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Journal of Arid Environments

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Evaluation of land performance in Senegal using multi-temporal NDVI and rainfall series

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Received 13 February 2004; received in revised form 17 February 2004; accepted 23 March 2004

Abstract

Time series of rainfall data and normalized difference vegetation index (NDVI) were used to evaluate land cover performance in Senegal, Africa, for the period 1982–1997, including analysis of woodland/forest, agriculture, savanna, and steppe land cover types. A strong relationship exists between annual rainfall and season-integrated NDVI for all of Senegal ($r = 0.74$ to 0.90). For agriculture, savanna, and steppe areas, high positive correlations portray 'normal' land cover performance in relation to the rainfall/NDVI association. Regions of low correlation might indicate areas impacted by human influence. However, in the woodland/forest area, a negative or low correlation (with high NDVI) may reflect 'normal' land cover performance, due in part to the saturation effect of the rainfall/NDVI association. The analysis identified three areas of poor performance, where degradation has occurred over many years. Use of the 'Standard Error of the Estimate' provided essential information for detecting spatial anomalies associated with land degradation.

Keywords: Land cover performance; NDVI; Rainfall; Senegal; Correlation analysis; Vegetation change; Productivity

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0140-1963/$ - see front matter
doi:10.1016/j.jaridenv.2004.03.019

1. Introduction

Land degradation, or the loss of productivity of the land, is considered one of the major environmental problems of our time. It relates to reduction of land resource potential by one or a combination of processes acting on the land, including water and wind erosion, sedimentation, loss of soil structure and fertility, salinization, and other processes that result in long-term reduction in vegetation diversity and net primary production (Ward et al., 1998). With the effects of increased population and environmental changes occurring at local to global scales, there exists a need to develop environmental monitoring tools to better: (a) detect land degradation and map its occurrence; (b) assess the trends of land degradation over time; (c) understand the causes of land degradation; and (d) evaluate whether the approaches and tools for detecting land degradation can be applied regionally. This paper examines approaches developed for Senegal and potentially useful across the Sahel region of Africa.

According to a major study on worldwide soil degradation (Oldeman et al., 1990), the degradation of cropland and pastures is most extensive in Africa. Within Africa, the Sahel region is one of the most vulnerable to land degradation (Olsson, 1985; Thomas and Middleton, 1994). The region has experienced periods of drought as well as a general decline in rainfall over the past 100 years (Nicholson, 2000; Gonzalez, 2001). The major droughts of the last century have been 1910–1914 (Aubréville, 1949), 1942–1949, 1968–1973, and 1982–1984 (Charney et al., 1975; Le Houérou, 1989; Tappan et al., 1992). Gonzalez (1997) undertook intensive ground-based studies in northwestern Senegal and quantitatively documented that tree density and biodiversity have declined in the study area since the 1950s, resulting in a southward shift of the Guinean, Sudanian, and Sahelian ecological zones. Furthermore, he found that strong relationships with latitude and longitude suggest the predominance of climatic factors over anthropogenic factors in the loss of trees. Other investigators, however, have attributed the decline in tree densities and species to human population pressures, particularly the use of traditional agricultural practices and crop expansion in conjunction with rising rural populations (Lake and Touré, 1984; Lericollais, 1987; Michel, 1988; Stancioff et al., 1986; Tappan et al., 2000).

The status and rate of change in land cover performance may be estimated through a monitoring approach with remotely sensed data. A wide variety of data are available for different types of time-series analyses, ranging from high- and medium-resolution aerial photographs and satellite images (e.g. Corona, Landsat, IKONOS) to low-resolution, high temporal frequency data from National Oceanic and Atmospheric Administration (NOAA) satellites. Using NOAA Advanced Very High Resolution Radiometer (AVHRR) data, researchers have successfully extended satellite data analysis to large-area vegetation monitoring (Kogan, 1990) and biomass productivity estimates (Townshend and Justice, 1986; Harrington and Wylie, 1989; Hunt, 1994). Since vegetation indices derived from the AVHRR sensor are directly related to plant vigor, density, and growth conditions, they may also be used to detect unfavorable environmental conditions, especially drought occurring in semiarid regions. Among the various AVHRR-derived vegetation indices, NDVI is accepted as a primary tool for monitoring seasonal vegetation changes (Holben, 1986), and it shows promise for assessing the impact of climate on longer-term changes in land cover and productivity.

1.1. Study objectives

In this study, the relationship between annual rainfall and growing-season integrated NDVI (iNDVI) (Reed et al., 1994) in Senegal was investigated through stratification into four major land cover regions. In addition, the rainfall-iNDVI relationship was evaluated as a measure for quantifying land cover performance. Reed et al. (1994) derived a series of "metrics" from the NDVI time series that characterized the growing season, including start of growing season, duration of greenness, end of season, and time-integrated NDVI. In this paper, we are only evaluating the time- (or season) integrated NDVI metric, as one measure of the land cover performance. iNDVI is a measure of the magnitude of greenness available through time and therefore quantitatively reflects the capacity of the land to support photosynthesis and primary production. Our assumption, that iNDVI is a good indicator of green vegetation productivity, is supported in the literature, especially in mesic and semiarid systems where strong relationships with net primary production across large regions were established (Paruelo and Lauenroth, 1995; Tieszen et al., 1997; Diouf and Lambin, 2001; Holm et al., 2003).

Our first premise is that NDVI is highly correlated with rainfall in the Sahel region. Yang et al. (1998) have shown the influence of climate forcing and time-integrated NDVI on grasslands over the US Northern and Central Great Plains. Climate should have a substantial control on iNDVI through annual rainfall. This control, however, should be predictable and spatially consistent across regions of similar geology, soils, and management practices. A second premise is that the rainfall-iNDVI correlation can be used to assess land cover performance, ranging from areas where the land responds well to rainfall with high vegetation production, to areas where productivity is low, indicating possible land degradation. In the latter case, where the coupling of land cover performance to moisture is low, iNDVI should be poorly correlated with rainfall, indicating that there are other factors accounting for poor vegetation production. The causes of poor production might be related to the physical nature of the land resources, i.e. naturally unproductive soils or geological constraints. However, a decreased correlation with rainfall in an otherwise responsive area could also be the result of human activity and influence. A review of these relationships illustrates that a low correlation, in fact, would be expected under conditions of human-induced degradation of soil, as well as under conditions where land management practices result in predictable improvements in land cover performance, such as irrigated areas. Consequently, the rainfall-iNDVI correlation can be used as a general indicator of land productivity, both for land degradation and land improvements. Specifically, this paper reports on three research objectives:

(1) development of tools and procedures for assessing land cover performance in Senegal using coarse resolution NDVI;
(2) investigation of historical trends (from high land productivity to degradation) using 16 years of rainfall and NDVI time series data; and
(3) attempts to determine if human influences on land cover performance can be inferred from the results.

1.2. The study area

We chose Senegal as the study area because of the diversity of ecological regions (Sahelian, Sudanian, and Guinean) and land cover types found both in Senegal and across West Africa (Stancioff et al., 1986; Grosenick et al., 1990). Furthermore, members of the research team are very familiar with the natural resources in Senegal, having led previous efforts to map and monitor the country's resources (Tappan et al., 2000). These efforts resulted in the collection and compilation of extensive geographic data sets for Senegal.

We prepared a generalized map of the vegetation and land cover of Senegal, derived from detailed maps from the mid-1980s (Stancioff et al., 1986). The generalized land cover map presents four major types—steppe, savanna, woodland/forest, and agriculture (Fig. 1). Three of the land cover classes are strongly related to latitude and, thus, precipitation. The fourth class–agriculture–is a result of human modification of the natural vegetation cover. The relationship between rainfall and iNDVI is examined for these four land cover types.

1.3. The NDVI and rainfall data sets

The National Aeronautics And Space Administration (NASA) Global Inventory Monitoring and Modeling Studies (GIMMS) computed the NDVI by taking the

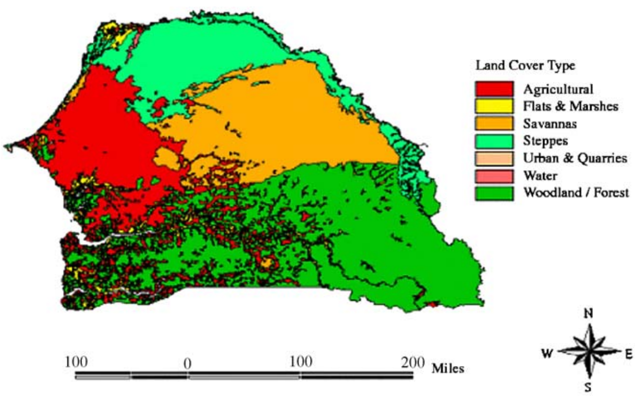


Fig. 1. Land cover map of Senegal.

difference between AVHRR near-infrared (NIR) and visible (VIS) channel reflectance values and then normalizing by the sum of these two channels: NDVI = (NIR − VIS)/(NIR + VIS). Half-monthly NDVI data were generated using the maximum value composite, which is used to select the maximum NDVI value within the half-monthly period for each pixel. Pixel resolution is 8 km. The NDVI data were temporally smoothed and seasonally integrated at the US Geological Survey EROS Data Center to further reduce cloud contamination effects (the procedures are described in Swets et al., 1999). Fig. 2a shows mean iNDVI for 1982–1997.

Rainfall station data for Senegal for the period 1982–1997 were obtained from the *Centre de Suivi Ecologique*, Dakar. The number of stations varied from 30 to 40, depending upon the year; the dekadal (or 10-day) rainfall data were summed for the year to provide annual rainfall data. The data were georegistered to the NDVI data and kriged with trend in order to generate annual rainfall maps for each of the 16 years. Fig. 2b shows mean annual rainfall in millimeters (mm) for 1982–1997. Rainfall gradient as a function of latitude is very apparent. One of our main concerns was the use of interpolated rainfall data in a semiarid region. The rainfall

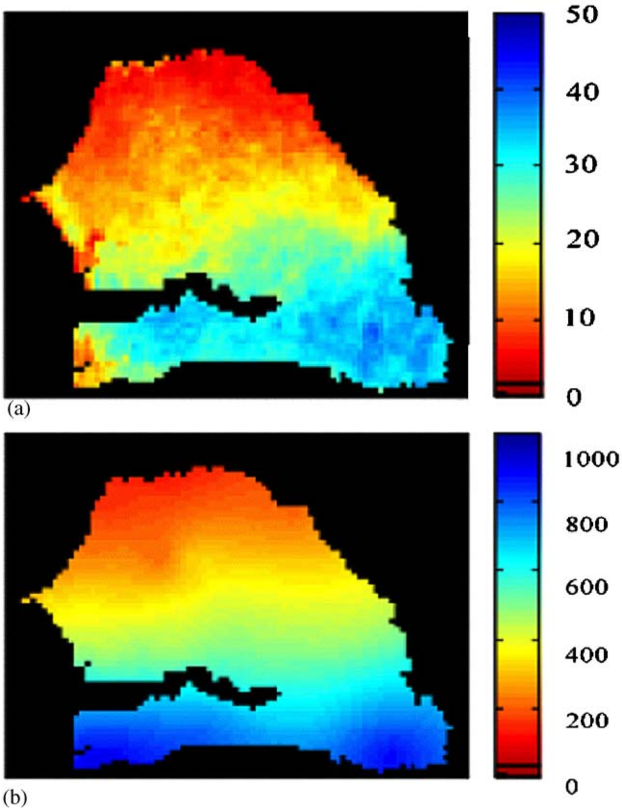


Fig. 2. (a) Mean season integrated NDVI for 1982–1997 and (b) mean annual rainfall for 1982–1997.

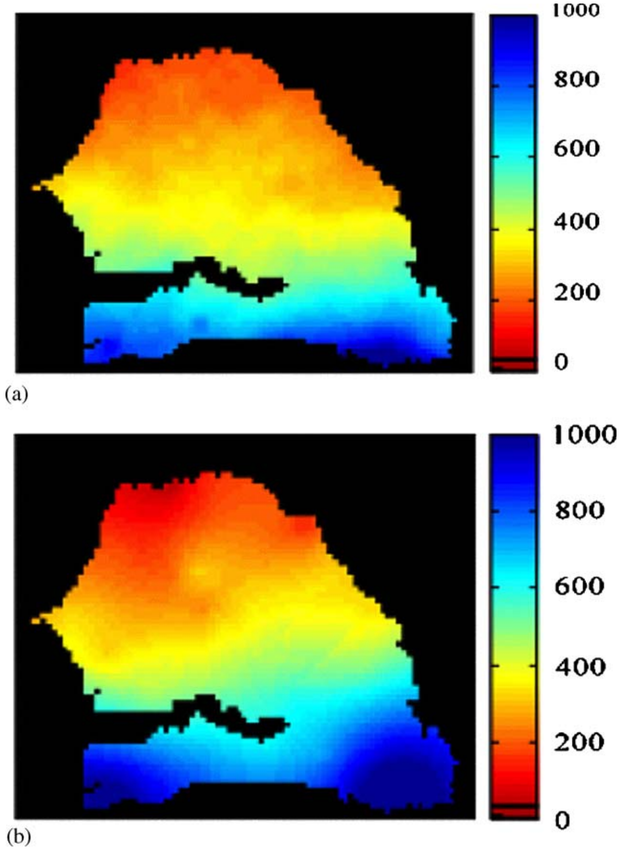


Fig. 3. (a) Mean satellite-derived rainfall estimate for 1995–1997 and (b) mean interpolated rainfall for 1995–1997.

stations are unevenly distributed, and the number of stations changed over the 16-year period. To address this concern, we compared rainfall estimates derived from Meteosat images to the interpolated point rainfall data for 3 years (1995–1997). The overall map patterns for calculated 3-year means (Fig. 3) are similar for the two maps (correlation = 0.96), although there are a few areas that show local differences. The high correlations provide confidence to use the 16 years of interpolated rainfall data in our analysis.

2. The statistical relationship between NDVI and rainfall

Fig. 4 provides a visual comparison of rainfall and iNDVI for two individual years—1984 was a drought year in Senegal, while 1988 had normal to above normal rainfall. To assess this association more rigorously, we performed correlation analysis on annual rainfall and iNDVI for the period 1982–1997. Even though no inferential statistics were performed on the data set, in order to address the concern of spatial autocorrelation we used a random sampling of pixels ($n = 391$) to generate all country-level statistics. This method resulted in rainfall/iNDVI correlations ranging from 0.74 to 0.90, with a mean value for all years of 0.84. The consistently high correlations indicate a strong association between rainfall and iNDVI, although there is some interannual variation in the magnitude of the correlation coefficients.

Table 1 shows the correlation coefficients for all years between rainfall and iNDVI for the four classes of vegetation. The number of sampled pixels is 132, 160, 139, and 126 for steppe, agriculture, savanna, and woodland/forest, respectively. The coefficient is low for woodland/forest, indicating the potential for less direct dependency upon rainfall. For the other vegetation groups, there is a strong statistical relationship between rainfall and iNDVI.

The correlation coefficient is particularly high for the steppe region. This indicates the strong control rainfall has as a limiting factor on iNDVI (or vegetation production) in the drier areas. Davenport and Nicholson (1993) and Nicholson and

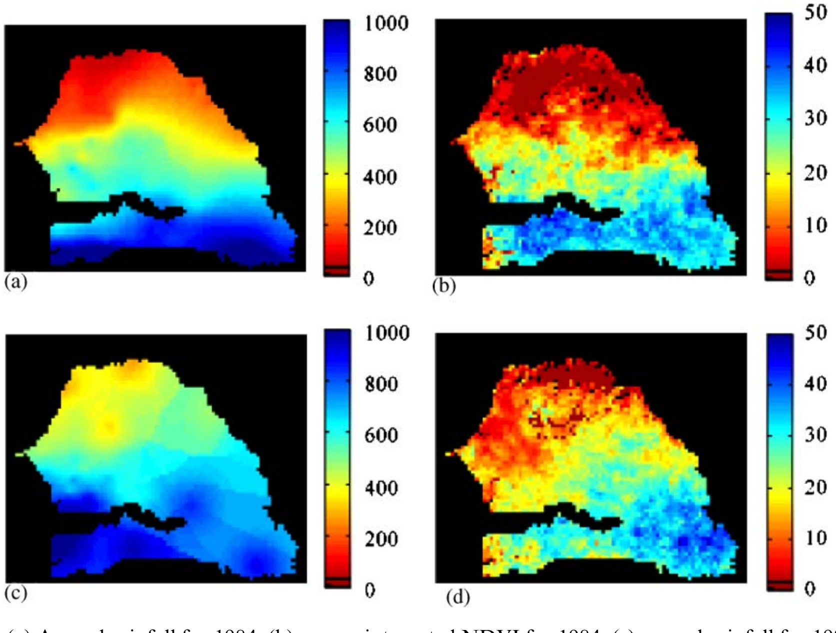


Fig. 4. (a) Annual rainfall for 1984, (b) season integrated NDVI for 1984, (c) annual rainfall for 1988 and (d) season integrated NDVI for 1988.

Table 1
Correlation coefficients between rainfall and iNDVI for four vegetation types

Land cover type	Steppes	Agriculture	Savanna	Woodland/forest
Correlation coefficient	0.89	0.71	0.73	0.30

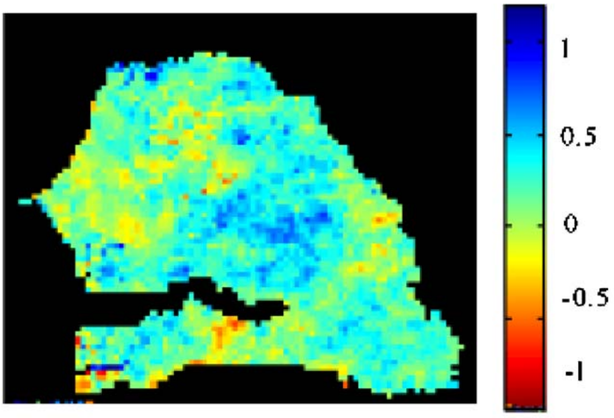
Farrar (1994) examined the relationship between rainfall and NDVI in semiarid Botswana and East Africa, finding a linear relationship between rainfall and NDVI as long as rainfall does not exceed approximately 500 mm yr^{-1} or 50–100 mm mo^{-1}. Above these limits, a ‘‘saturation’’ response occurs, and NDVI increases with rainfall at a slower rate. In our study, these limits were reached at 700–800 mm yr^{-1}.

3. Time trends and correlation analysis

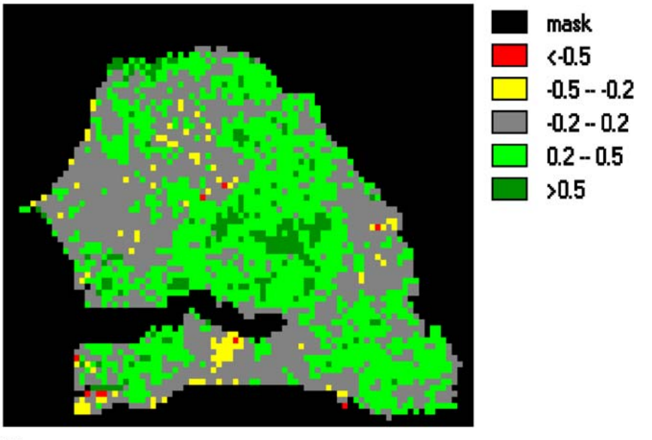
For agriculture, savanna, and steppe areas, high correlation coefficients portray ‘normal’ land cover performance in relation to the rainfall-iNDVI association. Regions where correlation coefficients are negative or have low positive values (with low iNDVI values) would indicate areas where land resources are naturally unproductive or areas impacted by human activity. However, when low, yet positive, correlations combine with high NDVI, good land cover performance would be indicated. Moreover, negative or low positive correlation values in wooded or forested areas, combined with low NDVI values, might suggest poor land cover performance, although the partial decoupling of the rainfall-iNDVI relationship in woodland/forest areas (due to saturation of NDVI with rainfall, and increased atmospheric moisture, or haze) makes this approach less appropriate for this land cover type (Rasmussen, 1998).

We analysed correlation coefficients from the rainfall-iNDVI relationship on a pixel-by-pixel basis to assess land cover performance for Senegal. Time series were developed for each pixel from 16 images (16 iNDVI and 16 annual rainfall images). Fig. 5 shows the overall iNDVI time trend for the 16-year period. Values greater than 0.2, or less than –0.2, for the regression slope coefficient were considered positive, or negative, trends, respectively. Positive trends appear in the southeast and east central regions of Senegal. The land cover of these areas is considered very stable (Tappan et al., 1992). A slight increase in rainfall over the 1982–1997 period, resulting in more vegetation production, may account for the indicated increase in iNDVI. Areas of negative trend are much more localized. Widely scattered negative areas are sprinkled throughout north-central Senegal. According to Fuller (1998), this trend is attributed to decreasing amounts of rainfall for this region during the later part of the time period he studied, which was 1987–1994. In addition, the major agricultural region of west-central Senegal exhibits slightly negative values (best seen in Fig. 5a). Much of this region has been cultivated for over 100 years. The natural vegetation has been largely replaced by an agricultural landscape. Years of continuous cultivation have depleted the soils of their fertility and organic matter, resulting in low yields (Bucknall et al., 1997). The iNDVI images reflect the general degradation of this region relative to other areas of Senegal within a similar climatic regime.

A distinct negative region occurs in south-central Senegal (Casamance region). This trend is difficult to explain. Analysis of several Landsat images from 1972 to 1999 for the Casamance indicates that this area has been relatively stable over the last 20 years (predominantly open woodland with small areas of cultivation).



(a)

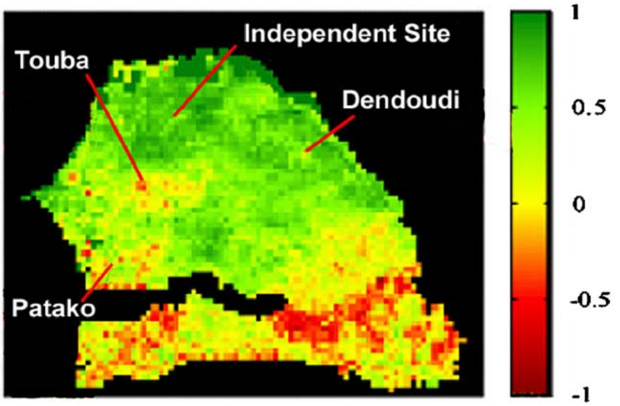


(b)

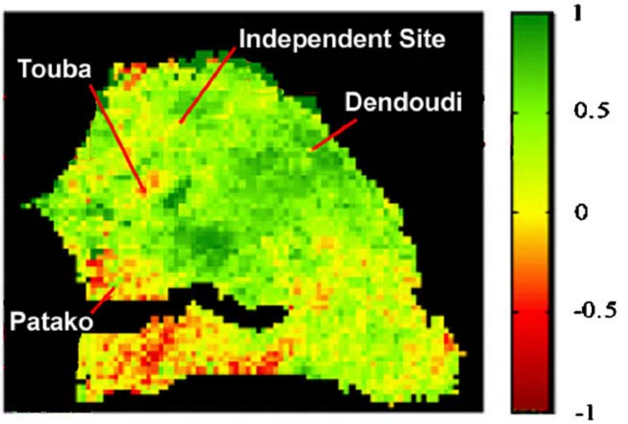
Fig. 5. (a) Slope of regression equation for iNDVI over time (1982–1997) and (b) classified map of slope coefficient for iNDVI (1982–1997).

However, assessing land cover performance trends in the woodland/forest vegetation type with NDVI is problematic. In areas of over 700–800 mm annual rainfall, the rainfall-NDVI correlation is generally very low, indicating the lack of sensitivity of NDVI or forest cover to variations in rainfall. Furthermore, southern Senegal is more subject to cloud cover and high water vapor content, both of which are known to reduce NDVI values. However, the specific cause for this local negative anomaly is unknown.

We processed two overlapping 12-year intervals (1982–1993, 1986–1997) in an effort to detect changes in land cover performance between the early and later periods of the time series (given the stable, consistently high rainfall/iNDVI correlations throughout the time period). Twelve-year intervals were chosen to retain as large a sample size as possible. A correlation between rainfall and iNDVI was



(a)



(b)

Fig. 6. (a) Correlation coefficients of rainfall and iNDVI (1982–1993), and (b) correlation coefficients of rainfall and iNDVI (1986–1997).

performed on each pixel for the 12 years. Fig. 6 shows the correlation coefficient maps generated from the 1982–1993 and 1986–1997 time series. During 1982–1993, the agricultural region of west central Senegal displays negative or low positive correlation, indicating potentially poor land cover performance. Low positive or negative correlation coefficients also occur in a belt running from the eastern border of The Gambia (the area of no-data), through the woodland region, continuing east to the border (with Mali). A second area of negative correlation occurs in southwestern Senegal (Casamance). For 1986–1997 the distribution of negative and low positive coefficients is similar in the Casamance, and in local areas of the west-central agricultural region. However, differences between the two periods occur in the eastern woodland region: the belt of negative values is replaced by positive values. As discussed above, the land cover of the southeastern woodland zone of Senegal has been quite stable (Tappan et al., 2004). The observed variations in the correlation coefficients are influenced by other factors, including the reduced relationship between NDVI and green vegetation production in the southern zone. The coefficient map for 1986–1997 also reveals areas of low or negative coefficients in the Senegal River valley of northwest Senegal. The NDVI for this area does not change substantially with rainfall because of widespread irrigation (Fuller, 1998). Thus our approach identified these areas where human management has resulted in enhanced productivity and a decoupling with rainfall.

This temporal analysis suffers from the small sample size ($N = 12$), which produces statistical random variability in the correlation coefficient; however, this was not apparent from the annual correlation values (cited above). Even though the correlation coefficients may have substantial sampling error due to small sample size, we selected three sites for which validation has confirmed land degradation or land cover change for comparison. Two of the sites, Dendoudi and Touba, were selected on the basis of anomalies characteristic of persistent degradation on high-resolution Landsat TM images. The third site, the Patako Forest Reserve, was selected as an example of a positive anomaly where the vegetation is protected from the surrounding agricultural lands by the forest service. The correlation coefficients for the Dendoudi and Touba sites show generally low positive or negative values. Results for these sites are shown in Table 2. An independent site was added to portray a transitional area between agriculture and steppe that showed low positive or negative values similar to the degraded sites. A description of the sites, including general results for each site, follows.

1. *Dendoudi*. This site reveals areas of degraded soil and vegetation around a borehole in the Sahelian semiarid pastoral region. Degradation has occurred since about 1950 because of livestock concentration. For 1982–1993 this site reveals a low correlation coefficient (0.34) and an even lower coefficient (0.1) for 1986–1997.
2. *Patako*. This is a large forest preserve that has been protected since about 1933. It is in relatively good condition, though slightly degraded from thinning of the forest by selective cutting since the early 1980s (Tappan et al., 2000). This site has relatively higher correlation coefficients for both time periods. Patako, surrounded by extensive agriculture, appears to be less affected by problems of high humidity that complicate the NDVI signal for the woodland/forest region in southern Senegal.
3. *Touba*. This is Senegal's fastest growing city. Rapid urban expansion, coupled with a ring of very degraded, unproductive land result in a strong negative anomaly. It lies within the generally degraded agricultural region discussed above

Table 2
Correlation coefficients for selected sites for 1982–1993 and 1986–1997

Site/years	Dendoudi	Patako	Touba	Independent site
1982–1993	0.34	0.55	−0.04	0.31
1986–1997	0.10	0.36	−0.13	−0.03

(west central Senegal). This area has slightly negative correlation coefficients for both periods.

Generally, for each of these sites, the correlation coefficients decrease from the first period to the second, implying a decreased ability of the land surface to respond to rainfall over this period.

Two sites (Dendoudi and Touba), plus the 'independent' site, which had correlation values similar to Dendoudi, were then chosen to examine their difference from the surrounding area. Six pixels were extracted for the individual sites and then compared to a surrounding 20×20 pixel window during the 16-year period. Results show that these sites are anomalous when compared to the area around them. z-scores were employed to test for statistical significance for the target site compared to its surroundings (Table 3). In all cases the z-scores for the three target sites were statistically significant at the 95% level, which indicates that these sites are different in character from their surroundings. Therefore, these sites can be marked as potential indicators of anomalous land cover performance and, in the absence of an underlying geological explanation, are indicative of human impacts.

4. Analysis of outliers

In order to strengthen the previous argument, we conducted an additional assessment of the outliers from a regression analysis. A measure of the scatter about the regression line can be calculated using the equation shown on Fig. 7. For a given value of x (rainfall), a value of y_{est} (iNDVI) is obtained for each pixel and for each year from individual regression of iNDVI on rainfall. This measure is the standard error of the estimate (SEE). The SEE has properties analogous to those of the standard deviation. A 'local' SEE was defined by conducting a regression analysis on

Table 3
z-score values (and associated) probabilities to test for significant difference of three sites from the surrounding values

		1982–1993	1986–1997
Touba	Group	0.143 ± 0.11	0.377 ± 0.15
	Site (6 pixels)	−0.04	−0.13
	z-score	−1.66	−1.65
	Prob.	95.3%	95%
Dendoudi	Group	0.647 ± 0.1	0.64 ± 0.13
	Site (6 pixels)	0.34	0.1
	z-score	−2.79	−4.15
	Prob.	99.7%	100%
Independent site	Group	0.725 ± 0.1	0.396 ± 0.21
	Site (6 pixels)	0.31	−0.03
	z-score	−3.77	−2.03
	Prob.	99.99%	97.9%

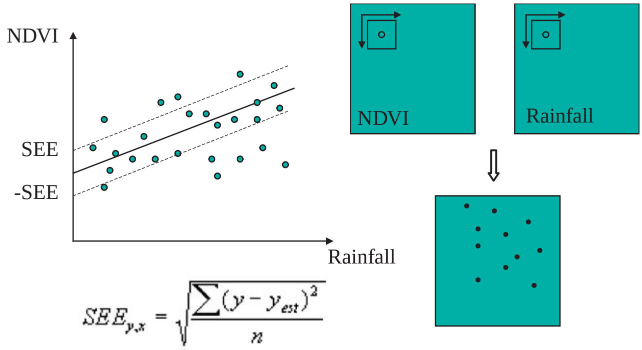


Fig. 7. Linear regression analysis on rainfall and iNDVI for local area.

a 15×15-pixel window. The larger boxes on Fig. 7 represent the Senegal image, whereas the smaller boxes represent the 15×15-pixel windows. In an image, each pixel (except around the edge) can be considered the center of a moving 15×15 window for which the SEE of the 15×15 values is computed. If the central pixel of each window is greater/less than ± 1 SEE, respectively, the pixel is regarded as a positive/negative outlier for this window (i.e. local region). An inherent assumption is that the climate regime is similar throughout the area defined by the 15×15-pixel window, thus allowing the outliers to be defined as anomalous behavior regarding the rainfall-iNDVI association. Negative outliers (less than –1 SEE) indicate those pixels that have low NDVI values and high precipitation for the local area. The 'local' SEE was generated for each pixel within Senegal for each year. Thiam (2003) used the mean NDVI minus 0.5 standard deviation as a measure of pixels under "threat", showing that below-normal NDVI generally coincides with below-normal rainfall in southern Mauritania. However, we feel that a 0.5 standard deviation value is too low to highlight the very sensitive areas undergoing land cover change.

Fig. 8 displays a series of maps for the 'local' SEE of 6-year running sums of negative outliers; i.e. the frequency of values less than –1 SEE for the 6-year period. The 'local' SEE appears to be a fairly insensitive measure as is evident from the widespread character of at least one year in 6 having a value less than -1 SEE throughout much of Senegal. However, the maps do indicate that variability increases in a northward direction, demonstrating the increased effect of rainfall variability (spatial and temporal) on NDVI in the drier regions of Senegal. Also, the frequency of negative outliers decreases from the earlier 6-year periods to the later 6-year periods, corresponding to rainfall differences between these periods, in which the latter periods were generally wetter than the former (implying less spatial variability associated with the wetter years).

If we combine the negative SEE outliers for the entire series, and focus on two of the test sites (Dendoudi and Touba), plus an additional site (Revane) of known land degradation, these sites are conspicuous as significant anomalies from their surroundings as shown in Fig. 9. Recall that similar patterns occurred for Dendoudi and Touba in the rainfall-iNDVI correlation analysis. Touba has negative outliers in

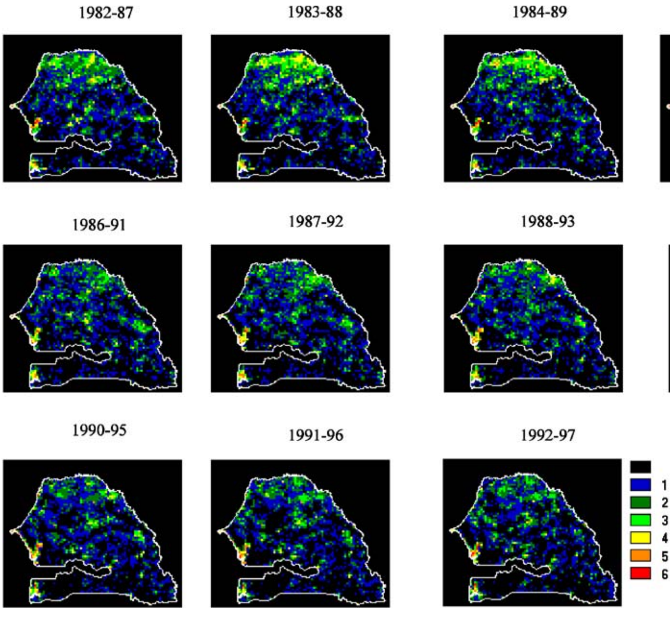


Fig. 8. Frequency maps of negative outliers (⩽1 SEE) for rainfall and iNDVI in 6-year intervals.

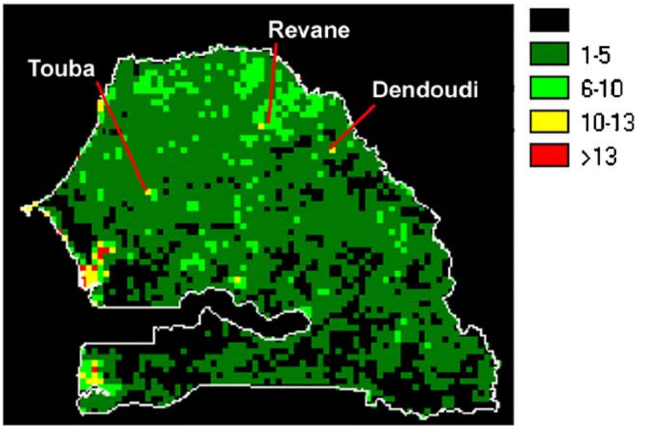


Fig. 9. Frequency map of negative outliers (⩽1 SEE) for rainfall and iNDVI for 1982–1997.

the 6–10 and 10–13 year categories. Dendoudi also falls in the 10–13 year category of negative SEE outliers. Revane falls within the 6–10 year negative outlier category. These pixels as identified on the image can be marked as statistically significant indicators of low production or degraded environment since independent satellite and ground evidence show that these sites display evidence of human impact. Thus, it follows that other pixels within Senegal that show similar conditions (10 or more years of negative SEE outliers) could be sites of poor land cover performance. In fact, at 8-km pixel resolution, there are few pixels that show this dramatic anomalous behavior. Most all other pixels in the category of 10 or more years of negative outliers are in estuary zones, comprising a heterogeneous mix of open water, mangroves, and mud and salt flats. This heterogeneity of the land cover, along with inherent poor spatial registration of AVHRR data, results in the identification, or classification, of spatially anomalous pixels when compared to the climatically similar surrounding area; these pixels are then not necessarily considered degraded areas. It is of interest that a large number of pixels are identified in the 6–10 year category of anomalous departure, especially in the north of Senegal. We have yet to establish whether these represent areas of lesser degradation, temporal variability in the spatial comparison, or noise.

5. Summary and conclusion

There is a strong relationship between annual rainfall and integrated NDVI (or vegetation development) for the northern two-thirds of Senegal. At a regional scale, high rainfall coupled with low NDVI provides an indication of areas of low production and possible degradation of ecosystems (Hiernaux, 1984). Specifically, our results indicate:

(1) The correlation coefficient between rainfall and iNDVI, along with the use of regression diagnostics, provides useful information for assessments of land cover performance, primarily for areas with high correlation between rainfall and iNDVI (steppe, savanna and agriculture).
(2) In the Sahelian (northern) region of Senegal, local areas with low positive correlation or slightly negative correlation identify sites where years of human activity and/or heavy concentrations of livestock may have induced land degradation. The analysis identified local areas of degradation at Dendoudi, Touba, and Revane, where land degradation is now known to have prevailed for many years.
(3) The small sample size (of the time series), which may generate high statistical variability in the correlation of rainfall and iNDVI, produced some uncertainty. In addition, the use of this technique was inappropriate for woodland areas.
(4) The SEE analysis provided useful information for detecting spatial anomalies associated with potentially human-induced land degradation. The SEE analysis also increased the sample size and, more importantly, confirmed interpretations derived from the correlation results.
(5) Correlation coefficients and a local regression approach for annual rainfall and integrated NDVI provide useful information for assessing land cover performance.

In general, for semiarid areas iNDVI is a sensitive indicator of the interannual and spatial variability of rainfall. If one can account for the effect of climate, then one may assume that part of the remaining variability is related to human-induced effects on the land. This is particularly true in the semiarid regions where vegetation response is highly dependent upon rainfall. In woodland/forest areas, however, NDVI exhibits little change from year-to-year even when rainfall varies significantly.

The procedures used identified areas where land degradation has been verified by independent methods (Landsat image interpretation, ground site observation), suggesting a general applicability of coarse resolution imagery to identify other areas of similar anomalous land cover performance. In order to confirm the applicability of these approaches, we recommend that other test sites be examined and that selected comprehensive long term monitoring programs for biomass/land cover change be implemented for the Sahel region of Africa.

An important obstacle is the coarse spatial resolution of the 8-km pixel of this long-term AVHRR record. Many local areas of degradation certainly fall below the size threshold of 8×8 km pixels. An area of 64 km^2 inherently contains variability, either in soil, vegetation, land use, or other surface characteristics, particularly in the crop-growing areas of the semiarid Sahel region. Nevertheless, the results do suggest that this approach may be applied to rainfall and NDVI data sets as a potential *regional* indicator for a rapid evaluation of land cover performance in semiarid Africa. Furthermore, this approach uses high-temporal-frequency satellite data that are readily available for cost-efficient annual monitoring. Additional analysis, using higher resolution (1-km) NDVI data, is also recommended (Budde et al., 2004). Current programs at EROS Data Center are reprocessing 1-km NDVI for West and southern Africa, in conjunction with NASA Goddard Space Flight Center, the AGRHYMET Regional Center (Niamey, Niger), the Satellite Applications Center (Pretoria, South Africa), and the Southern African Development Community (SADC) Regional Remote Sensing Unit (Harare, Zimbabwe). These data will provide an archive of time series data available to the public for detailed analyses of land cover performance at a resolution of 1 km. Current efforts to archive Moderate Resolution Imaging Spectroradiometer (MODIS) data and to calibrate these data (250-m resolution) with coarser resolution AVHRR data will allow still greater resolution and comprehensive analyses.

Acknowledgements

Work was performed under SAIC Contract 03CRCN0001.

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