RELATION BETWEEN COLD CLOUD DATA, NDVI AND MOPANE IN EASTERN BOTSWANA

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ABSTRACT:

Studies on vegetation geographical distribution patterns are often associated with the causal factors such as rainfall, soils or temperature patterns. Reasonably accurate and reliable maps of the climatic and edaphic factors are not always readily available, and when they are, their usefulness in biogeographical investigations is constrained by the quality of the data. Variability of rainfall in Botswana is very high in both spatial and temporal terms, but reliable rainfall measurements are taken on only a few (14) existing meteorological stations countrywide. More efficient methods of data capture that provide a complete coverage of the country's entire surface are therefore used to complement the existing point data. Meteosat Cold Cloud Duration (CCD) data were used as a surrogate for rainfall patterns. The reasoning behind the use of CCD data was based on the premise that rainfall is related to cloud cover. A relationship between the two is determined for Botswana using CCD data and existing rain gauge data. Patterns in vegetation primary production in a north to south direction in eastern Botswana (covering the mopane belt) were sought through the use of NOAA NDVI data. A relationship between CCD's and rainfall justifies the use of CCD patterns in the search for matching patterns of the mopane distribution. Although results show no indications of a match between the southern limits of mopane and mean annual rainfall, there is a general trend of declining correlation southeastwards. This indicates that mopane responds to a declining rainfall gradient and hence the differences in mopane structural types from north to south.

1. INTRODUCTION

Plant distribution limits have been studied world-wide, often giving rise to attempts to explain reasons for their existence. Many plant species are found only in certain geographic locations, something that prompted biogeographers to believe that species distribution patterns respond to environmental conditions. Variations in different components of climate have been associated with plant distribution patterns and as a result vegetation classifications around the world have been drawn on the basis of climatic regions e.g. Köppen (1931), Holdridge (1947). These conditions force a change in distribution patterns. These changes according to Carter and Prince (1988), can be characterised as a reduction in the abundance towards the limits. With well-defined vegetation boundaries at broad scales, attempts have been made to study distribution patterns in association with environmental factors at finer scales.

In Botswana, a species known as *Colophospermum mopane* (Kirk ex Benth.) Kirk ex J. Leonard (commonly known as mopane) exhibits a peculiar distribution pattern. It is found only in the northern and eastern parts of the country. The southern limit of *C. mopane* is almost an abrupt boundary at approximately 23º south. We however believe that the only noticeable characteristic on the distribution pattern of mopane is that there is a change in the growth structure from north to south.

In this study, we attempt to use rainfall patterns to account for the heterogeneity found in biogeographical zones of the mopane woodlands in eastern Botswana. The influence of rainfall, as a dominant determinant in controlling inherent heterogeneity is evident in its control over soil moisture, hence nutrient uptake, rates of decomposition/mineralisation, and overall plant growth (e.g. Frost *et al.*, 1986). Often the cyclic and structural development of savannah ecosystems both in southern Africa and elsewhere are regarded as being highly dependent on seasonal rainfall and temperature variations (Sarmiento, 1984; Johnson and Tothill, 1984; Walker, 1984). A number of studies have described the vegetation-rainfall relationship as linear, based on the assumption that total primary production or biomass increment is a function of plant available moisture (PAM) (e.g. Scholes and Walker, 1993; Nicholson and Farrar, 1994).

One of the main problems in pursuing biogeographical studies in Botswana concerns the scanty climatic data resulting from the sparse distribution of synoptic weather stations. Gauge data is available from many of the villages in the country, but still a large portion of the country is not represented because of two main reasons. Firstly, distances between the stations are too large (Figure 1) (also Nicholson and Farrar, 1994). Secondly, some stations are placed on schools and police stations, which means they are not manned by trained staff from the department of Meteorological Services. Our analysis showed that these stations have problems of missing data for long periods. The stations therefore only provide a rough indication of the rainfall distribution and are not all used in the calculation of long term

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rainfall averages. For some stations, the data are unreliable, possibly due to lack of commitment and negligence of people or institutions who have been entrusted with the rain gauges (Mmopi, Department of Meteorological Services, personal communication). Data from only 14 synoptic stations throughout the 581 730 km^2 land area of Botswana are therefore used to draw rainfall maps of the country. With such a low density of weather stations, the result is that of generalised isohyet maps, that are unsuitable for detailed biogeographical studies aimed at determining the underlying causes of spatial heterogeneity in terms of growth form. Satellite technology has however, provided a potential means of estimating rainfall data over the entire Earth's surface (Barrett, 1974; Dugdale *et al*., 1991).

Up till now, rain gauge data remain the only reliable source of rainfall measurement, but because of their low spatial distribution, it is often difficult to determine seasonal rainfall deficits or excesses. Rainfall estimation is now gaining wide usage especially in the semi-arid to arid areas of developing countries where the density of rain gauges is very low. Rainfall estimates have been used in Africa by the FAO to determine seasonal deficits and hence predict food shortfalls (Herman *et al*., 1997). In Botswana however, the technique has not been adequately researched so as to yield accurate estimates of rainfall. But given the sparse distribution of rain gauges countrywide, the authors felt it necessary to use the CCD data as proxy for rainfall patterns.

In previous related studies undertaken in Botswana, rainfall-vegetation relationships have been based in part on sparsely distributed point (rain gauge) data and averaged image (NDVI) data (Nicholson and Farrar, 1994). The Normalised Difference Vegetation Index (NDVI) is known to be indicative of areas of enhanced photosynthetic activity (Tucker and Sellers, 1986; Townsend and Justice, 1986; Sellers, 1989). The NDVI has been used in Botswana in a number of projects directly relating to rangeland productivity and growth (e.g. Prince and Tucker (1986) and Ringrose *et al.* (1997)). However there is still some uncertainty as to what the NDVI means on the ground in terms of woody cover species types and in terms of the tree: grass ratio. In work intended to help overcome this uncertainty, Ringrose *et al*. (1989), Ringrose and Matheson (1991) and Matheson and Ringrose (1994), determined that the NDVI was predominantly useful in semi-arid areas after the rains by indicating the extent of woody vegetation re-growth and (green) grass cover. In terms of the normal dry season and frequent drought conditions the NDVI has limited value over Botswana because it can imply a bare soil condition (low NDVI) when sparse to dense, microphyllous leafed woody plants are prevalent on the ground (Ringrose *et al*., 1998). The kinds of vegetation that lead to a lower than anticipated NDVI are referred to as darkening species (Otterman, 1974; Ringrose *et al*., 1989; Chavez and MacKinnon, 1994; Ringrose *et al*., 1998; Moleele, 1999).

The NDVI was used in this paper to provide a basis for the degree of structural heterogeneity within the mopane vegetation zone in north-eastern Botswana. Mopane is a deciduous species of the family Leguminocae. The species' distribution limits range from the southern parts of Angola/Northern Namibia into Botswana, Zambia and Zimbabwe, stretching to the eastern part of the continent to Malawi, Mozambique and South Africa (Mapaure, 1994) (Figure 2). The distribution pattern of mopane conforms to the theory of island biogeography, in that its distribution in the region is discontinuous and fragmented (MacArthur and Wilson, 1967; Kent, 1987). The southern limits of the species in Botswana and South Africa have been well-documented (Bekker and De Wit, 1991; Timberlake, 1980; Weare and Yalala, 1971; Van Rensburg, 1971; Coates-Palgrave, 1983; Madams, 1990; Carter and Prince, 1988).

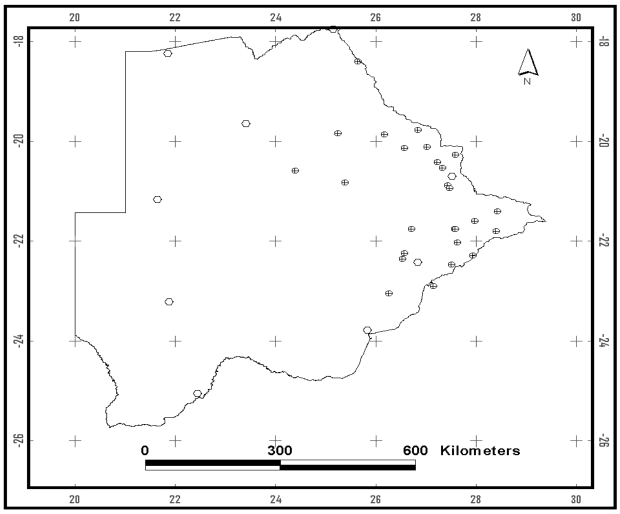


Figure 1. Map of Botswana showing the distribution of agrometeorological (1) and Synoptic stations (o)

One of the unique characteristics of mopane is that it occurs with no or few other species and the fact that it develops into a number of structural forms. These vary from tall (cathedral) mopane with limited grass growth, open mopane woodland with intermittent grass, mixed mopane woodland/scrubland and dense shrub or gumanae mopane (e.g. Timberlake (1980) and Ringrose *et al*. (1998)). The overall distribution of the different structural forms is believed to be related to soil conditions and drainage (Henning, 1976; Prince, 1981; Madams, 1990; Dye and Walker, 1980). However little work has previously been undertaken on predicting the structural composition or density of mopane woodlands in relation to relatively local rainfall patterns. Given the background of linear relationships between soil moisture and vegetation productivity (e.g. Nicholson and Farrar, 1994), the NDVI values of different mopane types may well be related to background environmental conditions, of which spatial rainfall distribution may be significant.

The extent to which the spatial characteristics of mopane vegetation are related to rainfall is here analysed by determining the degree of spatial and temporal correlation between decadal rainfall and decadal NDVI data between 1988 and 1995 along the eastern mopane belt in Botswana.

2. STUDY AREA

The study area lies in the east central third of Botswana (Figure 3**)**, most of which constitutes the hardveld (Moganane, 1989; Thomas and Shaw, 1991). Approximately 40-50% of the hardveld and about 10% of the sandveld is occupied by the species mopane. The rainfall was examined for the whole country and in more detail in the east central mopane belt which lies between 25° E and 20° S and 29° 30' E and 24° S in the Central and North East Districts of Botswana (Figure 3). Areas south of the southern boundary of mopane vegetation were included in this analysis for comparative purposes.

East central Botswana comprises variable soil formations owing to the underlying parent material (Moganane, 1989). Soils in the study area have been mapped and described under the Soil Mapping and Advisory project of the Ministry of Agriculture (Verbeek and Remmelzwaal, 1990). Soils range from major units such as arenosols, luvisols, calcisols, lixisols, cambisols, and vertisols. The northern portion is mainly underlain by arenosols with some calcisols around the periphery of the Makgadikgadi saltpans. The central portion is dominated by a wide variety of luvisols with lixisols bisecting the area eastwards. The south is characterised by an eastward extension of the sandveld with arenosols and calcisols. Land-use mainly comprises cultivated agriculture on the lower ground, with cattle grazing (and browsing) on the hilltops and in the vicinity of the major pans. Intermediate areas have mixed land uses including scattered fields and small stock browsing combined with livestock grazing and browsing.

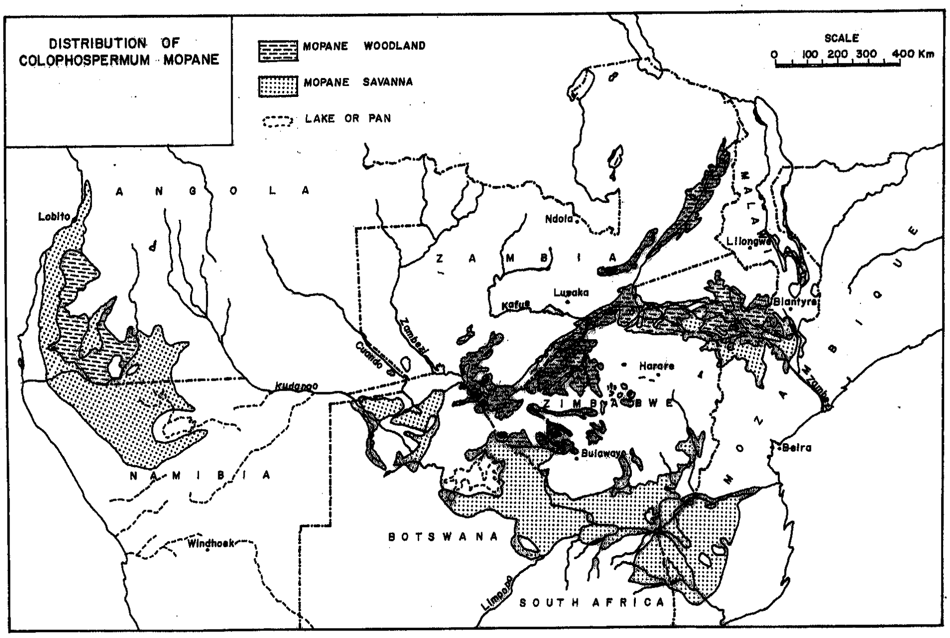


Figure 2. Distribution of mopane in Southern Africa (Source: Mapaure, 1994)

3. RAINFALL DATA AND FIELDWORK

Average rainfall changes across the study area with the north experiencing up to 650 mm annually. This declines south-eastwards to around 350 mm per year while increases (to 550 mm) are again evident further south (Figure 3). Rainfall distribution over Botswana is generalised since it is based on data collected mainly from nine synoptic stations up to 1980 (Bhalotra, 1985, 1987).

A more detailed continuous data set is needed to relate rainfall to vegetation cover. Cold Cloud Duration (CCD) images derived from Meteosat Thermal Infrared (TIR) images were used as a proxy for rainfall patterns across the study area over the period 1988-1995. The use of CCD images as a surrogate for rainfall patterns is based on the premise that there is a linear relationship between Cold Cloud Duration and rainfall (Dugdale *et al*., 1991). The rain gauge data were plotted against CCD data for selected stations to establish the strength of this relationship.

Raw data transmitted from satellites are converted from radiance to thermal images using the Autosat software at the Botswana Department of Meteorological Services receiving station. The thermal images are then transformed into CCD images using the TAMSAT rainfall estimation software (TRES) (Grimes *et al*., 1998). Image data were processed in the Image Data Analysis (IDA) software developed by Pfirman (1992) for the Famine Early Warning Systems project of the USAID. Decadal data were extracted in point and thematic mode and 23 decadal estimates were produced for each of the wet seasons starting with the 1988/89 wet seasons and finishing with the 1994/95 wet season. This produced a database of 161 CCD maps, which were subsequently used for statistical and spatial analyses. For a thematic representation, the same images were summed-up in a GIS to produce periodical cumulative images of surrogate rainfall patterns.

Fieldwork was undertaken during the 1998/99 wet and dry seasons to establish the nature of the vegetation cover and to characterise the different structural types of mopane and surrounding vegetation types. The location of sample sites was recorded on a Magellan 7000AX Global Positioning System. Dominant mopane types were identified during fieldwork based on the identification of specific units on aerial photographs and existing vegetation maps. Within each cover type a representative area was selected based on structure, composition and percent canopy cover. The actual percent canopy cover was later measured using the Bitterlitch method (Bonham, 1989). A total of five different types of mopane vegetation were recognised along with mopane dry deciduous woodland mixes to the northwest and Acacia dominated savannah in the southeast.

- Open mopane with intervening dry deciduous forest (includes 30% grass cover).
- Tall mopane woodland (7-8 m)
- Tall mopane shrubland (4-5 m)
- Low mopane scrubland (2-3 m)
- Acacia dominated savannah

Location of sample sites was undertaken by stratification along the different growth forms of mopane shown in existing maps (Figure 3). There is however, a possibility of errors in locating the correct trends of pixels in the satellite images owing to slight misregistration.

3.1 Derivation of NDVI Data

Vegetation indices were applied to determine whether the different types of mopane woodlands are a response to different rainfall patterns and whether changes in these types of woodland are apparent over time. This may be reflected in the fact that varying levels of chlorophyll should be apparent during different stages of plant development (Mather, 1987). It may also be particularly reflected in mopane where certain shrub-like growth forms appear to persist. In Botswana, the Department of Meteorological Services continuously derives a generalised vegetation distribution status scenario from NOAA imagery using the NDVI. Consistent with the CCD data, NDVI data were obtained for the wet seasons (October to May) between 1988 and 1995. The mopane woodlands in eastern Botswana are deciduous; leafless or senesced in the dry season and only come into leaf after initial rains, in response to both moisture availability and warmer temperatures. The NDVI is a ratio summarised by the expression (Jensen, 1986):

$$NDVI = \frac{(NIR - RED)}{(NIR + RED)}$$

where RED = the reflectance value from the red band, and NIR = the reflectance value from the near infrared band.

3.2 Rainfall Estimation

The closeness of the relationship between actual rainfall and CCD data is confirmed for northeastern Botswana using synoptic rainfall stations of Kasane, Nata and Francistown. Results show a reasonable correlation between the two data sets for the 1988/89 rainfall season (Figure 4). Hence rainfall over Botswana may be estimated using the model:

Rainfall Estimate (mm) = 0.9796x + (CCD hours) 6.5456

The goodness of fit method used here did not yield an impressive result (R^2 = 0.59) of rainfall estimation. Other studies elsewhere in Africa have also not obtained any better results, e.g. satellite-gauge correlation coefficients ranging from 0.63 to 0.83 (Laurent *et al*., 1988; Grimes *et al*., 1999).

The 1988/89 wet season represents the end of the latest major drought (1983-88) although the average rainfall for this period using synoptic stations within the study area shows a high degree of inter-annual variability as indicated by the r^2 value. The 1988/89 wet season in particular was very wet with rainfall exceeding the annual average for both Francistown and Mahalapye for example. Within the period 1988 to 1995, variability was more pronounced in Francistown where above and below average rainfall occurred in alternate seasons. Mahalapye on the other hand showed fewer inter-annual variations with above normal rainfall recurring in all seasons between 1988 and 1995. The rainfall estimates were undertaken during the wet season, (October to May). The wet season itself also shows a degree of variability with often heavy early rains followed by an inter-seasonal low and relatively heavy late rains (Bhalotra, 1985).

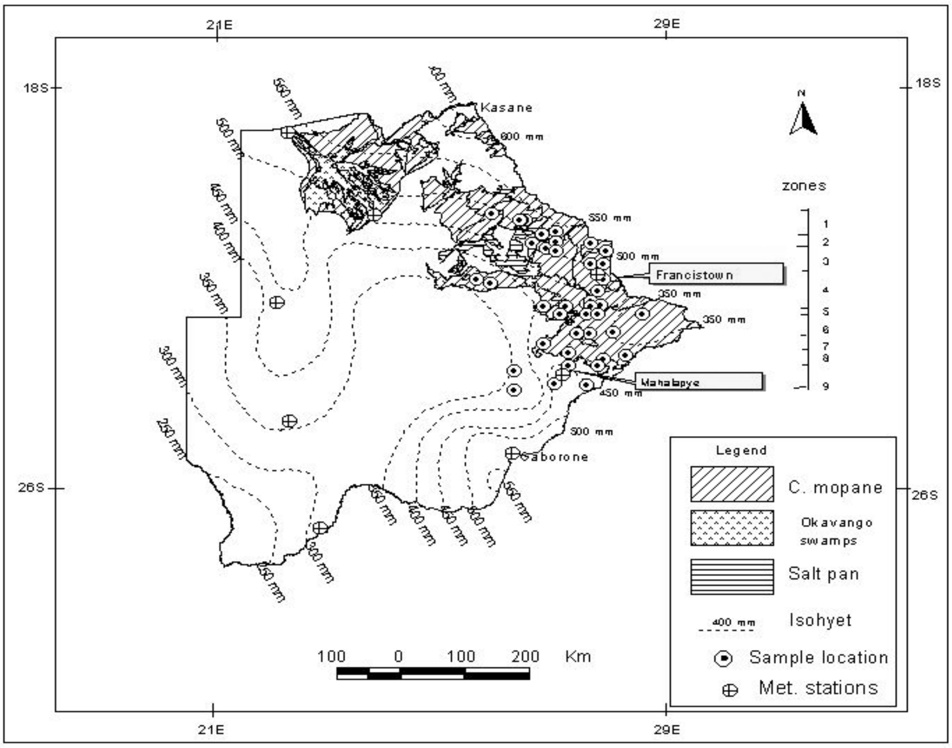


Figure 3. Distribution of mopane, mean annual rainfall and sample point locations in Botswana

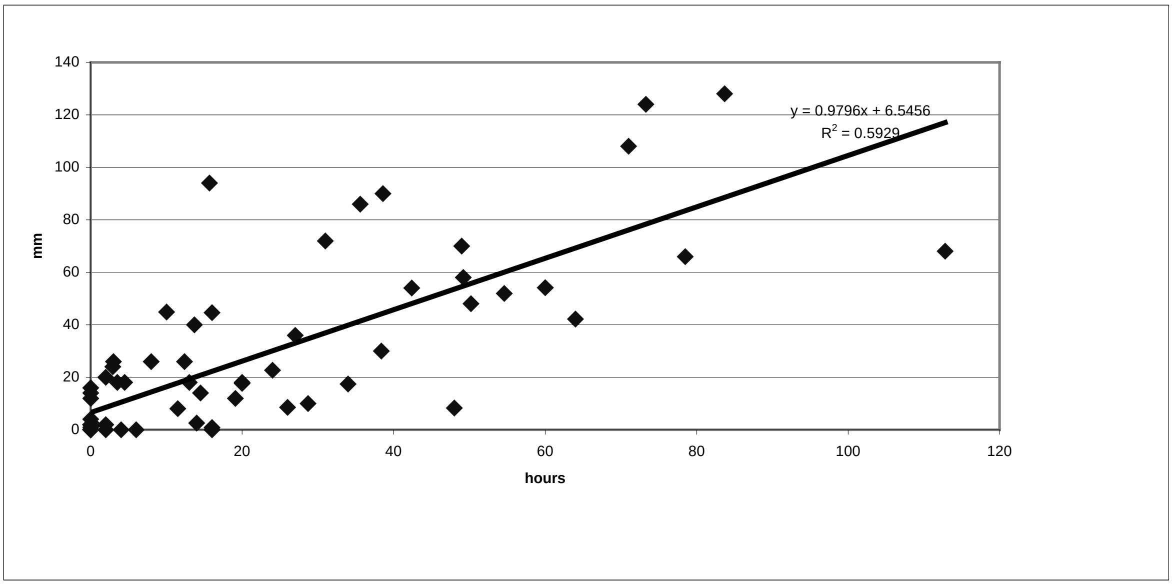


Figure 4. Relationship between actual decadal rainfall (mm) and decadal Cold Cloud Duration (hours) for northeastern Botswana using 1988/89 data from Francistown, Kasane and Mahalapye

3.3 Cumulative Rainfall Distribution from CCD Data

Both CCD and NDVI estimates from co-incident locations across the study area were averaged for every decade throughout the wet season, for each year between 1988 and 1995 (Table 1). The Meteosat data were compiled as IDA images in graphic-binary format then reformatted and resampled to a geographic grid of 0.1° resolution (Herman *et al*., 1997). Sample points were digitised in vector form and labelled for data association purposes. At each point readings were extracted using the Extract module in IDA to represent 3 decads for each month. This results in time series data displaying temporal variation for both NDVI and CCD (as a surrogate for rainfall) for each point. The data set also provide variation between point locations. The results on Table 1 show a wide spread of CCDs across the different mopane types.

4. RESULTS

The extent of mopane and average rainfall isohyets were superimposed over the cumulative rainfall data. The general pattern shows the extreme variability of events in the region (Figure 5-8). Representation of rainfall patterns from observed gauge data is generally in agreement with that of satellite data in showing areas of low rainfall in contrast to high rainfall areas. The 1988-89 season shows a distinct rainfall gradient across the eastern mopane belt from northwest to southeast (Figure 5). This is reflected though less strongly on the 1990-91 cumulative CCD map (Figure 6).

The following year was relatively dry, with a deepening of the low rainfall area in the south and with patchy low rainfall in the northeast (Figure 7). Towards the end of the period, the lower rainfall area dispersed and the areas of higher potential rainfall in the northwest and southeast decreased the low to high gradient over the mopane belt, with some slightly lower rainfall towards the centre of the mopane area (Figure 8).

The overall picture is one of inter-annual variation in which higher rainfall in one year is superseded by patchy or lower rainfall in the next year. In considering the results displayed in Figure 5 to 8, the possibility of obtaining an accurate rainfall distribution pattern is limited by the sparse distribution of rain gauges. A study carried out in the Sahel region has demonstrated a higher accuracy (35% error) of rainfall estimation using a high density of rain gauges (Laurent *et al*.,1999). One of the existing theories on the distribution of mopane is that it is restricted within the range of 200-800mm of annual rainfall (Henning, 1976). But within the geographical confines of Botswana, the range is between 350 and 650mm of annual rainfall. The transitional zone for the mopane at its southern limit coincides approximately with the transition from 350-400 mm mean annual rainfall. Our data suggest that there is no co-incidence between the occurrence/non-occurrence of mopane and the 350-400mm limit. This is confirmed by the gradual increase of average rainfall in the southern in addition to the northern direction (see also Figure 9). The increase in rainfall beyond the southern extent of mopane infers that:

- either there is a threshold rainfall amount, in combination with other factors beyond which mopane cannot tolerate, or
- there are some other factors controlling the distribution of mopane other than mean annual rainfall**.**

	Average CCDs								Average NDVI							
Site no.	**88/89**	**89/90**	**90/91**	**91/92**	**92/93**	**93/94**	**94/95**	**% cover**	**88/89**	**89/90**	**90/91**	**91/92**	**92/93**	**93/94**	**94/95**	**Structure**
S1	21.5	32.3	25.64	14.3	15.7	18.9	20.4	40	0.26	0.27	0.29	0.25	0.35	0.33	0.22	Open mopane with
S2	24	34.1	25.55	14.0	16.1	21.2	20.5	46	0.28	0.23	0.29	0.26	0.31	0.33	0.26	intervening dry
S3	27.3	36.3	26.18	16.8	17.9	22.1	22.2	20	0.23	0.24	0.24	0.19	0.25	0.28	0.14	deciduous forest
S4	26.5	35.7	26.73	16.8	18.1	22.5	22.4	15	0.21	0.23	0.23	0.17	0.21	0.25	0.15	
S5	27.2	34.7	26.45	15.6	18.2	22.1	21.5		0.20	0.2	0.2	0.16	0.2	0.22	0.14	
S6	27.3	35.4	28.09	16.3	19.4	22	22.6	33	0.23	0.24	0.24	0.2	0.24	0.25	0.18	**Zone 1**
S7	23.4	34.2	25.09	13	16.6	18.6	20.8	19	0.23	0.21	0.26	0.23	0.32	0.31	0.18	Tall mopane
S8	23.3	30.5	24.18	9.2	12.6	18	20.6	65	0.28	0.25	0.25	0.2	0.25	0.27	0.22	woodland
S9	22.8	29.5	25.55	9.3	13.5	17.4	20.9	63	0.24	0.22	0.25	0.18	0.23	0.23	0.21	
S10	23.4	32.3	26.09	12.6	16.4	19.1	22.5	30	0.26	0.28	0.3	0.26	0.3	0.32	0.23	
S11	21.6	32.9	26.73	12.6	15.6	18.6	23.2	17	0.25	0.26	0.27	0.25	0.28	0.31	0.21	
S12	21.4	33.7	26.36	13.1	15.6	18.1	22.5	28	0.29	0.29	0.3	0.28	0.3	0.35	0.26	
S13	21.5	32.8	27.73	11.7	14.8	18.1	23	17	0.24	0.27	0.31	0.26	0.28	0.31	0.2	**Zone 2**
S14	22.5	34.8	26.91	14.0	15.6	20.6	23.9	14	0.23	0.23	0.23	0.21	0.27	0.3	0.21	Tall shrub
S15	22.2	33.1	25.64	10.2	15.6	18.9	21.6	35	0.24	0.26	0.26	0.22	0.25	0.25	0.2	mopane
S16	19.3	35.3	25.00	10.9	15.1	18.6	22.1		0.23	0.21	0.24	0.2	0.24	0.28	0.2	
S17	16.5	33.9	25.82	11.5	15.6	16.6	22.6		0.26	0.24	0.28	0.22	0.29	0.29	0.21	
S18	15.3	34.8	24.55	12.4	14.0	15.4	20.6	39	0.25	0.24	0.27	0.23	0.28	0.28	0.25	
S19	14.2	32.9	24.91	11.0	15.4	13.8	19.3	52	0.24	0.24	0.3	0.2	0.22	0.23	0.22	**Zone 3**
S20	18.1	32.3	23.64	9.1	12.5	15.7	19	68	0.26	0.23	0.28	0.2	0.26	0.24	0.24	
S21	15.1	33.0	24.55	9.4	12.9	15.5	20	63	0.28	0.19	0.29	0.22	0.22	0.2	0.2	Tall mopane
S22	15.8	33.9	24.00	10.2	12.4	15.3	21.3	64	0.28	0.22	0.28	0.22	0.27	0.24	0.26	woodland
S23	14.5	31.4	24.00	10.6	13.2	13.6	21.3	50	0.31	0.24	0.32	0.23	0.28	0.27	0.25	
S24	14.2	32.7	24.27	10.9	13.1	12	20.1		0.26	0.26	0.33	0.24	0.26	0.29	0.26	
S25	14.2	32.7	24.27	10.9	13.1	12	20.1		0.26	0.26	0.33	0.24	0.26	0.29	0.26	
S26	12.6	32.2	24.00	9.9	12.7	13.2	18.6	49	0.26	0.25	0.32	0.21	0.23	0.26	0.24	**Zone 4**
S27	12.5	32.6	24.64	10.3	13.0	12.5	19.9		0.28	0.24	0.33	0.22	0.25	0.27	0.25	
S28	13.3	32.5	24.09	9.6	12.7	13	19.5	28	0.30	0.23	0.31	0.22	0.21	0.25	0.24	Low scrubland (mopane) **Zone 5**
S29	12.5	30.7	23.36	10.7	12.5	12.6	18.3	39	0.28	0.27	0.34	0.21	0.2	0.26	0.26	Tall mopane woodland
S30	10.9	29.1	22.00	9.7	11.9	11.7	18.4	43	0.27	0.24	0.32	0.25	0.2	0.3	0.25	**Zone 6**
S31	13.9	28.1	22.91	10.9	11.8	12.5	18.9	49	0.25	0.21	0.31	0.21	0.19	0.29	0.24	Low scrubland
S32	15.3	28.8	22.82	11.1	12.8	13.1	19.2	44	0.26	0.22	0.28	0.21	0.18	0.25	0.25	(mopane)
S33	11.3	29.0	22.55	10.4	12.7	11.2	19.3	36	0.28	0.25	0.28	0.23	0.24	0.24	0.21	**Zone 7**
S34	17.9	29.4	25.73	9.7	11.6	14.5	21.2		0.30	0.27	0.29	0.2	0.25	0.19	0.27	
S35	12.8	30.3	23.36	10.1	15.0	12.3	19.6	55	0.25	0.19	0.28	0.2	0.25	0.21	0.21	
S36	11.6	30.3	22.45	10.1	13.2	11.4	18.3	51	0.27	0.22	0.3	0.19	0.26	0.22	0.21	
S37	14.9	30.5	23.82	10.0	12.9	12.7	21.1	28	0.26	0.25	0.28	0.21	0.24	0.24	0.24	Tall mopane
S38	20.5	33.2	28.00	10.1	13.5	15.1	24.3	36	0.23	0.21	0.23	0.16	0.24	0.26	0.2	shrubland
S39	15.7	34.3	23.73	11.5	13.7	11.4	19	49	0.23	0.21	0.25	0.17	0.23	0.22	0.21	**Zone 8**
S40	14.3	33.3	23.18	11.3	14.6	12.4	19.8		0.26	0.21	0.28	0.21	0.24	0.22	0.22	Acacia dominated
S41	17.9	36.6	27.27	9.7	13.3	14.5	22.4		0.24	0.25	0.24	0.2	0.22	0.25	0.21	savannah
S42	15.4	32.7	27.82	12.2	13.7	14.2	22.1	60	0.26	0.18	0.2	0.2	0.28	0.22	0.21	
S43	15.0	37.4	25.18	11.1	15.6	12.7	21.2		0.23	0.19	0.26	0.19	0.29	0.22	0.23	**Zone 9**

Table 1. A summary of CCDs, NDVI, and vegetation structure along the sample points, north to south

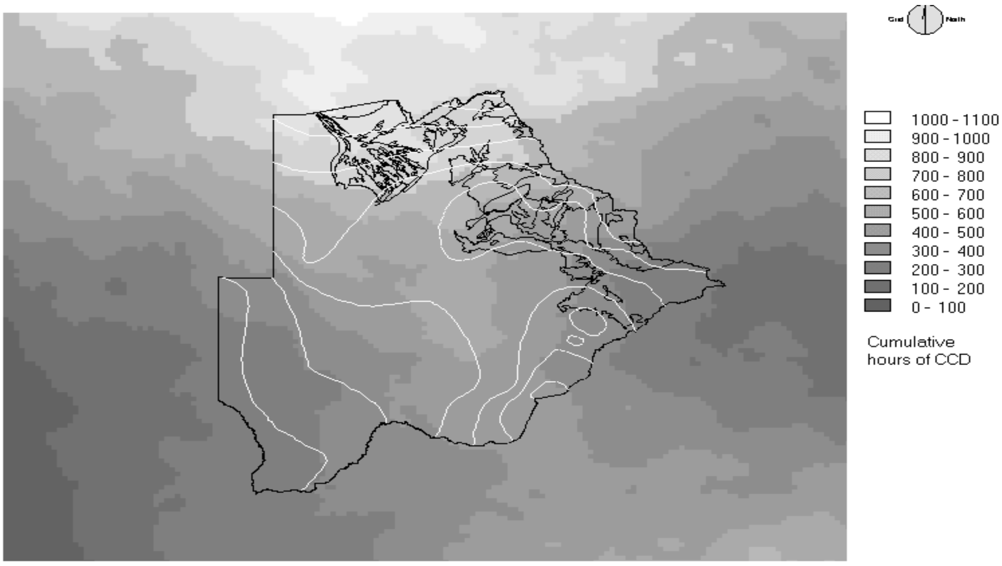


Figure 5. Cumulative CCD map for the 1988/89 rainy season

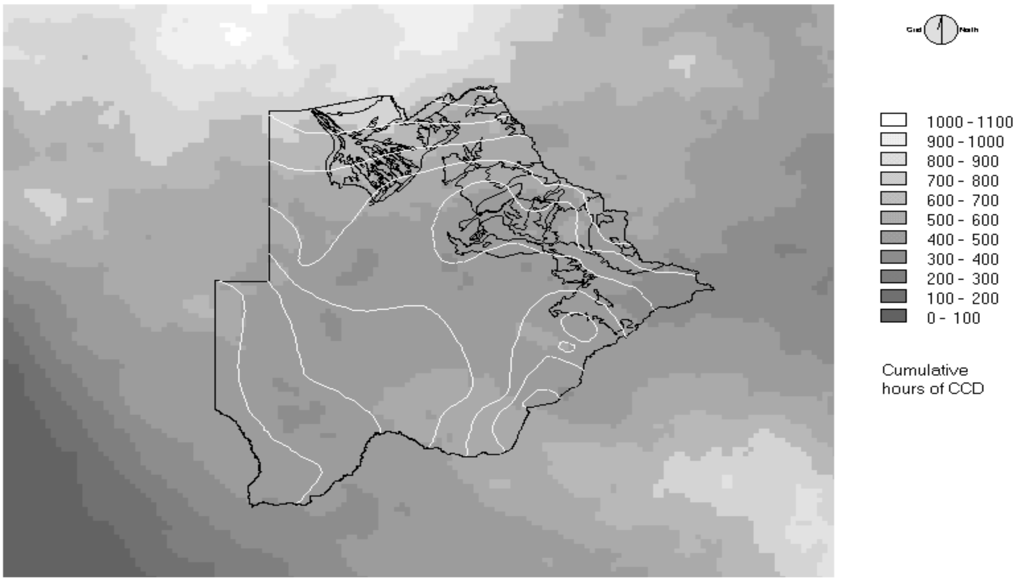


Figure 6. Cumulative CCD map for the 1990/91 rainy season

4.1 Distribution of NDVI Data

As NDVI was used as the basis for studying the degree of structural heterogeneity within mopane vegetation zones, the study area was divided into nine zones on the basis of vegetation structure. The reason for this was to study the response of NDVI to rainfall between the structural types and over the study period. Averaged values for each zone were plotted (Figure 9). The distribution of NDVI across mopane structural types is characterised by variations between different locations/zones. There is no particular vegetation response pattern to moisture that is unique to any structural type, as one would expect from a higher (northern) to a lower (southern) rainfall region. However, there is less variation between the northern zones (1-4) compared to southern zones. Inter-annual variability of NDVI shows a moisture–related response as variability is shown as a response to the annual variations in rainfall.

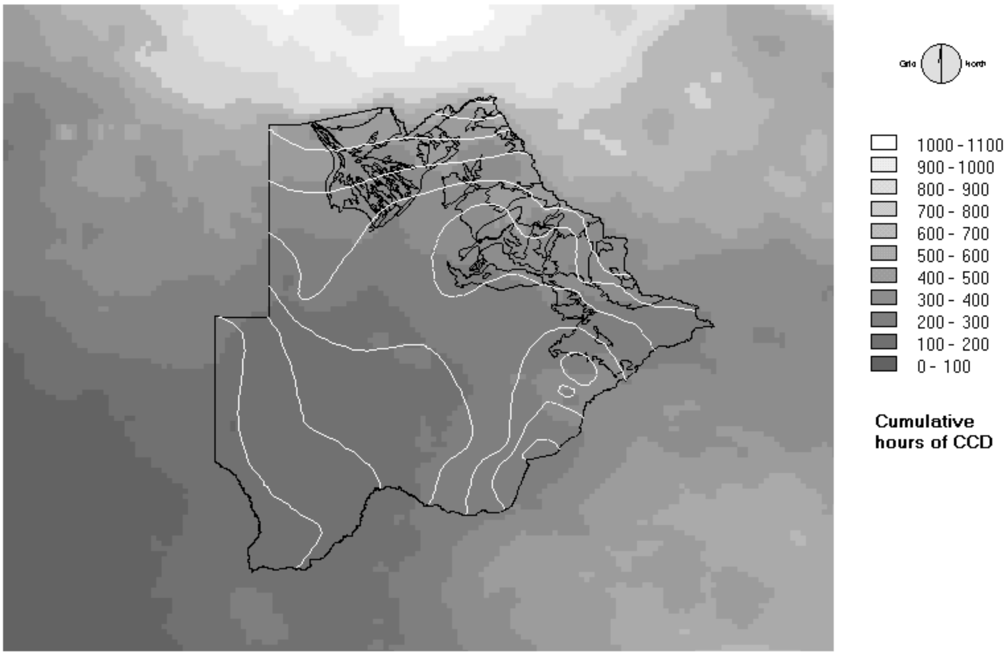


Figure 7. Cumulative CCD map for the 1992/93 rainy season

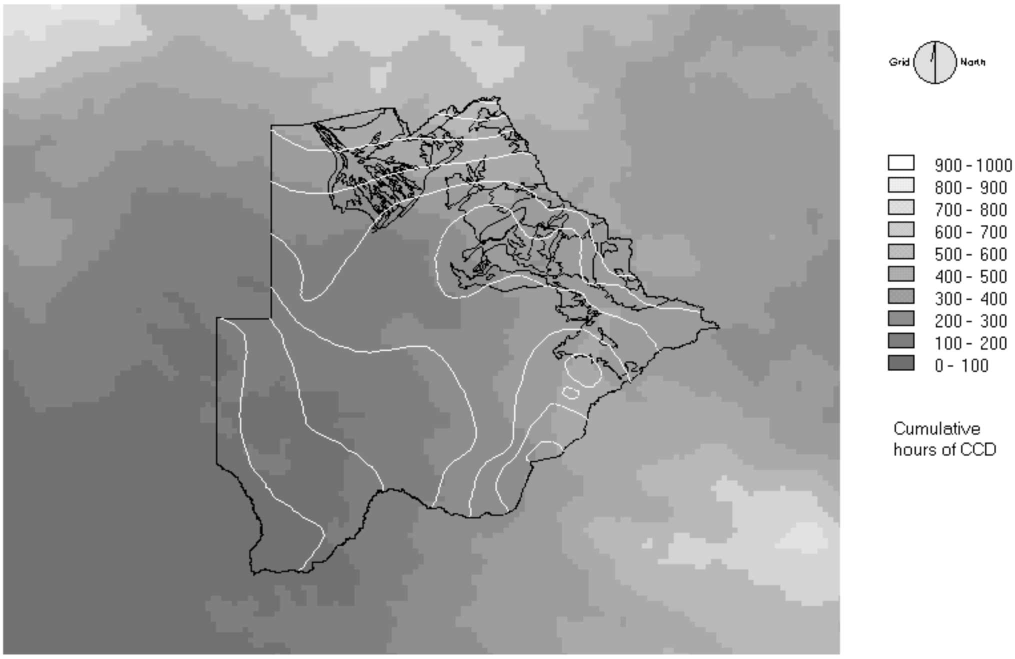


Figure 8. Cumulative CCD map for the 1994/95 rainy season

4.2 Correlation of NDVI and CCD Rainfall Estimates

Correlation analysis was undertaken to study the relationship between the mopane-NDVI and CCD rainfall across the study area. This was done throughout the different mopane structural types mapped from northwest to southeast over the seven wet season periods. Correlation analyses were carried out between the cumulative percentage of rainfall and NDVI (Table 2), firstly, to determine how well mopane responds to estimated rainfall and secondly to uncover any spatial or temporal trends.

In zone 1, open mopane with dry deciduous forest, relatively high correlations were achieved for the 1989-90, 1990-91, 1992-93 and 1993-94 wet seasons. Similar results are also apparent for Zone 2, tall mophane woodland. Relatively high correlations are only apparent in 1990-91 and 1992-3 in the

Zone 3 tall mophane shrubland and Zone 4 tall mopane woodland, although in the latter case, high correlations were also apparent in the 1994-95 wet season. This trend (high correlations in rainfall seasons 1990-91, 1992-3 and 1994-95) continues southeastwards through the remaining mophane zones 5-7 and the Acacia dominated savannah, zone 8.

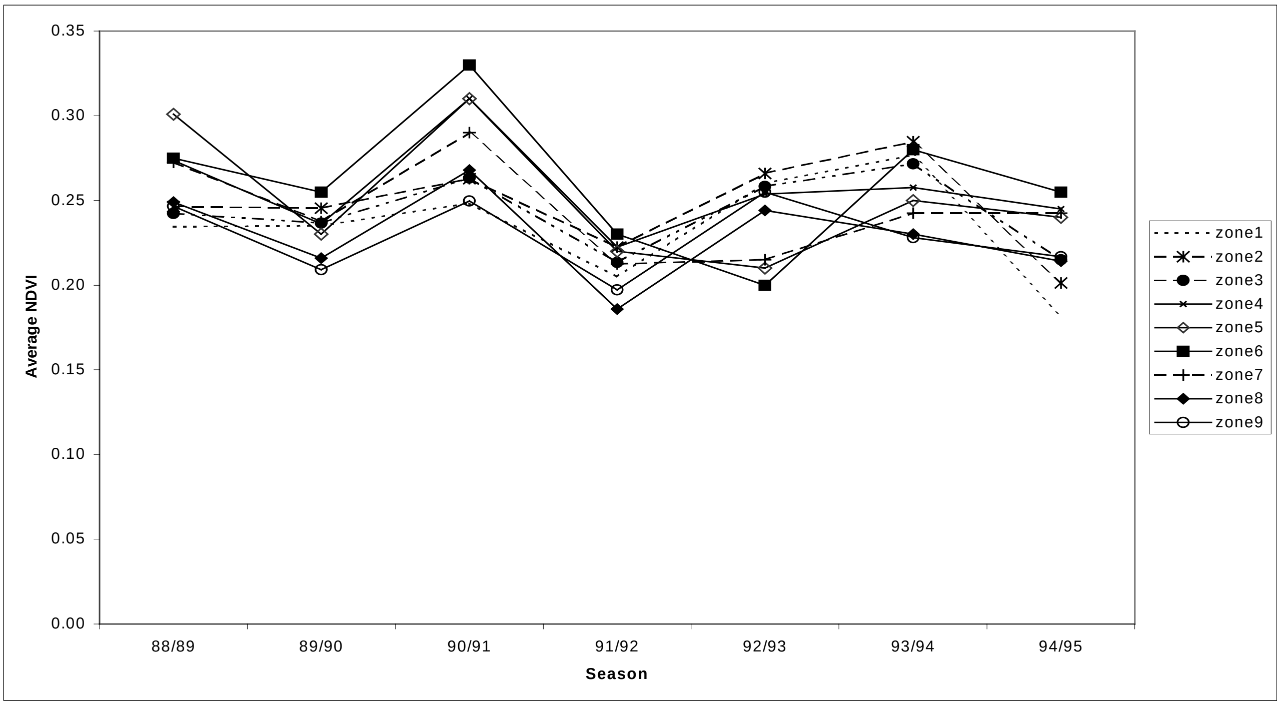
These results imply:

- high correlations between NDVI and CCDs do not occur in every wet season within individual zones.
- the taller mopane woodlands are correlated more frequently (and in different years) than the shrublands in the southeast, hence
- there is evidence of spatial variation in both rainfall and NDVI from northwest to southeast along the mopane belt, with declining correlation between the two factors to the southeast, despite some increase in rainfall to the southeast.

Results show an increase in NDVI with increasing percent canopy cover (Table 1), thus NDVI can be correlated with rainfall over mopane structural zones. The annual averages of the maximum correlations between NDVI and rainfall ranges between $r^2 = 0.01$ to $r^2 = 0.96$, with an overall annual average per sample point ranging between 0.43 and 0.73. Inter-annual variations in NDVI occur in response (through primary production) to variations in rainfall. These spatial variations of the highest correlation indicate that the highest correlation between the years is dependent on rainfall distribution during a particular year rather than being site specific. There are marked differences in correlation between mopane structural types and these differ in magnitude from year to year.

	88/89	**89/90**	**90/91**	**91/92**	**92/93**	**93/94**	**94/95**
zone1	0.33	0.72	0.86	0.43	0.86	0.64	0.26
zone2	0.39	0.62	0.84	0.50	0.86	0.66	0.41
zone3	0.42	0.47	0.90	0.58	0.89	0.50	0.32
zone4	0.36	0.48	0.79	0.53	0.81	0.37	0.71
zone5	0.73	0.38	0.81	0.34	0.82	-0.10	0.63
zone6	0.68	0.64	0.85	0.47	0.87	0.56	0.72
zone7	0.37	0.26	0.73	0.51	0.77	0.47	0.75
zone8	0.50	0.46	0.84	0.49	0.86	0.46	0.67
zone9	0.57	0.25	0.85	0.25	0.85	0.46	0.76

Table 2. Average annual correlation coefficients between rainfall and NDVI



Zone 1. Open mopane with intervening dry deciduous forest
Zone 2. Tall mopane woodland
Zone 3. Tall shrub mopane
Zone 4. Tall mopane woodland
Zone 5. Low scrubland (mopane)
Zone 6. Tall mopane woodland
Zone 7. Low scrubland (mopane
Zone 8. Tall mopane shrubland
Zone 9. Acacia dominated savannah

Figure 9. Inter-annual distribution of NDVI across mopane structural types divided into zones as indicated below. Zones are numbered in a North to South direction

Results were further analysed for each wet season by plotting the CCD-NDVI correlation coefficient against the sample points from northwest to southeast along an initially decreasing rainfall gradient. The purpose being to demonstrate the extent to which the CCD-NDVI relationship varied through time. In 1988/89, a year of high rainfall, there was no real trend throughout the gradient although the CCD-NDVI relationship was lower in the northwest than the southeast even though rainfall was slightly higher in the former (Figure 10a). In the years of intermediate rainfall, 1989/90, 1990/91 and 1991/92 there is a more consistent correlation with distance southeastwards. The year 1989/90 shows a decreasing correlation form northwest to southeast. The different mopane types were responding equally to the higher rainfall events during 1990/91. No trends were apparent for 1991/92. During the later, drier years (1992/93 and 1993/94) the overall trends show a decrease in the correlation coefficient with distance southeastwards towards the drier end of the gradient (Figures 10e and 10f). This trend is reversed however in 1994-95 when there was higher rainfall towards the southeastern end of the gradient (Figure 10g) in response to the higher rainfall incidence for the southern part of the study area in that year. The relationship between rainfall distribution and NDVI as shown in Figure 10 is a reflection of the inter-annual variation in rainfall and its overall effect on primary production across the mopane belt.

5. CONCLUSION

The basis of this study was the relationship between rainfall and NDVI in mopane vegetation located at different distances from its southern geographical distribution boundary. The study was very dependent on the CCD/rainfall relationship from which maps of rainfall patterns were derived. Results have shown that there is a reasonable relationship between CCDs and actual rainfall, which suggests that the spatial representation of rainfall by CCDs can be used to relate rainfall to vegetation growth patterns.

The distribution pattern of mopane from the north down to its southern limits displays alternating structural types with low shrubs prevalent towards the southern limit. This paper concentrated on determining whether there is any gradient in the way the structural types responded to the spatial rainfall distribution from the north to its southern limits. The final conclusion to this is that within a span of seven growing seasons the response of mopane dominated woodlands to rainfall within each structural zone (as determined from the correlation coefficients of within site and NDVI) was varied. Two rainfall seasons 1990/91 and 1992/93 showed the highest correlation between incidence of rainfall and the response of mopane throughout the mopane belt. The two seasons had a slightly below average rainfall also following high rainfall years. Two rainfall seasons, (1988/89 and 1994/95) with above average annual rainfall did not yield high mopane/rainfall correlation as would be expected. Results show a declining correlation with increasing rainfall between the years. Generally, the variations reflect a pattern of decreasing correlation with distance south-eastwards.

In summary, the fact that there is a pattern of decreasing correlation between NDVI and rainfall along the mopane belt suggests that the incidence of rainfall is to some degree a limiting factor for the distribution of mopane especially towards its southern limits. However, an overlay of mopane distribution and mean annual rainfall suggests that rainfall could not be a limiting factor because there is an immediate increase in mean annual rainfall from the southern boundary of mopane southwards. Results suggest two possibilities, firstly, that the distribution of mopane has the potential of drifting southwards with no restriction or, secondly, that rainfall and a combination of other factors limit the expansion of the species beyond the present mopane line.

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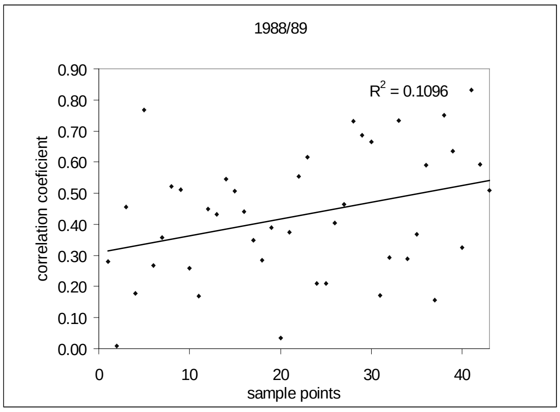

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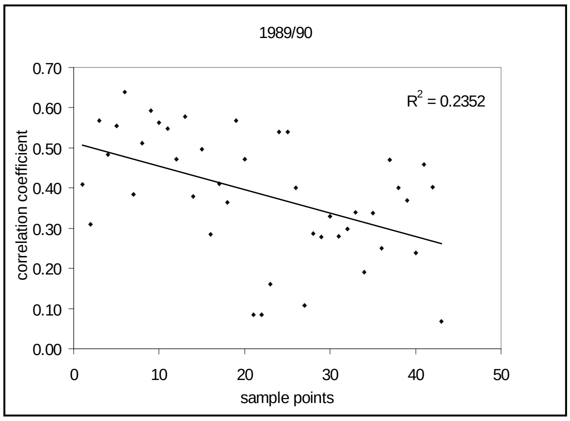

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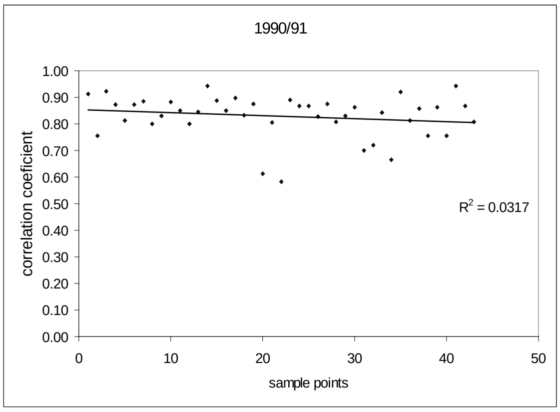

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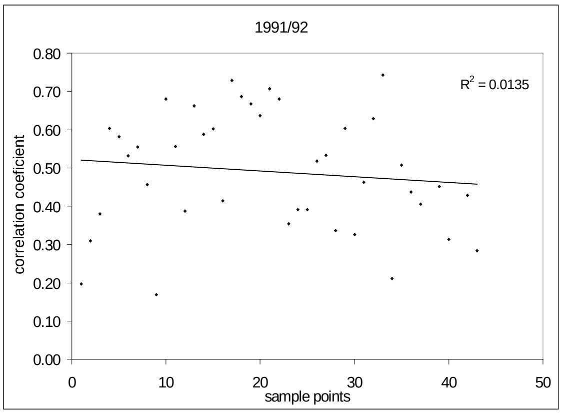

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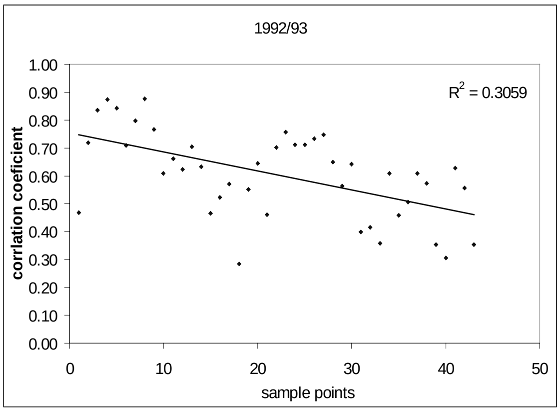

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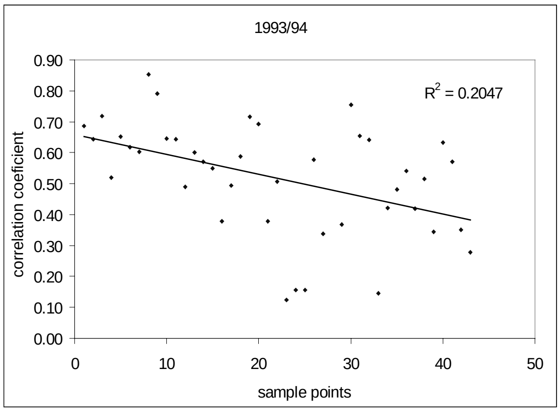

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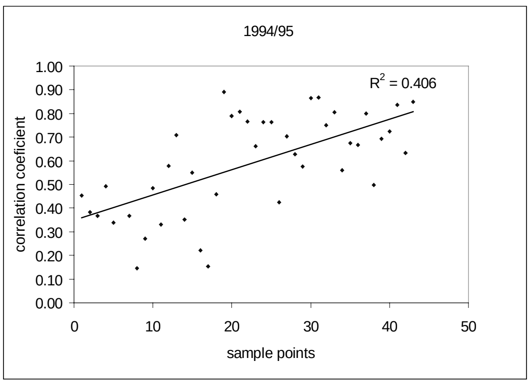

g)

Figure 10(a-g). Scatter graphs of Correlation Coefficients relating to point locations along the mopane belt between north and south of the country

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