervio 1987, Justice *et al.* 1991). This is due, primarily, to a lack of data: some countries have been mapped by various groups, but no consistent mapping effort has been performed across the continent.

For the purpose of crop assessment, stratification would involve mapping geographic units that are more or less homogeneous in their climate, soils, agricultural land use, ethnic composition, crops, and cropping practices. Presently, in continent-wide systems such as FEWS, some stratification is used in the analysis of NDVI data, but it is done more or less arbitrarily, that is by separating desert from non-desert areas, based on the interpreter's knowledge of the area. Data are also stratified by administrative unit, but mainly for reporting rather than interpreting.

Given the diversity found across the African continent, it would appear that the definition of coherent agricultural regions and the development of region-specific models for interpretation as well as NDVI-crop relations (see §4.2) is a prudent approach to improving the existing technology.

5. Summary and conclusions

Within the past four years, a number of national and international monitoring systems have been deployed that attempt to identify populations that are at famine risk in sub-Saharan Africa. Much of the risk to which these groups are exposed comes as a consequence of drought and its attendant crop and forage failures.

Data that describe weather, crop and forage conditions are seldom available for this large region in a form that is consistent, accurate, or timely; however, the geostationary Meteosat and polar-orbiting NOAA satellites provide daily observations of the entire region. Satellite data can be used in combination with other data, such as meteorological observations, market prices, and field observations, to develop estimates of precipitation as well as crop and rangeland conditions. All regional early warning systems use Meteosat and NOAA AVHRR on a routine basis, and assessors have come to rely heavily on the AVHRR NDVI data in their assessments.

The ultimate users of the data system and the nature of their needs are rarely defined in system design; however, among other things, user needs determine the selection of methodology, the scale at which the system should operate the types of information it considers, how quickly information must be delivered, and how accurate it should be. In general, these have not been defined.

Examination of the experiences of existing early warning systems and other applications in the region suggests the following general conclusion to issues that have arisen in early warning debates:

(*a*) Scale. Although AVHRR LAC offers higher resolution, the higher costs in processing and storage appear to outweigh potential advantages in scale at the regional level; moreover, the absence of a comprehensive historical LAC archive severely reduces its value for monitoring at the present time.

(*b*) Crop yield estimates. Simple regression models (yield versus integrated NDVI) have not proved satisfactory in predicting yields. It is suggested that other models based on satellite data be examined that consider both the duration of the cropping season as well as plant conditions at initiation of the reproductive stage.

(*c*) Qualitative assessment. Early warning and crop forecasting are different activities. The speed of response in existing EWSs probably outweighs the current lack of precision, particularly where phased approaches are used. First-order qualitative assessments, that is better/worse/same as last year, are probably more appropriate than quantitative estimates for current needs.

(*d*) Stratification. A single crop assessment method—either quantitative or qualitative—cannot be applied to the entire Sahel. Significant improvement in the accuracy and credibility of both means of assessment could be achieved by defining coherent agricultural regions and treating each independently.

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