The spatio-temporal relationship between rainfall and vegetation development in Burkina Faso

Morten Lind & Rasmus Fensholt

Abstract

In this paper remote sensing data and micro climatological data are combined. We examine the coupling between precipitation and vegetation development in the Sudano-Sahelian Zone through the combined use of precipitation point measurements and the vegetation index NDVI derived from the NOAA AVHRR Pathfinder Land data product (8x8 km's resolution). This examination consists of both a temporal and a spatial analysis. To gain spatial continuity in the precipitation/NDVI relationship a method for scaling precipitation from a local level (precipitation stations) to a national level is applied. This is done by use of the geostatistical parameter semivariance and the kriging interpolation method.

Furthermore, an estimation of the photosynthetically active radiation absorbed by vegetation (APAR) is carried out for 1992. This includes the transformation of NDVI into the fraction of PAR absorbed by vegetation (f_{APAR}) through a linear relationship derived from satellite image data.

The results show a strong relationship between rainfall and vegetation development, temporally as well as spatially. A comparison of the spatial relationship for different years indicates a multi-annual rainfall influence on vegetational development for the single year in question.

Keywords

Sudano-Sahelian zone, rainfall, vegetation development, NDVI, APAR estimation, semivariance, remote sensing.

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The Sudano-Sahelian zone is a marginal area in respect to a stable presence of vegetation in general and to cultivation in particular. This is related to the variations in rainfall from one year to the next. The large gradient in rainfall observed in the north-south direction causes a corresponding gradient in the density of vegetation, and precipitation is found to be the limiting parameter for growth in large parts of the area (Hielkema et al., 1986; Hendricksen & Durkin, 1986; Malo & Nicholson, 1990). Traditionally, analyses of bioclimatological relationships have been limited to point measurements of the parameters under review. Satellite remote sensing offers data which represent a spatial continuity and a temporal repetition that usually exceed what is possible to cover from ground measurements alone. The Advanced Very High Resolution Radiometer (AVHRR) carried on the NOAA series of polar-orbiting satellites produces images with a temporal frequency well suited for analyses of changes in terrestrial surface conditions with respect to biospheric activity. Deriving the Normalized Difference Vegetation Index (NDVI) from the combination of channel one (the red reflectance spectrum) and channel two (the near infrared reflectance spectrum) makes it possible to monitor the vegetational development.

During the last couple of decades the overall aim has been to develop satellite-based methods to monitor plant production. In a number of these studies (Tucker et al., 1983; Tucker et al., 1985; Rasmussen, 1996) the direct linkage between the integrated vegetation index NDVI and yield/NPP has been analysed. This approach, however, is based on the assumption that insolation and conversion efficiency from light to dry matter are constant in time and space, which is not always the case. The ongoing research has therefore sought to establish more physically based relationships between vegetational development and NDVI. Thus, emphasis has been put on the light absorption of plant canopies through the linkage of NDVI with the fraction of photosynthetically active radiation absorbed by vegetation, f_{APAR} (Goward & Huemmrich, 1992; Bégué, 1993; Hanan et al., 1995). However, the applicability of modelling plant production using this approach depends on the possibilities of taking into account variations in the physical environment regarding temperature, stresses from lack of water and nutrients, and proper modelling of respiration for maintenance and growth.

In other plant production studies, the linkage between water status parameters and growth has been analysed, i.e. precipitation (Malo & Nicholson, 1990, Eklundh, 1996), soil moisture (Hendricksen & Durkin, 1986) and transpiration (Boegh, 1993; Friborg, Boegh & Soegaard, 1997).

The objective of this study is to examine the strength of the relationship between precipitation and NDVI, temporally as well as spatially. One purpose is to examine the relationship within a single year, but a further purpose is to analyse the consistency of the relationship for more years. This is done through a three-year comparison of the spatial relationship between seasonal rainfall and seasonally integrated NDVI. NDVI is, furthermore, converted into the Absorbed Photosynthetically Active Radiation, APAR. This conversion is accomplished using a linear relationship between NDVI and f_{APAR} and a subsequent scaling of the estimated f_{APAR} value by incoming PAR. Precipitation is correlated with both NDVI and APAR to determine whether the conversion from NDVI to APAR increases the explained variance.

Data

The NOAA AVHRR record

This study is based upon the NASA NOAA AVHRR Pathfinder Land data product (PAL) which is a product consisting of a full earth coverage on a daily basis with a resolution of 8x8 km. With support from the Remote Sensing Laboratory at Lund University, PAL data for the Sudano-Sahelian zone was extracted with the following scene frame boundaries: 20° W, 42° E , 10° N and 20° N. Three years of image data, i.e. 1989, 1990 and 1992 were extracted and the analysis places emphasis on the year 1992. The PAL data is corrected for Rayleigh Scattering and ozone absorption, but no correction was originally made for the influence of atmospheric water vapour and aerosols.

Precipitation measurements

In Burkina Faso rainfall is measured at 154 locations and daily rainfall data are made available from the Institute of Meteorology in Ouagadougou. However, due to missing readings, the quality of these data is not sufficiently high all over the country, so from the original 154 stations, the 138 stations shown in Figure 1 were selected.

The average distance between stations is approximately 45 km, and each station represents an area of approximately 2000 km^2, which is a considerably better representation than the overall average for West Africa, where each station covers approximately 5000 km^2 (Flitcroft et al., 1989).

Methods and techniques

Ground truth measurements of NDVI and f_{APAR}

The ground truth measurements were carried out near the village of Petakolé in the northern part of Burkina Faso (Figure 1). Measurements of NDVI and f_{APAR} were conducted at a single sorghum field and at various millet fields and savanna/bushland areas at varying phenological stages. Selecting different sites ensured a large range in the NDVI/f_{APAR} values for the measurement period of August-October. The instrumentation consisted of two quantum sensors (LI-COR Inc., Lincoln USA), which measured PAR, and two pyranometers, LI-200 (LI-COR), modified with a filter cutting at 715 nm, which measured the near

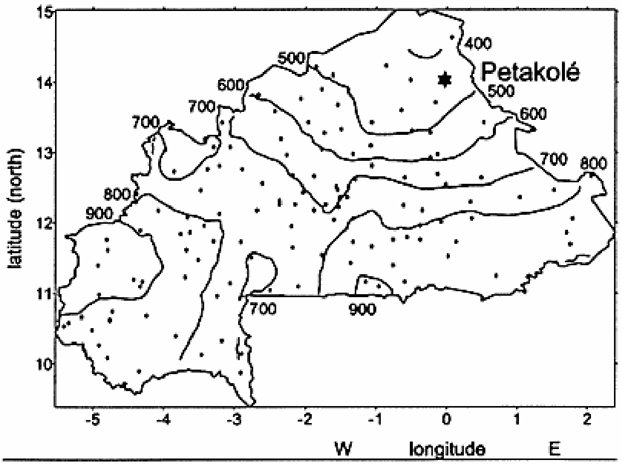

Figure 1: Spatial distribution of the 138 rainfall stations in Burkina Faso used in the analysis. The ground truth location, Petakolé, is labelled with an asterisk. An isohyet map of seasonal precipitation (mm) for 1992 is shown as well.

infrared part of radiation (NIR). The sensors were positioned for the purpose of measuring both incoming and canopy-reflected PAR/NIR.

The f_{APAR} is calculated from the difference in energy entering the canopy and energy leaving the canopy (Bégué et al., 1991) divided by incoming PAR:

$$f_{APAR} = \frac{(PAR_i - PAR_{cr})_{(a)} - (PAR_{tr}\,(1 - \alpha_s)\cdot PAR_i)_{(b)}}{PAR_i} \qquad (1)$$

where PAR_i is incoming PAR; PAR_{cr} is reflected PAR from the canopy; α_s is the soil albedo; (a) and (b) refer to net PAR above and below the canopy respectively; and the transmitted part of PAR through the canopy can be described by a Poisson probability function:

$$PAR_{tr} = e^{\frac{(-G)\cdot LAI}{\sin\beta}} \qquad (2)$$

where β is solar elevation and G is the mean direction cosine between the solar zenith angle and the leaf normals. G takes the value of 0.5 for all solar elevation angles, assuming that the leaf inclination angles are distributed uniformly over the surface of a sphere (Baldocchi, 1993). The leaf angle distribution function is considered to be spherical for millet (Bégué, 1994), thus meeting this assumption. The soil albedo was derived over bare soil using the two PAR quantum sensors. Leaf area indices were measured approximately every third day using an LAI-2000 Plant Canopy Analyser (LI-COR Inc., Lincoln USA). Modelling the transmitted PAR was preferred because of the difficulties associated with measuring below the plants in partially vegetated areas. In order to measure average radiation conditions below a partial canopy it would be necessary to include several sensors that were not available at the time of the analysis.

Satellite image processing

Some of the image processing steps were carried out using the image processing system "Winchips" developed at the Institute of Geography, University of Copenhagen. Other processing steps were accomplished with the aid of the programming language C++ and the Geographical Information System, ARC/INFO. An application was made converting digital numbers to geophysical values using the gains and offset proposed in the PAL documentation, and the NDVI images were combined with the cloud flagging and quality control flagging images. Only pixels classified as "clear" in the cloud flagging condition and pixels classified as "normal" in the quality control flagging condition have been used in the analysis.

In addition to the influence from Rayleigh Scattering and ozone absorption, which have already been corrected for, the Pathfinder NDVI product is influenced radiometrically by other factors not related to the green vegetation signal. The following factors are important: (1) atmospheric influence due to water vapour and (2) contamination from soil background and withered material in the canopy. A commonly used procedure for reduction of the atmospheric influence is the Maximum Value Compositing method, MVC (Holben, 1986; Cihlar et al., 1994). An MVC application was made to reduce atmospheric water vapour- and aerosol effects. A period of 13 days was found to be the best compromise between correction for atmospheric influence on the one hand and the preservation of an adequate temporal resolution for monitoring the vegetational development on the other. Thus, extending the MVC period from nine days (the NOAA AVHRR repetition cycle) to 13 days resulted in a significant reduction of noise and almost a full elimination of pixels classified as clouds, even for the rainy season period in the southern part of Burkina Faso.

However, the MVC procedure predominantly selects pixels in the forward scatter direction (Figure 2), because

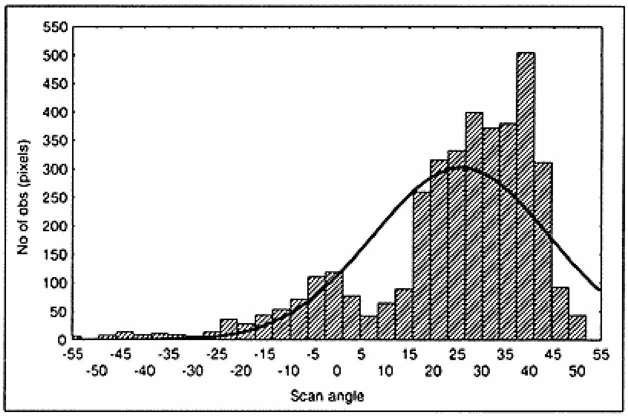

Figure 2: Histogram of scan angles associated with the selected NDVI values for a 13-day MVC period in June 1992 after applying the Single-Criteria Compositing Algorithm. The line represents the normal function of the distribution. Total number of pixels is 3834.

pixels in this direction obtain "artificially" high NDVI values. This circumstance is caused by the magnified anisotropic reflectance response in the red spectrum compared with the response in the near infrared spectrum (Huete et al., 1992; Cihlar et al., 1994). To overcome this problem, a Two-Criteria Compositing Algorithm was produced in C++ and applied to the data set. This algorithm takes into account both the NDVI values and the associated scan angles for every pixel in a series of images. For a given pixel in a given period the algorithm considers the 15% highest NDVI values and from among these, the NDVI pixel value associated with the smallest scan angle is chosen. This technique is also used by Cihlar et al. (1994), who found the threshold of 15% by trial and error. The effect of this procedure is illustrated in Figure 3. A significant alteration in the distribution of scan angles is found after applying the Two-Criteria Compositing Algorithm. Thus, the algorithm strongly suppresses the forward scatter scan angle effect on NDVI, which then approaches the nadir signal.

After applying the Two-Criteria Compositing Algorithm, some atmospherically induced variations were still persisting in the form of abrupt unrealistic declines in the NDVI development. Besides the compositing procedure we therefore produced an NDVI time series noise reduction algorithm similar to the Best Index Slope Extraction method (BISE) described by Viovy et al. (1992).

The background reflectance from soil can be considerable in partially vegetated areas due to the differences in absorption, reflectance and transmittance of PAR and NIR between soil and canopy (Huete, 1988). Correction for soil background was carried out by subtracting a part of NDVI proportional to the extent of the soil background. Thus, the part to be subtracted has been scaled between the limits of no-vegetation ground cover and full-vegetation ground cover, corresponding to a range in NDVI values of 0.022-0.55. The basic value of the soil background NDVI was derived from a dry season average in northern Burkina Faso (NDVI=0.022). The NDVI value of 0.55 corresponding to a vegetation fraction of one is an average consideration of vegetation-cover conditions based on work by Carlson & Gillies (1993).

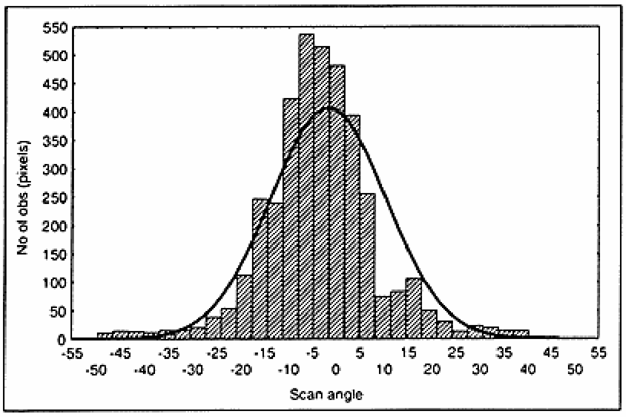

Figure 3: Histogram of scan angles associated with the selected NDVI values after applying the Two-Criteria Compositing Algorithm. For the same 13-day period as shown in Figure 2. The line represents the normal function of the distribution. Total number of pixels is 3834.

Correction for withered material in the canopy has been based on the assumption that senescence develops from the bottom of the canopy and upwards and is subsequently to be regarded as an additive part to the overall NDVI value (Huete & Jackson, 1987; Van Leeuwen & Huete, 1996). This assumption is valid for millet and sorghum, and thus for the major part of cultivated areas in Burkina Faso, whereas senescence for non-agricultural vegetation is more complex. However, a simple correction is made by subtracting a part of NDVI between the time of maximum NDVI observed and the end of the growing season. In this period senescence is considered to increase exponentially with time and by the end of the growing season all plant material is considered withered. The end of the growing season is determined by combining visual interpretation of the NDVI development and the method described by Hendricksen & Durkin (1986).

The temporal relationship between precipitation and NDVI

In the temporal correlation procedure, the NDVI development in the period from the start of the growing season until maximum NDVI is reached is examined in relation to the temporal distribution of rainfall for every station. The series of MVC NDVI values (13-day-periods) is correlated with a time displaced series of cumulated 13-day-precipitation (Figure 4, see next page). By shifting the two series one 13-day-period at a time, several correlations are carried out and the highest coefficient resulting from these correlations is assumed to indicate the lag between time of rainfall and response in vegetational growth.

Interpolation of precipitation point measurements

Relating rainfall to NDVI in a spatial analysis means relating a discrete set of data to a continuous variable. This

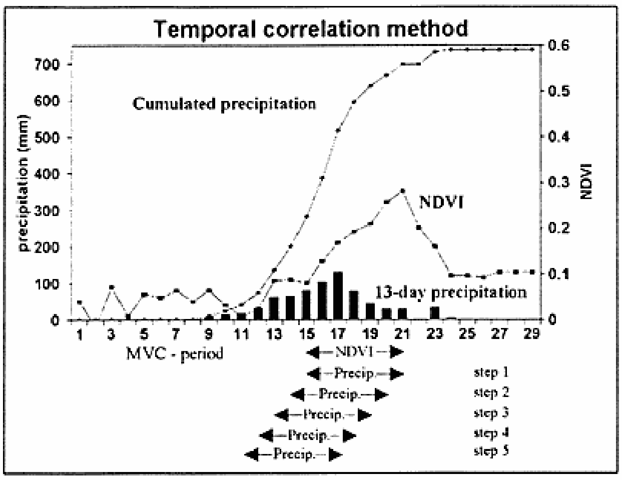

Figure 4: Illustration of the temporal correlation procedure.

will display a statistical discrepancy and a divergence in the spatial representation. As a consequence, rainfall point measurements are transformed into rainfall maps by use of interpolation. The number of rainfall stations required for carrying out interpolation with reasonable accuracy in the Sudano-Sahelian zone depends on the period considered. One has to consider the strong variation in the local precipitation pattern on a short term, i.e. days or weeks (Flitcroft et al., 1989) compared with the continuity present in the precipitation gradient on a longer term, i.e. seasonally. A method for analysing the spatio-temporal aspect of the rainfall distribution is the semivariance approach. Semivariance expresses the change of a regionalized variable along a certain direction and, when presented as a variogram (Figure 5 and 6), this parameter provides a good indication of the spatial continuity present in a variable. The distribution of precipitation behaves like a regionalized variable having continuity from point to point, though it cannot be described by any tractable deterministic function. The presence of continuity in the semivariogram is decisive for the interpolation result obtained from the kriging procedure. The kriging method used here ("universal kriging" in ARC/INFO) allows for the existence of a *structural component (drift)* in the data. With regard to interpolation this makes it possible to account for the trend present in the precipitation gradient over a long term, i.e. seasonally. Such a trend evidently exists for seasonal rainfall when comparing a semivariogram for the direction perpendicular to the gradient (Figure 5) with a semivariogram for the direction parallel to the gradient (Figure 6). The gradient present in the seasonal Sudano-Sahelian rainfall distribution results in an anisotropic distribution when modelling the semivariograms for all directions (Figure 7, see next page). Such a model is an example of the interpolation basis for kriging. The semivariance analyses of seasonal rainfall based on the 138 stations supports the basic requirements for carrying out interpolation for the three years in question.

The spatial relationship between precipitation and NDVI
When interpolation between precipitation point measure-

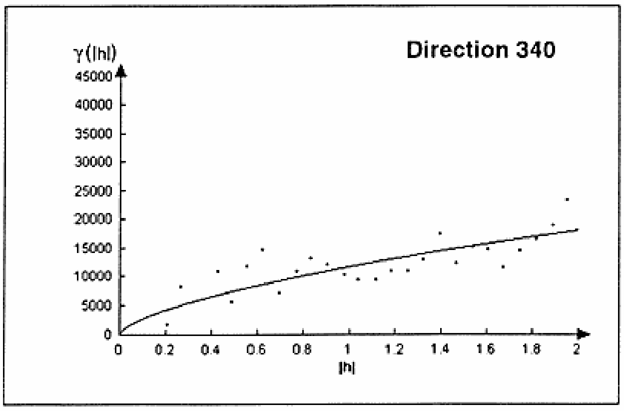

Figure 5: Power model ($\gamma(h) = 11904*h^{0.62}$) fitted to the semivariance points for seasonal rainfall, 1992. The direction is 340 ° from east, i.e. ESE-WNW, perpendicular to the precipitation gradient. The separation vector (h) on the x-axis is the lag distance in decimal degrees.

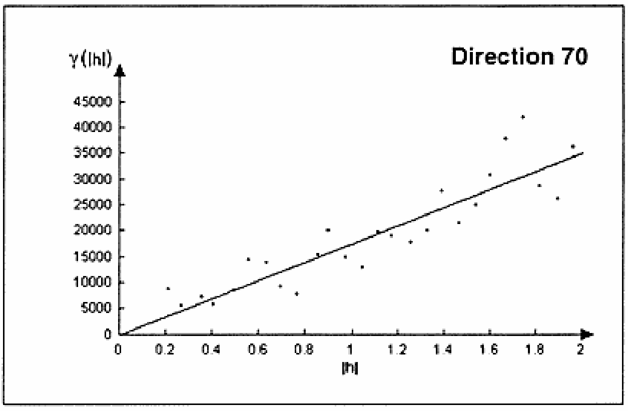

Figure 6: Power model ($\gamma(h) = 17635*h^{1}$) fitted to the semivariance points for seasonal rainfall, 1992. The direction is 70 °from east, i.e. NNE-SSW, parallel to the precipitation gradient. The separation vector (h) on the x-axis is the lag distance in decimal degrees.

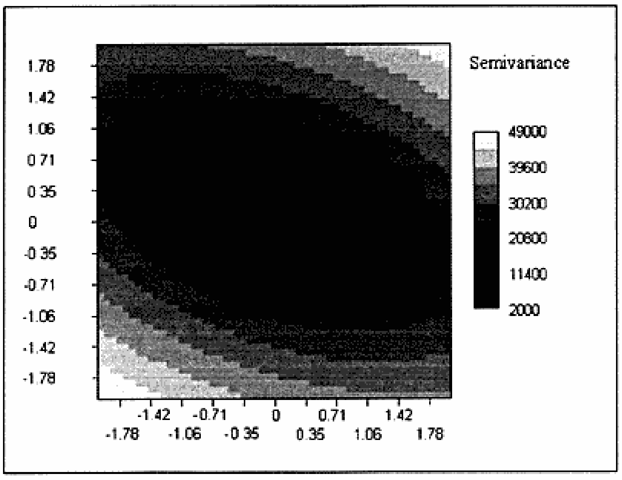

Figure 7: 2D plot of the power models which are illustrated in Figure 5 and 6 for the seasonal rainfall distribution in 1992. The axes are in decimal degrees.

ments using the kriging method has been completed, the resulting rainfall maps for the three years are in the form of raster images with a grid size corresponding to the area represented by a PAL pixel, i.e. approximately 64 km^2. In the image processing system, Winchips, all cell values are extracted with matching coordinates for use in the correlation procedure. Subsequently, a correlation procedure between seasonally integrated NDVI and seasonally interpolated precipitation is carried out for the three years under review. A correlation between seasonal precipitation and seasonally integrated APAR is additionally carried out for 1992.

Estimation of f_{APAR} from PAL data

The asymptotic limits of f_{APAR}, i.e. 0 for bare soil and 0.95 for full canopy cover (Ruimy et al., 1994; Myneni & Williams, 1994) are scaled linearly to minimum and maximum NDVI observed in the PAL product - a widely accepted method (Sellers et al., 1996). This means solving two equations with two unknowns:

$$\begin{aligned} f_{APAR}(\min) &= \alpha \cdot NDVI(\min) + \beta \\ f_{APAR}(\max) &= \alpha \cdot NDVI(\max) + \beta \end{aligned} \qquad (3)$$

from which we obtain the values of α and β.

Estimation of APAR

The satellite derived relationship is obtained by solving equation 3 mentioned above and it is subsequently used for the conversion of NDVI to f_{APAR}. The f_{APAR} values are scaled to APAR using daily sunshine records recorded by heliographs at nine synoptic stations in Burkina Faso. Insolation at station level has been calculated from solar radiance geometry according to latitudinal position of stations and by use of an atmospheric transmissivity of 0.7 and a solar constant of 1356 W m^{-2}. Seasonal insolation values have been interpolated between stations for the derivation of incoming PAR at pixel level. Although the small number of synoptic stations makes it impossible to validate the interpolation by means of semivariance analyses, the spatial distribution of insolation indicates a homogeneous first order trend surface in the north-south direction. In the calculation of APAR a value of 0.48 is used for the PAR fraction of insolation (Frouin & Pinker, 1994). This fraction is close to the average fraction of 0.466 found for Niamey by Bégué et al. (1991).

Results and discussion

NDVI/f_{APAR} relationship

Minimum and maximum NDVI values in the PAL product were found to be 0.022 and 0.610 respectively. The value of 0.022 for bare soil is derived as an average value for the dry season for the northern part of Burkina Faso. The value of 0.610 for full canopy cover is derived as a maximum value for the growing season for highland tropical forest at the border between Sudan and Ethiopia. Scaling the values between these limits results in the following linear relationship:

$$f_{APAR} = 1.62 NDVI_{PAL} - 0.04 \qquad (4)$$

This concurs with a similar relationship ($f_{APAR} = 1.67 NDVI_{PAL} - 0.08$) derived by Prince & Goward (1995) for Pathfinder data of 1987.

The relationship between NDVI and f_{APAR} has been interpreted as linear or approximately linear for green vegetation (Goward & Huemmrich, 1992; Bégué, 1993). However, certain factors have an influence on the linearity of this relationship and these can be divided into (1) *external factors*, which are: solar zenith angle and satellite scan angle and (2) *canopy-related factors*, which are: LAI, soil-canopy reflectance interactions, withered material in the canopy, leaf optical properties and to a minor degree Leaf Angle Distribution (LAD) and canopy heterogeneity. The influences of soil background and withered material are accounted for in the correction procedure. The effect of variations in leaf optical properties due to varying pigment concentrations, pubescence and internal structural changes is mainly related to large values of NDVI (Goward & Huemmrich, 1992). The influence of this factor is therefore of minor importance in the Sudano-Sahelian region.

The strongest influence originates from variations in the solar zenith angle and the satellite scan angle in relation to the reflecting properties of the canopy. Solar zenith angles below 60° have a minor effect on the relationship and larger angles are not likely to occur in the PAL data product for the Sudano-Sahelian region, although there is considerable drift in the overpass time for NOAA-7, NOAA-9 and NOAA-11. Satellite scan angles above 40° have a pronounced effect in partial canopies, especially in the forward scatter direction (towards the sun), which results in a magnified NDVI due to a larger portion of the vegetation being shadowed in this direction. This is the result of the anisotropic reflectance response in the red part of the spectrum (RED) relative to the more isotropic response in the near infrared spectrum (NIR) when considering the full span in scan angles, i.e. -56° to +56° for NOAA AVHRR. Thus, reflectance in RED is significantly reduced in the forward scatter direction due to shadows, while reflectance in NIR is maintained in this direction due to a high transmittance at leaf level (Cihlar et al., 1994). The scan angle effect on the relationship is accounted for by use of the Two-Criteria-Compositing Algorithm.

An important aspect regarding the relationship between NDVI and f_{APAR} is the apparent insensitivity to pixel heterogeneity, which is expressed as variations in LAD and partial/non-partial canopy structure. This insensitivity makes the relationship applicable on larger scales (Goward & Huemmrich, 1992; Bégué, 1993; Myneni and Williams, 1994). Even when considering the extremes of leaf area distributions, i.e. planophile and erectophile distributions, the influence on the relationship between f_{APAR} and NDVI is low (Goward & Huemmrich, 1992). When considering partial versus non-partial canopies an insensitivity is found as well (Myneni & Williams, 1994). The insensitivity to pixel heterogeneity is pronounced when solar zenith angles are within the 30° to 60° range (Bégué, 1993), and this prerequisite is fulfilled for nearly every scene in the PAL data product. It is noticeable that the NOAA crossing time about 2.00 - 3.00 p.m. for this region is optimal for monitoring vegetation in respect to the influence from both very low and very high solar zenith angles.

The ground truth derived f_{APAR}/NDVI relationship is predominantly based on measurements conducted on millet fields (see Figure 8) and results in a linear relationship showing a high coefficient of determination ($r^2 = 0.96$):

$$f_{APAR} = 1.42 NDVI_{GROUND} - 0.39 \tag{5}$$

This concurs well with regressions found by others (Asrar et al., 1984; Bégué, 1993). Regression slopes found in literature usually lie within 1.2 and 1.4 and regression intercepts lie within -0.31 and -0.06. The difference between relationships obtained at satellite level and ground truth level can be attributed to the atmospheric aerosol effect decreasing satellite NDVI by as much as 0.25-0.30 for high values of NDVI (Goward et al., 1991; Prince & Goward, 1995). Thus, the missing correction for atmospheric water vapour combined with an apparent underestimation of corrections for Rayleigh scattering and ozone absorption in the PAL product (NASA Goddard Space Flight Center) can explain the difference between the satellite relation and the ground relation. The magnitude of the underestimated correction, as performed by the NASA

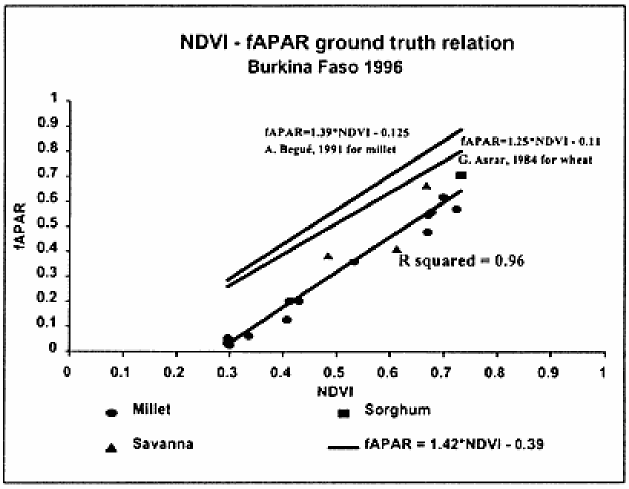

Figure 8: *Relationship between* $NDVI_{GROUND}$ *and* f_{APAR} *derived from measurements on millet fields, a sorghum field and in savanna areas. Based on fieldwork for the growing season of 1996 near the village Petakolé. Similar relationships obtained by others for millet and wheat are shown.*

Goddard Space Flight Center, is from zero NDVI at low absolute NDVI (NDVI ≈ -0.1) to approximately 0.08 NDVI at high absolute NDVI (NDVI ≈ 0.5).

Temporal correlations

From the temporal correlations the lag between precipitation and NDVI, as illustrated in Figure 4, is derived for every station and displayed as an isoline map in Figure 9. In contrast to the continuity found in the spatial distribution of precipitation on a seasonal basis, the lag distribution showed a high degree of variance (large "nugget effect") and therefore did not reveal a spatial continuity which supports interpolation.

A distinction is made between herbaceous vegetation and woody vegetation according to the dissimilarities in life cycle and utilization of rainfall. In relation to herbaceous vegetation the lag originates from several factors concerning the movement of water in the soil profile, the species composition and the phenological stage of the plants. The onset of germination is triggered by the first seasonal rainfall events but a detectable increase in NDVI is delayed due to (1) an initial wetting/filling-up of the dried-up soil and (2) a germination phase restricted to the top soil layer before the shoots penetrate the surface. At the end of the growing season, the lag between last rainfall and last detectable growth is partly the result of the soil-water magazine being adequately filled to supply the plants for some time after receiving the last precipitation. Moreover, at this time the roots of most plants are well developed and their abilities to extract water from deep soil layers are at a maximum.

When considering woody vegetation, another important factor regarding the lag is rooting depth. Due to the already developed roots, woody vegetation is not dependant on the first rain to the same extent as herbaceous vegetation. From Figure 9 it is evident that lag lengths decrease southwards. The areas which display low lags are to a marked extent identical with the presence of woody vegetation (Fontès et al., 1994).

The spatial distribution of the coefficients of determination obtained through the temporal correlation analysis between cumulated precipitation and NDVI is shown in Figure 10. The highest correlations are found for large areas in the northern part enclosing some smaller areas with lower coefficients of determination. These local deviations in coefficients are most likely a consequence of terrain-induced differences in water availability. The presence of "run-in" at the location of a depression (*bas fond*), for example, results in an "artificial" contribution of water to vegetational growth. The southern part is characterized by markedly low correlations. Again, this indicates that woody vegetation does not respond to rainfall in the same straightforward manner as herbaceous vegetation does.

Reasons for this are: (1) the presence of an extended root system for woody vegetation, (2) woody vegetation has a robustness towards environmental stress caused by long-

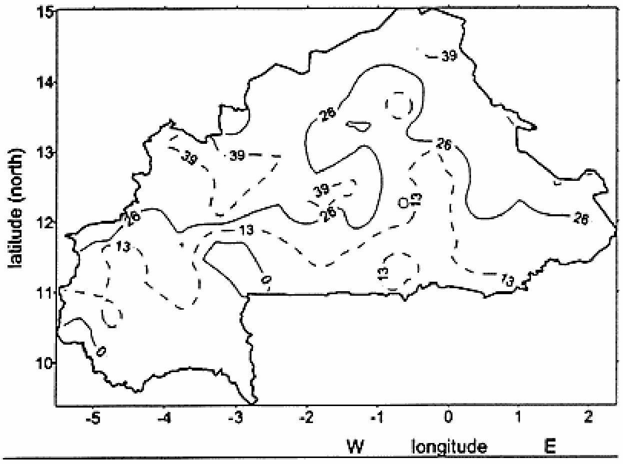

Figure 9: Isoline map for the lag length between cumulated precipitation and NDVI, Burkina Faso, 1992. Values are given in days.

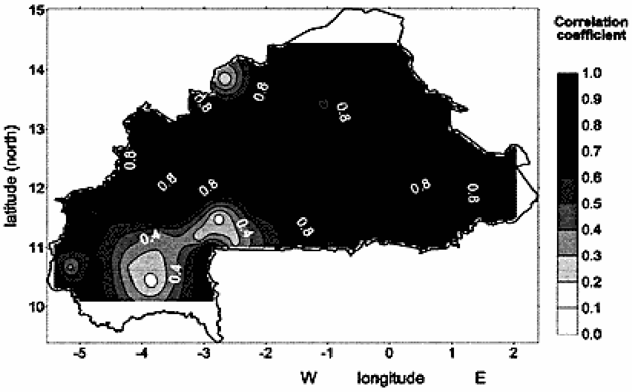

Figure 10: Distribution of correlation coefficients obtained from the temporal correlations between cumulated precipitation and NDVI. Interpolation has been accomplished with kriging. Burkina Faso 1992.

term adaptation, (3) some trees are out of phase with the rainy season period, e.g. trees of *Faidherbia albida* which are only green in the dry season period, and (4) the amount of precipitation in the southern part has reached a level where other factors like nutrient availability and PAR intensity, rather than water availability, are limiting factors for growth. Another factor causing apparent independency in the southern part may be a saturation in reflectance for high vegetation densities. This causes NDVI values to stabilize despite increasing vegetation density (Goel, 1989; Carlson et al., 1990).

An indication of the strength present in the relationship between precipitation and NDVI is given in Figure 11. The level of significance associated with the correlations display a pattern of considerably higher levels of significance (i.e. lower values in Figure 11) in the central part of Burkina Faso. This band of high significance mainly corresponds to areas receiving precipitation amounts of 650 to 850 mm seasonally (see Figure 1). Again the southern part is characterized by a weak relationship showing low significance in the correlations. Although the northern part displays high coefficients of determination, these areas are characterized by relatively low significance levels. This is a consequence of the short growing season, which leaves only a few data for correlation.

In similar studies for other water-limited environments, water status parameters like soil moisture and precipitation have been found to correlate well with time displaced (lagged) NDVI. Hendricksen & Durkin (1986) found a lag of five weeks between a soil moisture index and NDVI for Ethiopia; Groten (1993) found a lag of one to four decades between precipitation and NDVI for the growing season start in Burkina Faso and Eklundh (1996) found a lag of one to seven decades between precipitation and NDVI for East Africa.

Spatial correlations

The precipitation/NDVI relationship

A regression between interpolated precipitation values and NDVI derived on a pixel basis for 1992 is shown in Figure 12. The coefficient of determination (0.70) is found for precipitation values below 900 mm/year and is associated with a high level of significance. The best mathematical description for the relationship between seasonal precipitation and integrated NDVI depends on the range in precipitation values for the year in question. Below 900 mm/year the relationship is best described by a linear function, whereas a logarithmic function is found to be a better description when considering the full range of precipitation values, e.g. for the year of 1990 (Figure 13, see next page).

The asymptotic behaviour of the precipitation/NDVI curve above precipitation values of 900 mm/year is associated with the decreasing influence of precipitation as the controlling factor for growth and with the saturation of

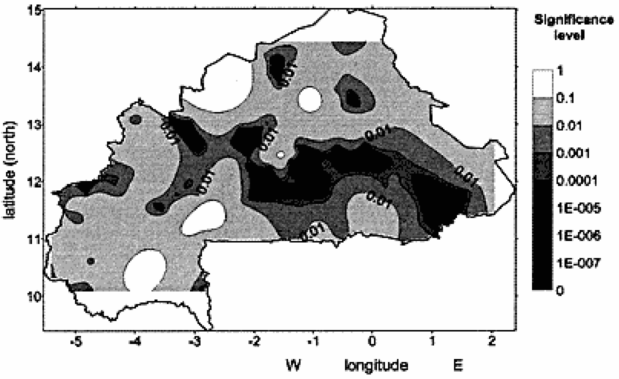

Figure 11: Distribution of the significance levels corresponding to the correlations shown in Figure 10. Burkina Faso 1992.

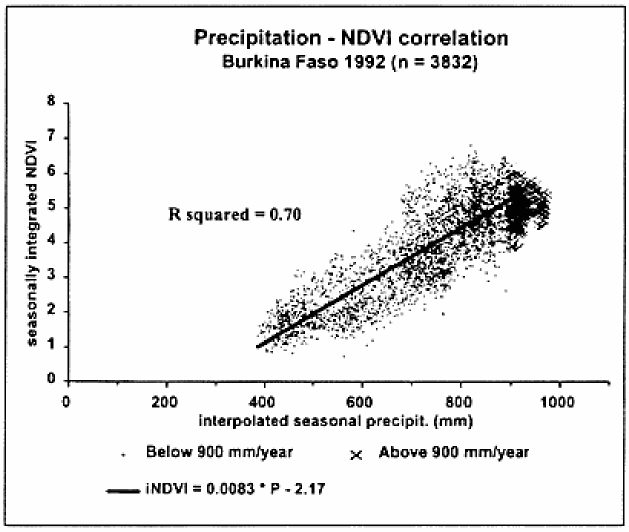

Figure 12: Regression between seasonal precipitation and seasonally integrated NDVI, Burkina Faso 1992.

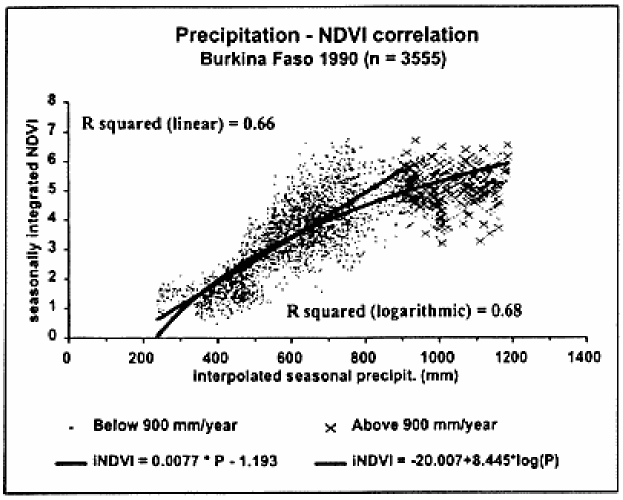

Figure 13: Regression between seasonal precipitation and seasonally integrated NDVI. A linear and a logarithmic relationship are shown, Burkina Faso 1990.

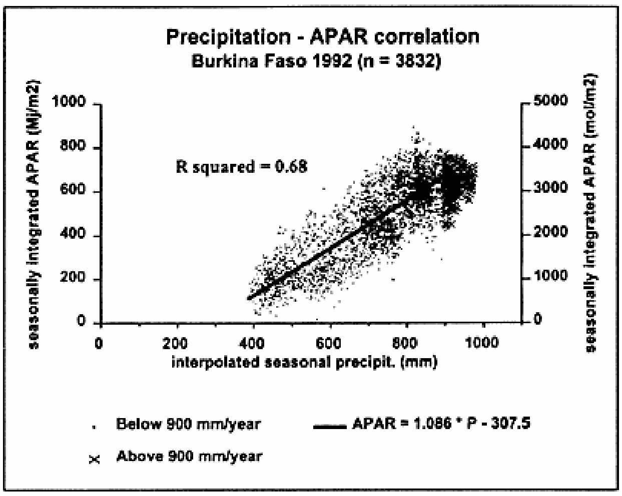

Figure 14: Regression between seasonal precipitation and estimated seasonal APAR, Burkina Faso, 1992.

reflectance for high vegetation densities. This pattern is not evident in the 1992 data, but it is found for years when the southern part of Burkina Faso receives higher seasonal precipitation values, i.e. 1989 and 1990.

The scatter of values observed in Figure 12 and 13 can be expressed as differences in rain use efficiency (RUE). Several factors influence RUE and these can be divided into groups according to their type of influence: (1) Climatological factors controlling the loss of water through bare soil evaporation and transpiration, i.e. net radiation, temperature, humidity, wind speed and advective conditions. (2) Soil related factors influencing the potential for growth, i.e. soil nutrients, soil material, soil structure, crusting-induced and terrain-induced differences in water availability (e.g. run-in/run-off). (3) Factors directly connected to the physiological development of the vegetation, i.e. species composition, resource competition and the water use efficiency (WUE) of the individual species. (4) Factors related to the anthropogenic influence on vegetational development, i.e. soil preparation, time of sowing, time of harvesting, livestock grazing etc. The influence from the factors mentioned in (1) and (2) suggests the application of a comprehensive soil water model. Such a model has to account for variations in retention characteristics, in evapotranspiration and in runoff, in order to model the plant available soil water. Attempts to include such a model in the current analysis were made (Lind & Fensholt, 1997), but no improvement was found in explaining the variance in the precipitation/NDVI relationship. Apparently this is a consequence of an inadequate quality of data concerning soil related factors.

In other studies for the Sahelian region, integrated NDVI for a growing season has similarly been shown to correlate with annual precipitation (Malo & Nicholson, 1990; Eklundh, 1996). Coefficients of determination for these studies are usually within the interval of 0.65 - 0.92. It is, however, difficult to compare these coefficients because of differences in correlation method and data preparation. An important similarity in the results, however, is that the precipitation threshold for the transition between linearity and log-linearity is found to be within the interval of 900-1000 mm/year.

The precipitation/APAR relationship for 1992

In Figure 14, a regression between interpolated precipitation values and APAR is shown. In this regression f_{APAR} is estimated from equation 4 and multiplied with interpolated values of PAR insolation based on the daily sunshine records for 1992. The coefficient of determination (r^2 = 0.68) is obtained for correlation with precipitation values below 900 mm/year and is marginally lower than the coefficient obtained from the precipitation/NDVI relationship (r^2 = 0.70). The fact that the portion of explained variance does not increase if APAR replaces NDVI, could indicate that incoming PAR is not the limiting factor for vegetational growth in the northern and central parts of

Burkina Faso. This is partly a consequence of the overall high radiation load and partly a consequence of the usually sparse non-agricultural vegetation cover and the large distance in-between plants typical in agricultural areas. This implies that the PAR load, even at the bottom of the canopy, is usually at a level where saturated conditions are present.

The inter-annual precipitation/NDVI relationship

Regression lines for the three years are shown in Figure 15 and through T-tests these are found to have slopes which do not deviate significantly from one another.

Within those parts of the country that receive less than 900 mm/year, this slope constancy indicates that vegetation responds equally in magnitude to a given precipitation input in different years. The intercept of the 1992 regression is significantly lower than the 1989 and 1990 intercepts. This difference is not due to changing sensor platforms since image data from all three years are recorded by NOAA-11. The lower intercept for 1992 is a consequence of the northern and central parts of Burkina Faso receiving above average rainfall without a corresponding increase in produced phytomass. This situation could have one of two possible explanations: (1) An unfavourable intra-annual variation of rainfall in relation to optimal growth conditions (e.g. few events of high rainfall and/or an uneven distribution throughout the season). However, an analysis of the temporal distribution of precipitation in 1992 does not indicate the presence of such an inexpedient distribution. (2) An inter-annual influence from rainfall in preceding years influencing the growth conditions for the current year under review. When considering vegetation dynamics, factors like the initiation of buds in the previous growing season, seed production, the competition for resources and long-term adaption to the environment are all possible explanations for non-seasonal behaviour and delays in vegetation response to variations in rainfall. Thus, stress on vegetation caused by dry conditions can be quite persistent and influence the potential for growth for years ahead, as was the situation after the severe drought of 1984 (Goward & Prince, 1995). Rejecting explanation (1), it seems most likely that vegetational development in 1992 not only is a function of rainfall within the current year, but additionally is a function of rainfall from preceding years. The full revelation of this multi-annual influence requires the analysis of data for a longer period of years.

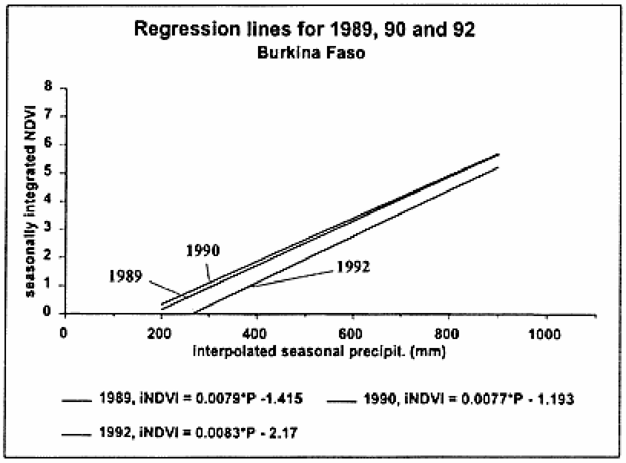

Figure 15: Regression lines for the seasonal precipitation/integrated NDVI relationship for three years.

Conclusions and perspectives

The present study has shown that NDVI derived from Pathfinder AVHRR data and rainfall point measurements are useful data when analyzing the complex relationship between rainfall and vegetation development.

In practice, the study has shown a method for quality enhancement of MVC NDVI by accounting for varying scan angles. This is considered an important improvement for future use of NDVI as an indicator of vegetation dynamics. A thorough analysis of rainfall semivariance has laid the foundation for interpolation, resulting in a unification of the spatial representation of both rainfall and NDVI as continuous variables.

The temporal correlations between precipitation and NDVI for 1992 show the strongest relationship within the range of precipitation values between 650 and 850 mm/year, indicating a zone of certain continuity in vegetation response to rainfall. From the temporal correlations at station level, we obtained the lag length which nowhere exceeds seven weeks. Furthermore, the lag length is found to decrease in areas with woody vegetation.

The spatial relationship between seasonal precipitation and respectively seasonally integrated NDVI and seasonal APAR for 1992 is best described by a linear function and expresses a coefficient of determination of respectively 0.70 and 0.68 with a high degree of significance. This leads to a possibility of modelling seasonal APAR from seasonal precipitation. However, one has to consider the

variations between years. Though the three-year comparison of regressions for the spatial relationship results in regression slopes which do not deviate significantly from one another, the intercepts differ significantly and this is thought to be linked with an inter-annual rainfall influence on vegetation development. In a modelling context this favours the application of a multi-annual weighting of the precipitation input to increase the portion of explained variance in the relationship between precipitation and growth-related parameters. In relation to slope constancy and intercept variations, the multi-annual rainfall influence on vegetation dynamics will be an important subject in future research. An inter-annual slope constancy will facilitate a prediction of growth response to rainfall, and predictions based on rainfall data will be of increasing interest as the ongoing research into monitoring rainfall from satellite data progresses.

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