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Desertification in the Sahel: a reinterpretation

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Abstract

The impact of human management, in particular livestock grazing, on the vegetation cover of the Sahel is still debated. In a range of studies, satellite images have been used to analyze the development of the Sahelian vegetation cover over time. These studies did not reveal any significant degradation of the Sahel in the last two decades. In this paper, we examine the ecological assumptions underlying the use of satellite imagery to analyze degradation of the Sahel. Specifically, we analyze the variability of the rain-use efficiency (RUE), which is often used as an indicator for the state of the vegetation cover. We detect a fundamental flaw in the way RUE has been handled in most remote sensing studies; they ignored the relation between annual rainfall variation and RUE. Because of the upward trend in annual rainfall that occurred during the 1980s and 1990s, this leads to a bias in the interpretation of the satellite images. In this paper, we show the importance of the variability in RUE for the analysis of remote sensing imagery of semiarid rangelands. Our analysis also shows that it is likely that there has been anthropogenic degradation of the Sahelian vegetation cover in the last two decades. This has important consequences for the debate on the impacts of grazing on semiarid rangelands. Furthermore, the occurrence of anthropogenic degradation is relevant to explain the magnitude of 20th century Sahelian droughts. The analyses also indicate that the population of the Sahel may be more vulnerable for droughts than currently assumed.

Keywords: desertification, rain-use efficiency, remote sensing, Sahel, semi-arid rangeland

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Introduction

The Sahel is the semiarid transition zone between the Sahara desert and the subhumid savanna zone, with an average annual rainfall of some 200–600 mm. It stretches across northern Africa from Senegal in the west to Sudan in the east. Since the 1960s, the Sahel has suffered a number of extreme droughts that have been related to climate change (Giannini *et al*., 2003; Zeng, 2003). These droughts caused large losses of livestock and brought famine to millions of people. In order to define optimal management strategies for the Sahel in the face of a changing climate, it is crucial to understand the dynamics of the Sahelian rangelands. However, the dynamics of semiarid rangelands are still subject to discussion. Two perspectives have dominated the debate (Briske *et al*., 2003).

According to the *equilibrium* approach to rangeland dynamics, sustained anthropogenic pressure causes degradation of the Sahelian ecosystem. Livestock is the main source of income for the local population, and, under the open access conditions prevailing in the Sahel, pastoralists tend to favor high stocking densities (Le Houérou, 1989; De Leeuw & Tothill, 1990). High stocking densities affect the structure and composition of the herbaceous layer, which reduces the productivity of the rangeland and increases the system's vulnerability for drought (Breman & de Wit, 1983; Schlesinger *et al*., 1990; Illius & O'Connor, 1999). The *nonequilibrium* approach stresses the importance of stochastic, external disturbances as drivers for ecosystem change (Westoby *et al*., 1989). In this view, annual rainfall and its variability are the main drivers for the Sahelian ecosystem, and heavy grazing pressure only has a marginal impact on the productivity of the herbaceous layer. After a drought, a few years with good rainfall can fully restore state and productivity of the plant cover (Ellis & Swift, 1988; Sullivan & Rohde, 2002).

Recent studies suggest that both equilibrium and nonequilibrium approaches are required to understand

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the dynamics of semiarid rangelands (Briske *et al*., 2003; Vetter, 2005). Their relative importance depends on the characteristics of the rangeland (Fernandez-Gimenez & Allen-Diaz, 1999; Walker & Wilson, 2002) and the spatial and temporal scales under consideration (Ryerson & Parmenter, 2001; Vetter, 2005). In order to enhance the understanding of the dynamics of the Sahelian vegetation cover, it is necessary to analyze how the vegetation cover has changed in the past decades as a function of human management and climatic variability.

Furthermore, it has been suggested that degradation of the vegetation cover in the Sahel, and the accompanying changes in albedo, evapotranspiration and surface roughness, have contributed to the droughts that occurred in the Sahel in the 1970s and 1980s (Charney, 1975; Xue & Shukla, 1993). Using a coupled atmosphere–biosphere model to simulate 20th century Sahelian rainfall patterns, Wang *et al*. (2004) indicate that, besides sea-surface temperature changes and natural vegetation feedback (vegetation dynamics due to climate variability), anthropogenic land cover changes are required to explain the occurrence of 20th century droughts in the Sahel. Hence, understanding the impact of human management on the vegetation cover of the Sahel is also highly important to further the understanding of regional climate processes.

Remote sensing provides an efficient tool to assess the development of the vegetation cover in large tracks of rangelands. A range of studies have examined degradation of the vegetation cover in the Sahel using satellite images (Tucker *et al*., 1991; Nicholson *et al*., 1998; Prince *et al*., 1998; Anyamba & Tucker, 2005; Olsson *et al*., 2005). These studies concluded that there is no evidence for degradation of the Sahelian vegetation cover. In the words of Kerr (1998) 'the satellite record does not reveal any long-term degradation of the vegetated land (in the Sahel)'. To the contrary, recent studies found an increasing 'greenness' of Sahelian grasslands that cannot be fully explained by the increasing rainfall since the mid-1980s (Anyamba & Tucker, 2005; Olsson *et al*., 2005). An unequivocal explanation for the occurrence of the 'greening' of the Sahel, however, has not yet been found (Olsson *et al*., 2005).

Because satellite images appear to indicate no impact of high grazing pressures on the vegetation cover of the Sahel, there is now a tendency to focus on the climatic drivers of land management patterns in the Sahel. This interpretation is in line with the insights in rangeland dynamics provided by the nonequilibrium approach (Mortimore & Turner, 2005).

This article analyses one of the key ecological assumptions underlying the use of satellite imagery to assess desertification in the Sahel. Based on an analysis of the rain-use efficiency (RUE) of the Sahelian vegetation, we detect a fundamental flaw in the way remote sensing images have been interpreted. This leads us to question the conclusion that satellite images do not show any long-term degradation of the Sahelian vegetation cover. Our study is highly relevant for the discussion on equilibrium vs. nonequilibrium approaches in rangeland dynamics as well as the debate on the drivers for climate change in the Sahel. Furthermore, the implications of the findings of this study for the vulnerability of the Sahelian population to future droughts are examined.

Materials and methods

A key indicator for the functioning of semiarid ecosystems is the RUE (Le Houérou, 1984). RUE is the quotient of annual net primary production and annual rainfall, and is often expressed as the amount of dry plant material produced on 1 ha in 1 yr mm^{-1} of rainfall. Both the spatial and the temporal dimension of the RUE have been examined in numerous studies (Le Houérou *et al*., 1988). Spatial variation in RUE occurs as a consequence of, for instance, differences in average annual rainfall and vegetation type between sites (Huxman *et al*., 2004). Temporal variation in RUE occurs as a consequence of changes in the vegetation at a given site (Varnamkhasti *et al*., 1995).

For a given site, a decline in RUE over time is generally acknowledged to indicate ecosystem degradation (Varnamkhasti *et al*., 1995; Snyman, 1998). A decrease in RUE reflects a reduced capacity of the vegetation to transform water (and nutrients) to biomass. This can involve a range of processes, such as a loss of vegetation cover, a decrease in the availability of plant nutrients, or compaction of topsoil leading to increased run-off (Snyman & Fouché, 1991).

RUE is a key indicator in the studies that use satellite-derived data to analyze degradation in the Sahel. Satellite observations furnish the net primary production, which is combined with data on annual rainfall from climate stations in order to obtain the RUE. Net primary production can be derived from the normalized difference vegetation index (NDVI), which is calculated from the red and near-infrared reflectance bands. Hence, satellite images provide a means to measure RUE of the vegetation cover, on an annual basis, for large areas at a time (Hielkema *et al*., 1986; Malo & Nicholson, 1990).

In the remote sensing studies on degradation in the Sahel, it is assumed that, in the absence of degradation, *for a given site, RUE is constant over time* (Tucker *et al*., 1991; Nicholson *et al*., 1998; Prince *et al*., 1998; Anyamba & Tucker, 2005). In this paper, we examine if this assumption is in line with ecological insights in the dynamics of Sahelian grasslands, and if this assumption is supported by field measurements of the productivity of semiarid grasslands. This is done on the basis of a literature review of grassland dynamics, and an analysis of the grassland productivity data presented in several vegetation studies in semiarid grasslands. The paper focuses on herbaceous biomass as, in the Sahel, the ligneous stratum accounts for less than 10% of the ground cover (Breman & Cissé, 1977; Le Houérou, 1989; Breman & De Ridder, 1991).

Grassland productivity data are extracted from six studies that analyze the annual aboveground phytomass production in a semiarid rangeland over time. From these studies, we consider the aboveground herbaceous phytomass production, including annual and perennial grasses and forbs. Two of these sites are located in the Sahel, the four others are from different semiarid rangelands in three continents. The two sites in the Sahel are Gadabedji, Niger (16°02′N, 7°30′E) and Widou Thiengoly, Senegal (15°20′N, 16°21′W). The four other sites are Migda in the Negev dessert (Israel), Sulaibiya (Kuwait), Sydenham (South Africa) and Chubut, Patagonia (Argentina). Three of the six studies comprise an analysis of the RUE, specifically Sydenham (O'Connor *et al*., 2001), Patagonia, (Jobbagy & Sala, 2000) and the Ferlo (Hein, 2006). For the other studies, the RUE was calculated by dividing the annual above ground herbaceous phytomass production presented in the study by the annual rainfall. Subsequently, regression analysis has been employed to analyze the causal relation between RUE and annual rainfall. The statistical significance of the six examined relations between RUE and rainfall has been tested with a *t*-test.

Furthermore, the relevance of the found relation between annual rainfall and RUE for the interpretation of remote sensing images is examined. First, the rainfall pattern in the Sahel during the period 1980–2000 is analyzed. Rainfall data comprise the average normalized April–October rainfall from climate stations spread over the Sahel, as reported in Dai *et al*. (2004). The number of stations for which data were available declined from around 160 in 1980 to some 40 in 2000 (see Dai *et al*., 2004 for the implications of this considerable change in the number of operational rainfall stations). In the Sahel, the large majority of rain falls in the period April–October, and the little rain outside of this period is generally not absorbed by plants because it falls before or after the growing season (Tarhule & Lamb, 2003). Next, the annual rainfall in the period 1980–2000 is compared with the long-term average (1960–2000) in order to analyze the potential existence of trends in the rainfall. The period 1960–2000 is chosen for the establishment of the benchmark, long-term rainfall in order to have a representative sample of Sahelian rainfall including the slightly wetter conditions of the 1960s and the droughts of the early 1970s and early 1980s. This period also corresponds to the period for which the average annual rainfall is calculated for Gadabedji (Niger) and Widou Thiengoly (Senegal).

Subsequently, the paper analyses the probability of finding a constant RUE in the absence of degradation given the 1980–2000 rainfall pattern, for the two Sahelian sites for which annual phytomass measurements are available: Gadabedji (Niger) and Widou Thiengoly (Senegal). A constant RUE has been retrieved through analysis of satellite images as reported in Tucker *et al*. (1991), Nicholson *et al*. (1998), Prince *et al*. (1998), Anyamba & Tucker (2005) and Olsson *et al*. (2005). Based on the established relation between rainfall and RUE, and the rainfall pattern in the period 1980–2000, an expected value for the RUE is calculated for three 5-year periods. The first period is 1980–1984 and represents the state of the vegetation in the early 1980s, a particularly dry period. The second period is 1988–1992, and represents the somewhat wetter conditions that occurred during the late 1980s and early 1990s. The third period is 1998–2002, a period that has a rainfall relatively close to the long-term average. Periods of 5 years have been used in order to obtain representative samples of the rainfall conditions and to avoid a bias due to occurrence of years with a particularly high or low rainfall. In the absence of degradation, the relation between rainfall and RUE, retrieved through regression analysis, remains valid for the whole period 1980–2000, and can be used to calculate the expected value for the RUE in all three periods. For the second and the third period, the probability of finding a constant RUE (based on the 1980–1984 average) instead of the expected value is calculated with a *t*-test. A one-tailed *t*-test has been used because the tested hypothesis is that there has been degradation of the ecosystem which would lead to a lower RUE.

Results

Analysis of the rain-use efficiency

A literature review on the dynamics of Sahelian grasslands demonstrates clearly that there are substantial *interannual* variations in species composition, species cover and productivity for a given site (Breman & Cissé, 1977; Penning de Vries & Djitèye, 1982; Breman & de Wit, 1983; Le Houérou, 1989, Breman & de Ridder, 1991; Hérault & Hiernaux, 2003). Hence, substantial variations in RUE occur between years at any given location irrespective of any degradation process (Penning de Vries & Djitèye, 1982; Le Houérou, 1989). These are caused by three main factors. First, at low rainfall, relatively more water is lost through evaporation, leaving less water available to plants. Consequently, RUE decreases at low rainfall (Penning de Vries & Djitèye, 1982; Le Houérou, 1984). Second, at high rainfall, RUE decreases because ecosystem productivity becomes limited by nutrients rather than water (Breman & de Wit, 1983; Hooper & Johnson, 1999). Third, the Sahel is dominated by annual species, and the composition and the RUE of the plant community vary markedly between years (Breman & de Ridder, 1991; Wezel & Schlecht, 2004). In general, in wet years, the share of leguminous and other dicotyledonous species in the plant cover increases. As these C_3 species have a lower RUE than C_4 grasses, this leads to a further reduction of the RUE of the plant community in wet years (Penning de Vries & Djitèye, 1982; Le Houérou, 1989).

Therefore, for a given site, RUE as a function of annual rainfall follows a quadratic curve. RUE is highest for annual rainfall close to the average rainfall, and relatively low for both low and high rainfall. 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 relation between RUE and rainfall may be partly concealed by annual differences between the 'effectiveness' of the rainfall (i.e. the amount of rain that is not lost through run-off, evaporation, or because it falls before or after the growing season (Dunin, 1969; Snyman, 1998)). This may affect the significance of the relation between RUE and rainfall, in particular if measurements cover only few years. Furthermore, the quadratic relation can be expected to be most pronounced for sites dominated by annual species such as the Sahel. 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.

In the Sahel, the quadratic relation between rainfall and RUE is confirmed by measurements at Gadabedji in Central Niger (Fig. 1a) and at Widou Thiengoly in the Ferlo, Northern Senegal (Fig. 1b). Both sites are dominated by annual species. A quadratic curve is also found for other semiarid rangelands (Fig. 1c–f). These other sites comprise two sites dominated by annual grasses (Sulaibiya, Kuwait and Migda, Israel). The other two sites, Sydenham (South Africa) and Chubut (Argentina), are dominated by perennial grasses – but exhibit the same quadratic relation between annual rainfall and RUE. Note that there is substantial difference in the maximum RUE between the different sites (cf. Le Houérou, 1984). The significance of the relation between rainfall and RUE has been tested, for the six sites, with linear regression analyses and is presented in the figures. For all six sites, the relation is significant at $P < 0.05$. The quadratic relation between rainfall and RUE still allows for a decline in RUE following degradation of the vegetation cover. Measurements at Sydenham, South Africa, and in the Ferlo, Senegal, demonstrate how the whole curve shifts towards a lower RUE following degradation of the ecosystem (O'Connor *et al*., 2001; Hein, in press).

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.

The impact of the rainfall pattern in the period 1980–2000

The availability and resolution of satellite images has greatly increased since the early 1980s. This is reflected in the periods in which desertification in the Sahel is studied with satellite images. Tucker *et al*. (1991) analyzed degradation of the vegetation cover from 1980–1990, Nicholson *et al*. (1998) analyzed the period 1982–1994, and Prince *et al*. (1998) analyzed the period 1982–1990, whereas Kerr (1998) was largely based upon the latter two studies. Two more recent studies examine the period 1982–1999 (Olsson *et al*., 2005) and 1981–2003 (Anyamba & Tucker, 2005).

Characteristic for the last two decades is an upward trend in the annual rainfall in the Sahel (Fig. 2). This figure presents the normalized rainfall anomalies for the period 1980–2000, compared with the long-term rainfall average (1960–2000). The years 1980–1987 were very dry compared with the long-term average, with 1983 and 1984 representing the two driest years of the 20th century in the Sahel. The period 1988–1994 was drier than the long-term average, but nevertheless substantially wetter than the preceding years. From 1995 onwards, there was a further, modest trend towards higher rainfall (Tarhule & Lamb, 2003; Dai *et al*., 2004).

The previous section demonstrated that years with rainfall strongly below average (as in the period 1982–1987) tend to have a much lower RUE than years with an average rainfall. Consequently, the upward trend in the annual rainfall in the period of observation would, in the absence of degradation, lead to an *upward* trend in the RUE.

To the contrary, the various studies that use satellite images to analyze the development of the RUE in the Sahel find that the RUE does not significantly change in the examined periods (Tucker *et al*., 1991; Nicholson *et al*., 1998; Prince *et al*., 1998; Anyamba & Tucker, 2005;

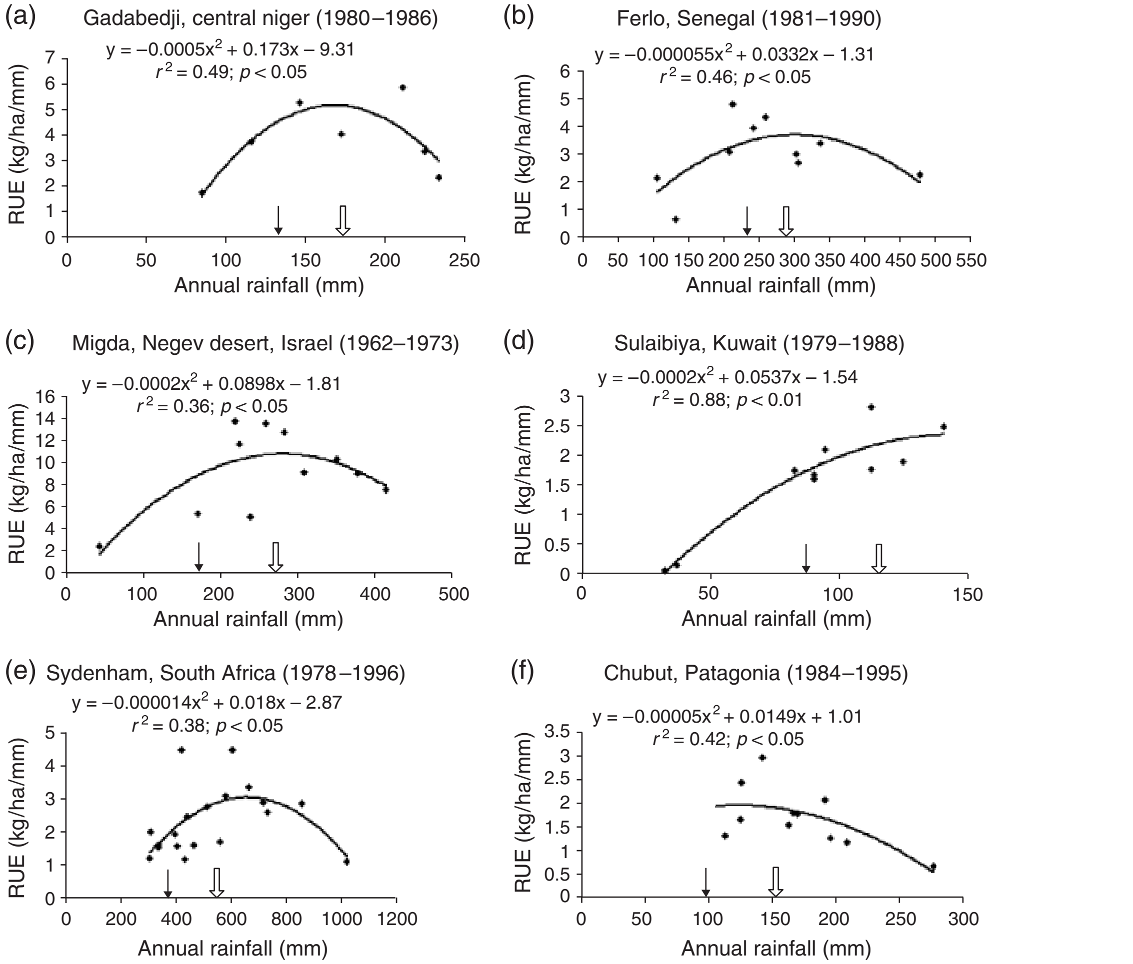

Fig. 1 Rain-use efficiency as a function of annual rainfall for six semiarid sites. The block arrows indicate the long-term average rainfall; the fine arrows the long-term average −1 SD. Sources (a) Wylie *et al*. (1992), (b) Hein (in press), (c) Tadmor *et al*. (1974), (d) Zanan (1997), (e) O'Connor *et al*. (2001), (f) Jobbagy & Sala (2000).

Olsson *et al*., 2005). The likelihood of not detecting a change in RUE in the absence of degradation has been examined for the two Sahelian sites for which data on rangeland dynamics were available (Gadabedji, Niger and the Ferlo, Senegal). This is illustrated in Table 1. The expected value for the RUE has been calculated for three 5-year periods that represent, respectively, the very dry conditions existing in the Sahel in the early 1980s, the dry conditions of the late 1980s and early 1990s, and the close-to-average rainfall conditions in the late 1990s.

In the absence of degradation of the vegetation cover, the equation describing RUE as a function of rainfall obtained through regression analysis of phytomass measurements (Fig. 1a and b), would be valid for each of the three periods. Hence, it can be used to calculate the expected value of the RUE in the three periods with the actual, average rainfall pattern under the assumption that there is no degradation. Table 1 shows that these expected values of the RUE are considerably higher for the wetter periods 1988–1992 and 1996–2000, as compared to the expected value of the RUE in the period 1980–1984. The probability of obtaining a constant RUE – as indicated by the remote sensing analysis – is calculated with a *t*-test (Table 1).

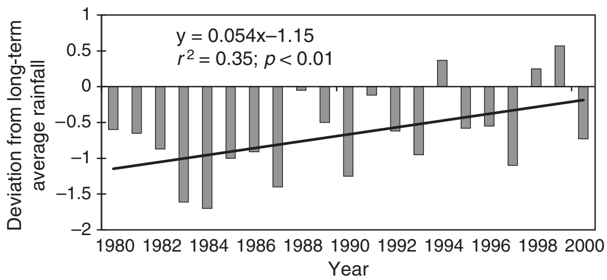

Fig. 2 Rainfall in the Sahel 1980–2000, expressed as the SD from the long-term (40 years) mean.

Table 1 Comparison of the rain-use efficiency (RUE) for two Sahelian sites in the absence of degradation

	Gadabedji, Niger				Ferlo, Senegal			
	Average Rain (mm)	RUE: expected value	RUE satellite imagery	Probability	Average Rain (mm)	RUE: expected value	RUE: satellite imagery	Probability
1980–1984	123	3.8	3.8		171	2.6	2.6	
1988–1992	155	4.8	3.8	0.07	279	3.1	2.6	0.08
1996–2000	186	4.9	3.8	0.05	307	3.6	2.6	0.03

Table 1 shows that, for both sites, for both periods, the hypothesis that there has been no change in RUE and, hence, no degradation, is rejected with a confidence level varying from $P<0.03$ to $P<0.08$. Clearly, the outcomes of the *t*-test for two sites can not be extrapolated to the entire Sahel, which has substantial spatial heterogeneity in terms of rainfall patterns as well as composition of the vegetation layer (e.g. Turner, 1999). Nevertheless, these results confirm that the detection of a constant RUE for the overall Sahel in the various remote sensing studies presents a strong indication that there has been degradation of the Sahelian vegetation cover in the last 20 years. Consequently, the conclusion that satellite data do not show long-term degradation in the Sahel in the period 1980–2000 is premature. Considering the relation between RUE and rainfall, and the rainfall characteristics of the examined years, the relatively constant RUE found in remote sensing studies indicates that a gradual degradation of the vegetation cover of the Sahel is likely.

Discussion and conclusions

We identified an important flaw in the way RUE has been used in remote sensing studies that examine desertification in the Sahel: these studies have ignored the relation between annual rainfall and RUE. Analysis of the processes and mechanisms underlying the vegetation dynamics of semi-arid rangelands suggests a quadratic relation between RUE and annual rainfall, in particular for sites dominated by annuals such as the Sahel. This quadratic relation is confirmed by phytomass measurements in six different semiarid rangelands, of which two in the Sahel. In the six examined rangelands, RUE is highest during a year with a rainfall close to the annual average rainfall, and significantly lower in dry years.

Sahelian rainfall in the period 1980–2000 is characterized by a significant upward trend. Whereas, 1983 and 1984 were exceptionally dry years, the period 1987–1994 was somewhat wetter, and rainfall in the period 1995–2000 was close to the long-term (40 years) average. The upward trend in rainfall observed in the period 1980–2000 corresponds to the first part of the quadratic relation between annual rainfall and RUE, as presented in Fig. 1. Hence, considering that RUE is low during droughts, and highest for rainfall close to the long-term average, RUE could be expected to show a gradual increase between 1980 and 2000 in the absence of degradation. However, remote sensing studies did not detect any significant change in the rain-use efficiency in the Sahel in the period 1980–2000.

Therefore, the conclusion that satellite data do not show long-term degradation in the Sahel is premature. This is further illustrated for two Sahelian sites for which multiyear data on rangeland productivity were available. 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*p levels varying from $P<0.03$ to $P<0.08$. We conclude 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; Hérault & Hiernaux, 2003), remote sensing analysis remains the preferred tool. Analysis of remote sensing images would need to be conducted for a period without a trend in rainfall, for instance the last decade (1994–2004).

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. nonequilibrium approaches to rangeland dynamics. It would confirm the relevance of the equilibrium approach with respect to the overall impact of grazing at the scale of the Sahel under current grazing pressures (cf. Le Houérou, 1989; Hérault & Hiernaux, 2004). Note that this does not contradict the importance of also considering non-equilibrium approaches to Sahelian rangeland dynamics (Westoby *et al*., 1989). For instance, non-equilibrium approaches are required to analyze the dynamics around the boreholes distributed throughout the Sahel. These boreholes provide drinking water to livestock and, around them, stocking density is substantially above the average (De Leeuw & Tothill, 1990). In these areas, a positive feedback mechanism (the occurrence of small sand dunes that burry and kill plant seedlings) may occur that accelerates the transformation of vegetation to bare soil once certain thresholds in plant cover have been passed (cf. Walker & Abel, 2002). Hence, both equilibrium and nonequilibrium approaches are required to understand the dynamics of the Sahel (cf. Fernandez-Gimenez & Allen-Diaz, 1999; Briske *et al*., 2003; Vetter, 2005).

In addition, if anthropogenic degradation of the Sahel 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 Charney (1975), Xue & Shukla (1993) and Wang *et al*. (2004) that anthropogenic 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. Hence, if new remote sensing analyses confirm anthropogenic degradation, 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.

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