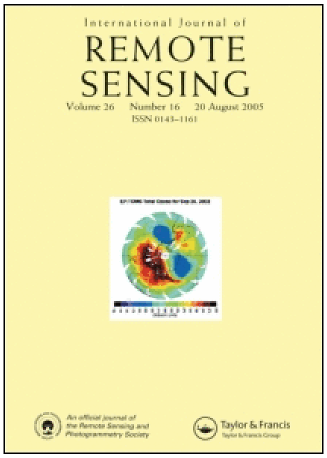

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Spatial patterns of the NDVI–rainfall relationship at the seasonal and interannual time scales in an African savanna

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Climate change is predicted to affect both the mean annual rainfall and its seasonal distribution over the African continent. Understanding their respective influences on primary production, an ecosystem's key feature, is therefore a major challenge for rangeland ecologists. We have investigated the change in intra- and interannual Normalized Difference Vegetation Index (NDVI) in relation to rainfall in Hwange National Park, Zimbabwe. Two distinct NDVI time series were built using NOAA/AVHRR data for the period 1982–2002. Long-term monthly means described the change in seasonal NDVI, whereas annually integrated NDVI related to year-to-year fluctuations. The rainfall–NDVI relationship was stronger along the seasonal course [with a lag of 1 month, Kendall's tau (τ)=0.879] than when studied interannually (τ=0.476). Principal component analysis (PCA) demonstrated that spatial patterns of the NDVI fluctuations differed when studied interannually or during the seasonal course. Field features such as topography or vegetation composition influenced seasonal NDVI values whereas only rainfall distribution played a role at the interannual time scale. Our results show that rainfall controls on primary production and their mitigation differ between time scales, and these findings bring insights on the future response of savannas to climate change.

1. Introduction

Primary production is related to carbon budgets, ecosystem processes and biological diversity (e.g. Loreau *et al.* 2001), and on a global scale it is strongly correlated to climatic variables, although ultimate controls (temperature, precipitation) differ among biomes (Nemani *et al.* 2003). Vegetation production therefore stands as a useful natural integrative index for studying ecosystem responses to climate change. Until recently, the lack of long-term production data prevented accurate investigations of the climate–vegetation production relationship at the temporal scales. However, the current use of remote sensing vegetation data has enabled us to overcome these limitations, and correlations between climate and primary production fluctuations, as well as climate change-associated trends in vegetation

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production, have been demonstrated worldwide (Kawabata *et al.* 2001, Ichii *et al.* 2002, Xiao and Moody 2005). The most commonly used index is the Normalized Difference Vegetation Index (NDVI) [NDVI=(NIR−RED)/(NIR+RED), where NIR and RED are respectively the reflectance in the near-infrared and red electromagnetic spectrums of objects on the Earth's surface]. Ultimately, the NDVI is a measure of absorbed photosynthetically active radiation, determined by leaf chlorophyll density and green leaf density (Tucker and Sellers 1986), and has been shown through numerous ground-truth validations in different biomes to be related to vegetation production (Tucker and Sellers 1986, Prince 1991, du Plessis 1999, Paruelo *et al.* 1999, Milich and Weiss 2000, Schmidt and Karnieli 2000, Wang *et al.* 2004). The extended spatial coverage of remote sensing data compared to ground-collected data has also been used to investigate directly the effects of known site characteristics on NDVI behaviour. For instance, the relative aridity of the site (Richard and Poccard 1998), soil types (Farrar *et al.* 1994, Fisher and Levine 1996), topography (Jobbágy *et al.* 2002), and also vegetation composition and structure (Davenport and Nicholson 1993, Peters *et al.* 1997) have been reported to be associated with different rainfall–NDVI relationships. However, how the relative importance of these factors changes across the scales is still unknown.

In Africa, comparative studies demonstrated decades ago that mean above-ground net primary production is strongly correlated with mean annual precipitation (Rutherford 1980, Le Houerou 1984, Walker 1987), and more recent remote sensing analyses revealed a temporal association between climate and vegetation production (Townshend and Justice 1986, Fuller and Prince 1996, Richard and Poccard 1998, du Plessis 1999, Vanacker *et al.* 2005). Although Africa did not experience a global long-term trend in rainfall along the course of the twentieth century, the past two decades have been more variable and drier than before in most places (Hulme *et al.* 2001, Nicholson 2001, Richard *et al.* 2001), and some long-term trends in vegetation production have been identified (Ichii *et al.* 2002, Nemani *et al.* 2003, Xiao and Moody 2005). However, not only the amount of long-term annual rainfall but also the seasonal distribution of rainfall is predicted to change in the course of the century (Walker 1991, Richard *et al.* 2001). There is recent evidence that rainfall distribution *per se* (Knapp *et al.* 2002), or some specific seasonal components of precipitation and temperature regimes (Xiao and Moody 2004), can have unexpected large effects on primary production, independently of any changes in the overall amount. Such intra-annual effects of seasonal shifts in precipitation on vegetation would complement the many reports in the northern hemisphere of phenology changes associated with temperature increase (Tateishi and Ebata 2004, de Beurs and Henebry 2005). However, the relative potential for seasonal and interannual effects of climate change remains poorly understood. In Southern and Central Africa, results from Fuller and Prince (1996) suggested that rainfall control over vegetation production could be stronger at the seasonal than at the annual time scale. Richard and Poccard (1998) also showed for Southern Africa that the monthly NDVI was strongly correlated with lagged monthly rainfall, whereas on an interannual scale, rainfall anomalies exerted an effective force on NDVI in only a few locations. Moreover, no clear factors apart from mean monthly rainfall explained the observed rainfall–NDVI relationships at the regional scale, and investigation of the potential factors causing spatial patterns in the seasonal or interannual NDVI changes remained inconclusive (Richard and Poccard 1998). There is therefore a need for further comparisons of the seasonal and interannual climate–vegetation production relationships to improve our predictions of ecosystem responses to climate change.

In this study we have compared the NDVI response to precipitation at both the seasonal and annual time scales in the semi-arid savanna of Hwange National Park (thereafter Hwange NP), Zimbabwe, using a common and well-established methodology. To understand the climatic context of the study we first compared rainfall patterns of the study period with past rainfall information. We then validated that rainfall is a major driver of vegetation productivity in the ecosystem studied, and then used a principal component-based approach that allowed us to study concomitantly spatial and temporal dynamics of the NDVI at the seasonal and interannual time scales.

2. Material and methods

2.1 *Study area*

Hwange NP (14 600 km^2) is located on the north-western border of Zimbabwe (19°00′ S, 26°30′ E). Its elevation ranges between 900 and 1100 m. Two-thirds of the park is covered by aeolian Kalahari sands, representing the eastern fringe of the larger Kalahari sands region centred over Botswana and extending into neighbouring countries. The North-West and extreme South-West of the park reflect a different underlying geology and are covered with clay-type soils. The climate is semi-arid and subtropical with occasional severe frosts (Childes and Walker 1987). Vegetation is predominantly deciduous woodlands and shrublands, with patchily distributed herbaceous savannas and edaphic grasslands (Rogers 1993). A mosaic of *Combretum* sp., *Terminalia* sp., *Acacia* sp. and *Baikiaea* sp. communities has developed on the Kalahari sands, while *Colophospermum mopane* dominates on clay-type soils (figure 1).

2.2 *Climate data collection*

In Hwange NP, precipitations are restricted to a single rainy season lasting from October to April. Monthly rainfall data were recorded from 1928 to 2002 at three stations in three different management units (thereafter called blocks; locations in figure 1). Annual rainfall at these stations were well correlated (all $r>0.586$, all $P<0.001$). Mean data for the whole park were calculated by averaging monthly raw data from these stations. All analysis were carried out for the whole park and the three blocks. However, as they yielded similar results, only statistics for the whole park are presented unless stated otherwise.

2.3 *NDVI data collection*

NDVI data were obtained from October 1981 to October 2002 from the African Data Dissemination Service of the Famine Early Warning System of the US Agency for International Development (USAID 2005). The raw NDVI data comprised a 10-day maximum value composite corrected for aerosols released by volcanic eruptions between April 1982 and December 1984 and June 1991 and December 1993 (Tanre *et al.* 1991, Vermote and Kaufman 1995). The NDVI data covered the whole African continent at the 8×8 km spatial resolution, but to avoid area-related biased results we performed all analyses using a mask extracting only the 198 pixels covering Hwange NP. The landscape was too heterogeneous, relative to the image

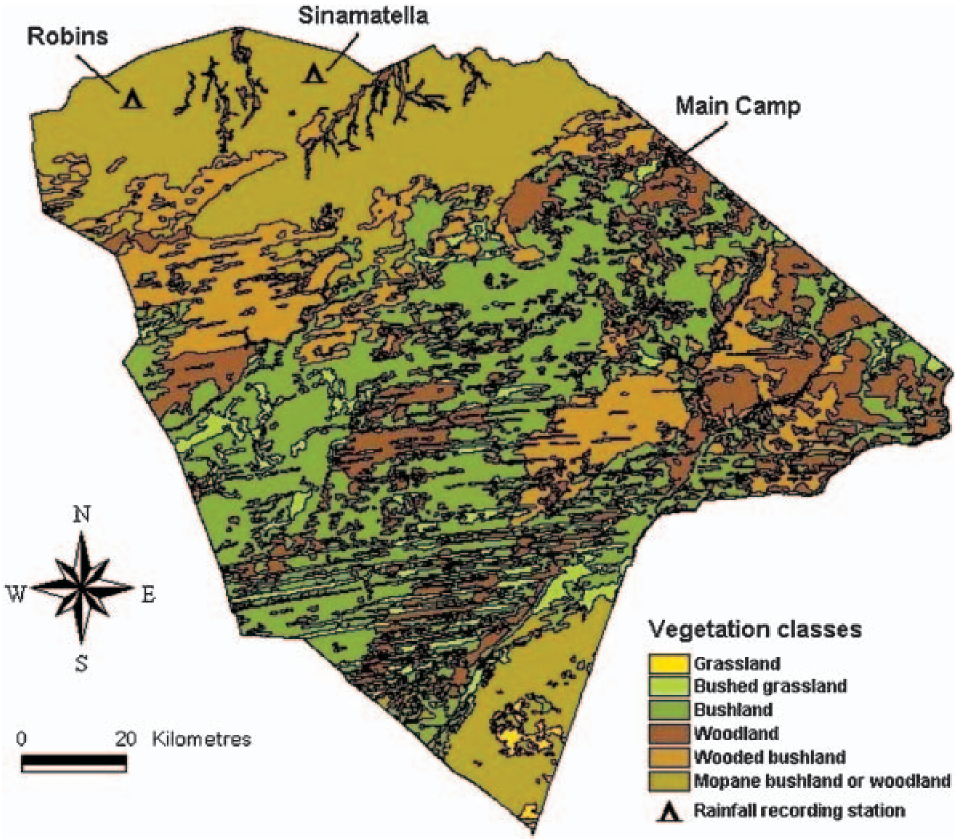

Figure 1. Map of vegetation structure in Hwange NP. The distribution of mopane trees (*Colophospermum mopane*) closely follows the distribution of clay-type soils.

resolution, to allow classification of pixels into distinct vegetation types, and we therefore did not make this *a priori* distinction in our analyses. Raw NDVI were obtained on a 0–255 scale (0 to 250: NDVI; 255: water mask). However, we rescaled the final NDVI results to a [−1, 1] scale for comparisons with other studies. Raw images were summed into monthly integrals, and annual NDVI images were calculated by summing monthly NDVI over a complete rainfall year (October to September of the following year). Integrated NDVI has been shown to successfully describe vegetation-related measurements and is highly correlated to more complex indices (Ricotta *et al.* 1999). Annual values were identified by the calendar year of the dry season (the study therefore extended from 1982 to 2002).

2.4 *Statistical analyses*

Principal component analysis (PCA) is a multivariate technique that reorganizes through linear combinations the original dataset in uncorrelated vectors (the PCA components) of decreasing explanatory powers (i.e. the amount of total variance explained by such vectors). PCA therefore identifies patterns of change, and correlations with biological or physical factors can be tested to investigate the underlying mechanisms. As it allows both spatial and temporal patterns to be described in the same analysis, standardized PCA has become a widely used technique in remote sensing (e.g. Eastman and Fulk 1993, Eklundh and Singh 1993, Gurgel and Ferreira 2003, Rigina and Rasmussen 2003). PCA results are interpreted using the three items of information produced for each component: a percentage of the total variance explained, an image of the spatial distribution of component values at the same resolution as the original images, and a time series of the coefficients of correlation (loadings) between the image of the component values and each original image of the time series.

To compare seasonal and interannual patterns of changes in the NDVI, we created two distinct datasets on which we performed similar analyses. First, we analysed the seasonal evolution by creating a time series with the 12 images of NDVI monthly means, averaged over the whole study period. Second, we analysed the 21 annually integrated NDVI images to limit the study to interannual variability by removing seasonal variation. We investigated the relationships between rainfall and NDVI values or PCA loadings using the standard Pearson's product moment correlation coefficient (r) for interannual relationships with normally distributed data, and we used Kendall's tau (τ) correlations for seasonal relationships due to the non-normal distribution of the data (Sokal and Rohlf 1995). Sample sizes are respectively 12 and 21 for all seasonal and interannual analyses.

3. Results and discussion

3.1 *Climatic context of the study*

Annual rainfall over the park averaged 613 mm in the period 1928–2002 but showed high interannual fluctuations [coefficient of variation (CV)=25.6%]. There was no significant linear trend in annual rainfall ($F_{1,73}$=0.740, P=0.392). However, the study period 1982–2002 tended to be drier than the previous long-term records from (1928–1981) (respective average rainfall: 557 and 635 mm, t=1.967, P=0.057), with 71.4% (15/21) of the 1982–2002 years below the 1928–1981 average. This appeared to be caused particularly by the 20.2% decline in annual rainfall in the Robins block between the two periods (t=3.038, P=0.004), although the other stations showed non-significant lower averages (−6.6% for Sinamatella and −9.55% in Main Camp). There was, however, no trend in rainfall within the study period ($F_{1,19}$=0.603, P=0.447).

During the study period, Hwange NP was experiencing drier conditions than before, including the two worst droughts of its history, when annual rainfall reached only 50% of the long-term average (303 mm in 1995; 312 mm in 1982). These intense and extended dry periods covered most of southern Africa (Hulme *et al.* 2001, Nicholson 2001, Richard *et al.* 2001), and have been shown to be related to large-scale oceanic conditions, with El-Niño situations of the Southern Oscillation being the main driver of such events (Nicholson and Kim 1997, Richard *et al.* 2001). The need to understand and predict how decreasing rainfall and recurrent droughts, associated with the expected increased frequency of El-Niño events, would affect the Hwange NP ecosystem initiated this study.

3.2 *Temporal NDVI–rainfall relationships*

Hwange NP experiences only one growing season, extending from October to May (figure 2(*a*)). The intra-annual CV of NDVI was 25.1%, with mean monthly NDVI ranging from 0.63 in February to 0.30 in September (figure 2(*a*)). Along the seasonal course, monthly NDVI values were correlated with monthly rainfall (τ=0.545,

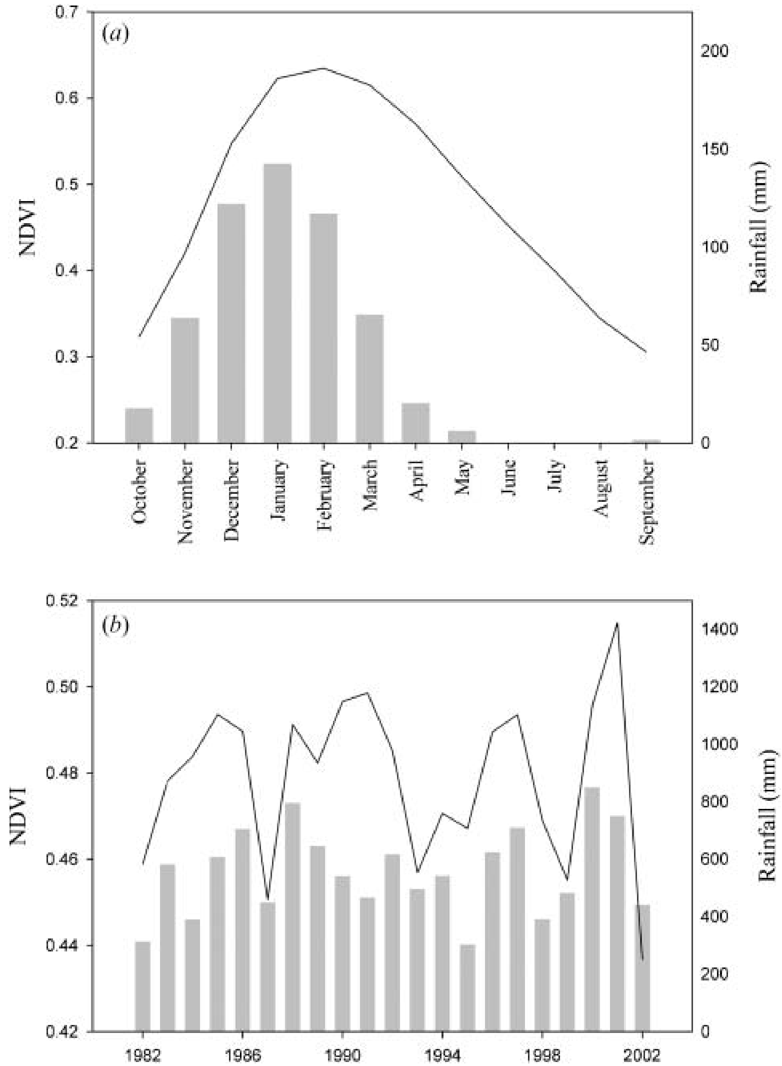

Figure 2. Changes in (*a*) seasonal and (*b*) interannual rainfall (bars) and NDVI (lines) in Hwange NP during 1982–2002.

$P=0.004$). The fit of that relationship improved greatly if monthly NDVI values were correlated with rainfall of the previous month ($\tau=0.879$, $P<0.001$). More important lags did not improve the fit ($\tau<0.728$).

During the period 1982–2002, the mean annual NDVI was 0.48 and the interannual CV was 4.0% (figure 2(*b*)). Annual NDVI over Hwange did not show any significant trend over the study period ($F_{1,19}=0.049$, $P=0.827$). Annual NDVI was highly correlated to annual rainfall ($r=0.652$, $P=0.001$), although with a lower fit than the seasonal model ($\tau=0.476$, $P<0.001$).

Our results confirm, at the scale of Hwange NP, the previous findings of Fuller and Prince (1996) and Richard and Poccard (1998), who showed that in southern Africa long-term monthly NDVI values are highly correlated to monthly rainfall (with various lags), but that interannual rainfall anomalies exert less pronounced control on annual NDVI departure from long-term means. Although the variance was much more important in the seasonal model, the better fit obtained with the long-term monthly means than with interannual changes suggests that plants anticipate climatic conditions rather than simply respond to their fluctuations (Fuller and Prince 1996). These results also suggest that any changes in the long-term rainfall distribution during the year are likely to have a major impact on vegetation production. The effect of the total amount of rain received each year, although positively correlated to annual vegetation production, appears less predictable. This could be linked to other unaccounted for factors that can affect the annual production in semi-arid ecosystems. For instance, although being somehow linked themselves to annual rainfall, fire (e.g. Bond *et al.* 2005) and previous-year rainfall (Wiegand *et al.* 2004) were shown to affect vegetation production in savannas. Overall, a better understanding of the mechanisms driving interannual fluctuations in NDVI is needed to disentangle the relative importance of amount and distribution of rainfall in driving primary productivity.

3.3 *Spatial patterns of NDVI changes*

3.3.1 Explanatory power: interpretable components of the PCA. The percentage of total variance explained by each but the first component of the seasonal and interannual PCAs are displayed in figure 3. The first component explained most of the variance in both cases (seasonal 74.0%; interannual 71.3%). The first few components with the highest explained variance generally have physical significance, and can be investigated for correlation with previously measured factors or field knowledge. Explanatory power then decreases with each successive component, this decrease becoming quasi-linear after component 3 in seasonal PCA and after component 2 in interannual PCA. Components in this linear decrease should not be interpreted, as the orthogonality constraint of the PCA can induce the creation of irrelevant components (Preisendorfer 1988). We therefore restricted our analyses to components 1, 2 and 3 of the seasonal PCA and to components 1 and 2 of the interannual PCA.

3.3.2 Seasonal variations. As usual with PCA conducted on spatially explicit time series, the first component explained most of the variance (74.0%) and described the mean spatial structure of the variable, here NDVI (figure 4(*a*)). Long-term mean vegetation productivity around rainfall-recording stations and their respective mean annual precipitation were similarly ordered; that is the Main Camp area was the wettest and most productive area, followed by the Sinamatella and then the Robins area. More generally, NDVI values were lower on the western side on the park, and notably on the south-west border along Botswana. Although we did not produce a rainfall distribution map, erratic data from rain gauges spread all over the park showed that this area experienced the lowest long-term rainfall mean of the park (mean July to June rainfall in 1983–2000 was *ca*. 470 mm). These results confirmed previous findings that long-term mean NDVI values can be used as a proxy for mean annual rainfall over a wide range of the geographical scale (Davenport and Nicholson 1993, Paruelo *et al.* 1999, Kawabata *et al.* 2001).

Components 2 and 3 then explained respectively 18.8% and 4.89% of the total variance. These factors displayed marked differences in their correlation with NDVI during the seasonal course (figure 5(*a*)) and in their spatial distribution (figures 4(*b*) and 4(*c*)).

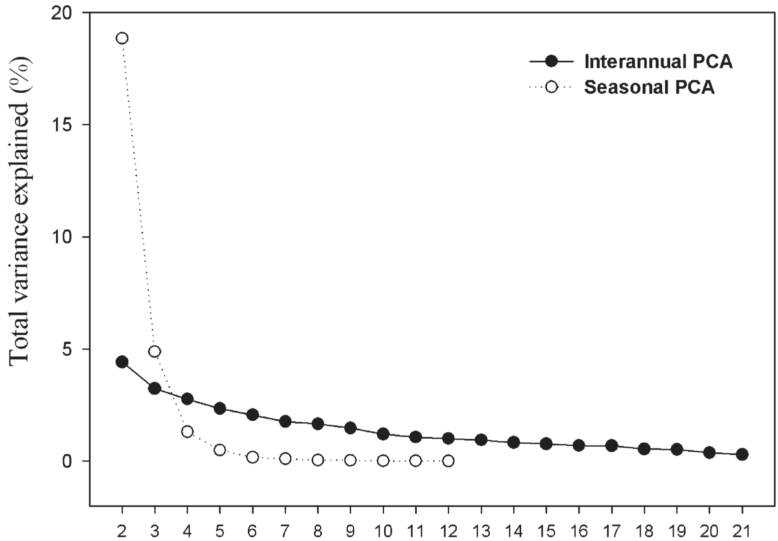

Figure 3. Percentage of total NDVI variance explained by successive components of the seasonal (dashed line) and interannual (continuous line) PCA. Component 1 of each PCA is not displayed (74.0% and 71.3% of the total variance, respectively).

Component 2 values were highly correlated to NDVI images during the rainy season, and negatively correlated to NDVI in the dry season. Loadings of component 2 were highly correlated to mean monthly rainfall calculated over the period 1982–2002 (τ=0.909, P<0.001). The fit was not improved if loadings were correlated to rainfall with a lag of 1 or 2 months (τ=0.697 and 0.364, respectively). Rainfall therefore appears as a major driver of NDVI changes during the seasonal course in Hwange NP. Spatial distribution of component 2 values indicated, however, that in the south-west of the park NDVI values were poorly correlated to monthly rainfall during the seasonal course (figure 4(*b*)). Investigation of the NDVI seasonal evolution in this area showed that NDVI values decreased much more slowly than in the rest of the park during the dry season. Topography explains such behaviour, as this area is a seasonally inundated mud flat with an underlying basalt geology and is likely to maintain a higher soil hygrometry during most of the year, allowing vegetation to remain active later in the season. Briggs and Knops (1995) and Jobbágy *et al.* (2002) similarly reported spatial variations in the rainfall–primary production relationship caused by topographic water run-in or run-off, disrupting locally the usual correspondence between rainfall and soil moisture seasonality (Farrar *et al.* 1994, Jolly and Running 2003).

Component 3 was negatively correlated with the NDVI images at the onset of the rainy season, then changed to become positive and maximal in March (late rainy season), and then decreased continuously up to the end of the dry season (figure 5(*a*)). Spatial distribution of component 3 values did not match any well-defined field characteristics (figure 4(*c*)). However, component 3 spatial pattern distinguished areas similar to the deciduous tree species distribution in Hwange NP. In southern African savannas, timing of leaf production in deciduous and evergreen is clearly separated, and leaf lifespan is reduced to 6 to 8 months in deciduous species (Medina 1982). In Hwange NP, *Colophospermum mopane* and

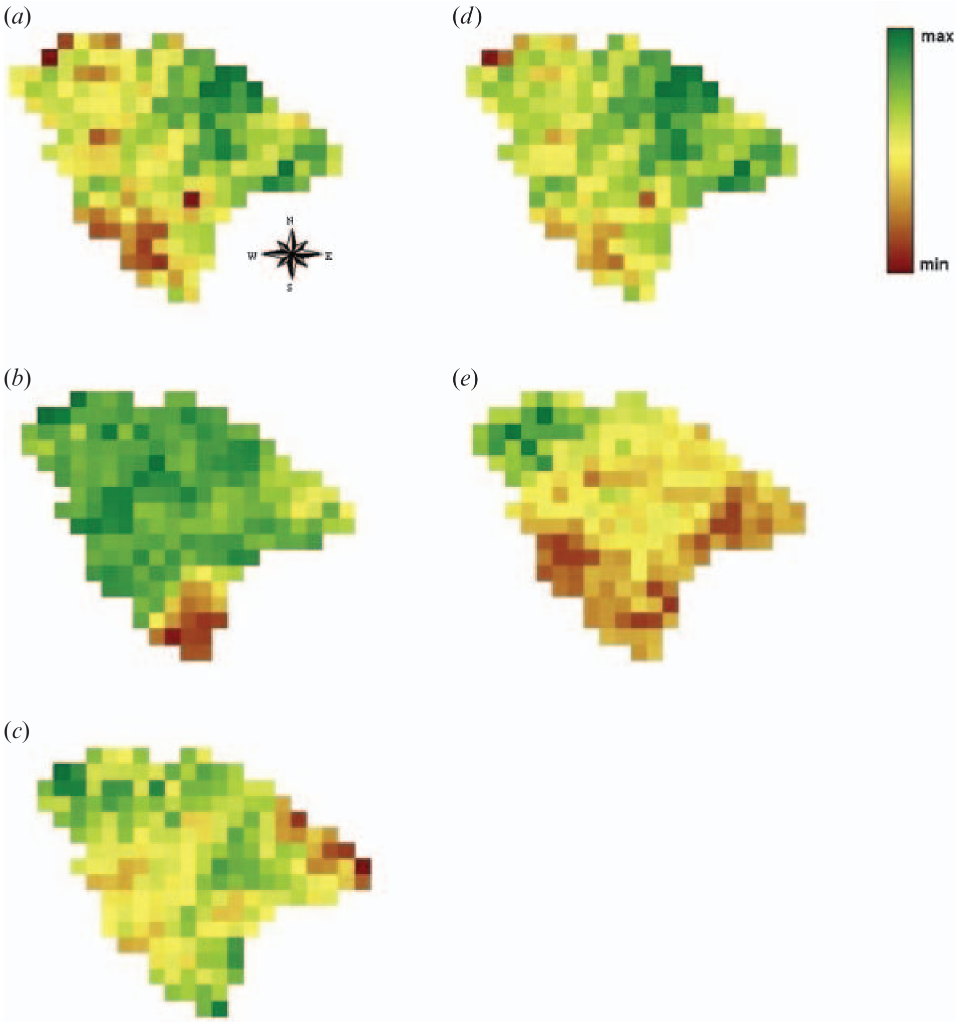

Figure 4. Spatial distribution of PCA component values: (*a*), (*b*) and (*c*) are the first, second and third components of the seasonal PCA, respectively; (*d*) and (*e*) are the first and second components of the interannual PCA, respectively. The same colour legend was scaled to the range of values of each component.

Combretum sp. tree species often occur on more arid soils and lose leaves during the dry season as an adaptation to face increased evapotranspiration. This foliar phenology therefore mechanistically decrease the NDVI values during the dry season in areas where these species are a non-negligible part of the vegetation, for example on the northern and south-western part of the park dominated by mopane trees, and in the centre of the park in the mixed communities with *Combretum* sp.

3.3.3 Interannual variations. Component 1 (71.3% of the total variance) described the mean spatial structure of the NDVI in Hwange (figure 4(*d*)), as did component 1 in the seasonal PCA. Component 1 loadings showed a low significant increase with time (figure 5(*b*); $F_{1,19}=10.105$, $P=0.005$). We found no support in any physical or biological factors explaining such trend and therefore relate it to the orbital drift of

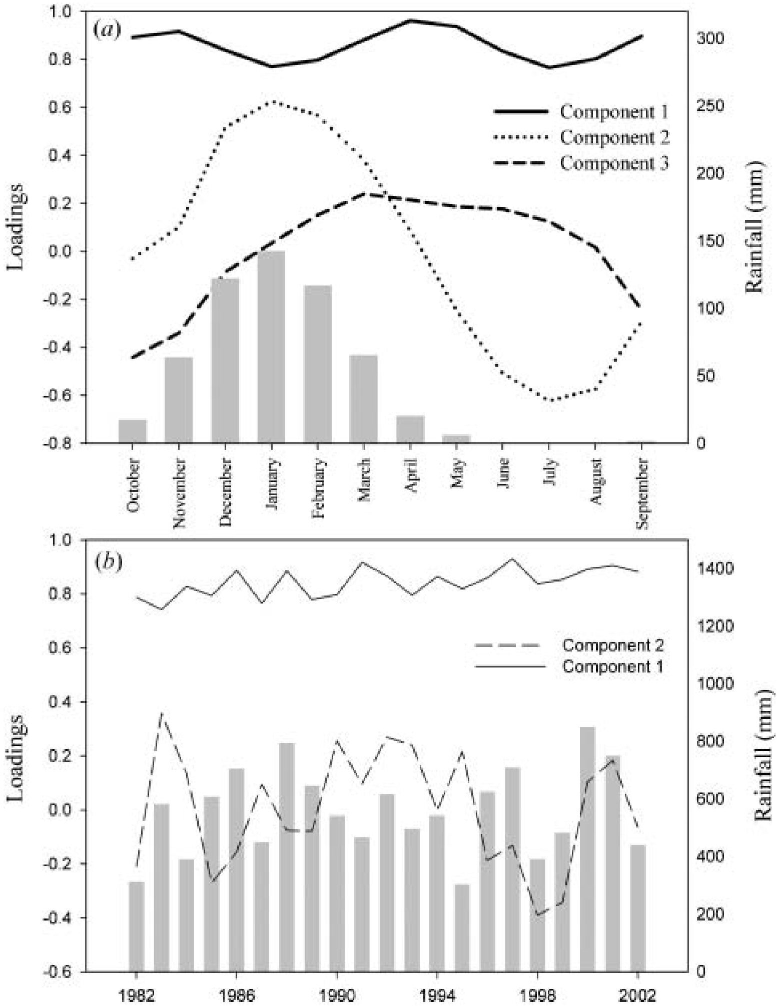

Figure 5. Temporal evolution of loadings of (*a*) components 1, 2 and 3 of the seasonal PCA and (*b*) components 1 and 2 of the interannual PCA.

the AVHRR satellite, which was shown to cause a slight increase in NDVI values over time (Gutman and Ignatov 1995). However, these changes were negligible when compared to changes brought about by other factors (Kaufman and Holden 1993), as shown by the low amount of variance accounted for by the trend (figure 5(*b*)). Loadings of component 1 were correlated with annual rainfall (figure 6; $r=0.436$, $n=21$, $P=0.048$), although the significance level decreased if the time series was first detrended ($r=0.411$, $P=0.064$). The statistical properties of PCA are such that temporal patterns of changes would be identifiable in component 1 only if the spatial distribution of these changes matched the long-term NDVI distribution. Applied to our results, this shows that rainfall is the major driver of NDVI changes at the interannual time scale, spatial distribution of annual rainfall is generally similar to the long-term spatial pattern of NDVI, and at least part of the rainfall signal is independent of field features (topography, soil types, vegetation structure

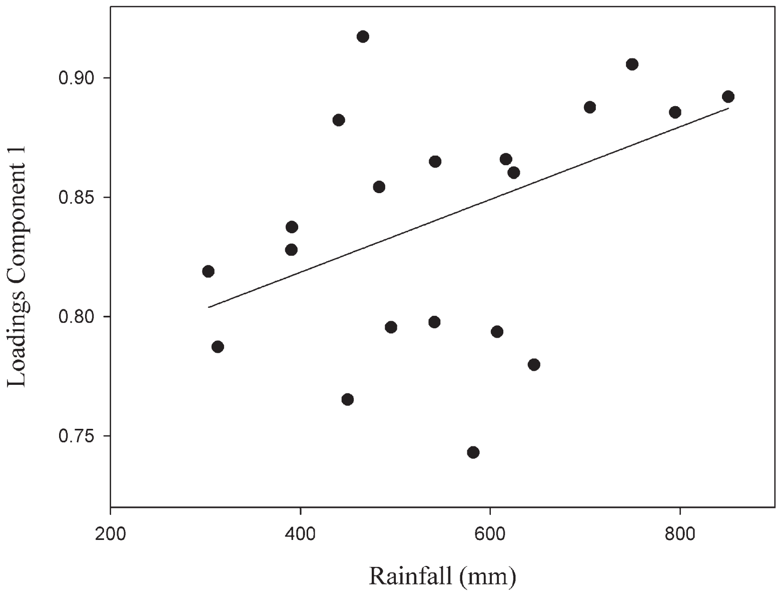

Figure 6. Relationship between loadings of component 1 (interannual PCA) and annual rainfall (line: correlation; r=0.426; P=0.048).

and composition). These results are consistent with the fact that we found no differences in the slopes of the rainfall–NDVI relationship between the three blocks for which we had rainfall data (rain: $F_{1,57}$=7.499, P=0.008; blocks: $F_{2,57}$=3.926, P=0.025; rain × blocks: $F_{2,57}$=1.098, P=0.340).

Component 2 loadings were not correlated with annual rainfall (r=0.046, n=21, P=0.843). Component 2 explained 4.4% of the total variance in annual NDVI and showed a clear spatial distribution of its values. Positive values were found in the North-West (Robins block), then decreased towards strong negative values along a North-West–South-East gradient. This spatial pattern did not match any known field feature such as soil type, topography or vegetation composition and structure. We therefore investigated the potential relationship with interannual changes in spatial distribution of rainfall. Information about spatial distribution of rainfall in Hwange NP was scarce, as only the three rain gauges on stations provided continuous reliable data. We created a rough index of the relative dryness of the Robins area, independent of the overall 'wetness' of the year, by dividing annual rainfall in Robins by the mean of the annual rainfall of Sinamatella and Main Camp. Loadings of component 2 were not correlated to that index (figure 7; r=0.303, P=0.182; τ=0.124, P=0.209). However, as loadings represent the spatial correlation of component values with the original images, years when absolute values of loadings are low do not exhibit such spatial patterns, and are therefore driven by other factors (bearing in mind that component 2 explained only 4.4% of the total variance). We therefore restricted our analysis to years when component 2 loadings were above 0.2 or below –0.2 (median of absolute loadings values=0.184), and found a significant relationship (figure 7; τ=0.500, n=9, P=0.030). Although based on a low number of years, this analysis suggested that the spatial variability in rainfall distribution along a North-West–South-East gradient was driving the

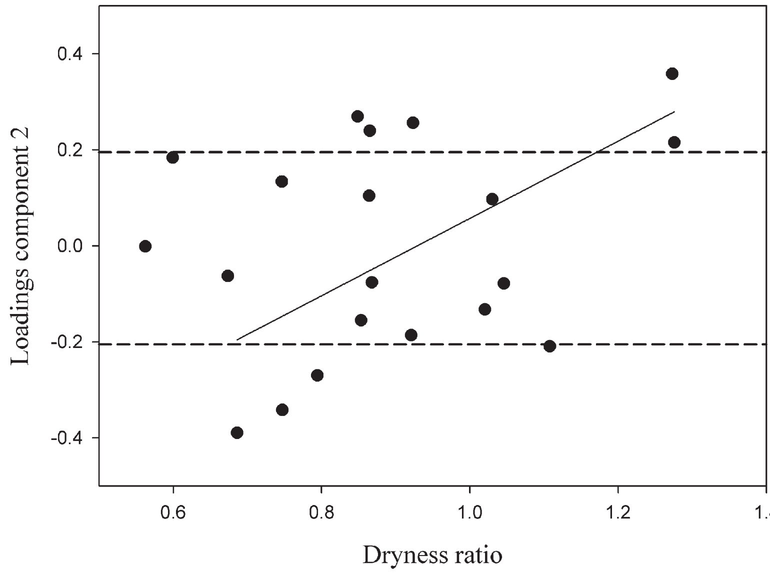

Figure 7. Relationship between loadings of component 2 (interannual PCA) and the relative dryness of the Robbins block; dryness ratio is rainfall over Robbins block divided by the mean rainfall over Sinamatella and Main Camp blocks (line: correlation with loadings of absolute value >0.2; t=0.500, n=9, P=0.03).

spatial differences in the year-to-year changes in NDVI, although this pattern was not apparent every year.

Overall, although interannual fluctuations in rainfall and NDVI averaged over the park were correlated positively, there was no evident spatial structure in this relationship. In particular, no field features were apparent in the interannual PCA, and any signal loss due to the orthogonal constraint of the PCA would not have explained more than 3.2% of the total NDVI variance. Interannual changes in primary production were likely to be caused by the interaction of a multiplicity of unidentified factors of low explanatory power, as highlighted by the large amount of variance left unexplained (25.3%) by components 1 and 2 of the interannual PCA. Therefore, although on a larger scale it is necessary to take into account field factors to predict vegetation responses to climatic fluctuations (Vanacker *et al.* 2005), at the spatial scale of our study no field features influenced interannual NDVI changes.

4. Conclusion

Our study has shown contrasting vegetation responses to precipitation between the seasonal and interannual time scales. We have highlighted the facts that: (1) intra-annual variation of NDVI is very strongly linked to rainfall seasonality with a lag of 1 month, but field characteristics that influence soil–water balance mitigate this relationship; and (2) the amount of rainfall and its spatial distribution are correlated with interannual productivity patterns, but observed NDVI variations are low and remained partially unexplained. Overall, the NDVI–rainfall relationship becomes much weaker when studied at the interannual time scale. These results suggest that the stability of the seasonal rainfall pattern is likely to be a major factor in the long-term sustainability of these ecosystems, possibly as important as changes in the amount of global rainfall. Moreover, our study showed that factors influencing the rainfall–NDVI relationship differ between time scales, with field characteristics (topography, vegetation composition and structure) having a major influence only at the seasonal time scale. If these results prove to be general, they could affect predictions on ecosystems responses to climate change and help in setting a hierarchy of potential mitigating factors of climate change. Other comparisons of the relative strength of rainfall controls on primary production at different time scales are therefore needed, whereas data at the appropriate resolution in time and space are already available from remote sensing imagery.

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