ISPRS Book Series
in Photogrammetry, Remote Sensing and Spatial Information Sciences

Book Series Editor: Paul Aplin

Volume 8

Recent Advances in Remote Sensing and Geoinformation Processing for Land Degradation Assessment

Land degradation and desertification are amongst the most severe threats to human welfare and the environment, as they affect the livelihoods of some 2 billion people in the world's drylands, and they are directly connected to pressing global environmental problems, such as the loss of biological diversity or global climate change. Strategies to combat these processes and mitigate their effects at the land-management and policy level require spatially explicit, up-to-date information, which can be provided based on remote sensing data and using geoinformation processing techniques.

Recent Advances in Remote Sensing and Geoinformation Processing for Land Degradation Assessment introduces the current state of the art in this field and provides an overview of both conceptual and technological advances of the recent past. With a specific focus on desertification and land degradation, the volume covers the assessment of related biophysical indicators, as well as complementary qualitative information at different spatial and temporal scales. It is shown how remote sensing data may be utilized in the context of assessing and monitoring affected ecosystems and how this information may be assimilated into integrated interpretation and modelling concepts. In addition, different case studies are provided to demonstrate the implementation of these methods in the frame of different local settings.

The volume will be of interest to scientists and students working at the interface of ecosystem services, land degradation/desertification, spatial ecology, remote sensing and spatial modelling, as well as to land managers and policy makers.

Achim Röder is a senior scientist and lecturer with the Remote Sensing Department, University of Trier, and has been involved in research on desertification and land degradation for more than 10 years. His present research focuses on the characterization of landscape trends using time series analysis, and the derivation of biophysical indicators under consideration of scaling effects and transitions.

Joachim Hill has been head of the Remote Sensing Department, University of Trier, since 1994. His research focuses on the application of hyper- and multispectral remote sensing techniques to derive biophysical vegetation parameters and their assimilation in ecosystem models, and on mapping and monitoring land degradation phenomena in dryland ecosystems.

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6000 Broken Sound Parkway, NW
Suite 300, Boca Raton, FL 33487
270 Madison Avenue
New York, NY 10016
2 Park Square, Milton Park
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ISBN-13: 978-0-415-39769-8
9 780415 397698
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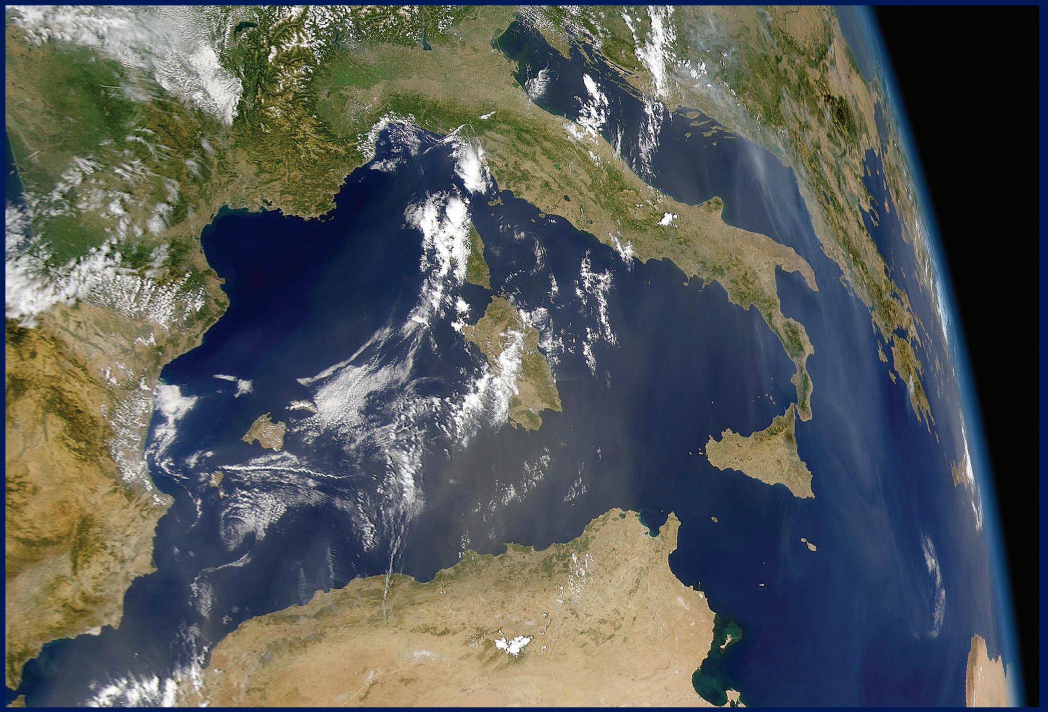

Recent Advances in Remote Sensing and Geoinformation Processing for Land Degradation Assessment

Edited by Achim Röder and Joachim Hill

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Taylor & Francis Group
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CRC Press/Balkema is an imprint of the Taylor & Francis Group, an informa business

Typeset by Vikatan Publishing Solutions (P) Ltd., Chennai, India
Printed and bound in Great Britain by TJ International Ltd, Padstow, Cornwall

Published by: CRC Press/Balkema
P.O. Box 447, 2300 AK Leiden, The Netherlands
e-mail: Pub.NL@taylorandfrancis.com
www.crcpress.com – www.taylorandfrancis.co.uk – www.balkema.nl

British Library Cataloguing in Publication Data

Library of Congress Cataloging-in-Publication Data
Recent Advances in Remote Sensing and Geoinformation Processing for Land Degradation Assessment/editors, Achim Röder & Joachim Hill.
p.cm. -- (International Society for Photogrammetry and Remote Sensing (ISPRS) Book Series; v. 8)
Includes bibliographical references and index.
ISBN: 978-0-415-39769-8 (handcover: alk. paper) -- ISBN: 978-0-203-87544-5 (e-book)
1. Land degradation -- Remote sensing. 2. Remote sensing. I. Röder, Achim. II. Hill, Joachim. III. Title.

GE140.R425 2009
551.41028--dc22

2009002727

ISBN: 978-0-415-39769-8 (hbk)
ISBN: 978-0-203-87544-5 (e-book)
ISSN: 1572-3348

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CRC Press
Taylor & Francis Group
Boca Raton London New York Leiden

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Recent Advances in Remote Sensing and Geoinformation Processing for Land Degradation Assessment – Röder & Hill (eds)
© 2009 Taylor & Francis Group, London, ISBN 978-0-415-39769-8

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Recent Advances in Remote Sensing and Geoinformation Processing for Land Degradation Assessment – Röder & Hill (eds)

Ongoing desertification processes in the sahelian belt of West Africa: An evidence from the rain-use efficiency

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ABSTRACT: The implementation of the UNCCD needs the identification of areas that record declining productivity of the vegetation over long-time periods. In this scope, we analyze the state of the vegetation productivity using 1982–1999 time series of NOAA-AVHRR NDVI data and compare it to rainfall data. For this, 354 rain gauges data distributed from yearly average isohyets 100 to 900 mm in five countries of West Africa are analyzed. We use for trends analysis, the ratio between integrated vegetation index (iNDVI) during the growing period (June to October) and the May to October sum of rainfall (RR). This ratio is a proxy of the Rain Use Efficiency is the widely accepted. Overall, 91% and 94% of RR and iNDVI data recorded positive trends over the 1982–1999 periods. Most stations in the Sahel were stable for the iNDVI/RR (49.5%). However, 37.8% showed strong to very strong negative change in the iNDVI/RR ratio, while only 1.3% showed positive trend. These strong negative trends recorded in more than 1/3 of the analyzed stations may reflect ongoing desertification processes in the Sahel and could be a starting point for the identification of hot-spots areas to determine where to take action within the National Action Programs (NAP) or Sub-Regional Action Programs (SRAP) to combat desertification.

1 INTRODUCTION

After about two decades of dramatic rainfall deficits that started in the late 1960s (L'Hôte et al. 2002), the Sahel of West Africa has experienced increasing precipitation since the early 1990s (Ozer et al. 2003, Dai et al. 2004). Although increasing human pressure on the environment over the same period may have enhanced desertification processes, some authors suggested that the Sahel has been greening from the early 1980s to the late 1990s (Eklundh & Olsson 2003, Pearce 2002).

Since the mid-1970s, desertification benefited from a considerable interest from scientists, politics and the public. Land degradation in arid lands is now recognized as one of the major environmental problems for the 21st century (World Bank 2003) and the Sahel of West Africa is often quoted as the most seriously affected region. Yet, desertification processes often evoke an image of advancing desert with moving dunes threatening houses, roads, oasis and fertile lands and leaving behind a barren and sterile environment. The term desertification has been misused for a long time due to the lack of data, objective indicators and rigorous scientific studies, and because of the inexistence of a widely accepted definition (Nicholson et al. 1998). Many authors have experienced a wide range of indicators in order to map the occurrence and severity of desertification (Mouat et al. 1997, Ozer 2000). Although many of these indicators were unsatisfactory because of their prohibitive costs and time-consuming for the process of data collection, low resolution satellite remote sensing data provide a good source of stable, reliable and long-term measurements (Symeonakis & Drake 2004, Prince 2002).

Methods have been developed to assess the vegetation net primary production (NPP) from the Normalized Difference Vegetation Index (NDVI). These techniques were developed in the mid of 1980s (Justice 1986, Prince & Justice 1991) but it is only recently that a medium-term archive has accumulated with a long enough record (20 years) to allow studies at the appropriate time scale (Prince et al. 1998). In addition, previous studies measured a strong, linear relationship between NDVI and primary production or above-ground total dry-matter accumulation in herbaceous vegetation in the Sahel, based on data for one or two successive years (Tucker et al. 1985, Prince 1991). This relationship was established both through a modelling of interactions between radiation and vegetation, and through empirical studies. In this paper, a proxy of the rain use efficiency (as detailed below) is used in order to identify areas suffering from desertification.

2 DATA AND METHODS

2.1 *Meteorological station data*

Monthly rainfall data were made available from an archive assembled by the "Projet Alerte Précoce et Prévision des Productions Agricoles (AP3A)" of the Centre Régional Agrhymet from station observations. Database includes meteorological stations through the nine countries that are grouped in the Inter-States Committee for Drought Control in the Sahel (CILSS). 354 rain gauges with complete monthly rainfall data from 1982 to 1999 were selected in five countries of West Africa (Mauritania, Senegal, Mali, Burkina Faso and Niger). Here we used the total rainfall records during rainy seasons (RR) that extend from May to October. The bioclimatic subdivision as defined by Ozer (2000) is:

- sahelian zone of the north (Z1): yearly rainfall between 100 and 300 mm
- sahelian zone of the central north (Z2): yearly rainfall between 300 and 500 mm
- sahelo-sudanese of the central south (Z3): yearly rainfall between 500 and 700 mm
- sudanese zone in the south (Z4): yearly rainfall between 700 and 900 mm

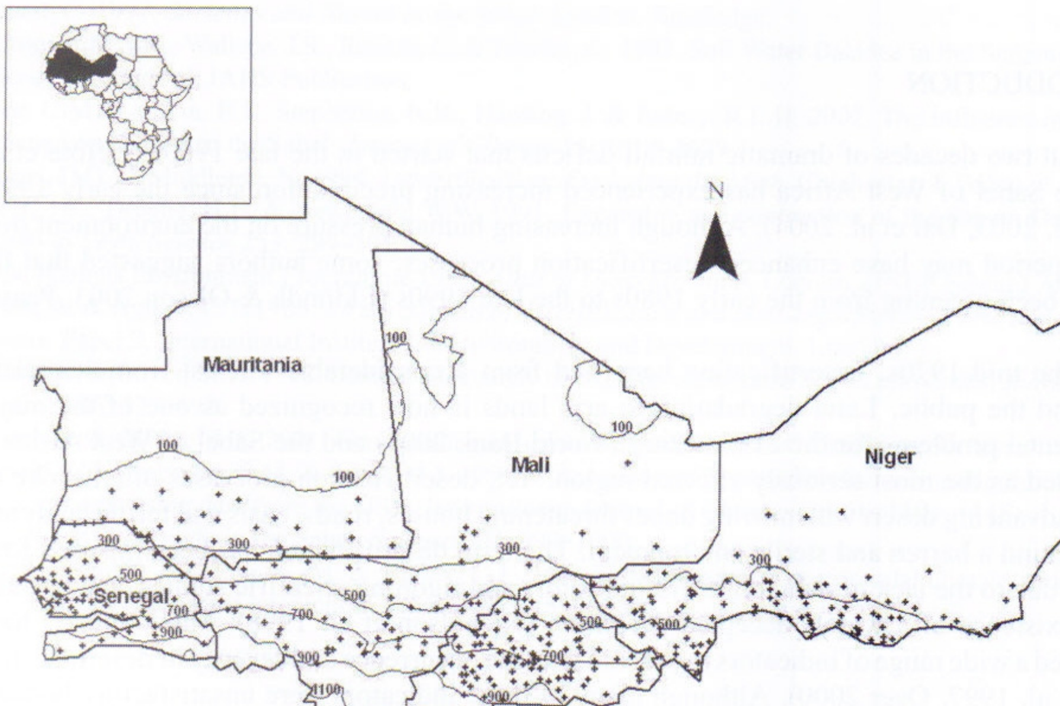

Figure 1. Geographical position of the 354 studied stations (black crosses) and bioclimatic zones (isohyets defined by kriging on average rainfall value for the 1980–2000 periods).

Table 1. Selected stations in West Africa within the 100 to 900 mm isohyets.

Country	Number of selected stations per climatic zone				Total
	Z1: 100–300	Z2: 300–500	Z3: 500–700	Z4: 700–900	
Burkina Faso	0	12	38	49	99
Mali	10	14	16	20	60
Mauritania	27	4	0	0	31
Niger	32	58	16	2	108
Senegal	9	21	18	8	56
Total	78	109	88	79	354

The distribution and repartition of the stations according to four bioclimatic zones (Ozer 2000) are shown in Figure 1 and Table 1.

2.2 *Satellite data*

For the purpose of analyzing vegetation dynamics at sub-continental scale, satellite data from the NOAA AVHRR sensing system for the period 1982–1999, using the Normalized Difference Vegetation Index (NDVI) were used. The NASA/NOAA Pathfinder AVHRR Land (PAL) dataset (James & Kalluri 1994) has been generated as monthly maximum value composites at a 8 × 8 km pixel resolution. Noise levels can be very high over many areas in Africa but are comparatively low over arid to sub-humid areas where cloudiness is limited (Chappell et al. 2001). Quality issues of the Pathfinder database have been discussed by Prince and Goward (1996). The NDVI has proved useful in numerous monitoring studies of vegetation and drought. It is calculated as the normalized difference in reflectance between the red band (0.55–0.68 μm) and the near infrared band (0.73–1.1 μm). This quantity is considered to be a "greenness" index. In arid and semiarid regions, it is well correlated with such parameters as leaf area index, greenleaf, biomass, vegetation cover, etc. (Nicholson et al. 1990). Although it is well known that, especially in sparsely vegetated areas, there is considerable background influence, we will not take this criteria into account as the analysis are systematically focused on similar areas where soil composition is not likely changing during the considered period.

In the present study, the time series was restricted to the period 1982–1999 because, after 1999, a systematic shift in the remotely sensed data resulting from a very high shifting solar zenith angles has been detected (Eklundh & Olsson 2003), probably caused by late afternoon overpass of NOAA-14. In addition, year 1994 was not taken into account because of Pinatubo volcanic dust diffusion into the stratosphere (Tanaka et al. 1994). A total of 354 pixels were selected when including a rain gauge station. For all pixels, the seasonal vegetation index integrals (iNDVI) covering the entire growing season from June to October were computed in order to assess the annual net primary production (Diallo et al. 1991). This approach has been preferred to the use of rasterized rainfall data obtained from satellite estimations, because of stormy features and high spatial variation of sahelian rainfall. Previous studies in Sahel (Amani & Lebel 1997) exhibit a significant difference in annual rainfall score within a distance of 10 km. This implies that the spatial rainfall variability on a small scale is more significant than on the survey level scale.

2.3 *Method*

2.3.1 *Indicator of rain use efficiency*

The net annual increase of biomass, or net primary production, is a measure of the production of an ecosystem. This quantity bears a direct relationship to photosynthesis and NDVI is strongly correlated with both, particularly in arid lands. Le Houérou (1984) suggests that the ratio of primary production to rainfall, iNDVI/RR (rain use efficiency) is a better parameter to characterize arid and semi arid regions like the Sahel. In the Sahel, the dynamic of the vegetation is strongly linked to the rainfall evolution (Symeonakis & Drake 2004, Hess et al. 1996). For regions laying in the annual rainfall 100 mm to 900 mm, the iNDVI/RR ratio is regarded as a useful proxy for rain-use efficiency (Nicholson et al. 1998, Foody 2003). As mentioned by previous studies in the West African Sahel with spatially comprehensive measurements such as these, the incidence of the individual components of desertification could be detected (Diouf & Lambin 2001, Tottrup & Rasmussen 2004). For this research, we derived this ratio during the growing season. The total rainfall amount taken into account is the sum of the May to October precipitation (hereafter referred as rainfall). This period was used here since it has a strong relationship with the iNDVI calculated during the growing season (Davenport & Nicholson 1989, Hess et al. 1996, Hountondji et al. 2006). Indeed, during that period, the monthly rainfall peak generally occurs between August and September (Hess et al. 1996, Ozer 2000) and previous studies showed that the monthly sum NDVI follows monthly rainfall with a lag of about one month (Justice et al. 1986, Justice et al. 1991, Davenport & Nicholson 1989). As for rainfall, the iNDVI calculation ends October. Thus, the ratio of primary production to rainfall formulation is equivalent to:

$$\text{iNDVI/RR} = \frac{\sum_{\text{june}}^{\text{october}} NDVI}{\sum_{\text{may}}^{\text{october}} RR} \qquad (1)$$

where RR = monthly rainfall, and NDVI = monthly normalized difference vegetation index.

2.3.2 *Trend analysis*

For each station, trends from 1982 through 1999 were estimated by linear regression considering the ratio iNDVI/RR as dependent variable and time (years) as independent variable. Regression slopes were recorded for each station as parameters characterising the global trends either for the rainfall or for NDVI. Moreover, each slope was mapped in seven classes indicating very strong, strong, weak positive or negative and stable trends, adapting a procedure suggested by Eklundh & Olsson (2003). The regression procedure supplies a Student-t test and its resulting significance p-level to analyse the hypothesis that the slope is different from 0. This p-level was used as a criterion to define the class boundaries. The trends, for the iNDVI/RR ratio, were labelled as "very strong" if the p-level exceeded 0.05 for the one-tailed t-test, "strong" if the p-level ranged between 0.05 and 0.1, "weak" if the p-level is between 0.1 and 0.2 and otherwise "stable" if the p-level is up to 0.2. These long-term linear trends for each pixel in the iNDVI/RR ratio may be understood as a combination of a number of interrelated factors including variations of biophysical and human influences. As the iNDVI/RR ratio is thought to remain stable through time, such trends can be interpreted as a measure of possible degradation or improvement of the vegetation growth.

3 RESULTS AND DISCUSSION

3.1 *Rainfall*

A preliminary analysis of rainfall data indicates increasing rainfall in the Sahel of West Africa during the studied period (Fig. 2). Overall, 91.4% of May to October rainfall recorded positive slope over the 1982–1999 period (not shown). In detail, 48.9% of the stations showed a very strong to strong positive trend, and 11% recorded a weak positive change. Stability characterized 39% of the analyzed stations, while less than 1% recorded a weak negative trend. Stations that have recorded the most remarkable positive changes seem to follow a north-south geographic gradient and one station out of two shows a stable tendency in the rainfall fringe between 700–900 mm. Such results were expected especially when considering that the drought period culminated in the early 1980s (L'Hôte et al. 2002, Dai et al. 2004, Nicholson 1985) that is the beginning of the analyzed dataset. In addition, these results are in accordance with recent investigations on rainfall variations in the Sahel suggesting that the drought may have ended in the early 1990s (Ozer et al. 2003).

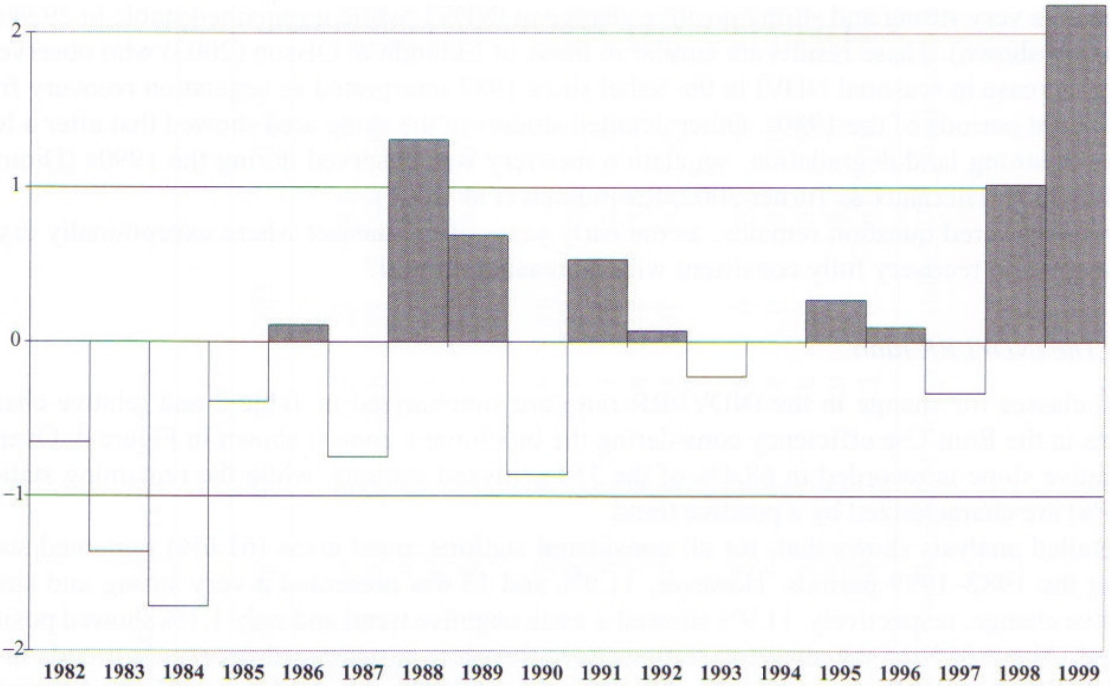

Figure 2. Average Z-scores (expressed as standard deviations) of rainfall for the 354 stations selected throughout the Sahel.

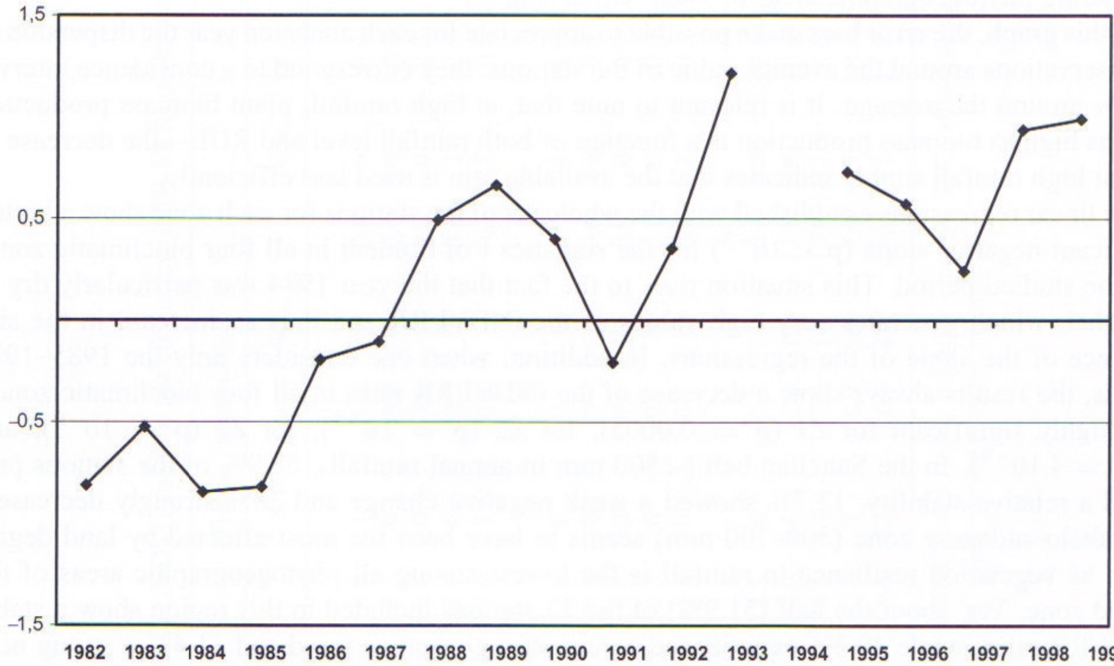

Figure 3. Average Z-scores (expressed as standard deviations) of iNDVI for the 354 stations selected throughout the Sahel. (note that 1994 is not considered because of the Pinatubo effect).

3.2 *The seasonal vegetation index (iNDVI)*

As expected, a substantial increase in the seasonal vegetation index was noticed consecutively to wetter conditions observed during the studied period. Yet, Figure 3 shows a constant below average iNDVI Z-score during the six first years of the analysis (1982–1987) that were among the driest years of the 20th century (L'Hôte et al. 2002, Nicholson 1985) while this value is systematically above average during the eight latest years (1992–1999) logically due to the strong rainfall recovery (Ozer et al. 2003). Overall, throughout the 354 pixels analyzed in the Sahel of West Africa, 62.8%

presented a very strong and strong positive change in iNDVI, while it remained stable in 29.9% of cases (not shown). These results are similar to those of Eklundh & Olsson (2003) who observed a strong increase in seasonal NDVI in the Sahel since 1982 interpreted as vegetation recovery from the drought periods of the 1980s. Other detailed studies in the same area showed that after a long period of strong land degradation, vegetation recovery was observed during the 1990s (Diouf & Lambin 2001, Hiernaux & Turner 2002, Rasmussen et al. 2001).

An unanswered question remains: as the early years of the dataset where exceptionally dry, is this vegetation recovery fully consistent with increasing rainfall?

3.3 *The iNDVI/RR ratio*

Trend classes for change in the iNDVI/RR ratio are summarized in Table 2 and relative change classes in the Rain Use efficiency considering the bioclimatic zone is shown in Figure 4. Overall, a negative slope is recorded in 68.4% of the 354 analyzed stations, while the remaining stations (31.6%) are characterized by a positive trend.

Detailed analysis shows that, for all considered stations, most areas (61.6%) remained stable during the 1982–1999 periods. However, 11.9% and 13.6% presented a very strong and strong negative change, respectively. 11.9% showed a weak negative trend and only 1.1% showed positive change. About 38% of the analyzed stations have therefore experienced decreasing trends in the iNDVI/RR ratio that may reflect possible degradation of the vegetation growth, and therefore ongoing desertification processes. The geographical distribution of downward weak to strong trends is fuzzy and may indicate localized land degradation processes in some places while few others may experience improved land management. Differences in changes are highlighted when considering phytogeographic areas of West Africa (Fig. 5).

On this graph, the error bars make possible to appreciate for each analyzed year the dispersion of the observations around the average value of the stations: they correspond to a confidence interval of 95% around the average. It is relevant to note that, at high rainfall, plant biomass production remains high as biomass production is a function of both rainfall level and RUE—the decrease in RUE at high rainfall simply indicates that the available rain is used less efficiently.

The linear regressions established with the whole set of the stations for each zone show a highly significant negative slope ($p < 10^{-3}$) for the statistics t of Student in all four bioclimatic zones over the studied period. This situation rises to the fact that the year 1984 was particularly dry in the Sahel, which generates very high values of the iNDVI/RR and thus an increase in the significance of the slope of the regressions. In addition, when one considers only the 1985–1999 periods, the results always show a decrease of the iNDVI/RR ratio in all four bioclimatic zones, with highly significant for Z1 ($p = 0.0005$), for Z2 ($p = 10^{-5}$), for Z3 ($p = 10^{-6}$), and Z4 ($p = 4.10^{-7}$). In the Sahelian belt (<500 mm in annual rainfall), 58.9% of the stations presented a relative stability, 12.7% showed a weak negative change and 28% strongly decreased. The sahelo-sudanese zone (500–700 mm) seems to have been the most affected by land degradation as vegetation resilience to rainfall is the lowest among all phytogeographic areas of the studied zone. Yet, about the half (51.9%) of the 79 stations included in this region show a stable iNDVI/RR ratio, while 20.3% experienced a very strong negative trend and 11.4% a strong negative change. In the Sudanese zone (700–900 mm), 72.2% of the stations appeared to be stable, while 16.5% and 8.9% suffered from a strong and weak negative change, respectively. However, it is worth mentioning that theses regions include the only stations of West Africa that display a weak positive change (2.5%). The obtained results in this southern region should be taken with precaution as previous studies mentioned that the relationship between NDVI and rainfall tends to weaken when annual rainfall is higher than 1000 mm. For sites dominated by woody and perennial herbaceous species, the same overall pattern can be expected. However, the relation may be less obvious because there is less interannual variation in the composition of the vegetation cover, and as woody and perennial herbaceous species can store nutrients and may tap groundwater reserves in deep soil layers. As primary production remains relatively constant, it seems that water is not a major limiting factor in these areas (Nicholson et al. 1990; Davenport & Nicholson 1989).

Table 2. Rainfall (RR), integrated NDVI (iNDVI) and rain use efficiency (iNDVI/RR) trends for 354 stations in West Africa (1982–1999).

	Slopes				Trends significance															
Parameters	POS	%	NEG	%	VSNC	%	SNC	%	WNC	%	S	%	WPC	%	SPC	%	VSPC	%	Total	%
RR																				
100 < P < 300	71	91.0	7	9.0	1	1.3	0	0.0	0	0.0	31	39.7	8	10.3	15	19.2	23	29.5	78	22.0
300 < P < 500	100	91.7	9	8.3	0	0.0	0	0.0	0	0.0	32	29.4	15	13.8	24	22.0	38	34.9	109	30.8
500 < P < 700	82	93.2	6	6.8	0	0.0	1	1.1	0	0.0	33	37.5	8	9.1	16	18.2	30	34.1	88	24.9
700 < P < 900	69	87.3	10	12.7	0	0.0	0	0.0	2	2.5	42	53.2	8	10.1	13	16.5	14	17.7	79	22.3
Total	322	91.0	32	9.0	1	0.3	1	0.3	2	0.6	138	39.0	39	11.0	68	19.2	105	29.7	354	100.0
iNDVI																				
100 < P < 300	76	97.4	2	2.6	0	0	0	0.0	1	1.3	19	24.4	2	2.6	5	6.4	51	65.4	78	22.0
300 < P < 500	100	91.7	9	8.3	0	0	0	0.0	0	0.0	34	31.2	10	9.2	15	13.8	50	45.9	109	30.8
500 < P < 700	82	93.2	6	6.8	0	0	0	0.0	0	0.0	31	35.2	6	6.8	5	5.7	46	52.3	88	24.9
700 < P < 900	77	97.5	2	2.5	0	0	0	0.0	0	0.0	22	27.8	7	8.9	6	7.6	44	55.7	79	22.3
Total	335	94.6	19	5.4	0	0	0	0.0	1	0.3	106	29.9	25	7.1	31	8.8	191	54.0	354	100.0
iNDVI/RR																				
100 < P < 300	14	17.9	64	82.1	6	7.7	13	16.7	10	12.8	49	62.8	0	0.0	0	0.0	0	0.0	78	22.0
300 < P < 500	19	17.4	90	82.6	14	12.8	15	13.8	18	16.5	61	56.0	0	0.0	1	0.9	0	0.0	109	30.8
500 < P < 700	18	20.5	70	79.5	15	17.0	14	15.9	7	8.0	51	58.0	1	1.1	0	0.0	0	0.0	88	24.9
700 < P < 900	61	77.2	18	22.8	7	8.9	6	7.6	7	8.9	57	72.2	2	2.5	0	0.0	0	0.0	79	22.3
Total	112	31.6	242	68.4	42	11.9	48	13.6	42	11.9	218	61.6	3	0.8	1	0.3	0	0.0	354	100.0

Legend: POS: positive; NEG: negative; VSNC: very strong negative change; SNC: strong negative change; WNC: weak negative change; S: stable; WPC: weak positive change; SPC: strong positive change; VSPC: very strong positive change.

Such contrasting evolutions along the bioclimatic gradients of the semi-arid belt West Africa are in accordance with recent findings of Hiernaux & Turner (2002). These authors stated that risks of environmental degradation are moderate and mainly climate-driven in pastoral systems at the drier edge, while they are serious and mainly management-driven in the crop-livestock systems of the sahelo-sudanese zone. Our results indeed show that 58.9% of the stations remained stable in the northern part of the studied area, while about 25% of the analyzed stations suffered from very strong, strong or weak negative changes in the sahelo-sudanese zone in the central north. As a matter of fact, Henry & colleagues (2003) showed that migration flows from the northern ecologically marginal area to the sahelo-sudanese zone were partly explained by unfavourable environmental variables such as high rainfall variability, land degradation, and land availability at the origin, and favourable conditions at the destination for these variables. For this reason, there is currently less pressure in the northern part of the Sahel as people migrated because of drought while migrations are likely to contribute to negative environmental changes at the destination (Lambin et al. 2001).

Recent claims that the Sahel is greening since the 1990s because of improved land management (Mazzucato & Niemeijer 2000, Rasmussen et al. 2001, Niemeijer & Mazzucato 2002, Pearce 2002, Eklundh & Olsson 2003) may be only partly true. As an example, Mazzucato & Niemeijer (2000) closely studied two small areas (Bilanga and Fada-N'Gourma) in Eastern Burkina Faso and suggested that these areas showed no evidence of land degradation as crop yields increased. Our results on these two stations indeed show that if the iNDVI presented positive slopes, the iNDVI/RR ratio experienced a strong negative change in Bilanga and a weak negative change in Fada-N'Gourma, suggesting that the rain-use efficiency of the vegetation has been declining over the last two decades (Figs. 6, 7). In northern Burkina Faso (Gorom-Gorom), Rasmussen et al. (2001) suggested that desertification was in reverse demonstrating that vegetation was reclaiming fossil dunes revitalised during the droughts of the 1970s and 1980s. Our results at this station (Figure 8) suggest that the iNDVI strongly increased and that the iNDVI/RR ratio remained stable during the 1980s and 1990s. In this specific case, it can be accepted that the vegetation is resilient with the rainfall increase observed during the last decade.

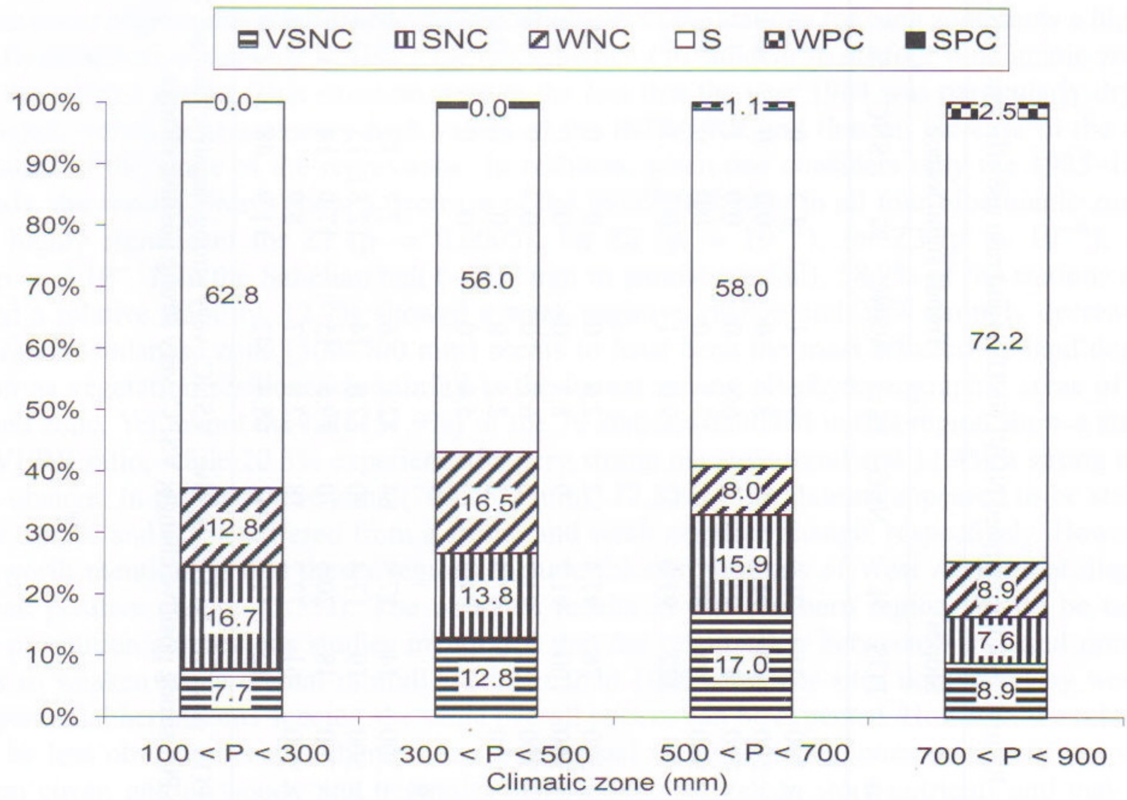

Figure 4. Relative change classes in the Rain Use efficiency considering the bioclimatic zones (100–900 mm). Legend: VSNC: very strong negative change; SNC: strong negative change; WNC: weak positive change; S: stable; VSPC: very strong positive change; SPC: strong positive change; WPC: weak positive change.

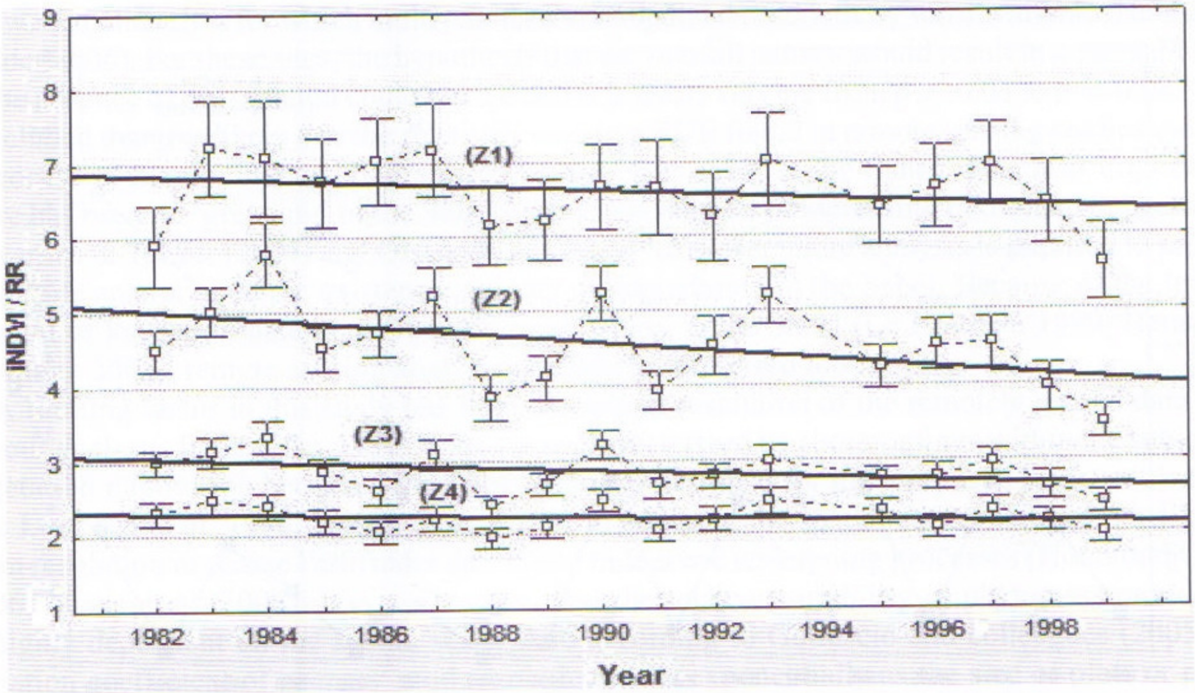

Figure 5. Rain Use efficiency trends considering the bioclimatic zone (100–900 mm) during 1982–1999 periods in the studied area.

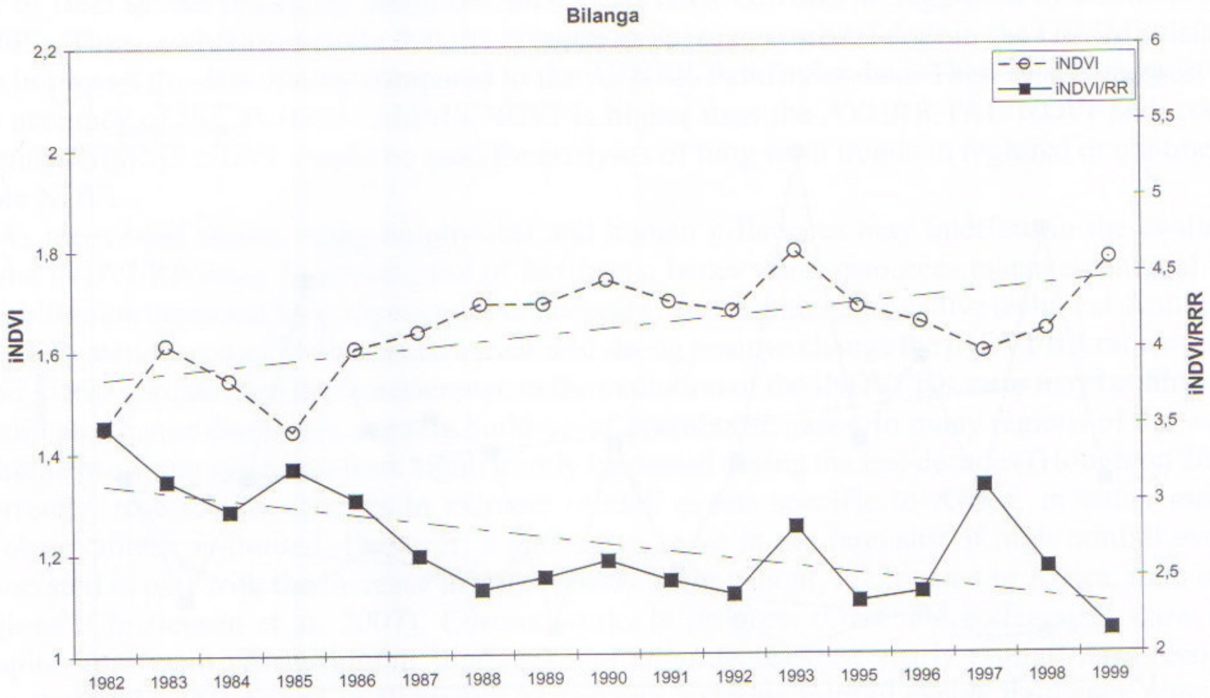

Figure 6. Interannual variability of integrated NDVI and iNDVI/RR ratio as a proxy of Rain Use Efficiency at Bilanga site (Eastern Burkina Faso) (Hountondji et al. 2006).

Elsewhere, Hein & De Ridder (2006) studying the relationship between RUE and rainfall at Sydenham, South Africa, and in the Ferlo, Senegal, demonstrated how the whole curve shifts towards a lower RUE following degradation of the ecosystem (O'Connor et al. 2001). These authors noticed that the quadratic relation between rainfall and RUE still allows for a decline in RUE following degradation of the vegetation cover. Hence, RUE is a function of both the state of the vegetation cover and annual rainfall, and analysis of degradation with satellite images requires consideration of the rainfall pattern during the time of satellite observations. If further analysis of remote sensing images confirms a process of degradation in the Sahel, this would have important consequences for the ongoing debate on equilibrium vs. non-equilibrium approaches to rangeland dynamics. It would confirm the relevance of the equilibrium approach with respect to the overall

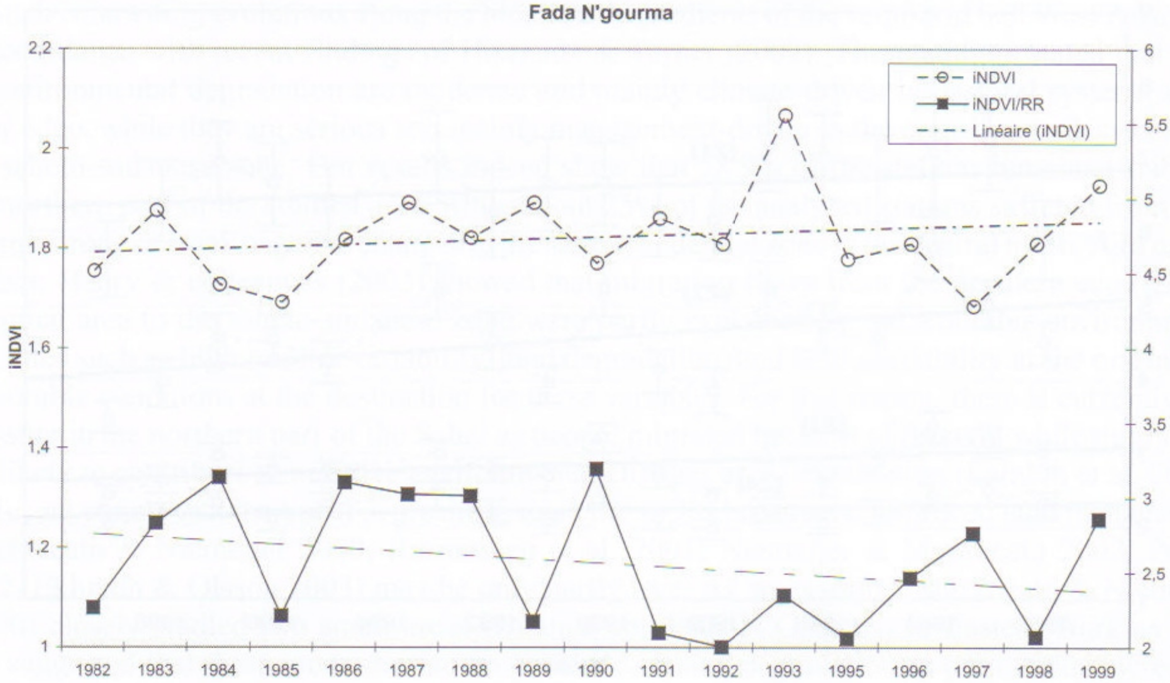

Figure 7. Interannual variability of integrated NDVI and iNDVI/RR ratio as a proxy of Rain Use Efficiency at Fada N'gourma site (Eastern Burkina Faso) (Hountondji et al. 2006).

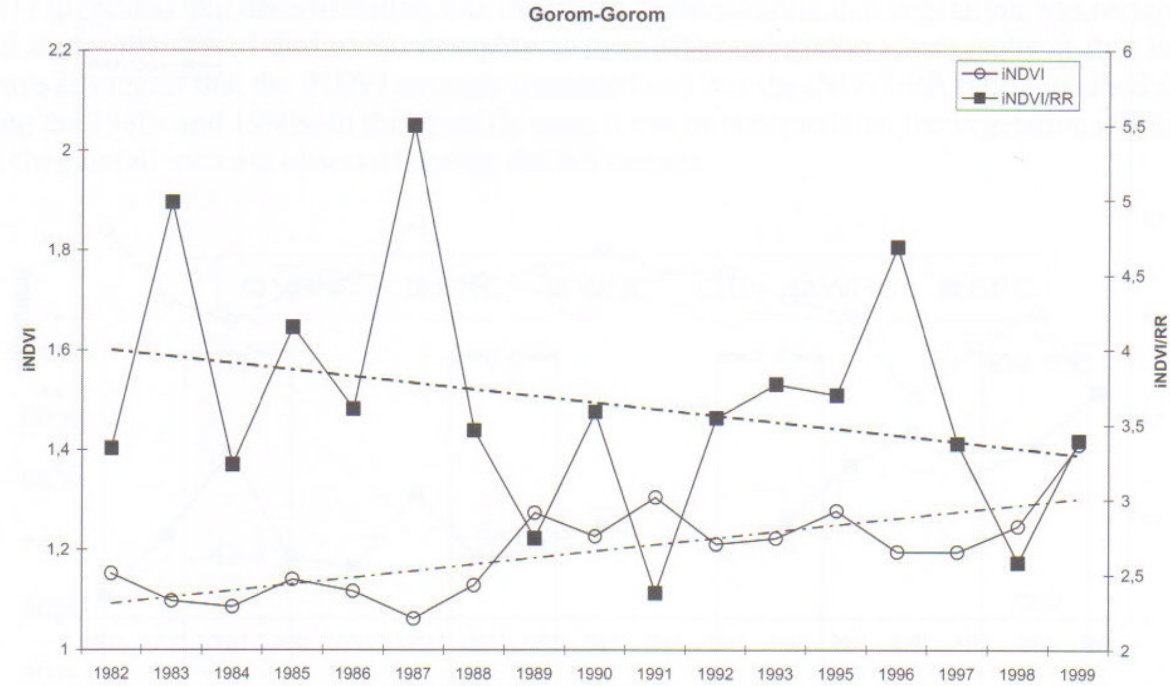

Figure 8. Interannual variability of integrated NDVI and iNDVI/RR ratio as a proxy of Rain Use Efficiency at Gorom-gorom site (Northern Burkina Faso) (Hountondji et al. 2006).

impact of grazing at the scale of the Sahel under current grazing pressures (cf. Le Houérou 1989; Hérault & Hiernaux 2004). In addition, if man-induced degradation of the Sahel (overgrazing, wood cutting, land mismanagement) is demonstrated, this would have repercussions for the debate on the causes of climate change in the Sahel. Currently, a weakness in the argumentations of Xue & Shukla (1993) and Wang et al. (2004) that anthropogenic-induced land cover changes have contributed to the occurrence of the extreme Sahelian droughts of the last decades of the 20th century is a lack of evidence of degradation from remote sensing data.

Therefore, the conclusion that satellite data do not show long-term degradation in the Sahel is premature (Hountondji et al. 2006, Ozer et al. 2007). This is further illustrated by recent findings on two Sahelian sites for which multiyear data on rangeland productivity were available (Hein & De Ridder 2006). For these sites, the hypothesis that the rainfall pattern would result in a constant RUE in the absence of degradation could be rejected at p levels varying from $p = 0.03$ to $p = 0.08$. They concluded that it is likely that the relatively constant RUE found in remote sensing studies indicate a process of human induced degradation of the plant cover in the Sahel. This also implies that there has been no 'greening' of the Sahel beyond the impacts of increasing rainfall, as suggested in Anyamba & Tucker (2005) and Olsson et al. (2005). However, more analysis is required to provide a definite answer as to the existence and rate of degradation in the Sahel. Because of the limited amount of long-term data on phytomass productivity in the Sahel (Le Houérou 1989, Herault & Hiernaux 2003), remote sensing analysis remains the preferred tool.

A limiting factor in this study has been the spatial resolution of the remotely sensed data used for our analysis. In fact, the AVHRR sensor is characterized by shortcomings within the subject of vegetation monitoring because it was not originally designed for this purpose (Teillet et al. 1997; Van Leeuwen et al. 1999, Steven et al. 2003). In addition, the spatial extrapolation from 1 km to 8 km resolution in coarse Pathfinder data could hide some undergoing processes (Hountondji et al. 2006; Niang et al. 2008). It is well known that the relative variability of phytomass production is highly dependent on the spatial scale. And according to Golluscio and colleagues (2005) the variation coefficient of primary production decreases exponentially as the size of plots or pixels increases. Therefore, it appears that the coarse resolution remote sensing estimates of vegetation production may underestimate the temporal variability of production as measured in smaller field sites (Diouf & Lambin 2001). An alternative solution for this weakness could be found through the use of finer spatial resolution imageries such as AVHRR GIMMS as suggested by Fensholt et al. (2006). These authors conclude that the correction for sensor orbital drift in the GIMMS data set has improved the data quality compared to the AVHRR Pathfinder data. Their results suggest that the accuracy of the AVHRR GIMMS NDVI is higher than the AVHRR PAL NDVI and, consequently, GIMMS NDVI should be used for analyses of long-term trends in regional or continental scale NDVI.

As mentioned above, many biophysical and human influences may interfere in the evolution of the iNDVI/RR ratio. Increasing use of fertilizers, better water resources management and land rehabilitation measures have improved over the years. But despite such positive technical evolutions, only four stations out of 354 recorded a weak and strong positive change the iNDVI/RR ratio over the 1982–1999 periods. Another interference in the evolution of the iNDVI/RR ratio may be attributed to climate change due to the ongoing build-up of greenhouse gases. In many regions of the world, extreme precipitation events have significantly increased during the last decades (Houghton 2001). Currently, research on changes in extreme rainfall events specific to Africa, in either models or observations, is limited. However, a general increase in the intensity of high-rainfall events, associated in part with the increase in atmospheric water vapour, is expected in Africa, as in other regions (Christensen et al. 2007). Current works in progress (Ozer and colleagues) show that, despite significant yearly rainfall shortages and large decrease of yearly rainfall days recorded over the 1941–2004 period in Niger and Mauritania, extreme rainfall events frequency remained stable and, sometimes, significantly increasing. This may partly explain a large increase of floods observed lately in several areas of West Africa (Sene & Ozer 2002, Tarhule 2005).

If this trend was confirmed, then the iNDVI/RR ratio may be negatively affected as extreme daily precipitation can not be fully used by vegetation and can further cause erosion and soil crusting.

4 CONCLUSION

Based on observations of increased crop yields and/or NDVI, recent studies have stated that desertification in the African Sahel was in reverse. However, using trends in the iNDVI/RR ratio, our results suggest that about 37.4% of the analyzed stations may have experienced ongoing desertification processes during the 1982–1999 periods. Our findings present an environmental situation that is probably more gloomy than recent papers stated although we are far from the concept of irreversible land degradation that was so fashionable until recently. Nevertheless, these results have to be taken with precaution because of the needs of biophysical significance of the stable trends recorded in the study. It is possible that the coarse spatial resolution of AVHRR data (64 km^2) may hide undergoing trends that are not detectable at this scale. Hence, if new remote sensing analyses confirm anthropogenic degradation (overgrazing, wood cutting, land mismanagement), this would support the hypothesis that degradation of the vegetation layer, in particular through sustained high grazing pressures, has contributed to the occurrence of the 20th century droughts in the Sahel. Furthermore, if degradation of the Sahelian vegetation cover is confirmed, this would indicate that Sahelian pastoralists may be more vulnerable for future droughts than currently assumed. Because degradation of the Sahel in the 1980s and 1990s has been masked by an upward trend in annual rainfall, the consequences of a future drought for the local population could be unexpectedly severe. Otherwise, for more accurate investigations, any remote sensing-based monitoring system of land degradation in such area must be complemented by field data collection, in particular with floristic composition data which is not detectable from space, even at fine spatial resolutions. This could be a starting point for switching from empirical approaches based on vegetation indices, which suggest an improvement of the environmental situation at the regional scale, but that may not reflect real situation.

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