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Assessing land cover performance in Senegal, West Africa using 1-km integrated NDVI and local variance analysis

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Abstract

The researchers calculated seasonal integrated normalized difference vegetation index (NDVI) for each of 7 years using a time-series of 1-km data from the Advanced Very High Resolution Radiometer (AVHRR) (1992–93, 1995) and SPOT Vegetation (1998–2001) sensors. We used a local variance technique to identify each pixel as normal or either positively or negatively anomalous when compared to its surroundings. We then summarized the number of years that a given pixel was identified as an anomaly. The resulting anomaly maps were analysed using Landsat TM imagery and extensive ground knowledge to assess the results. This technique identified anomalies that can be linked to numerous anthropogenic impacts including agricultural and urban expansion, maintenance of protected areas and increased fallow. Local variance analysis is a reliable method for assessing vegetation degradation resulting from human pressures or increased land productivity from natural resource management practices.

Keywords: Land degradation; NDVI; Sahel; Remote sensing; Senegal; Vegetation; Natural resource management

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1. Introduction

While variability in annual precipitation plays a vital role in land productivity in Sahelian Africa, long-term changes in vegetation condition are likely the result of other natural and anthropogenic factors. Physical features of geomorphology and soils in addition to human actions like changing land use practices, urban expansion, overgrazing, and protected resource areas all contribute to the productivity of land in the region.

Natural factors affecting vegetation productivity include precipitation variability, wind and water erosion, and fire. Of these, precipitation is the primary limiting factor on both cropland and natural vegetation systems. The semi-arid region of West Africa experienced periodic drought and declining rainfall throughout the twentieth century (Li et al., this issue).

Large-area studies of the Sahel have characterized the relationship between rainfall and vegetation productivity using the Normalized Difference Vegetation Index (NDVI) (Malo and Nicholson, 1990; Milich and Weiss, 2000; Li et al., 2004). NDVI is well established in the literature as being a good representation of vegetation growth and vigor at the land surface (Justice et al., 1985; Tucker et al., 1985; Reed et al., 1994). NDVI is calculated from reflected solar radiation in the near-infrared (NIR) and visible (VIS) wavelengths, using the following formula:

$$NDVI = (NIR - VIS)/(NIR + VIS),$$

$NDVI$ is a nonlinear function that varies between -1 and 1 (undefined when both NIR and VIS are zero). Values of $NDVI$ for vegetated land are generally greater than 0.1, with values exceeding 0.5 indicating dense vegetation.

A recent study by Thiam (2003) used these data to analyse the causes and spatial patterns of land degradation in a portion of West Africa. He used 1 km NDVI in conjunction with other measures of socio-economics, rainfall, soils, and aerosols to assess land degradation risk in southern Mauritania. These data provided a measure of primary biomass production that was used to identify areas at risk for degradation. Thiam identified overgrazing and erratic rainfall patterns as a major cause of land degradation.

Much of the research in the region has focused on using extended time-series of NDVI derived from the Advanced Very High Resolution Radiometer (AVHRR) aboard the National Oceanic and Atmospheric Administration (NOAA) series of polar-orbiting meteorological satellites. The AVHRR sensor has provided Global Area Coverage NDVI measurements from 1982 to the present at a spatial resolution of 4 km. These data are distributed globally at a degraded resolution of 8 km. Although it provides an extensive temporal record for comparison, the coarse spatial resolution of these data limits their effectiveness at detecting local scale variability.

The goal of this research is to examine the use of finer resolution NDVI imagery to identify time-series trends in individual pixel performance, thus allowing assessment and monitoring of areas that are either consistently productive or degraded when compared to their surroundings. Our preliminary analysis focuses on Senegal. Subsequent investigations will expand these techniques to the entire Sahel region.

Similar work by Tappan et al. (1994a) used measures of maximum NDVI to identify areas of Senegal with degraded soils and low vegetation productivity during the late 1980s and early 1990s. Many of these sites are revisited and expanded upon within the context of this analysis.

2. Study area

Senegal is located at the western-most edge of Africa's Sahel region (Fig. 1). A country of nearly 10 million people, it relies heavily on subsistence farming (i.e. millet, sorghum, cassava, rice, maize, vegetables, fruits, pulses) and the export of agricultural products such as groundnuts (peanuts).

Composed primarily of a gently sloping, poorly dissected plain, the country has relatively low relief compared to its neighbors. The northern border, shared with Mauritania, is defined by the Senegal River; the Faleme River delineates the eastern border with Mali; Guinea and Guinea-Bissau are Senegal's southern neighbors, and The Gambia forms an enclave along the Gambia River in the southern part of Senegal.

The country possesses a variety of land cover types. The pastoral domain of the north includes both the steppe and savanna regions underlain by sandy soils. The large agricultural region in the west-central area of the country includes the northern portion of the Peanut Basin, an area dramatically transformed from human agricultural activity. The southern portion of the country is made up primarily of dry tropical woodlands.

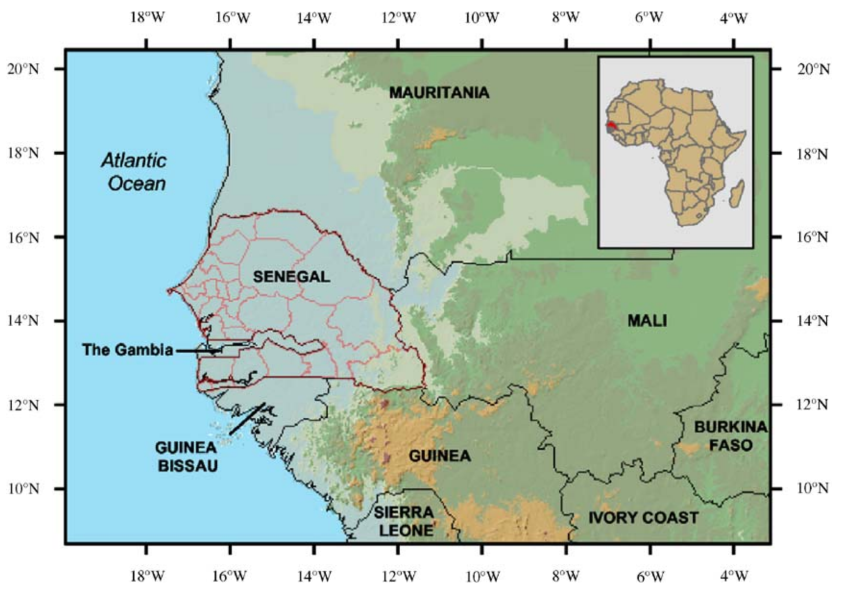

Fig. 1. Senegal, located on the western-most edge of Africa's Sahel region.

Fig. 2. Seasonal landscape comparison in Senegal showing the dry season conditions (left) and rainy season conditions (right).

As all of Senegal lies south of 17°N latitude, well within the tropics, temperatures are generally high throughout the year. Although Senegal is a relatively small country, it spans three distinct ecological zones: the Sahelian, the Sudanian, and the Guinean. These ecological regions are the result of large annual rainfall differences between the semi-arid north (with 200 mm average annual rainfall), and the moisture-rich south ($\sim$1200 mm annually) (Malo and Nicholson, 1990). Annual rainfall is almost entirely limited to the summer rainy season, which lasts up to 6 months in the south and decreases to 3 months in the north.

The dramatic landscape change (Fig. 2) that takes place between the dry season and wet season provides a suitable environment for the detection of spatial vegetation anomalies. Areas that fail to respond to seasonal rainfall in the same way as their surroundings may indicate localized degradation. Likewise, areas of unusually healthy vegetation conditions compared to the local area may indicate some level of improvement or protection against expanding cultivation or grazing.

3. Background

As a precursor to this work, we conducted extensive statistical and spatial analysis of the 8-km NDVI archive for Senegal. An examination of techniques such as principal component analysis (PCA), change vector analysis, standard error of the estimate, and regression analysis yielded promising results in identifying vegetation anomalies and establishing the statistical relationship between seasonal integrated NDVI and rainfall. Li et al. (2004) found correlation coefficients ranging from 0.74 to 0.90 annually when comparing seasonal integrated NDVI (iNDVI) and rainfall station data (acquired from *Centre de Suivi Ecologique*, Dakar) for the period 1982–1997.

In addition to establishing the rainfall–iNDVI relationship, the researchers performed time-series analysis for Senegal using iNDVI as the dependent variable. The analysis is similar to Fuller's (1998) work except that he used mean annual maximum NDVI. We mapped and analysed slope coefficients for the entire 16-year period. Coefficients greater than 0.2 were considered to be a positive trend, while areas less than −0.2 were considered a negative iNDVI trend. The south-east and east central regions of Senegal showed a broad region of positive trends, while areas of the peanut basin and north central region showed steady to negative trends.

Although these methods provided some indication of broad spatial trends, they did not address vegetation conditions at local scales. Therefore, we analysed local variance in seasonal integrated NDVI to identify how individual pixels performed when compared to their surroundings. Local variance techniques using the 8-km AVHRR data showed potential for identifying vegetation anomalies and provided the basis for our analysis using higher resolution NDVI data.

4. Data sets

Two NDVI data sets were used in the analysis. First, we assembled a 1-km NDVI data series from the global AVHRR archive for the years 1992, 1993, and 1995 (Eidenshink and Faundeen, 1994). These data represented the only years for which complete growing season coverage at 1-km resolution was available. Second, we acquired SPOT Vegetation index data at 1-km resolution for 1998–2001. We created both data sets from 10-day NDVI data generated using a maximum value composite (MVC) procedure, which selects the maximum NDVI value within a 10-day period for each pixel (Holben, 1986). This MVC procedure is used to reduce contamination of the NDVI signal due to cloud or other atmospheric perturbations. To further improve the quality of the two time-series, we applied a weighted-least-squares-linear-regression smoothing algorithm (Swets et al., 1999). The method used a moving window to form a series of regression lines associated with each point of the time-series. The regression lines were then averaged at each point and interpolated between points to create a smoothed signal. The technique applied weighting factors that emphasized peak points and minimized the influence of both sloping and valley points, thus eliminating sudden reductions in NDVI due to contamination.

We then compared the smoothed NDVI time-series to a time-lagged moving average of the same NDVI time-series to locate the onset of the growing season, defined as the point where the smoothed time-series data crosses the moving average in an upward direction (Reed et al., 1994). We determined the end of the growing season with the moving average applied to the NDVI time-series in reverse order. Once we identified the onset and end of growing season, we calculated the integrated NDVI (iNDVI) as the area under the NDVI curve from the start of season to the end of season (Fig. 3).

The algorithm for calculating iNDVI relies on adequate amplitude in the annual NDVI signal to define the growing season curve necessary for integrating the seasonal values. In areas of little annual variability (extremely dry or extremely moist), the algorithm may result in very low integrated values or in some cases no integrated value if the algorithm fails to detect a start of season. We masked out of the local variance analysis areas with no integrated value. The application of these techniques resulted in iNDVI images for each of the seven years.

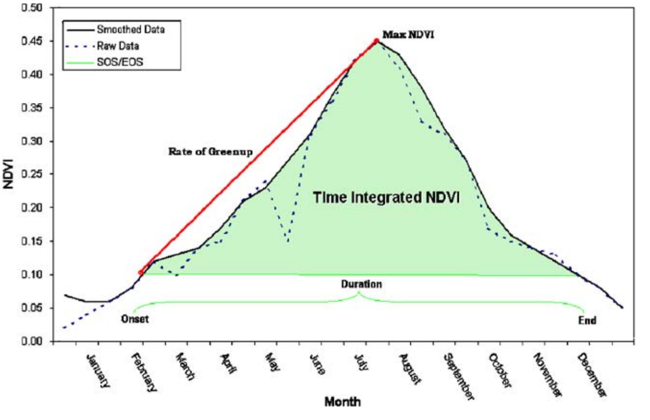

Fig. 3. Derivation of iNDVI using seasonal metrics (Reed et al., 1994).

Integrated NDVI values have been closely related to Net Primary Production (NPP) for a growing season (Tucker et al., 1981; Tucker and Sellers, 1986). An analysis of Sahelian grasslands showed strong linear relationships between seasonal production in a range of 0–3000 kg/ha and seasonal NDVI at the same locations (Prince, 1991). Therefore, seasonal-integrated NDVI provides a potentially robust indicator for identifying local areas of anomalous vegetation productivity.

5. Methodology

The researchers used a local variance method to detect local spatial anomalies of iNDVI for Senegal. Local variance is measured as the mean value of a moving $N \times N$ window (i.e. 9×9, 15×15, etc.) $\pm$ a predefined standard deviation threshold (*std_T*). Each pixel (except for those along the edge of an image) can be considered as the center of an $N \times N$ window. The mean and standard deviation for all pixels within a specified moving window for each iNDVI image are computed and assigned to the central pixel. We then compared the central pixel's integrated NDVI value to the mean $\pm$ the *std_T* to identify anomalies. If the central pixel value is less than $-1*std\_T+mean$, the pixel is flagged as a negative anomaly; if the pixel's value is greater than $1*std\_T+mean$, the pixel is flagged as a positive anomaly. We considered pixels that fall within the standard deviation range normal (Fig. 4).

The choice of a standard deviation threshold is at the discretion of the investigator. Low thresholds yield more anomalous results because the central pixel's value is less extreme in relation to the mean for the surrounding area. Likewise, a high threshold will produce fewer anomalous pixels because it limits the results to only those pixels that fall at the far ends of the distribution for a given window. Note that the advantage of using a moving window as opposed to some other spatial stratification is the ability to focus exclusively on localized vegetation anomalies (i.e. those pixels that differ significantly from their surroundings).

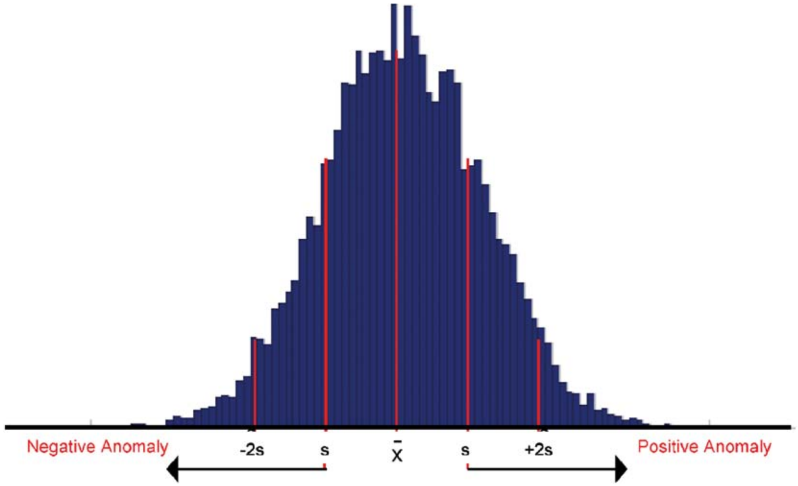

Fig. 4. Positive and negative anomaly detection using a standard deviation threshold of one.

The output images for each individual year appear to be non-uniform, showing no spatial patterns related to land cover type or precipitation patterns. Therefore, a critical step in the local variance analysis is to apply a quantitative threshold, whereby a pixel must be a significant deviator (as defined with the *std_T*) in at least *X* number of years. By applying such a threshold, we limit the results to only those pixels that show persistently anomalous behavior.

The local variance technique description cites three variables that are at the discretion of the investigator: the moving window size (spatial), the standard deviation threshold (statistical), and the number of years (quantitative) needed to show consistently anomalous conditions. Each of these thresholds impacts the results of the local variance analysis. While extensive sensitivity analysis has yet to be performed, we can present the rationale for our analysis thresholds and provide preliminary comments as to how these variables affect anomaly detection.

The moving window size defines the neighborhood within which a central pixel's integrated NDVI value is being compared. In the case of a large anomaly (e.g. 8×8 km), a small window size would fail to identify the central pixel as anomalous because as the window moves toward the center of the anomalous area, its iNDVI value will not significantly differ from those of the surrounding pixels. Likewise, small anomalies may go undetected using larger window sizes because the neighborhood would include a wider range of integrated values and likely not be flagged as an outlier. In addition to identifying these effects, further investigations must also address the role of anomaly shape.

The detection of linear shaped features versus clustered degradation around a borehole or urban area could also be impacted by the size of the moving window. We applied odd-numbered window sizes ranging from 3×3 to 55×55 to the 7-year time-series data. After analysing the results, we determined that a 31×31 moving window provided the best application to large-area analysis. We based this decision on comparisons of anomaly results with Landsat ETM+ imagery for a number of areas where anomalies are known to occur.

The standard deviation threshold is perhaps the easiest to quantify. Since the method is based on the detection of outliers in a normal distribution, we can simply apply the empirical rule to indicate the percent of anomaly detection for any given threshold. We examined the iNDVI data for seven years using *std_T*'s of 1, 1.5, and 2. Because areas with anomalies in excess of one standard deviation have been associated with significant environmental effects (Singh and Harrison, 1985), we have chosen to present the results of the analysis using a *std_T* of 1.

The last variable at the discretion of the investigator is the number of years that a pixel must be anomalous to be considered a persistent condition. Although this variable could be construed as subjective, the procedure accomplishes two important tasks. First, it provides quantitative limits upon which to base the identification of anomalies within the time-series. Second, it accounts for inter-annual climate variability. The result of the latter can be twofold. An increase or decrease in annual rainfall may cause an area to be flagged as a positive or negative anomaly for an individual year. A threshold that exceeds the number of years flagged due to such conditions will result in these pixels being eliminated from the final output results. Similarly, extended increases or decreases in annual rainfall may cause an area to be flagged positive or negative for a number of years that exceeds the threshold, thus causing retention of these pixels in the final results. Applying such quantitative limits allows us to concentrate on those areas showing persistently anomalous behavior.

6. Results

The analysis results show all anomalies that we detected in at least 4 out of the 7 years of the time-series. The final anomaly images color-code the number of years ranging from four to seven, so we can address these limits in our interpretation of individual anomalies. Using Landsat ETM+ imagery and 20+ years of field observation helped explain our results. Positive and negative anomaly images were overlaid on 30-m resolution Landsat imagery to identify and characterize those areas identified using the local variance technique.

Fig. 5 shows the distribution of positive anomalies (green) and negative anomalies (orange) for Senegal. We have chosen six sites of varied land use, ranging from urban areas to forest reserves, to illustrate the results of the local variance analysis. For each, we present the results in graphic form using both the Landsat ETM+ imagery (bands 5, 4, 3) without the anomalies and imagery with anomalies overlaid.

6.1. Touba, Diourbel, Darou Mousti

Fig. 6 shows three large cities that dominate the central Peanut Basin. Touba, the largest, is also the fastest growing city in Senegal; the anomaly detected here covers an area of approximately 42 km^2. These areas stand out because of their urban

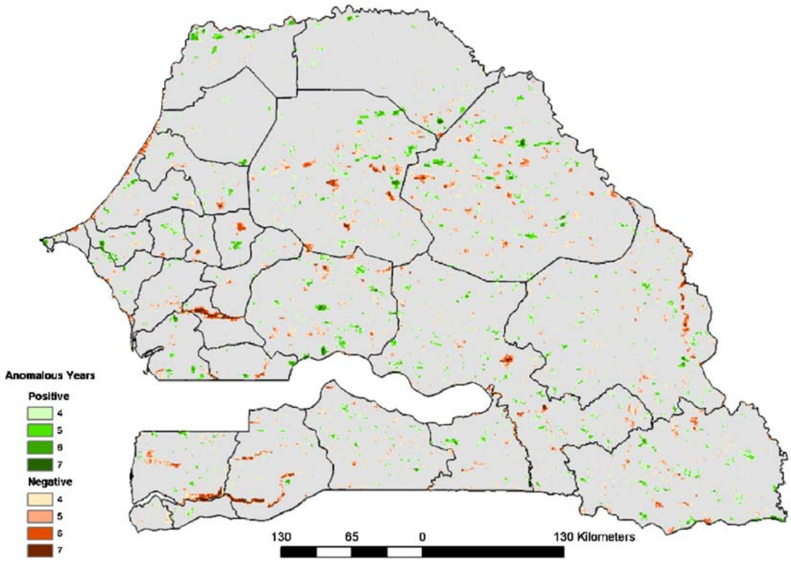

Fig. 5. Areas of positive and negative anomalies in more than 4 years of the time-series.

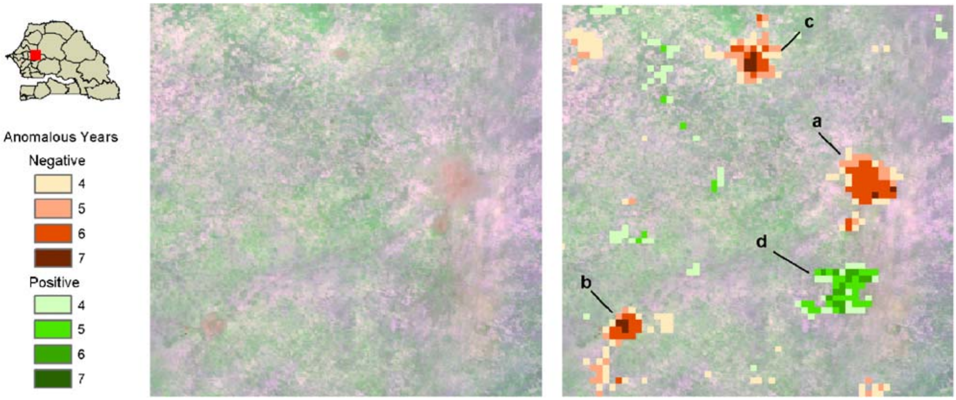

Fig. 6. Three large cities of the central Peanut Basin: Touba (a), Diourbel (b), Darou Mousti (c) and an increased long-term fallow area (d).

texture—low buildings, streets, housing lots, construction, and relatively few trees—all non-vegetated surfaces that produce a consistently low iNDVI value. They stand in contrast to the relatively productive agricultural landscapes of the Peanut Basin.

The striking positive anomaly that lies to the south of Touba appears to reflect the increase in long-term fallow in that local area. A trend in the 1990s toward an increase in fallow, resulted in large patches of grassland in the Peanut Basin. Close inspection of the 1999 Landsat ETM+ image shows this area to have a high percentage of grassy fallow. These areas contain annual grasses that respond quickly to seasonal rainfall, providing a high degree of herbaceous ground cover and a large iNDVI value.

6.2. Tambacounda

Tambacounda is the large regional capital of south-eastern Senegal (Fig. 7). Like its urban counterparts in the Peanut Basin, it stands out as an area of anomalously low vegetation productivity. Although the city itself has more vegetation in the form of shade trees than cities in the Peanut Basin, it lies in the midst of the Sudanian zone's wooded savannas with tall, perennial grasses that blanket the ground during the growing season. The anomaly represents not only the built-up area of the city, but also a ring of relative degraded vegetation around the city where tree cover has become very thin because of human and animal traffic that has resulted in trampling and overgrazing of the grasses. The shallow laterite soils of the surrounding plateaus have also been exposed due to vegetation disturbance.

Some of the positive anomalies in this area can be traced to sites where the ground cover (particularly the grasses) is relatively high, covering the thin soils that occur over laterite. One such anomaly occurs 20 km to the north-northwest of Tambacounda. These areas stand out in contrast to the majority of the low plateaus where shallow, rocky soils limit vegetation productivity.

6.3. Dendoudi and northern pastoral region

The ferruginous region in north-eastern Senegal is a relatively undeveloped area used primarily for pastoralism, where the soils are thin, gravelly, and relatively unproductive. The predominant vegetation cover ranges from shrub savanna to bushland, denser than the vegetation formations that occur to the west in the sandy pastoral regions. The local relief is quite pronounced, with broad laterite plateaus

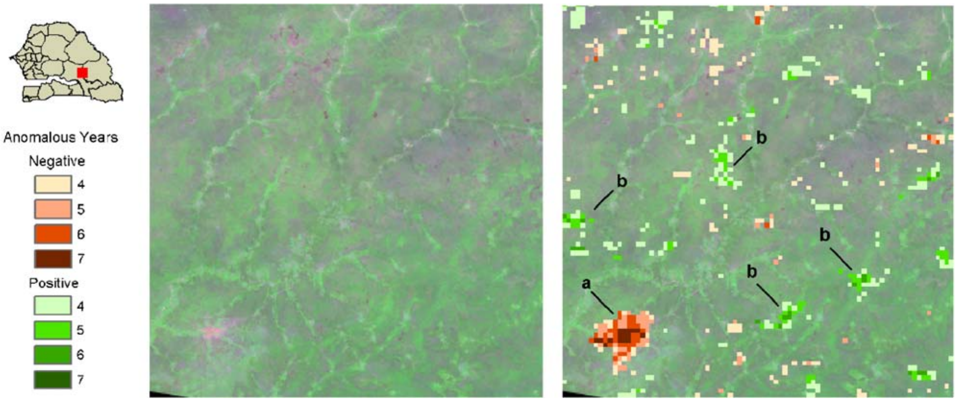

Fig. 7. The large regional capital of Tambacounda (a) and productive grassland areas (b).

dissected by fossil valleys, which give rise to variations in the vegetation cover. It is also a region replete with anomalous areas of both high and low productivity.

Fig. 8 shows the distribution of negative anomalies, many lying near or along, the fossil valleys (orange areas). These anomalies reflect extensive denuded surfaces, with severe water erosion problems. Water erosion has become particularly acute on the slopes of both minor and major fossil valleys throughout the region, resulting in a ''Badlands'' effect. Evidence from field visits conducted between 1983–84 and 1994–96 (Tappan et al., 1994b) suggests that the primary responsible forces are drought and livestock concentrations along the valleys.

Livestock densities are high during the early dry season when the few remaining natural ponds lie within the valleys. Furthermore, agro-pastoralists tend to settle along the valleys where ground water is shallower than on the uplands. These settlements also concentrate animals along the valleys. Overgrazing and trampling leads to loss of vegetative cover and a decrease in soil organic matter, making the soil more susceptible to water erosion. The poorly protected soils are also exposed to violent storms at the beginning of the wet season. Large quantities of quickly flowing water cut deep rilles and gullies, removing large quantities of soil in a relatively short time. Fig. 9 shows an eroded landscape as it appears in 1994 and again in 1997.

Degradation around the region's boreholes is particularly severe. One of the major negative anomalies seen in Fig. 8 represents the degradation around the Dendoudi *forage*, or borehole. Boreholes are year-round watering places, which concentrate people and livestock, exerting much pressure on the surrounding soils and vegetation. The degradation results from the interrelated factors of thin and gravelly soils, overgrazing, soil compaction, wind and water erosion, and the loss of woody vegetation cover. Typically, much of the herbaceous vegetation production is lost, even in years of good rains. Degradation is less severe near boreholes located on sandy soils, which are much less prone to compaction problems.

Fig. 8 also shows a number of positive anomalies. Two in particular stand out: one about 15 km north of Dendoudi and a second that forms an east–west patch some 20 km north-east of Dendoudi. These anomalies correspond with relatively

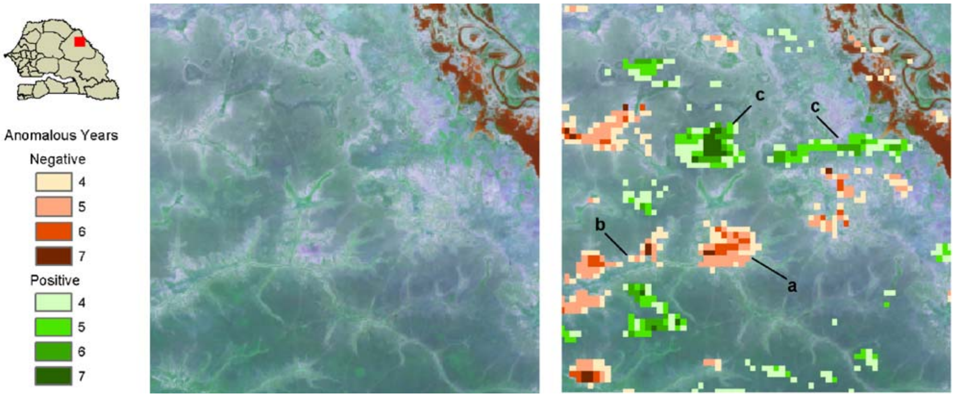

Fig. 8. Dendoubi borehole (a), eroded fossil valleys (b), and relatively undisturbed bushlands (c).

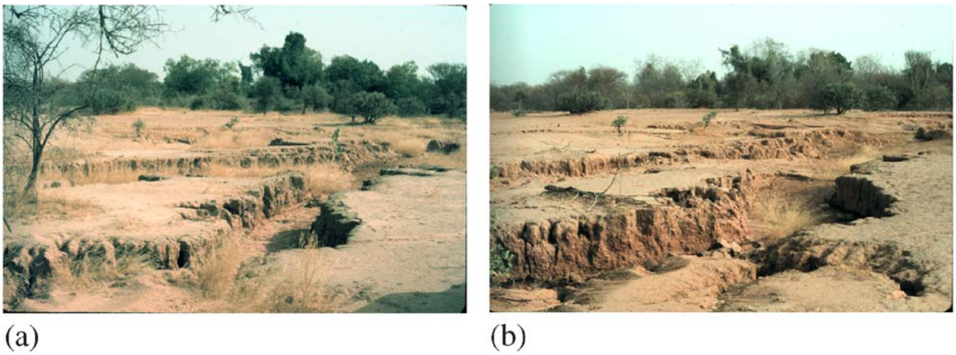

Fig. 9. Eroded landscape along a fossil valley in 1994 (a) and again in 1997 (b).

undisturbed, lightly grazed bushlands with little evidence of soil erosion. They tend to be flat, resulting in good water infiltration following rain. The east–west anomalous patch lies on a sheet of relatively productive sandy soils. Both areas are somewhat distant from water sources, so that grazing occurs mainly during the rainy season. Most of the positive anomalies in this region occur on flat plateaus where grazing and human pressures are light and the natural cover protects the soils from erosion.

6.4. North-central pastoral region

Another cluster of negative and positive anomalies occurs in an area east of Linguere in the ferruginous pastoral region (Fig. 10). The double-lobed negative anomaly just north of Loumbel Lana can be traced to barren, highly eroded, and unproductive slopes on short valleys that feed into the main trunk of the Ferlo Valley. As we have seen with anomalies farther to the east, a combination of factors in recent decades has led to the spread of the ‘‘Badlands’’ effect. There are at least two boreholes in the vicinity of this anomaly, leading to high concentrations of animals. Geomorphology and soil character are usually complicating factors; in this case, a slope allows water erosion to wash away the shallow topsoil.

Another major negative anomaly occurs to the south-east of Loumbel Lana. Here geomorphology also plays a role where myriads of small sand dunes cover the laterite plateau. Until recent decades, a dense shrub savanna stabilized the dunes, but drought and grazing pressure have disturbed this system resulting in degradation of the soils and low productivity of the area. The degradation is very local and patchy, primarily on the steeper dune slopes.

A noteworthy positive anomaly also occurs south-east of Loumbel Lana. Similar to other areas in this region, this anomaly represents a remote (from dry-season water sources), lightly grazed bushland on a flat plateau with little evidence of soil erosion.

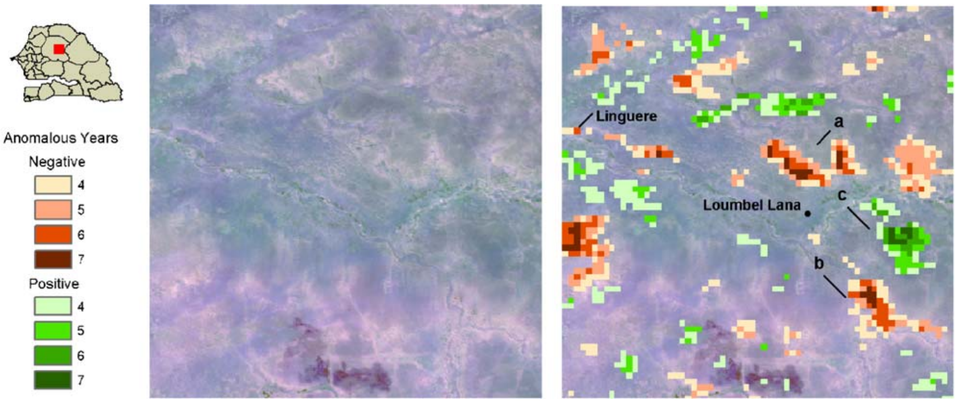

Fig. 10. Barren slopes (a), destabilized sand dunes (b), and productive bushlands (c) near the village of Loumbel Lana.

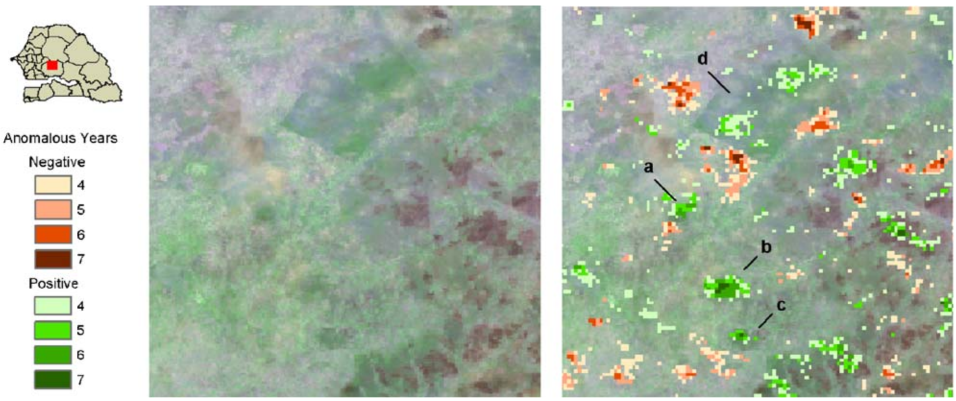

Fig. 11. Undisturbed area of the Forêt Classée de Mbégué (a), Forêt Classée de Delbi (b), Forêt Classée de Malem-Hodar (c), and the productive grasslands of the Doli ranch (d).

6.5. Doli ranch and reserves to the South

In the agricultural expansion region of central Senegal, three positive anomalies show up prominently in Fig. 11. These anomalies correspond to a portion of the Forêt Classée de Mbégué, the Forêt Classée de Delbi, and the Forêt Classée de Malem-Hodar. The French colonial administration created these reserves in 1936 to protect certain tracts of land from the rapid phases of colonization of new lands by farmers extending the eastern frontier of the Peanut Basin (Pélissier, 1966). Clearing in these 'forest' reserves was prohibited. While agricultural incursions have been for the most part limited (with the exception of the Forêt Classée de Mbégué), the vegetation within these small reserves has become degraded by illicit cutting for fuelwood and livestock browse material. Today they contain a shrub and tree savanna. Nevertheless, the near-continuous grass cover is relatively productive, resulting in a consistently positive NDVI signal. The south-east corner of the large Forêt Classée de Mbégué has been left intact, unlike the entire western half of the reserve, which was cleared for agriculture in 1991 (Freudenberger, 1991). The vegetation cover, both woody and herbaceous, is densest in the south-east corner of the reserve, precisely where there is a positive iNDVI anomaly.

Two anomalously productive areas occur within the Doli Ranch. Both areas reflect the relatively dense vegetation cover, particularly annual and perennial grasses, typical of undisturbed sites of the southern sandy pastoral region. These sandy ferruginous soils are relatively deep and more productive than the thin soils of the laterite regions to the east. Furthermore, both of these areas of the Doli ranch are lightly grazed, owing to the relative distance from approximately half a dozen wells established as water sources for livestock. In contrast, the northern and western portions of the ranch are heavily grazed, but erosion and vegetation loss is not yet severe.

The negative anomaly between the Forêt Classée de Mbégué and the Doli Ranch occurs in the strip of rain-fed agricultural land between the two managed areas. Although agricultural land usually generates a lower seasonal iNDVI response than adjacent grazing lands, in this case the anomaly is likely the result of its relative position to the productive grasslands of Mbégué and Doli, rather than a sign of truly unproductive soils. In this instance, we consider this to be a 'false anomaly'. Such anomalies underline the need to interpret each anomalous area within its geographical and environmental context.

6.6. *Saloum Forest Reserves and Koular Bolon Estuary*

Fig. 12 shows the local area anomaly detection approach performs well in highlighting protected vegetation in Senegal's forest reserves, particularly when other land cover types such as agriculture surround them. This area covers most of the Saloum agricultural region, important for its diversity of agricultural products. The four major forest reserves of the region were detected as significantly positive anomalies. They are the Forêt de Sangalo in the north-west, the Forêt de Fathala in the south-west, the Forêt de Patako in the east, and the Forêt de Baria in the south-east. Field surveys conducted in 1997–1999 (Tappan et al., 2000b) indicate that illicit wood harvesting has degraded these reserves, but they remain relatively productive, and have not experienced agricultural encroachment. In comparing the anomalous areas to the full extent of the reserves as seen in the Landsat base image, it is interesting that the anomalies do not represent their full extent. The explanation may be due to differences in productivity within these reserves. However, it is not entirely clear why the anomalies do not coincide more faithfully to the actual boundaries of the reserves.

The negative anomaly to the south-east is the Koular Bolon, an estuary that flows into the Gambia River. The tidal flats along the estuary harbored a dense mangrove forest until the 1970s and 1980s, when drought killed most of the trees (Hadj and

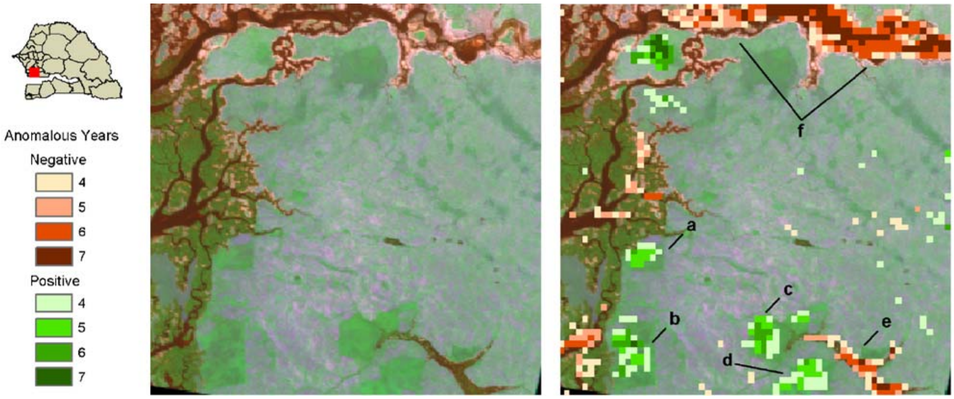

Fig. 12. Positive anomaly areas of Forêt de Sangalo (a), Forêt de Fathala (b), Forêt de Patako (c), and the Forêt de Baria (d) and negative anomalies along the Koular Bolon (e) and the Saloum (f) estuaries.

Fig. 13. Aerial view of degraded mangrove forest along a branch of the Saloum estuary.

Ndiaye, 1995; Tappan et al., 2000a). Other negative anomalies are clearly evident along the Saloum River in the northern portion of the Landsat image. Like the Koular Bolon, this broad estuary once contained a dense blanket of mangroves. Today little remains of the mangrove forest (Fig. 13). Dark, hydromorphic soils lie fully exposed, creating a consistent negative return on iNDVI images.

7. Discussion

It is important to emphasize that anomalies detected using these techniques are anomalous relative to their surroundings and may not represent absolute anomalous conditions. An area of agricultural land adjacent to a forest reserve or productive grassland may have seasonal integrated NDVI values similar to those of other agricultural regions, but its proximity to high productivity areas may cause the agricultural land to be classified as a negative anomaly. This distinction is critical when interpreting anomaly results.

A limiting factor in this analysis has been the lack of a temporally sufficient, consistently processed NDVI time-series. In our analysis, we used 3 years of AVHRR data and 4 years of SPOT Vegetation data. Although the local variance technique operates on the integrated NDVI values within a particular year and should not be affected by inter-sensor variation, we feel that a consistently processed time-series, covering a broader time period, will produce improved anomaly results. The AGRHYMET Center (Niamey, Niger) and the National Aeronautics and Space Administration (NASA) are currently reprocessing a time-series of 1 km NDVI for the Sahel. Once complete, this series will provide a consistently processed 1 km data set from 1990 to the present.

In addition to the extended time-series of AVHRR data, new sensor technologies offer an opportunity to perform analysis on finer resolution NDVI data. The Moderate Resolution Imaging Spectroradiometer (MODIS) instrument flown aboard the Terra and Aqua satellites provides vegetation index measurements at spatial resolutions of 1 km, 500 m, and 250 m. Using these data sets for similar analysis will allow identification of finer-scale vegetation anomalies.

8. Summary

This study illustrates the application of a local variance technique to assess land cover performance in Senegal using integrated growing season NDVI measurements. The resulting anomaly maps coupled with higher-resolution Landsat imagery and field-level knowledge of the region provide a good framework for analysis. The technique identified local vegetation anomalies from a number of different anthropogenic and natural influences. The researchers made strong visual associations between these anomalies and vegetation conditions evidenced in Landsat imagery.

Anomalies that exhibit low vegetation productivity related to their surroundings included areas of urban expansion, degraded mangrove forests, eroded fossil valley slopes, heavily grazed pastures, and degraded areas near boreholes. High productivity anomalies include forest reserves, lightly grazed bushlands, and areas of relatively undisturbed grasslands.

While it may be useful to discriminate anomalies caused by human action from those due to landscape characteristics such as geomorphology or soil characteristics, many examples show multiple factors having an influence on vegetation conditions. Degradation around the Dendoudi borehole provides a good example. The combined factors of thin gravelly soils and heavy grazing result in compaction of the soil and lead to the loss of herbaceous vegetation. Awareness of the possible causal relationship between human actions and natural resource conditions is imperative to accurately interpret local variance results.

Applications of the local variance technique are quite broad, offering a method for assessing relative vegetation anomalies over large areas with inexpensive and readily available data sets. By incorporating a trend element that identifies at what point in the time-series a pixel is anomalous compared to its surroundings, monitoring of trends in individual pixel performance may be possible. Preliminary efforts are also underway to build relationships between the detected anomalous areas and variability in NPP, thus allowing an assessment of carbon dynamics based on the spatial variability of vegetation condition over time. Establishing such associations will need to account for spatial variability in the integrated NDVI and biomass relationship. Diouf and Lambin (2001) found that integrated NDVI for a growing season is not the ideal proxy for biomass in the Ferlo pastoral region of Senegal. These findings indicate a need for further site-specific investigations of the iNDVI-biomass relationship.

The local variance technique shows promise toward assessing land cover performance in Senegal and throughout the Sahel. We need further investigation to assess how changes in the spatial, quantitative, and statistical thresholds defined in the local variance analysis affect anomaly detection. We suspect that both the size and shape of anomalous areas will impact the effectiveness of certain threshold parameters in identifying iNDVI anomalies. Sensitivity analysis to individual threshold parameters and assessment of the interaction between changes in multiple thresholds is necessary to better understand the local variance anomaly results. We also suggest investigating how changes in parameters can be used to improve results for specific applications.

References

Diouf, A., Lambin, E.F., 2001. Monitoring land-cover changes in semi-arid regions: remote sensing data and field observations in the Ferlo, Senegal. Journal of Arid Environments 48, 129–148.

Eidenshink, J., Faundeen, J., 1994. The 1-km AVHRR global land data set: first stages in implementation. International Journal of Remote Sensing 15, 3443–3462.

Freudenberger, K.S., 1991. Mbegué: the disengenuous destruction of a sahelian forest. International Institute for Environment and Development, Paper No. 29, 28pp.

Fuller, D.O., 1998. Trends in NDVI time series and their relation to rangeland and crop production in Senegal, 1987–1993. International Journal of Remote Sensing 19 (10), 2013–2018.

Hadj, A., Ndiaye, T., 1995. Aperçu sur l'Evolution du Couvert Végétal dans le Terroir de Soukouto par l'Approche de la MARP. Unpublished Report, USGS EROS Data Center, Sioux Falls, SD.

Holben, B.N., 1986. Characteristics of maximum-value composite images from temporal AVHRR data. International Journal of Remote Sensing 7, 1417–1434.

Justice, C.O., Townshend, J.R.G., Holben, B.N., Tucker, C.J., 1985. Analysis of the phenology of global vegetation using meteorological satellite data. International Journal of Remote Sensing 6, 1271–1318.

Li, J., Lewis, J., Rowland, J., Tappan, G., Tieszen, L., 2004. Evaluation of land performance in Senegal using multi-temporal NDVI and rainfall series. Journal of Arid Environments, this issue.

Malo, A.R., Nicholson, S.E., 1990. A study of rainfall and vegetation dynamics in the African Sahel using normalized vegetation index. Journal of Arid Environments 19, 1–24.

Milich, L., Weiss, E., 2000. GAC NDVI images; relationship to rainfall and potential evaporation in the grazing lands of The Gourma (northern Sahel) and in the croplands of Niger–Nigeria border (southern Sahel). International Journal of Remote Sensing 21 (2), 261–280.

Pélissier, P., 1966. Les Paysans du Sénégal: Les civilisations agraires du Cayor à la Casamance. Imprimérie Fabrègue, Saint-Yrieix, France.

Prince, S.D., 1991. Satellite remote sensing of primary production: comparison of results for Sahelian grasslands 1981–1988. International Journal of Remote Sensing 12 (6), 301–311.

Reed, B.C., Brown, J.F., VanderZee, D., Loveland, T.R., Merchant, J.W., Ohlen, D., 1994. Measuring phenological variability from satellite imagery. Journal of Vegetation Science 5, 703–714.

Singh, A., Harrison, A., 1985. Standardized principal components. International Journal of Remote Sensing 6, 883–896.

Swets, D.L., Reed, B.C., Rowland, J.R., & Marko, S.E., 1999. A weighted least-squares approach to temporal NDVI smoothing. In: Proceedings of the 1999 ASPRS Annual Conference: From Image to Information, Portland, Oregon, May 17–21. American Society for Photogrammetry and Remote Sensing, Bethesda, MD.

Tappan, G., Wood, L., Moore, D.G., 1994a. Identifying high production, low production and degraded rangelands in Senegal with normalized difference vegetation index data. In: Proceedings of the Pecora 12 Symposium, Land Information from Space-Based Systems, Sioux Falls, South Dakota, August 1993. American Society for Photogrammetry and Remote Sensing, Falls Church, VA, pp. 176–184.

Tappan, G., Wood, E., Hadj, A., Bodian, A., 1994b. Monitoring natural resource changes in Senegal: preliminary evidence from field sites. Unpublished Report, USGS EROS Data Center, Sioux Falls, SD.

Tappan, G., Hadj, A., Wood, E., Lietzow, R., 2000a. Use of argon, corona, and Landsat imagery to assess 30 years of land resource changes in west-central Senegal. Photogrammetry of Engineering and Remote Sensing 66 (6), 727–735.

Tappan, G., Wood, E., Hadj, A., Sall, M., 2000b. Monitoring climate and human impacts on the vegetation resources of senegal: drought, agricultural expansion, and natural resource management. Unpublished Report, USGS EROS Data Center, Sioux Falls, SD.

Thiam, A.K., 2003. The causes and spatial pattern of land degradation risk in southern Mauritania using multitemporal AVHRR-NDVI imagery and field data. Land Degradation & Development 14, 133–142.

Tucker, C.J., Holben, B.N., Elgin, J.H., McMurtrey, J.E., 1981. Remote sensing of total dry matter accumulation in winter wheat. Remote Sensing of Environment 11, 171–189.

Tucker, C.J., Vanpraet, C.L., Sharman, M.J., Van Ittersum, G., 1985. Satellite remote sensing of total herbaceous biomass production in the Senegalese Sahel: 1980–1984. Remote Sensing of Environment 17, 233–249.

Tucker, C.J., Sellers, P.J., 1986. Satellite remote sensing of primary production. International Journal of Remote Sensing 7, 1395–1416.