ANALYSIS OF 1982-2006 SUDANO-SAHELIAN VEGETATION DYNAMICS USING NOAA-AVHRR NDVI DATA AND NORMALIZED RAIN-USE EFFICIENCY

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ABSTRACT

Land cover dynamic has to be taken into account to analyze changes in water resources, especially in vulnerable environment such as the Bani catchment in Mali. To study the land cover changes, we used NDVI AVHRR time series (1982-2006, 8 km spatial resolution), and monthly rainfall data from 65 stations. To interpret the NDVI trends in terms of land cover changes, we had to eliminate the inter-annual rainfall variability. We used the concept of the Rain Use Efficiency (RUE) which is the ratio between NDVI (a proxy of the Net Primary Production) and precipitation. RUE and rainfall were calculated and modeled on a 0.5° x 0.5° grid scale. For each cell we normalized the evolution of the RUE through time (RUE_cor), and calculated its trend over the 25 years period. The results indicate that RUE_cor is stable or in light increase for most of the grid cells. In areas where water is not a limiting factor of NPP, this trend is positively correlated to the fraction of cropped area changes, as determined from a couple of Landsat images acquired during a similar period. However, RUE is a complex concept and further investigations are needed to consolidate our results and conclusions.

Index Terms— Rain Use Efficiency, Land cover change, AVHRR, Mali

1. INTRODUCTION

The Sudano-Sahelian region, a rainfed agriculture dependent zone, appears as a particularly vulnerable environment, subjected to major evolutions due to climate and man-induced changes. In this context, the RESSAC project has the objective to determine the combined effects of climatic and environmental changes on water resources on the Bani catchment (130 000 km²) in Mali. Conditions of streaming and drainage being very dependent on land cover, it is considered necessary to improve the hydrological models, taking into account the land cover dynamics [1].

Remote sensing appears to be a very good tool to characterize land cover on large territories. In particular, the NOAA-AVHRR images have been widely used for global studies of the Sahelian environment due to their archive size (27 years), free data, suitable wavebands and high temporal resolution. However, the land cover characterization still needs the development of methods for the monitoring of land cover at large scale by remote sensing.

To interpret NDVI trends, many factors have to be considered such as land degradation or improvement, climatic variability and land use change [2]. To interpret NDVI trends in terms of land use changes, we have to eliminate false alarms, especially the rainfall variability. For this, we used the concept of Rain Use Efficiency (RUE). It is the ratio between the Net Primary Production (NPP) to precipitation. Many studies have proposed to use NDVI as a proxy of NPP. However, the interpretation of RUE requires information on topography, soil texture, soil fertility, vegetation type, human population and management regime among others [3]. Nowadays it is not yet completely clear if there is dependence between annual RUE and rainfall. In arid and semi-arid regions, [4] and [5] defend the theory of the interaction based on ecological processes, while [6] incriminates a mathematical bias.

We tested different approaches by studying and modeling the effect of the annual precipitation on NDVI and RUE values calculated at a 0.5° x 0.5° grid over the Bani catchment (Mali). We analyzed the NDVI and RUE trends over a 25 years period (1982-2006), studied the sensitivity of these indices to the rainfall variability and tried to relate these trends to land cover changes derived from Landsat image analysis.

2. MATERIALS AND METHODS

2.1. Study area

The Bani river is the main tributary of the Niger river. Its catchment, stretching from latitude 9°1'N to 14°5'N, and from longitude 3°5’W to 8°5’W, drains an area of some 130 000 km² at its confluence with the Niger at Sofara. Eighty percent of the catchment is in southern Mali, the rest being in Ivory Coast and western Burkina. The North-South rainfall gradient is between 550 and 1150 mm year^{-1}.

The catchment is subject to strong pressure from the local human population combined with migration of sedentary groups from the north. It is also an area where large herds of grazing livestock are moved in search of fresh pasturage. As a result, crop areas have increased (cotton and cereals), while forests and pasture land have deteriorated.

2.2. Data

Monthly maximum-value NDVI composites at 8 km x 8km resolution were derived from daily AVHRR data by the Global Inventory Monitoring and Modelling Studies (GIMMS) Group at National Aeronautics and Space Administration/Goddard Space Flight Center (NASA/ GSFC). An additional quality control was applied to the NDVI dataset to filter out some persistent unrealistic values for the period 1982-2006 [7].

Rainfall data measured by 65 stations installed inside and around the study site were used to establish monthly rainfall series for the 1982-2006 period. A 0.5° x 0.5° grid interpolation was done by inverse distance weighted [1].

Land covers maps were issued from images processing. Two mosaics of Landsat images, acquired at the end of the rainy seasons in 1986 and 2000, were first performed and classified in order to provide twelve vegetation classes [8]. For this study, the land cover map was simplified to a two-classes map (crop/non crop).

2.2. Methods

The Rain Use Efficiency (RUE) is calculated at the 0.5° x 0.5° grid scale (interpolated rainfall grid), as the ratio between the sum of the monthly NDVI to the annual rainfall.

To eliminate the rainfall effect on RUE, we fit a linear regression (_mod) between annual RUE and rainfall for each grid, and normalize RUE values (_cor) to the average rainfall of the grid cell (_ref) as shown in Eq. 2.

$$RUE\_cor = RUE + (RUE\_mod - RUE\_ref) \quad \text{Equation 2}$$

RUE_cor trends were determined by linear regression with absolute change as the slope of the regression. The t-test was used to arrange the slope values in classes showing strong or weak positive or negative trends.

RUE_cor trends were compared grid cell per grid cell to the simplified land cover change map (LCC 1986-2000), assuming that these changes were representative of the whole period. To calculate LCC map, the majority class for each 0.5° x 0.5° cell was first calculated and differences in cropped areas between the two acquisition dates were mapped.

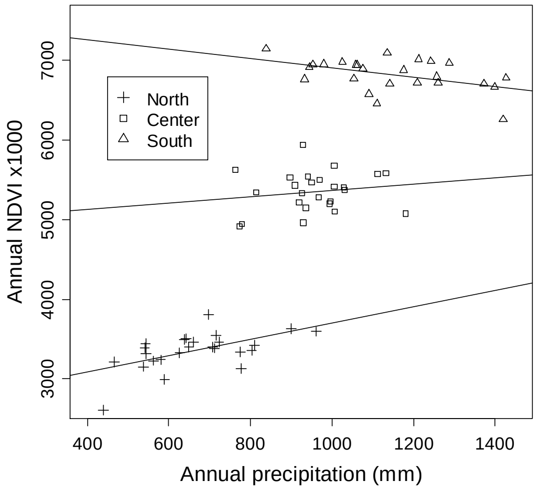

Figure 1. Relationship between NDVI and rainfall for three 0.5° x 0.5° grid cells localized along a longitudinal gradient in the Bani catchment (see text).

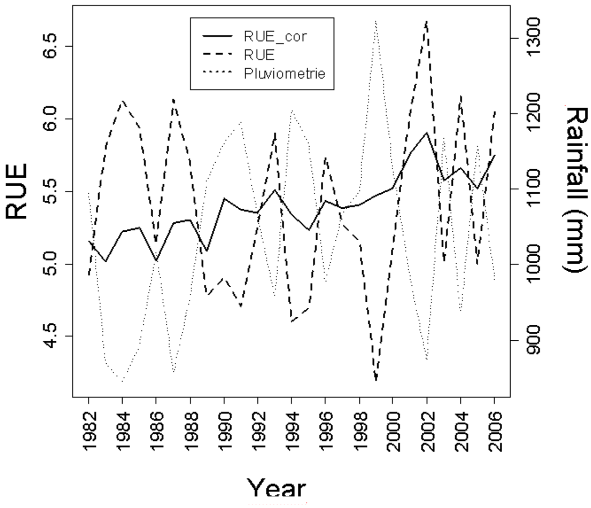

Figure 2. Rain Use Efficiency of the Southern grid cell in function of time, before (RUE; r^2=0.001) and after (RUE_cor; r^2=0.70) annual rainfall correction.

3. RESULTS AND DISCUSSION

Results were obtained for the fifty 0.5° x 0.5° grid cells of the Bani watershed. However we chose to present here the results of only three selected grids that are representative of the different climatic zones (660, 950 and 1150 mm).

3.1. Relation between NDVI and Rainfall

In the North and South parts of the Bani, there is a weak but significant relationship between the annual NDVI and rainfall, while in the Central part there is no correlation between these variables (Fig. 1). In the Sahelian part, the productivity is mainly limited by rainfall, but many factors such as the lag in the response of the vegetation to changes in rainfall or the rain seasonal distribution makes the correlation low. In the Guinean part, the correlation is negative and could be explained by nutrients, light deficiencies or residual cloud contamination of the images.

3.2. Rain Use Efficiency

At the watershed scale, RUE values are between 4.5 and 7.5 with a standard error of 0.5.

As observed by [9], the RUE values varied considerably from year to year, associated with varying rainfall (Fig. 2). When plotted against rainfall, RUE varies linearly and inversely to the annual rainfall (Fig. 3). Using ground observations in semi-arid regions, [4] and [5] observed an increase in RUE with decreasing rainfall for annual rainfall above about 500 mm.

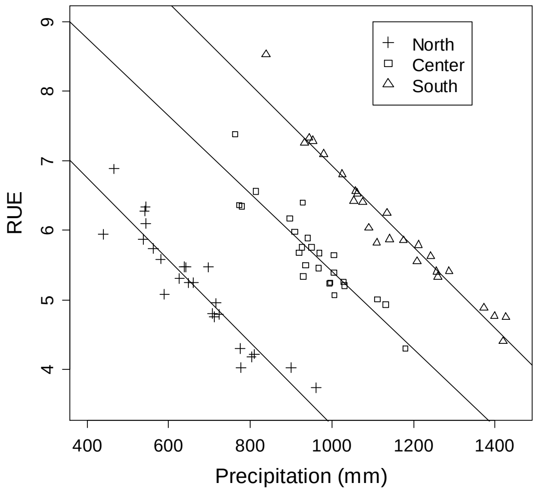

Figure 3. Linear regressions between RUE and precipitation for three 0.5° x 0.5° grid cells localized along a longitudinal gradient in the Bani catchment (see text).

3.3. Trend analysis and validation

The RUE trend with time is never significantly different from 0; the rainfall trend is also not significant. When corrected from the annual rainfall variations (Fig. 3), RUE_cor trend is more regular and statistically significant for most of the grid cells of the Bani watershed (Fig. 2).

By accounting for rainfall, the RUE correction permits to fit linear trends that are statistically significant. The rain-corrected RUE_cor generally exhibits positive trend during the 1982-2006 period (Fig.2), while during en equivalent period the cropped area increased from 13.5% to 22.9% for the Bani watershed. This RUE_cor trend can be interpreted as a change in land cover or land use.

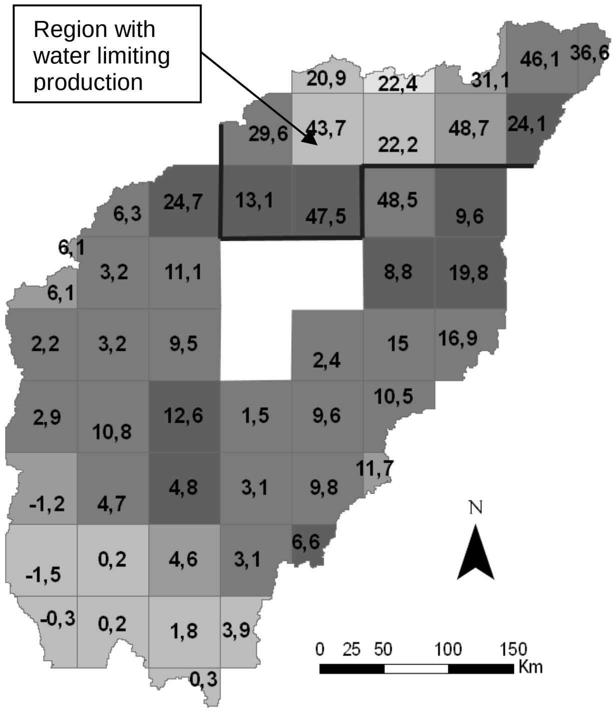

Figure 4. Geographic representation of the RUE_cor trend (color scale: the darker, the higher trend) and the crop cover change (given in percentage) at the 0.5 x 0.5° grid scale over the Bani watershed. Region with limiting water productivity are delineated by a black line. White cells correspond to missing land cover change data.

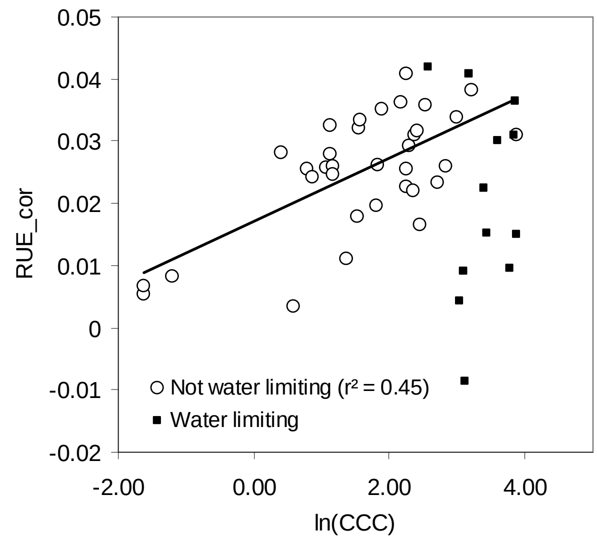

Figure 5. Comparison between the RUE_cor trends and the logarithm of changes in the fraction of cropped areas (CCC) at the 0.5° x 0.5° grid scale. The regression line is only fitted for the “not limiting water” conditions points.

When compared to the land cover change map, and considering only the non-limiting rainfall grid cells, cells with a low slope correspond to the regions with little land cover changes, while cells with a higher slope correspond to regions with significant land cover changes (Fig. 4). This is confirmed by the value of the correlation ($r^2 = 0.45$) between these two variables (Fig. 5), after logarithmic transformation of LCC. This transformation could be issued from the use of NDVI instead of NPP - this hypothesis will be tested in the future.

The positive trend of RUE with increased cropped area is in accordance with [3] who classified fertilizer use and changes in species composition (from C3 woody vegetation to C4 crops) as increasing RUE causes.

4. CONCLUSION

Generally used to in arid and semi-arid regions, RUE is more and more used at the global scale. RUE is easy to determine from NDVI data, but its interpretation is difficult because many factors are involved. This study is based on the premise that the main factors of NDVI variations are the rainfall and the land cover type, and that other factors such as soil type, vegetation degradation, or residual radiometric errors, are second-order factors in the Bani region.

We showed that land cover changes were correlated to the RUE_cor trend in Soudanian and Guinean areas, with increasing trend corresponding to an increase of the cropped area. However, this result should be consolidated, in particular because the use of NDVI as a proxy of NPP is not completely appropriate in regions with high level of biomass and potential saturated NDVI values, and because the RUE rainfall-correction is mathematically unsatisfactory despite ecological considerations.

5. ACKNOWLEDGEMNTS

The authors acknowledge the support of the French Agence Nationale de la Recherche (ANR), under grant RESSAC (ANR-06-VULN-017-01), and Nadine Dessay (IRD) for providing corrected AVHRR GIMMS data set.

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