Advances in crop yield assessment in the Sahel using remote sensing data

Michael Schultz Rasmussen

Abstract

Vegetation index data (NDVI) from the AVHRR instrument onboard the NOAA satellites have been used to quantify and characterize vegetation since the beginning of the nineteen eighties. At first the objective was to monitor and achieve a better understanding of the Sahelian environment after the droughts in the seventies. Today one objective is to use the technique to assess crop yields in the Sahel in the support of food security and economic planing as well as natural resource management at a national level. Experiences from Senegal have shown that a linear relation can be established between millet grain yield collected in the field and NDVI integrated during the period where the millet grains are produced. The consistency and accuracy of the model were improved by accounting for environmental variability within the regression model: it was found that the stratification of the agricultural domain and a multiple regression model with integrated NDVI, livestock densities and per cent cultivated land could explain as much as 88% of the millet yield variance. This result can comfortably be compared with results from more complex yield models. Further comparative advantages of using the NDVI - yield model are: the simplicity, early forecasts, data integrity and a low cost-benefit ratio. Finally, it is stressed that any operational use of NDVI-yield models in developing countries must be accompanied by the development and reinforcement of the traditional agricultural statistic program.

Keywords

Crops, yield, remote sensing, Senegal, NDVI, NOAA AVHRR, natural resource management, food security.

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The development of methods for crop yield assessment using remote sensed vegetation indices started in the beginning of the eighties. This happend uppon the international research community became aware of the ongoing degradation of the environment south of the Sahara in the Sahel. An initiative was taken to evaluate coarse resolution satellite data to provide information on vegetation in support of global monitoring and modelling (Justice, ed 1986). The primary sensor for coarse resolution monitoring was the Advanced Very High Resolution Radiometer (AVHRR) onboard the National Oceanographic and Atmospheric Administration's (NOAA) series of meteorological satellites. Data from this instrument cover the earth at a near daily frequency with a spatial resolution of approximately 1 km^2 and a spectral band composition of one visual (red), one near infrared, one mid infrared and two thermal bands. Reflectance from the vegetation in the near infrared band is high, whereas the reflectance in the red part of the spectrum is low, due to the absorption of photosynthetically active radiation (PAR) by the plants. Furthermore, there is a strong contrast in reflection from vegetation compared with bare soil in both bands. The most exploited index has been the Normalized Difference Vegetation Index (NDVI), defined as:

$$NDVI = (NIR - RED)/(NIR + RED) \qquad (1)$$

where NIR and RED are the near infrared and the red reflectance respectively. A study on monitoring grassland in Senegal was conducted by the Global Inventory Monitoring and Modelling Studies (GIMMS), associated with the United Nations Environmental Program (UNEP) and the Food and Agricultural Organisation (FAO) (Tucker et al. 1983 and 1985). It was found that dry, above ground seasonal net primary production collected in the savannah, correlated well with NDVI integrated during the rainy season. During the eighties the work was continued in other African countries and has been reported in details in Justice ed (1986) and Prince and Justice eds (1991).

The monitoring of the grassland in Senegal was continued by the UNEP/FAO pilot project, which eventually led to the creation of the Centre de Suivi Ecologique (CSE) (centre for ecological monitoring) in 1986. It was executed by the United Nations Sudanian and Sahelian Organization (UNSO) and financed by the Danish International Development Assistance (Danida). The CSE extended its activities to cover crop yield assessment using the principles of the technique developed by the GIMMS group.

The present paper aims at assessing the present state of satellite remote sensing assessment of crop yield for operational use vis a vis the results obtained in Senegal. Furthermore, a second objective is to highlight the advantages associated with remote sensing crop yield monitoring.

Yield assessment

Empiric and semi-deterministic models

It was shown by Pinter (1981) and Bartholomé (1988) that a high correlation could be obtained between either wheat or millet yield and integrated NDVI, determined from radiometer measurements in the field. Rasmussen (1992) tested this approach on NOAA AVHRR data in the most northern province of Oudalan in Burkina Faso. Millet grain yields were collected at village level and different NDVI integrals were computed from 18 AVHRR scenes covering the rainy season. High correlation was obtained for the regression between millet yields and the NDVI integral for the reproductive period (September 15 to October 20). This time period was justified since cereals in general allocate all energy to the grain production during the reproductive phase apart from a minor contribution to the maintenance. The retained linear regression model could explain 89% of the grain yield variance.

These results were applied in Senegal by CSE (Rasmussen 1991 and 1997) to the Peanut Basin area, which accounts for approximately 75% of the national agricultural production of principally millet for human consumption and groundnuts as a cash crop. The practice of crop rotation, the range of mean annual rainfall of 300 mm to 600 mm, the varying tree cover, differences in the intensity of cultivation including substantially animals husbandry; all contributed to a more complex scenario. This necessitated adopting a bio-physical frame to understand and reduce the environmental and climatic variability. A model developed by Kumar and Monteith (1981) was adopted, where seasonal Net Primary Production (NPP) could be estimated by integrating the absorbed photosynthetic active radiation (APAR) throughout the growing season and multiplying it with the biological efficiency coefficient ε (an energy to dry-matter conversion factor in kg dry matter per MJ):

$$NPP = \varepsilon \int_0^t f_{PAR} * PAR \, dt \quad (kg/ha) \qquad (2)$$

where f_{PAR} is the fraction of PAR absorbed by the plant canopy and 0 and t are the beginning and the end of the integration period. A number of studies have focussed on the bio-physical significance of the NDVI and found that the best explanation and/or correlation are obtained with the percent absorbed PAR (f_{PAR}) (Ruimy et al. 1994). Consequently the f_{PAR} could be estimated from the NDVI. If the PAR and ε are constant for the period considered and the area of interest, crop yield can be assessed using only NDVI data. However, the ε is reported to be influenced by the climate and the physical environment (Prince 1991 and Ruimy et al. 1994).

In Senegal Rasmussen (1991, 1997, 1998a and 1998b) used a number of environmental and climatic variables as means to distinguish between different production regimes to account for variation in ε: 1) Soil maps expressing general levels of potential water availability. 2) The percent cultivated land and the density of livestock expressing levels of cultivation conditions. 3) Mean day surface temperature as an indicator of water stress, the higher relative mean temperature, the less available soil humidity. Yields were sampled from field sites covering more than 1 km^2 by the end of the 1990 and 1991 rainy seasons and the NDVI integrals for the reproductive period were calculated from AVHRR data. Using multivariate regression technique along with a stratification of the agricultural domain into intensive and less intensive cultivated areas, the NDVI yield model could account for as much as 88% yield variance by square km within the Peanut Basin (Rasmussen 1998b).

Hamar et al. (1996) developed a slightly different approach by using time series of Landsat MSS data to assess corn and wheat yields in Hungary from the season integral of the greenness index from the Tasselled Cap Transformation (Kauth et al. 1979). A pilot study covering a limited geographical area demonstrated that 90% yield variance could be explained. However, when the method was applied to a regional study, the level of explained variance dropped to 52%.

A number of studies have assessed yield at a provincial level exploiting remote sensed data: Using the Condition Vegetation Index (CVI) developed by Kogan (1990), it was shown by Maselli et al. (1992) that NDVI AVHRR data from the end of July could explain 72% yield variance in 5 provinces in Niger. Groten (1993) correlated average millet yield from the seven northern provinces in Burkina Faso with the maximum NDVI for July from AVHRR data aggregated to 7.5 x 7.5 km pixels. Here 71% yield variance was explained. Correlating average yield for each province with integrated standardized NDVI, Potdar (1995) found that 50% sorghum yield variance could be accounted for in three districts in the state of Maharashtra, India. Hayes (1996) equally managed to explain 54% maize yield by reporting district in the corn belt in the USA by using the coarse global vegetation index (pixel size between 13 and 26 km) from the AVHRR. The retained model was of second order and had the mean CVI for selected weeks as the dependent variable.

Agro-meteorological models

The validation of agro-meteorological crop models continues to suffer from the problem of obtaining spatial information from point observations. These models require a number of parameters and variables that are not readily available for large areas. Thornton et al. (1997) exploit the CERES model to assess millet yields in Burkina Faso by using rainfall estimates from remote sensed data. One of the problems running the model is the initial value of soil nutrients, the N and P levels. Outputs from the model are yield mean values and yield distributions by province diverting 15% from the official statistics. Geographical Information Systems have been used by Carbone et al. (1996) to assess soyabean yields from SYGRO, a physical crop soyabean growth model. Remote sensed data were used to identify homogeneous areas with respect to vegetation and soil. Each area was characterised by statistics on historical yields and basic climate parameters and used to determine yield within 10 to 15% of the field values.

Results and discussion

Using remote sensing data alone can explain 90% of the crop yield variance within a limited area; however, when applied to larger areas the level declines to between 50 and 70%. Furthermore, the majority of the mentioned works had the weakness that the consistency between and within years was not proved. Maselli et al. (1992) did not prove that NDVI from July would always provide the best estimate of crop yield, regardless of the choice of year(s). Groten (1993), Hamar (1996) and Hayes (1996) did not show that their specific vegetation index parameters were consistent in time. Finally did Potdar (1995) not justify that the individual yield models for each province would not change significantly if the study period was changed.

Even though the majority of these studies included observations from more than one year, all data were treated as one data set. Only when environmental and climatic variability is accounted for, crop yield estimates from NDVI data are feasible with respect to the level of explained variance and the size of the area surveyed. Rasmussen (1998b) demonstrated that millet yield could be assessed with close to 90% explained variance at village level for the extended area of the Peanut Basin in Senegal, including two additional environmental variables: percent cultivated land and the density of livestock. At the same time it was justified that the retained models were consistent between two years. This needs to be verified further, covering data from more years.

Comparative advantages and changing objectives

Using NDVI-crop models including environmental and climatic variables do have some clear comparative advantages:

- The NDVI-yield models only require a minimum of input variables compared with traditional physiological or agro-meteorological crop models. Recent research on how to derive spatial information from physiological crop models has shown that the expected accuracy of crop yield estimates was in the order of plus minus 10 to 15% (Carbone et al. 1996 and Thornton et al. 1997). This level is the same as the one achieved in Senegal with the NDVI-yield model including environmental information. A synergy between the two methods has not been seen yet.
- Yield assessments can be made available early in the season. Millet yields in Senegal could be made available

one month before the harvest and two to three months before any results from the traditional campaign.

- The data integrity is high with the NDVI-yield models, because the same principle of estimation is applied in space and time. This is to be compared with traditional sampling of yield in the field by a number of institutions, each with a specific objective and accordingly a different sampling scheme. In Senegal the agricultural production accounted for nearly 50% of the gross national product of the primary sector in 1992 (PNUD 1993). This importance is reflected in the elevated number of national institutions collecting agricultural statistics. According to the annual report from the United Nations Development Program (PNUD 1993), more than 10 institutions were involved in this activity.
- The NDVI-yield models are well suited for long-term monitoring and 100% spatial databases can be built. Furthermore, models can be applied to historical data.
- A low cost-benefit ratio, since once the models have been developed and calibrated, they are easy to apply and the operational expenses can be kept at a minimum: The AVHRR data are public domain data; however, they require receiving facilities. Professional equipment, including a high level of automatisation based on a PC, can be purchased for less than 35,000 US$, eg the Dartcom WinHRPT system (Dartcom, 1998). The image processing can be handled by PC-based, high performance, public domain software packages such as the CHIPS (Hansen 1998). At CSE in Senegal it was estimated that the maintenance of the receiving facilities, images processing, producing yield forecasts and archiving data accounted for 20% of one technician's time seven months a year (the authors estimate). Initial costs must cover training of personnel and the necessary logistics.

These comparative advantages have been promoted principally by the research community (Prince et al. 1990, Rasmussen, K. 1993) and to some extent recognized by the development world (Oram 1988). However, in the past the focus has been on using the technique for famine early warning and as a support for food relief programs. Though some major activities were established, such as the Famine Early Warning System (FEWS) of the USAID, the Agrhymet centre in Niamey and the ARTEMIS of FAO, the author's experience from Senegal was that the specific early warning information was never on demand. Possibly because mobility is high and communication functions well in Senegal, but more likely because the capability of the traditional and the official network has been underestimated for this particular purpose. It should be mentioned that only limited incidents of drought affected Senegal during the years observed (1987 to 1998). The results from Senegal were exploited within the collaboration between the CSE and the Direction of Agriculture (DA) in Dakar for crop yield forecasting for economic and food security planning. However, due to a substantial lack of human resources and funding at the DA, the traditional sampling scheme was never accomplished and consequently no independent assessment of the quality of these data was made possible. In this situation the millet yield forecasts derived from the AVHRR data were exploited as a supplementary data set that could be compared and used to adjust DA's own data and to fill out gaps in the traditional statistics. Rather than serving as a timely, 100% spatial and independent input to agricultural statistics for yield forecasting, the model was used as a support to an existing limited yield survey.

Future perspectives

At least two issues have to be dealt with if NDVI-yield forecast models are to be fully implemented in Senegal or elsewhere in the Sahel: 1) more data covering a number of years must be available to test the model and 2) funding and allocation of resources to the official agricultural statistic institution must be assured to facilitate and complete the ordinary statistical yield program. An obvious solution would be the implementation of an Area Sampling Frame (ASF) to replace the demographic frame used in most Sahelian countries. The principles of the ASF are to map and stratify the agricultural domain and subsequently divide the strata into sampling units. This permits a random selection of a number of sampling units from where the crop statistics will be collected. Yield determined from these sampling units with a size of 30 to 50 ha, is perfectly suited to be used to calibrate the NDVI-yield forecast model. However, the implementation of the ASF is costly in terms of resources and time, see Carfagna et al. (1992) for more information on the ASF.

Beyond the use of NDVI-crop yield models for forecasting purposes, the potential for extracting useful information from a multi annual database is most promising. For natural resource management and implementation of the Rio conventions on desertification; historical yield maps at local or national levels could be created and used in

decision making: constant or increasing yields might indicate a potential expansion of the production, whereas areas with consistently decreasing yields might become subjects to further research and allocation of extension services. Seen in a wider perspective, the yield map database could constitute a supplementary layer in a national environmental and natural resource database from where the agro-ecological framework could conveniently be characterized as described by Oram (1988). The idea of Oram is to use social and physical parameters to identify areas of intervention for research, extension service and development projects, rather than the existing administrative boundaries or other arbitrary entities.

Conclusion

It is possible to use NDVI data from the AVHRR to forecast millet grain yield for national statistics or natural resource management purposes in the Sahel. To fully exploit this potential a high level of consistency, understood as no significant inter annual variation in regression models, is required. This can be achieved by: applying environmental information to the model. The level of the explained yield variance was as high as 88%.

The comparative advantages of using simple NDVI - yield regression models are numerous: 1) the accuracy can be compared with what has been achieved from more complex agro-meteorological models; 2) early forecasts can be made; 3) the data integrity is high, compared to when a number of institutions are collecting the same information; 4) spatial databases can be built for long term monitoring and 5) the cost-benefit ratio is low, the data can be made available and processed at limited costs and the approach is easy to employ.

It was seen from the implementation in Senegal that data from the NDVI - yield models could be used for the benefit of the official statistics, whereas more qualitative information, such as early warnings or general projections, were not requested. To support national statistics and fully exploit the developed NDVI method, it is crucial that any implementation will be associated with the development of the existing agricultural statistics structure.

Acknowledgement

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