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Relationship between herbaceous biomass and 1-km^2 Advanced Very High Resolution Radiometer (AVHRR) NDVI in Kruger National Park, South Africa

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The relationship between multi-year (1989–2003), herbaceous biomass and 1-km^2 Advanced Very High Resolution Radiometer (AVHRR) Normalized Difference Vegetation Index (NDVI) data in Kruger National Park (KNP), South Africa is considered. The objectives were: (1) to analyse the underlying relationship between NDVI summed for the growth season (ΣNDVI) and herbaceous biomass in field sites (n=533) through time and (2) to investigate the possibility of producing reliable herbaceous biomass maps for each growth season from the satellite ΣNDVI observations. Landsat Enhanced Thematic Mapper Plus (ETM+) and Thematic Mapper (TM) data were used to identify highly heterogeneous field sites and exclude them from the analyses. The average R^2 for the ΣNDVI–biomass relationship at individual sites was 0.42. The growth season mean biomass and ΣNDVI of most landscape groups were strongly correlated with rainfall and each other. Although measured tree cover and MODIS estimates of tree cover did not have a detectable effect on the ΣNDVI–biomass relationship, other observations suggest that tree cover should not be ignored. The ΣNDVI was successful at estimating inter-annual variations in the biomass at single sites, but on an annual basis the relationship derived from all the sites was not strong enough (average R^2=0.36) to produce reliable growth season biomass maps. This was mainly attributed to the fact that the biomass data were sampled from very small field sites that were not fully representative of 1-km^2 AVHRR pixels. Supplementary field surveys that sample a larger area for each field site (e.g. 1 km^2 or larger) should account for the variability in biomass and may improve the strength of ΣNDVI–biomass relationships observed in a single growth season.

1. Introduction

The Normalized Difference Vegetation Index (NDVI) derived from the Advanced Very High Resolution Radiometer (AVHRR) has been widely used to estimate vegetation production (Prince and Justice 1991, Tucker *et al.* 1991a,b, Myneni *et al.*

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1997, Nicholson *et al.* 1998, Prince *et al.* 1998, Diouf and Lambin 2001). NDVI captures the marked contrast between the strong absorptance in the visible wavelengths and strong reflectance in the near-infrared wavelengths which uniquely characterizes the presence of photosynthetically active vegetation (PAR) (Tucker 1979). NDVI has a strong linear relationship with the fraction of (PAR) absorbed by the plant (f_{PAR}) which sets the upper limit for Net Primary Productivity (NPP) (Monteith 1977, Kumar and Monteith 1982, Asrar *et al.* 1984, Sellers *et al.* 1997). Therefore, in arid and semi-arid lands the seasonal sums of multi-temporal NDVI have been reported to be strongly correlated with vegetation production (Prince and Tucker 1986, Prince 1991, Nicholson and Farrar 1994, Nicholson *et al.* 1998).

Comprehensive field data on NPP are rare since these require measurements of components (e.g. below-ground production, decay and herbivory) that are difficult to make (Reich *et al.* 1999). Above-ground biomass is relatively easy to measure and is therefore frequently used to estimate production (Scurlock *et al.* 1999, Zheng *et al.* 2003). A number of studies have evaluated the relationship between AVHRR NDVI and field measurements of vegetation production (Prince and Tucker 1986, Nicholson *et al.* 1990, Diallo *et al.* 1991, Prince 1991, Wylie *et al.* 1991, Diouf and Lambin 2001). These studies reveal that the nature of the relationship (coefficient of determination, slope and *y*-intercept) between NDVI and field measurements varies considerably between studies and study areas (Du Plessis 1999). In southern Africa the biomass–AVHRR NDVI relationship has been tested in Namibia (Du Plessis 1999) and Botswana (Prince and Tucker 1986), but so far not in South Africa.

Consistent field measurements of vegetation over multiple years are relatively rare (Scurlock *et al.* 1999, Zheng *et al.* 2003). In the Kruger National Park (KNP) of South Africa various vegetation measurements, including end-of-season above-ground herbaceous biomass, have been collected at approximately 533 locations since 1989 (Trollope 1990, Zambatis 2002). These Vegetation Condition Assessments (VCA) are used to monitor the effect of management practices on vegetation, e.g. man-made watering points, game culling and burning. Although the KNP VCA data were not initially intended for validating coarse resolution remote sensing data, they constitute the best field data available in South Africa and are used here to assess the ability of 1 km^2 AVHRR NDVI data summed for the growth season (ΣNDVI) to monitor vegetation production.

The purpose of this study was twofold, (i) to develop spatial maps of herbaceous biomass from AVHRR NDVI data to aid management decisions in KNP and (ii) to evaluate the ability of AVHRR NDVI data to monitor vegetation production in KNP so that it may be used to monitor land degradation the region.

Firstly, since the extent of fires in KNP is strongly related to the amount of grass fuel accumulated during the preceding growing season, fire management decisions are largely dependent upon spatially explicit estimates of herbaceous fuel load (Trollope and Potgieter 1986, Van Wilgen *et al.* 2004). The adaptive fire management policy of KNP strives to ensure the maintenance of biodiversity through a combination of planned and unplanned fires (Biggs 2002, Van Wilgen *et al.* 2004). During the dry season, park managers apply planned patch mosaic burns after identifying 'burn targets' based on estimates of standing herbaceous biomass fuel load. Currently these fuel load estimates are either based on subjective visual estimates by rangers or spatial interpolation of the VCA point measurements. Since the distance between VCA sites is 3–12 km, the interpolations do not provide reliable spatial biomass maps. Fire management and other research in KNP could benefit significantly from more reliable spatial biomass data. To date, there have been no attempts to compare the VCA biomass data to the 17 years of 1-km^2 AVHRR data.

Second, there is an urgent need for an objective and repeatable measure of land degradation in South Africa, since the former homelands (current communal lands) that abut KNP are widely regarded as severely degraded (Palmer *et al.* 1999, Hoffman and Todd 2000, Wessels *et al.* 2000, Hoffman and Ashwell 2001, Pollard *et al.* 2003, Wessels *et al.* 2004). Establishing the relationship between vegetation production and AVHRR ΣNDVI is essential to developing a reliable land degradation monitoring approach based on these satellite observations (Wessels *et al.* 2000, 2004, Pollard *et al.* 2003).

The objectives of this study were: (1) to analyse the underlying relationship between growth season ΣNDVI from 1-km^2 AVHRR data and herbaceous biomass for KNP and (2) to investigate the generation of herbaceous biomass maps for each growth season from the ΣNDVI.

2. Methods

2.1 *Study area: KNP*

The KNP is situated on the eastern side of the Limpopo and Mpumalanga provinces of South Africa, between 30° 53′ 18″ E, 22° 19′ 40″ S and 32° 01′ 59″ E, 25° 31′ 44″ S (figure 1(*a*)). The KNP extends 360 km from north to south and covers an area of almost 2 000 000 ha, making it one of the largest conservation areas in the world (Mabunda *et al.* 2003). The KNP falls within the savanna biome with a mean annual rainfall of 537, that ranges from 350 in the north to 950 mm in the south-western parts of the park. The inter-annual coefficient of variation of rainfall ranges from 25% in the south to 35% in the north (Venter *et al.* 2003). KNP experiences a 4- to 8-month hot, wet season (October to April) and a mild, dry winter (May to August).

KNP is crossed by seven major river systems, all of which originate to the west of the KNP and drain a combined area of about 8 860 000 ha (Mabunda *et al.* 2003). The tree canopy cover ranges from 5 to 60% and is dominated by *Acacia* spp., *Combretum* spp. and *Colophospermum mopane* (Venter *et al.* 2003). At least 2 million people reside within 50 km of the western boundary of KNP with the vast majority concentrated in the former homelands, which are densely populated and managed as communal rangelands and subsistence agriculture (Pollard *et al.* 2003).

2.2 *Landscape groups*

The diverse landscape of KNP has been classified into significant environmental units for the purpose of practical conservation planning and management. Thirty-five landscapes have been identified based on geomorphology, climate, soil, vegetation pattern and associated fauna (Gertenbach 1983). A simplified classification joined the 32 landscapes into 17 landscape groups (LG) (figure 1(*b*)) according to the scheme outlined in table 1 (Solomon *et al.* 1999). The dominant topography, geology and vegetation of the landscape groups are described in table 1.

2.3 *1-km^2 AVHRR NDVI data*

The AVHRR instruments are carried onboard the National Oceanic and Atmospheric Administration (NOAA) polar-orbiting satellites. Daily AVHRR

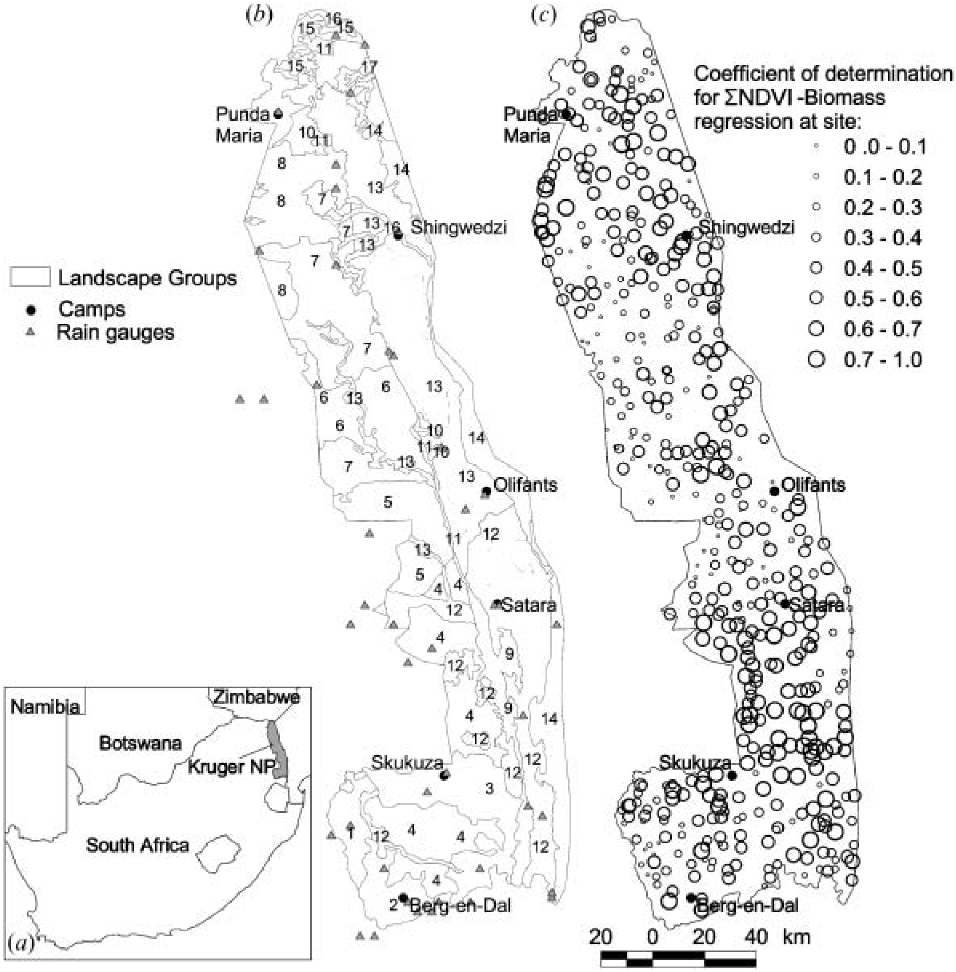

Figure 1. (*a*) Location of KNP within southern Africa. (*b*) Landscape groups (see table 1 for descriptions) and location of rain gauges. (*c*) R^2 for ΣNDVI–biomass relationship at each field site. The size of the circle at each site indicates the R^2 and not the size of the field site.

High Resolution Picture Transmission (HRPT, 1.1 km^2 resolution) data were received by the Satellite Application Centre (SAC) at Hartebeeshoek, South Africa and processed by the Agricultural Research Council, Institute for Soil, Climate and Water (ARC-ISCW). Data from 1985 to 2003 were consistently processed and calibrated to correct for sensor degradation and satellite changes (Rao and Chen 1995, 1996). Due to the failure of NOAA-13, data for 1994 were unavailable.

The daily images were geometrically corrected by using the orbital parameters and an automated georeferencing system based on 300 ground control image subsets. Images were processed to the Plate Carrée map projection at 1 km^2. Although atmospheric correction of time-series AVHRR data is desirable for inter-annual comparison of NDVI data (El Saleous *et al.* 2000, Cihlar *et al.* 2004), no atmospheric correction was performed since atmospheric water vapour and aerosol optical depth data were not available for the entire time-series at sufficiently high resolution—for example, National Center for Environmental Prediction (NCEP)

Table 1. Description of landscape groups of KNP (figure 1(*b*)) (after Gertenbach 1983).

Landscape group	Gertenbach landscapes	Description
1	1	Moderately undulating granitic flats with *Terminalia sericea* Tree Savanna.
2	2	Low granitic mountains with *Combretum apiculatum* Bush Savanna.
3	4	Lowlands with *Acacia grandicornuta* Tree Savanna.
4	3, 5	Moderately undulating granitic plains with *Combretum zeyheri*, or with *Combretum apiculatum* Bush Savanna.
5	6, 7	Slightly irregular granitic plains with *Colophospermum mopane* Bush Savanna, or irregular granitic hills with *C. mopane* Tree Savanna.
6	9, 10	Slightly undulating metalava plains with *Colophospermum mopane* Tree Savanna, or very irregular granitic plains with *C. mopane* Tree Savanna.
7	8, 11	Moderately undulating granitic plains with *Colophospermum mopane* Bush Savanna, or slightly undulating plains with *C. mopane* Bush Savanna.
8	12, 33	Metalava plains with *Colophospermum mopane* Tree Savanna, or andesitic plains with *Combretum collinum* Shrub Savanna.
9	13, 14	Karoo sediment plains with *Acacia welwitschii* Tree Savanna, or with *Terminalia sericea* Bush Savanna.
10	15	Karoo sediment plains with *Colophospermum mopane* Tree Savanna.
11	16, 34	Very irregular Clarens sandstone hills with *Terminalia sericea* Bush Savanna, or low Soutpansberg Group mountains with *Burkea africana* Tree Savanna.
12	17, 18, 19, 20	Basaltic plains with *Scleorcarya birrea* Tree Savanna; or slightly undulating basaltic plains with *Acacia nigrescens* Shrub Savanna; or moderately undulating basaltic plains with *A. nigrescens* Bush Savanna; or moderately undulating basaltic plains with *A. nigrescens* Tree Savanna.
13	21, 22, 23, 24	Irregular basaltic plains with *A. nigrescens* Bush Savanna; or with *Colophospermum mopane* Bush Savanna; or basaltic plains with *C. mopane Shrub Savanna*; or slightly undulating gabbroic plains with *C. mopane* Shrub Savanna.
14	27, 29, 31	Slightly undulating basaltic plains; or low rhyolitic mountains with *Combretum apiculatum* Bush Savanna; or low rhyolitic mountains with *Colophospermum mopane* Bush Savanna.
15	25, 26	Moderately undulating gabbroic plains with *Colophospermum mopane* Shrub Savanna; or irregular calcitic plains with *C. mopane* Shrub Savanna.
16	28, 35	Alluvial plains with *Faidherbia albida*; or with *Salvadora angustifolia* Tree Savanna.
17	30, 32	Recent sand plains with *Terminalia sericea* Bush Savanna; or with *Baphia massaiensis* Bush Savanna.

precipitable water vapour data are only available at a $2.5^\circ \times 2.5^\circ$ resolution (Cihlar *et al*. 2001, 2004, DeFelice *et al*. 2003). A cloud mask was applied based on channel 1, channel 4 and the difference between channels 4 and 5. NDVI was calculated from channel 1 (0.55–0.68 μm) and channel 2 (0.73–1.1 μm) bands (NDVI=(ch2−ch1)/(ch2+ch1)).

Ten-day maximum NDVI value composites were calculated to remove residual clouds, reduce atmospheric effects and the influence of varying solar zenith angles (Holben 1986). Several other procedures have been described that remove noise caused by cloud contamination, atmospheric perturbations or variable solar zenith angles from time-series data (Yang *et al.* 1998, Swets *et al.* 1999). Here a statistical filter was applied to interpolate cloud flagged or atmospherically affected data, identified whenever a relative decrease in the signal of 5% or more was followed within 4 weeks by an equivalent increase (Lo Seen Chong *et al.* 1993). The 10-day composites were weighted by the number of days in each composite and summed over the entire growing season, October to April (hereafter referred to as ΣNDVI) (Prince 1991, Lo Seen Chong *et al.* 1993, Yang *et al.* 1998, Diouf and Lambin 2001). The above-mentioned 10-day compositing, data interpolation and growth season sum procedures all contributed to reducing the atmospheric effects. However, the multi-temporal ΣNDVI data may be influenced by the remaining atmospheric effects (Cihlar *et al.* 2004).

2.4 *Herbaceous biomass data*

Vegetation condition assessments (VCA) have been conducted at approximately 533 field sites (number varies slightly from year to year) in KNP since 1989 (Trollope 1990). The number of sites assigned to each landscape (Gertenbach 1983) was proportional to the area of the Park covered by the specific landscape. The sites were placed evenly throughout each landscape type and in a small number of cases, following field inspection, their positions were adjusted to avoid local conditions not representative of the landscape as a whole. Fixed sampling areas were then marked at each site.

The VCA surveys are carried out between the end of March and mid-April, commencing whenever the herbaceous vegetation first appears to be drying out. At each site vegetation composition, structure and herbaceous biomass were surveyed (Zambatis 2002). Within each $50\,\mathrm{m} \times 60\,\mathrm{m}$ site ($0.003\,\mathrm{km}^2$), 100 herbaceous biomass estimates were recorded at 2-m intervals along four 50-m transects, using a disc pasture meter. The disc pasture meter was calibrated for wet grass fuel loads (herbaceous biomass: $\mathrm{kg\,ha}^{-1}$) in the seven main landscapes of the KNP by sampling areas that had been lightly, moderately and heavily grazed (Trollope and Potgieter 1986). Moisture content was estimated using gravimetric methods. A regression equation was derived which accounted for 89.5% of the variation in grass fuel load over these diverse grassland communities (Trollope and Potgieter 1986):

$$y = -3019 + 2260\sqrt{x} \tag{1}$$

where y is the estimated herbaceous biomass ($\mathrm{kg\,ha}^{-1}$), x is the mean disc pasture meter height of 100 measurements (cm), and $R^2 = 0.895$

The confidence limits ($p \leqslant 0.05$) of the herbaceous biomass estimates from the disc pasture meter were $286\,\mathrm{kg\,ha}^{-1}$ for the mean biomass estimate of $4200\,\mathrm{kg\,ha}^{-1}$ and ranged from $328\,\mathrm{kg\,ha}^{-1}$ for $1500\,\mathrm{kg\,ha}^{-1}$ to $526\,\mathrm{kg\,ha}^{-1}$ for $9360\,\mathrm{kg\,ha}^{-1}$. This level of precision was considered more than adequate for fire studies in KNP (Trollope and Potgieter 1986).

The $0.003\,\mathrm{km}^2$ sampled at each VCA site in KNP may not be fully representative of the average conditions in the 1-km^2 area covered by each AVHRR pixel due to local landscape variations (Reich *et al.* 1999, Scurlock *et al.* 1999, Cramer *et al.* 2001). Field measurements of herbaceous biomass for comparison with 1-km^2

AVHRR data typically sampled sites between 4 and 9 km^2 (Du Plessis 1999, Diouf and Lambin 2001), or multiple transects (or plots) within larger 25–100 km^2 homogeneous sites (Diallo *et al.* 1991, Wylie *et al.* 1991). Therefore Landsat Enhanced Thematic Mapper Plus (ETM+) and Thematic Mapper (TM) data were used assess the spatial heterogeneity of the 700 m radii around the VCA sites (§2.5).

2.5 *Removing highly heterogeneous field sites*

Landsat 7 ETM+ and Landsat 5 TM NDVI images were used to quantify the heterogeneity of the field sites (Fensholt *et al.* 2004). Two images were selected for each of the two Landsat scenes to coincide with the end of a low rainfall season (169-76: 18 March 1998, 168-77: 28 April 2001) and a high rainfall season (169-76: 24 April 2000, 168-77: 9 April 2000). The standard deviation of the Landsat NDVI pixels within a 700-m radius centred at each field site were calculated. The standard deviations in the NDVI of sites were slightly higher in the low rainfall seasons (1997–1998 and 2000–2001), but in all the images the sites with very high standard deviations were generally closer than 600 m to rivers and often contained riparian woodland vegetation along drainage channels with seasonal water or bare sand. These sites (n=37) were therefore excluded from further analysis. After this removal there was no relationship between the Landsat NDVI variation in the sites and their coefficient of determination between biomass and AVHRR ΣNDVI (§3.2.1). Visual inspection of the Landsat images around each field site, showed that the spatial patterns within the 700 m radii were representative of the surrounding landscape pattern. Therefore all remaining sites (n=464) were included in the subsequent analyses.

2.6 *Rainfall data*

Rainfall measurements were recorded at rain gauges (n=44) in and around KNP (figure 1(*b*)). Rain gauges were assigned to one or more landscape groups during visual interpretation based on distance and topography. The total growth season rainfall (October to April) was calculated for each rain gauge. For each landscape group the average growth season total rainfall was calculated from all its assigned stations.

2.7 *Overview of data analyses*

The underlying relationship between ΣNDVI and biomass was first analysed with ΣNDVI as the dependent variable (§2.8). Thereafter regression analyses were used to predict biomass for each growth season using ΣNDVI as an independent variable to potentially map herbaceous biomass (§2.9).

2.8 *ΣNDVI–biomass relationship*

The underlying relationship between ΣNDVI and biomass was first analysed with ΣNDVI as the dependent variable.

2.8.1 Correlation between growth season mean biomass, mean ΣNDVI and rainfall of landscape groups. The underlying general relationships between biomass, ΣNDVI and rainfall were investigated by plotting the mean growth season values of all the sites in each landscape group and calculating the correlation between these means.

2.8.2 Regression between ΣNDVI and biomass per site, through time. ΣNDVI values were extracted from the single pixels coinciding with the location of each field site. Since both the dependent and independent variables (ΣNDVI and biomass, respectively) were subject to error, the geometric mean regression (also known as MODEL II regression) was calculated since ordinary least squares tends to underestimate the true slopes of regression lines (Riggs *et al.* 1978). Only field sites with more than nine growth seasons (n=9–13) of biomass data were used and whenever zero biomass was measured at a site, such data were excluded, since these created extreme outliers.

2.8.3 Regression between ΣNDVI and biomass, per landscape group, through time. Data for all the sites and all the years were lumped together for each landscape group to test the strength of the relationship between ΣNDVI and biomass through time. The geometric mean regression was again used because both the ΣNDVI and biomass data were subject to error (Riggs *et al.* 1978).

2.8.4 Influence of tree cover on ΣNDVI–biomass relationship. In 1996 woody vegetation cover was measured along two 5 m × 50 m ($500 m^2$/0.0005 km^2) transects at approximately 100 of the VCA sites. The percentage tree cover of each field site was calculated from the crown diameter of all the trees taller than 1.5 m. Multiple regression models were created for each landscape group with ΣNDVI as the dependent variable and biomass and tree cover being successively added as independent variables. In this manner it could be tested whether adding tree cover increased the total variance in ΣNDVI accounted for by the linear model.

Fixed point photographs taken in 1984 and in 1996 showed that the density of trees 2–5 m in height increased from 10.1% to 12.2% and trees taller than 5 m decreased from 4.7% to 2.9% on soils derived from basalt (landscape groups (LGs) 12, 13, 15) (Eckhardt *et al.* 2000). While on granite soils (LGs 1, 2, 4–7) 2–5-m tree density increased from 3.5% to 4.5% and trees taller than 5 m decreased from 4.6% to 3.9%. Although these changes were statistically significant and the decrease in the density of large trees (>5 m) is a major management concern, these relatively small changes are unlikely to have had a major influence on the signal detected by the AVHRR sensor (Prince 1987, Fuller *et al.* 1997). Therefore, it was assumed that tree cover remained unchanged throughout the study period.

2.9 *Estimating biomass from ΣNDVI*

To investigate the potential for producing biomass maps from the ΣNDVI data (e.g. (Diallo *et al.* 1991), regression analyses were used to predict biomass (dependent variable) for each growth season.

2.9.1 Predicting biomass using multiple independent variables. The landscape group was added as a categorical variable to establish how much of the remaining variance in biomass could be accounted for after using ΣNDVI and the Moderate Resolution Imaging Spectroradiometer (MODIS) tree cover estimates as independent variables in multiple regression models. The percentage of the total variance (sums of squares) accounted for by the overall model and each of the independent variables were determined. This percentage is always dependent upon the order in which the independent variables are added to the model, i.e. ΣNDVI, MODIS tree cover and landscape group. The inclusion of interactions between the variables did not significantly increase the amount of variance explained by the model and therefore interactions were not considered.

2.9.2 Estimating biomass using smoothed data. Since there was considerable variability in the biomass data collected from the small sampling sites, a smoothing procedure was applied to the data to elucidate the predictive ability of ΣNDVI. As described by Du Plessis (1999), ranges of 10 consecutively paired values of biomass and ΣNDVI (ordered according to biomass) were smoothed by calculating the arithmetic means of the pairs. This smoothing method was chosen to demonstrate the underlying relationship between the variables. Other smoothing methods, e.g. moving average smoothing, Gaussian kernel smoothing or spline smoothing, are more appropriate for time series analyses.

3. Results and discussion

3.1 *Correlation between growth season mean biomass, mean ΣNDVI and rainfall*

There was a positive relationship between the growth season mean biomass and mean ΣNDVI of all the sites in a landscape group (figure 2). Both mean biomass and mean ΣNDVI were strongly correlated with rainfall and each other (figure 2; table 2). The average of the correlation coefficients of all the landscape groups for ΣNDVI–biomass, biomass–rainfall and ΣNDVI–rainfall were 0.76, 0.76 and 0.84, respectively. However, if the extreme dry (low biomass) growth seasons and the wet (high biomass) growth seasons were excluded (figure 2), the relationship for the remaining average growth seasons would not be as strong.

The biomass measured in any growth season varied considerably within a LG, with an average range (maximum – minimum) of 4570 kg ha^{-1}. The corresponding average standard deviation was approximately 50% of the mean biomass (figure 2). The influence of herbivory by vertebrates and insects on the end-of-season biomass could not be taken into account because detailed data of the distribution and intensity of herbivory are not available. Differences in the intensity of herbivory at the sampling sites may have contributed to the large variation in biomass measurements observed within a landscape group for a single growth season (figure 2).

The ΣNDVI of KNP was strongly related to rainfall (figures 3 and 4). The effects of the 1991–1992, 1997–1998 and 2002–2003 El Niño and the 1999–2000 La Niña conditions on the ΣNDVI were clearly visible (figures 3 and 4) (Anyamba *et al.* 2002). The geographical pattern of ΣNDVI reflected the general patterns of rainfall and biomass.

3.2 *ΣNDVI–biomass relationship*

3.2.1 Relationship between ΣNDVI and biomass per site, through time. The coefficients of determination (R^2) for the field sites varied from 0.01 to 0.93 with an average of 0.42 (figure 1(*c*)). In general $R^2>0.3$ were statistically significant ($p \leqslant 0.05$, degrees of freedom = 7–11). Sites with similar strength of the relationship were somewhat clumped with high values occurring in groups (figure 1(*c*)). The reason for this clumped pattern has not yet been determined. Figure 5 provides an example of a single field site near Skukuza with a strong ΣNDVI–biomass relationship ($R^2=0.8$). It was clear that rainfall had a very strong influence on the biomass and therefore the ΣNDVI (figure 5).

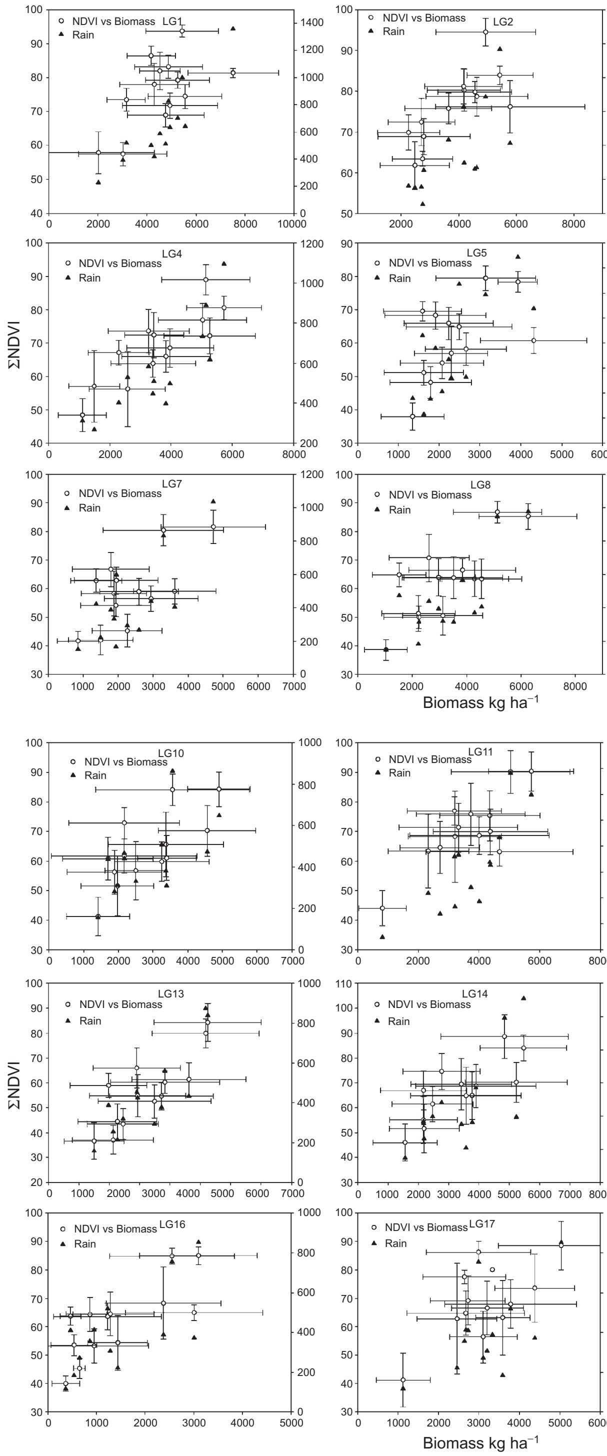

Figure 2. Growth season average ΣNDVI, biomass and rainfall for each landscape group (LG). The landscape groups are described in table 1 and mapped in figure 1(*b*). Error bars indicate ±1 SD.

Table 2. Correlation coefficients (r) for each landscape group's relationships derived from growth season average ΣNDVI and biomass data.

	r		
Group	ΣNDVI–biomass	Biomass–rainfall	ΣNDVI–rainfall
1	0.64	0.88	0.63
2	0.76	0.71	0.76
3	0.86	0.90	0.81
4	0.85	0.85	0.82
5	0.52	0.71	0.82
6	0.67	0.70	0.87
7	0.67	0.75	0.88
8	0.80	0.78	0.91
9	0.92	0.83	0.87
10	0.74	0.55	0.88
11	0.82	0.82	0.83
12	0.89	0.89	0.93
13	0.84	0.85	0.94
14	0.80	0.71	0.85
15	0.75	0.63	0.77
16	0.65	0.72	0.92
17	0.67	0.60	0.82
Average	0.76	0.76	0.84

The heterogeneity of the sites, as estimated by the standard deviation of Landsat NDVI, did not appear to affect the strength of the site's biomass–ΣNDVI (AVHRR) relationship. The sites had coefficients of variation in Landsat NDVI of 8–16%. Visual inspection of the 700-m radius area around sites with low R^2 values using the Landsat imagery did not reveal any obvious landscape features that may have caused weak relationships, except for only two cases in which there was a reservoir and a large area of bare ground, respectively. Some adjacent sites which had contrasting R^2 values, appeared to have the same landscape pattern according to the Landsat imagery.

Low R^2 values could have been the result of outliers that often have large impacts on the strength of linear relationships determined from the short time series available for the study (9–13 seasons). Senesced material of the previous growth season, which had not been utilized or decomposed, can affect the disc pasture meter. No attempt was made to differentiate this 'old' material from the material of the current growth season. The ratio of 'old' to 'new' material depends on the rainfall of the previous and current years and thus varies from year to year. Since senesced material does not contribute to ΣNDVI, but influences the biomass estimates, it may have weakened the ΣNDVI–biomass relationship. Variations in the timing of rainfall can lead to variations in the onset and duration of the actual growth period between growth seasons. This could affect the relationship between the end-of-season measurements and the actual vegetation production, which may further have weakened the ΣNDVI–biomass relationship.

3.2.2 Regression between ΣNDVI and biomass, per landscape group, through time. The coefficients of determination ranged from 0.08 (landscape group (LG) 17) to 0.41 (LG 4), with an average of 0.26 (table 3; for all landscape groups, $p<0.03$). These R^2 values were generally much lower than those calculated for the individual

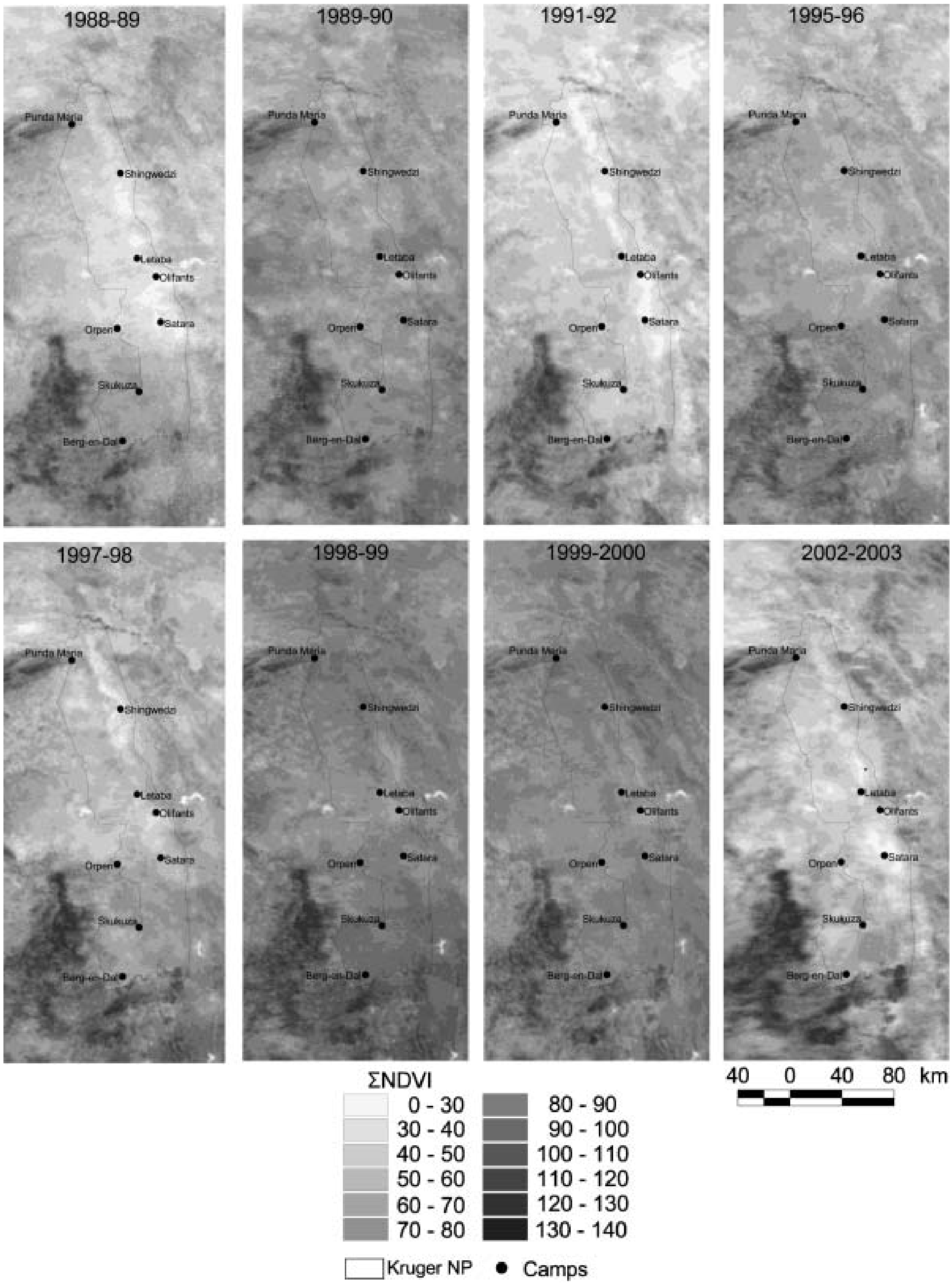

Figure 3. ΣNDVI of Kruger National Park for selected growth seasons.

sites (§3.1.1 above). Thus, grouping data together from different sites within a specific landscape group may obscure the relationship that exists on a site-to-pixel basis due to landscape variation in the landscape group. When all the data were grouped together for all growth seasons and all landscape groups, the overall $R^2=0.28$, which was much lower than the $R^2=0.56$ reported by Prince and Tucker (1986) for a similar analysis in Botswana.

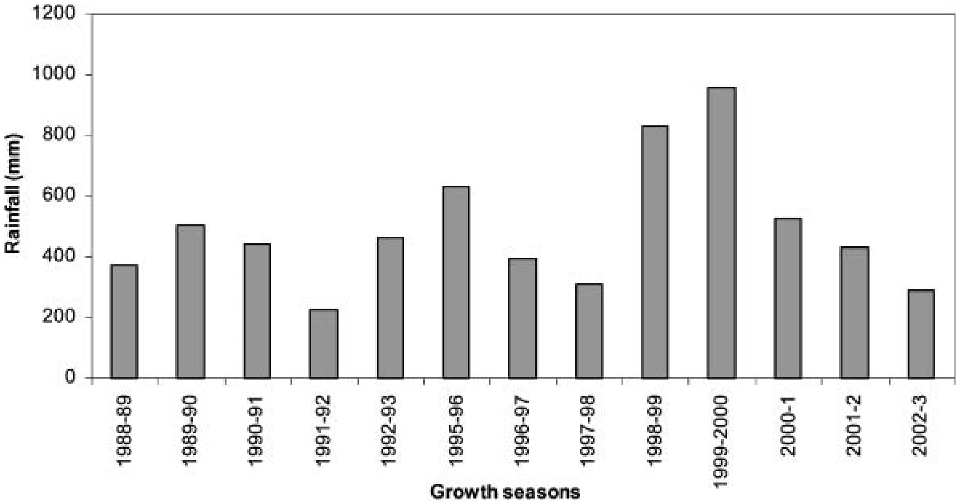

Figure 4. Average growth season rainfall of KNP for 1988–1989 to 2002–2003.

3.3 *Influence of tree cover on biomass–ΣNDVI relationship*

The average tree cover for all the sites in KNP was approximately 20%. LGs 8, 9, 10, 11 and 15 showed some increase in R^2 after adding the tree cover to the multiple regression model ($p<0.01$) (table 3). There was no clear relationship between the increase in R^2 by adding tree cover to the model and the average tree cover of the landscape groups (table 3). For example, some landscape groups with tree covers ranging from 0 to 54% showed no improvement in the R^2 after adding tree cover to

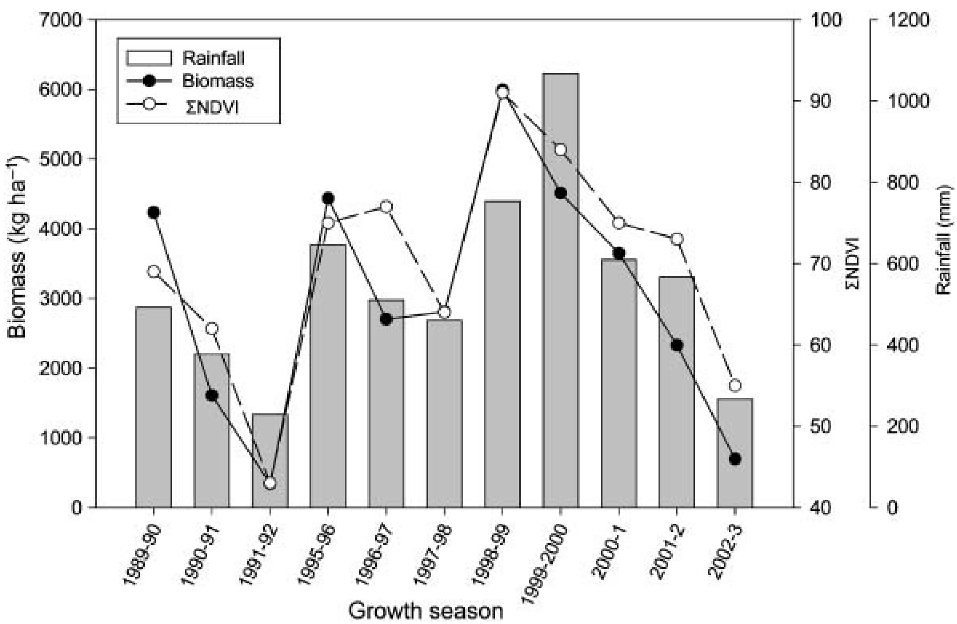

Figure 5. Herbaceous biomass and ΣNDVI for a field site near Skukuza where the rainfall was recorded.

Table 3. Coefficients of determination (R^2) for ΣNDVI–biomass relationships for each landscape group and changes in R^2 after adding tree cover to the regression. Tree cover was measured at a total of 100 sites (tree sites).

Group	R^2 ΣNDVI–biomass, all sites	% tree cover	R^2 ΣNDVI–biomass, tree sites	R^2 ΣNDVI–biomass, +tree cover	Increase in R^2
1	0.17	32.1	0.15	0.15	0.00
2	0.26	9.6	0.39	0.43	0.04
3	0.27	40.1	0.36	0.39	0.03
4	0.41	17.7	0.50	0.50	0.00
5	0.11	23.5	0.05	0.12	0.07
6	0.24	33.0	0.33	0.33	0.00
7	0.21	28.6	0.20	0.20	0.00
8	0.31	28.6	0.17	0.23	0.06
9	0.40	19.4	0.21	0.67	0.46
10	0.11	67.0	0.16	0.53	0.37
11	0.37	31.4	0.24	0.46	0.22
12	0.39	12.8	0.32	0.33	0.01
13	0.31	6.8	0.30	0.30	0.00
14	0.33	12.3	0.41	0.42	0.01
15	0.12	42.7	0.14	0.31	0.17
16	0.36	54.2	NA	NA	NA
17	0.08	2.8	NA	NA	NA
Average	0.26	27.20	0.26	0.36	0.10

the model. These results were expected, since radiative transfer models and field observations have shown that the herbaceous layer in savanna woodlands dominates the signal detected by AVHRR or other sensors, especially during the growth season (Prince 1987, Fuller *et al.* 1997).

As described in Botswana (Prince and Tucker 1986), there appears to be a negative correlation between herbaceous cover and tree cover (figure 6). All the growth seasons showed similar trends to the 1995–1996 season which was plotted

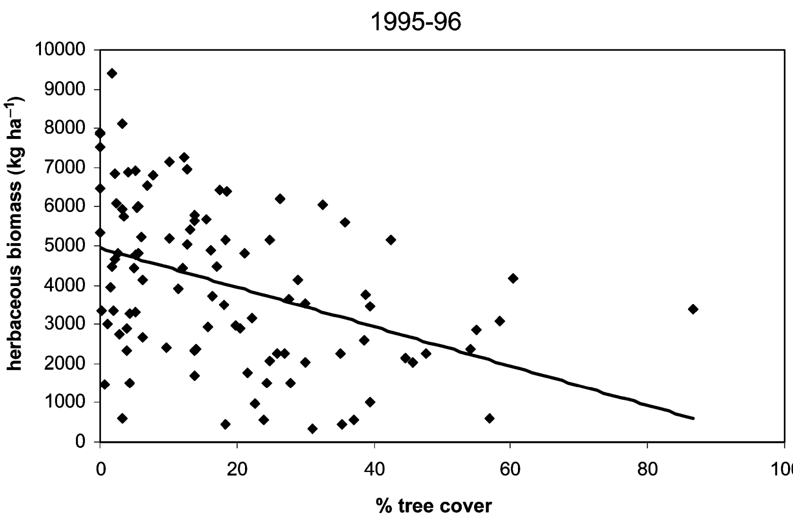

Figure 6. Relationship between herbaceous biomass and percentage tree cover measured at selected field sites (n=100) for the 1995–1996 growth season.

here (figure 6). The correlation coefficients of the different growth seasons ranged from −0.2 to −0.4 for the relationship between herbaceous biomass and tree cover. Plotting the trend lines of biomass vs ΣNDVI for all the sites and all the years, grouped into classes according to tree cover, revealed that sites with higher tree cover had higher ΣNDVI values for a specific level of herbaceous biomass (figure 7). The same effect was described by Prince (1991) and Diallo *et al.* (1991). Therefore, although the tree cover in KNP did not appear to have a major influence on the biomass–ΣNDVI relationship, the results suggest that tree cover should not be ignored. Unfortunately measurements of woody vegetation were only conducted at 100 of the sites and therefore the influence of the woody component could not be specified for all sites. It is also uncertain to what extent the 0.0005 km^2 area sampled in the woody component surveys was representative of the surrounding 1 km^2 landscape.

3.4 *Estimating biomass from ΣNDVI*

3.4.1 Predicting biomass using multiple independent variables. The R^2 values of the models for the individual growth seasons varied between 0.23 and 0.48, and all were highly significant ($p<0.001$; table 4). The average R^2 of all the growth seasons was 0.36. The amount of variance accounted for by ΣNDVI varied considerably between growth seasons from 0% to 25%. During the three driest growth seasons (1991–1992, 2001–2002, 2002–2003, figure 4), ΣNDVI explained the smallest percentages of the variance (⩽4%, table 4). For individual growth seasons, the ΣNDVI generally accounted for less variance than reported by similar studies, e.g. $R^2=0.68$ (Diouf and Lambin 2001). In accordance with the findings of Diouf and Lambin (2001), the relationship between biomass and ΣNDVI changed between growth seasons. When the data for all the growth seasons were analysed together, and the growth seasons (e.g. 1996–1997) added as the final categorical independent variable to the overall multiple regression model, the R^2 increased to 0.5, which was slightly lower, but comparable to the results of similar regression analyses (Prince and Astle 1986, Prince and Tucker 1986). The MODIS tree cover accounted for only 1–4% of the variance. Although these contributions were statistically significant ($p<0.01$),

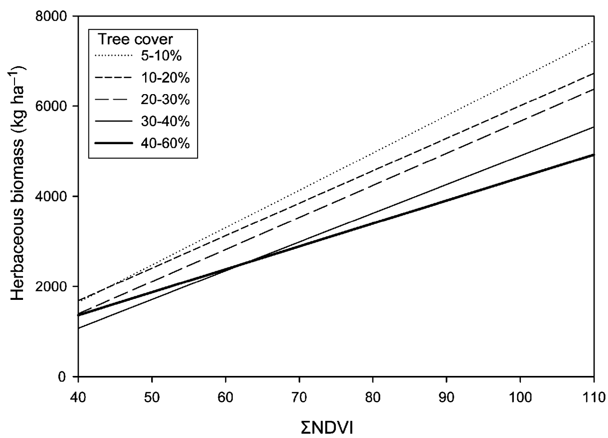

Figure 7. Trend lines of ΣNDVI versus herbaceous biomass for field sites grouped according to tree cover ranges.

Table 4. Multiple regression analyses to predict biomass from independent variables ΣNDVI, MODIS tree cover and landscape group and the percentage of the total sums of squares explained (and significance levels) by successively adding the variables to models. R^2 and average standard error of maximal model including all variables.

Growth season	Variables	R^2	Average standard error	Percentage of total sums of squares	F-value	p
1988–89		0.41	346			
	ΣNDVI			25.3	178.4	<0.001
	MODIS tree cover			1.4	10	<0.001
	Landscape Group			13.9	6.1	<0.001
1989–90		0.42	352			
	ΣNDVI			24.2	194.9	<0.001
	MODIS tree cover			1.8	14.5	<0.001
	Landscape Group			16.4	8.2	<0.001
1990–91		0.38	380			
	ΣNDVI			8.2	60.5	<0.001
	MODIS tree cover			2.6	19.1	<0.001
	Landscape Group			27.0	12.4	<0.001
1991–92		0.26	301			
	ΣNDVI			4.0	20.9	<0.001
	MODIS tree cover			0.7	3.9	0.04
	Landscape Group			21.9	7.1	<0.001
1992–93		0.43	332			
	ΣNDVI			23.8	187.3	<0.001
	MODIS tree cover			3.2	25	<0.001
	Landscape Group			16.2	7.9	<0.001
1995–96		0.42	440			
	ΣNDVI			20.9	175.4	<0.001
	MODIS tree cover			3.6	30.6	<0.001
	Landscape Group			18.3	9.6	<0.001
1996–97		0.34	409			
	ΣNDVI			12.0	88.6	<0.001
	MODIS tree cover			3.5	25.9	<0.001
	Landscape Group			18.5	8.5	<0.001
1997–98		0.39	372			
	ΣNDVI			22.2	178.8	<0.001
	MODIS tree cover			2.2	17.6	<0.001
	Landscape Group			15.1	7.5	<0.001
1998–99		0.4	439			
	ΣNDVI			19.5	164.1	<0.001
	MODIS tree cover			4.2	35.5	<0.001
	Landscape Group			16.9	8.8	<0.001
1999–2000		0.4	444			
	ΣNDVI			9.1	52.8	<0.001
	MODIS tree cover			1.9	10.9	<0.001
	Landscape Group			29.5	10.6	<0.001
2000–1		0.28	465			
	ΣNDVI			13.2	82.48	<0.001
	MODIS tree cover			2.6	16.02	<0.001
	Landscape Group			12.3	4.79	<0.001
2001–2		0.28	432			
	ΣNDVI			4.2	22.4	<0.001
	MODIS tree cover			3.6	19.2	<0.001
	Landscape Group			20.4	7.21	<0.001

Table 4. (*Continued.*)

Growth season	Variables	R^2	Average standard error	Percentage of total sums of squares	F-value	p
2002–3		0.23	327			
	ΣNDVI			0.0	0.001	0.98
	MODIS tree cover			3.5	19.8	<0.001
Average	Average	0.385	381.5			

including the MODIS tree cover did not lead to any substantial improvements in the predictive ability of the model (table 4).

The landscape groups accounted for 13–30% of the total variation in biomass (table 4). This indicates the importance of including landscape group in the predictive model. The average 95% confidence limits over the entire range of the predicted biomass values were $\pm 700\,\mathrm{kg\,ha^{-1}}$.

3.4.2 Estimating biomass using smoothed data. The coefficient of determination increased considerably after performing the regressions on the smoothed data, from an average of R^2 of 0.14 to 0.56 (table 5). With the exception of the 2002–2003 season, all regressions were highly significant, $p<0.01$ (degrees of freedom=38–47). The very dry 2002–2003 season had a very weak relationship. When the 2002–2003 season was excluded, the average R^2 for the smoothed data was 0.6, comparable to studies where larger field sites were sampled (Prince and Tucker 1986, Nicholson *et al.* 1990, Diallo *et al.* 1991, Prince 1991, Wylie *et al.* 1991, Diouf and Lambin 2001). Based on the 95% confidence intervals associated with the predicted biomass, the error of the prediction was $\pm 300\,\mathrm{kg\,ha^{-1}}$ around the average biomass measured in a specific growth season (figure 8). Predictions of biomass were less accurate in dry years where biomass values were very low (e.g. 2002–2003, 1991–1992, 2001–2002) (figure 8; table 5).

Table 5. Coefficients of determination (R^2) for predicting biomass from ΣNDVI using smoothed data.

	R^2	
Growth season	Raw data	Smoothed data
1988–1989	0.25	0.79
1989–1990	0.24	0.83
1990–1991	0.08	0.4
1991–1992	0.04	0.4
1992–1993	0.24	0.76
1995–1996	0.21	0.73
1996–1997	0.12	0.52
1997–1998	0.22	0.77
1998–1999	0.2	0.64
1999–2000	0.1	0.53
2000–2001	0.13	0.63
2001–2002	0.04	0.28
2002–2003	0.007	0.007
Average	0.14	0.56

When the smoothed data of all the growth seasons were included in a single regression analysis, the ΣNDVI explained 35% of the variance. This increased to 66% after adding the growth season as a categorical variable, thus allowing different regression lines for each year. These results were in agreement with other studies (Prince and Astle 1986, Diallo *et al*. 1991, Diouf and Lambin 2001) and suggest that separate predictive equations should be developed for each growth season using annual field measurements.

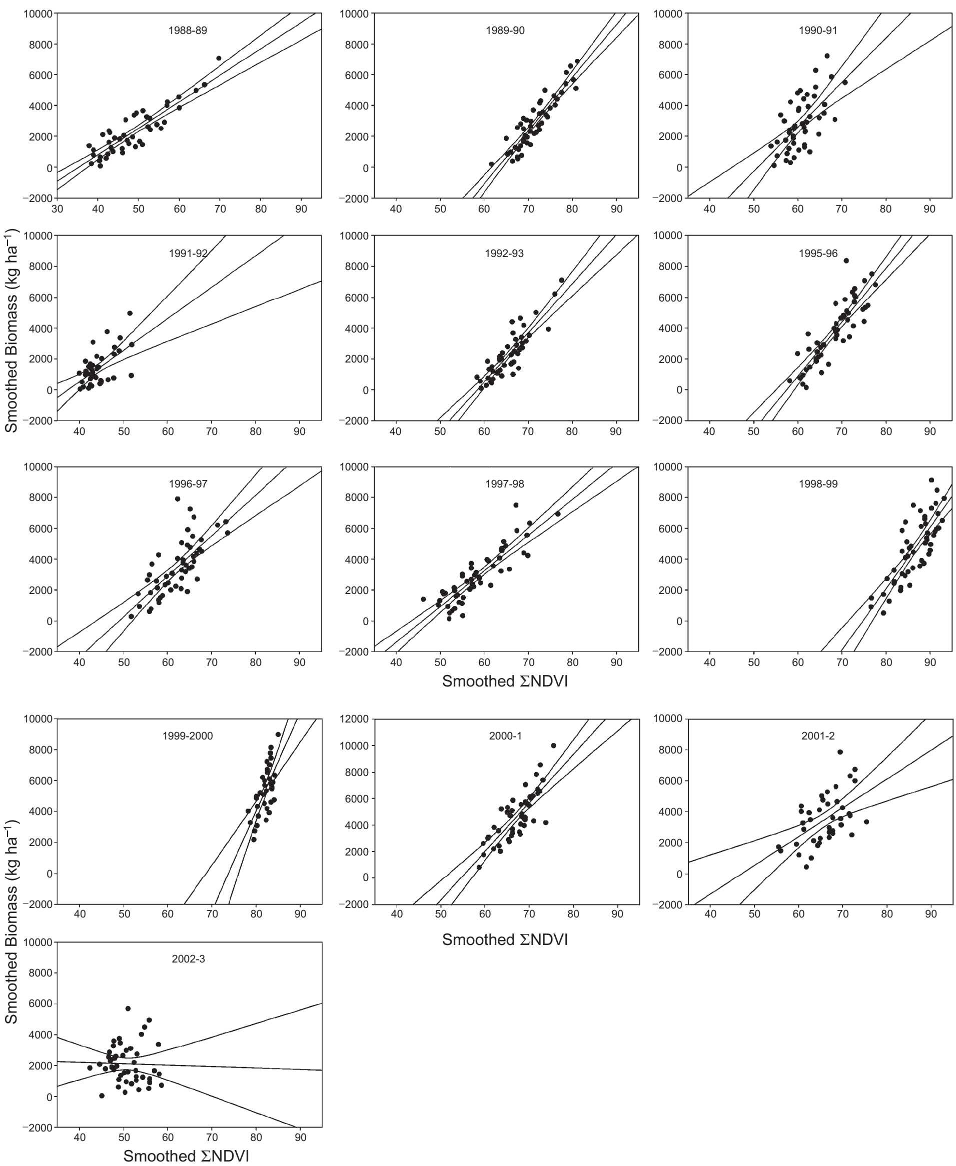

Figure 8. Linear regressions of smoothed biomass and ΣNDVI data for each growth season. The 95% confidence limits are also indicated.

4. Conclusions

This study analyses two unique, long-term (1989 to present) datasets, herbaceous biomass measurements at 533 sites and a consistently processed 1-km^2 AVHRR NDVI archive, in one of the largest protected areas in the world. The long-term data allowed the ΣNDVI–biomass relationships to be investigated at each individual field site. Although the R^2 values varied greatly, they were moderately high (average R^2=0.42, figure 1(*c*)). Landsat imagery enabled highly heterogeneous field sites to be omitted, but did not help to explain why some sites had very weak ΣNDVI–biomass relationships, while similar, adjacent sites had strong relationships. The ΣNDVI–biomass relationship could have been weakened by (i) variations in distribution and intensity of herbivory, (ii) the influence of senescent material from the previous growth season on the biomass measurements and (iii) variations in the onset and duration of actual growth period in relation to the end-of-season biomass measurements.

Growth season mean values for biomass, ΣNDVI and rainfall calculated for each landscape group were highly correlated (figure 2; table 2). ΣNDVI images also clearly reflected the impacts of contrasting rainfall conditions (figures 3 and 4). Thus, this study demonstrated a relatively strong underlying relationship between biomass, rainfall and ΣNDVI for this new region in accord with studies of other areas (Nicholson *et al.* 1998, Du Plessis 1999, Diouf and Lambin 2001). The KNP biomass estimates can also be compared to other remotely sensed estimates of vegetation activity, e.g. SPOT-VEGETATION derived estimates of dry matter productivity, NPP or Net Ecosystem Production (NEP) (Veroustraete *et al.* 2002), Global Production Efficiency Model (GLO-PEM) NPP (Prince and Goward 1995, Cao *et al.* 2004), or MODIS products (Huete *et al.* 2002, Fensholt *et al.* 2004).

Although the regression analyses showed that measured tree cover and MODIS estimates of tree cover did not have a major influence on the ΣNDVI–biomass relationship (tables 2 and 5) (Prince 1987, Fuller *et al.* 1997), other results presented here suggest that tree cover should not be ignored when trying to predict herbaceous biomass (figure 6 and 7). Although the coarse resolution MODIS tree cover data were not useful, more accurate tree cover data derived from higher resolution Landsat ETM + data and Ikonos data (e.g. Hansen *et al.* 2002) might be employed to improve herbaceous biomass estimates from the AVHRR data.

The predictive value of the ΣNDVI may have been underestimated in this study, since the biomass measurements were taken from very small sites (50 m × 60 m) which are shown here to exhibit considerable variability (figure 2). The standard deviation of biomass measured at all the sites in one growth season for a single landscape group was approximately 50% of the mean (figure 2). This variability appeared to be the reason for the relatively low R^2 values attained when predicting a growth season's biomass from ΣNDVI using the raw (unsmoothed) data (table 5). The regression analyses based on the smoothed data significantly increased the coefficients of determination to values comparable with other studies (table 5) (Prince and Tucker 1986, Nicholson *et al.* 1990, Diallo *et al.* 1991, Prince 1991, Wylie *et al.* 1991, Diouf and Lambin 2001).

The AVHRR ΣNDVI was able to adequately estimate inter-annual variations in the biomass at single sites, but on an annual basis the relationship derived from all the sites was not strong enough for the generation of a reliable growth season biomass maps. However, the biomass data were sampled from very small field sites that were not fully representative of 1-km^2 AVHRR pixels and thus it was not possible to test the full capability of remote sensing of biomass using these data. A supplementary sampling strategy that consists of a number of biomass measurements over a larger area for each field site (e.g. 1 km^2 or larger) is likely to be able to account for the variability in biomass observed in KNP (Zheng *et al.* 2003) and this would improve the strength of biomass–ΣNDVI relationships observed in a single growth season. Therefore, although there is little doubt that the ΣNDVI-derived growth season biomass maps should be more reliable than the currently used interpolations of the point measurements, supplementary field sampling will be needed to establish the true accuracy of the biomass maps. KNP scientists have stated that the desired accuracy of the biomass maps is $\pm 500\,kg\,ha^{-1}$ (95% confidence limits) and in the current study the accuracy was $\pm 700\,kg\,ha^{-1}$. It is therefore conceivable that the desired accuracy can be achieved with more appropriate field sampling.

This research has clearly illustrated the ability of 1-km^2 AVHRR ΣNDVI to monitor inter-annual variations in accumulated herbaceous biomass. The historical time-series of 1-km^2 AVHRR data can therefore provide essential spatial information on ecosystem variability and resilience in KNP (Wessels *et al.* 2004). KNP has adopted a Strategic Adaptive Management (SAM) programme with clear ecosystem management goals based on environmental indicators and their thresholds potential concern (Biggs and Rogers 2003). It is envisaged that remotely sensed environmental indicators, e.g. measures of vegetation production derived from AVHRR ΣNDVI, will be incorporated into KNP's operational monitoring system to assist the SAM programme. This approach could be expanded beyond KNP to monitoring and management natural rangelands and combat land degradation throughout South Africa.

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