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VEGETATION RESPONSE TO RAINFALL AND SOIL MOISTURE VARIABILITY IN BOTSWANA

By

TAMMY JANE FARRAR

A Thesis submitted to the
Department of Meteorology
in partial fulfillment of the
requirements for the degree of
Master of Science

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Abstract

This paper presents the results of a study of the relationships between rainfall, soil moisture, and the Normalized Difference Vegetation Index (NDVI) in Botswana. Soil moisture values were calculated via a surface hydrologic model. Spatial and temporal relationships between the variables were examined through statistical analyses. Time series were evaluated and linear regressions/correlations were performed on the data according to vegetation and soil type.

Good agreement between NDVI, rainfall, and soil moisture was found on both monthly and annual time scales. The NDVI cycle was found to lag that of rainfall by 1-2 months, but no lag was evident between the NDVI and soil moisture cycles. The relationships between the variables indicate that NDVI may be used in climatic studies to monitor rainfall and soil moisture variations.

The dependence of the interrelationships upon soil composition is presented. Best relationships are found for soils with relatively even mixtures of sand and clay. In addition, the sensitivity of the hydrologic model to variations in clay content is shown.

Water-use-efficiency by the vegetation was found to vary within Botswana for different soil and plant zones. In addition, plant productivity per unit rainfall was found to be greater in Botswana than in either West or East Africa. It is shown that irrigation effects, vegetation differences, and soil moisture generation per unit rainfall do not explain the higher production efficiencies, which are attributed to a combination of the effects of temperature and soil productivity differences and exogeneous water.

The application of the NDVI/rainfall/soil moisture interrelationships to climatic rainfall and hydrologic studies must be regionally specific, due to the dependence on soil composition and other regional characteristics.

Chapter 1

Introduction

The semi-arid lands of Africa are highly sensitive to climatic fluctuations and degradation due to anthropogenic factors (termed *desertification*). Recent studies have indicated that large-scale monitoring of the land surface by satellites can provide a better understanding of the mechanisms driving regional climates. One mechanism important in the study of semi-arid lands is the response of vegetation to variations in moisture availability.

Knowledge of how the the plant life in a region reacts to changes in water supplies may prove useful in several ways. First, it may be used to determine the sensitivity of specific vegetation types to climatic variations. In addition, the monitoring of vegetation patterns may allow for the evaluation of the extent of anthropogenic alterations and effects on agricultural production. More importantly, understanding vegetation dynamics may enable researchers to monitor drought situations in regions that are inherently data-sparse due to either the lack of reporting stations in remote, climatically extreme areas or due to political and economic instabilty (Nicholson *et al.*, 1990; Justice *et al.*, 1986; Justice and

Hiernaux, 1986; Prince and Tucker, 1986; Prince and Astle, 1986).

Previous studies (Tucker and Sellers, 1986; Justice *et al.*, 1985; Townshend and Justice, 1986; Tucker, 1979; and Tucker *et al.*, 1983,1985a,b) have shown that physical characteristics of plant life may be monitored via satellite sensors. Recent studies (Malo and Nicholson, 1990; Davenport and Nicholson, 1991; and Nicholson *et al.*, 1990) have utilized remotely sensed data to examine in detail the spatial and temporal responses of vegetation to rainfall variability. These studies have been confined to the Sahelian regions of West Africa and East Africa. These studies demonstrated, among other things, that the rate of vegetation growth per unit rainfall (termed "rain–use–efficiency") (LeHouérou, 1984) is considerably higher in East Africa than in the Sahel. A number of studies have also documented the association between satellite-based estimates of vegetation and rainfall (Tucker *et al.*, 1985a,b; Hielkema *et al.*, 1986; and Choudhury and Tucker, 1987).

The purpose of the current study is threefold: to extend the vegetation/rainfall study to a third African region, specifically the country of Botswana, to determine to what extent soil moisture affects the differential responses of vegetation growth, and to examine the effects of different soil types on the vegetation growth/rainfall relationship. The goals are to determine whether differences in the water-use-efficiency merely reflect differences in the rate of soil moisture generation per unit rainfall and to what degree soil type affects the efficiency of plant growth.

Three variables will be examined in the study: rainfall, soil moisture, and the satellite-derived Normalized Difference Vegetation Index (NDVI). Soil moisture values will be calculated via a surface hydrologic model (*evapoclimatonomy*). Spatial patterns and interrelationships will first be examined on monthly and annual time scales. Next, the data will be compared through examination of time series and linear regressions/correlations. The data will be stratified by vegetation type, soil type, and also according to the different vegetation types on each soil type. An examination of plant productivity per unit rainfall and soil moisture will follow. Finally, a vegetation mapping technique based on "rain-use efficiency" will be explored.

The discussion of the study begins with a look at the regional climate and geography of Botswana. A description of the *evapoclimatonomy* model and its inputs and parameterizations will follow. The data to be analyzed, including vegetation and soil classifications, will be described in detail. The results of the study, conclusions and recommendations for future study will then be presented.

1.1 Regional Climate and Geography

The country of Botswana encompasses roughly 71×10^4 km^2, a region slightly larger than France. It extends from 18 – 27°S and 20 – 29°E, and sits atop a plateau with average elevation of 1000 m. Figure 1 shows the location of Botswana in Africa and Figure 2 shows the geography of Botswana and indicates the major features to be described herein. Approximately 84% of the country is composed of a Kalahari sand surface with open grasslands and scrub savanna woodlands (Campbell, 1983).

The weather in the region is dominated by a high pressure belt which leads to a dry, warm semi-arid climate, though it is somewhat modified by maritime air masses. There is a distinct rainy season which runs from approximately October to April. Mean annual rainfall is shown in Figure 3. The northeastern parts of the country are wetter, with a mean yearly rainfall of about 650 mm, while southwestern areas have mean rainfall averages of only around 300 mm. Rainfall is generally convective in nature, highly variable interannually, and extremely localized. Sixty percent of the total rainfall comes from short, heavy showers. Evapotranspiration rates are high during the rainy season, resulting in low soil moisture storage (Campbell, 1983).

Water resources in Botswana total about $18 \times 10^9 m^3$, 95% of which is obtained through river inflow from Angola. However, these rivers run only a portion of the year. The only perennial lake is the Ngami, which itself can stand dry for several decades at a time. The only surface water is found in the Okavango Delta, which covers approximately 15,000 km^2 in the northern part of Botswana. It is fed by the Okavango River, which traversing the northern parts of the Kalahari is the third largest river in Southern Africa. Much of the inflow to the Delta is lost through evapotranspiration, with only 5% lost to outflow. It is joined with the Makgadikgadi Pans by the Boleti River; it is thought that this system may have once been a giant lake, and, as will be discussed later, this is reflected in the soil types of the region (Campbell, 1983).

Approximately three-fourths of the human and cattle population depend on a highly variable supply of ground water. This supply is basically "fossil water", trapped in rocks

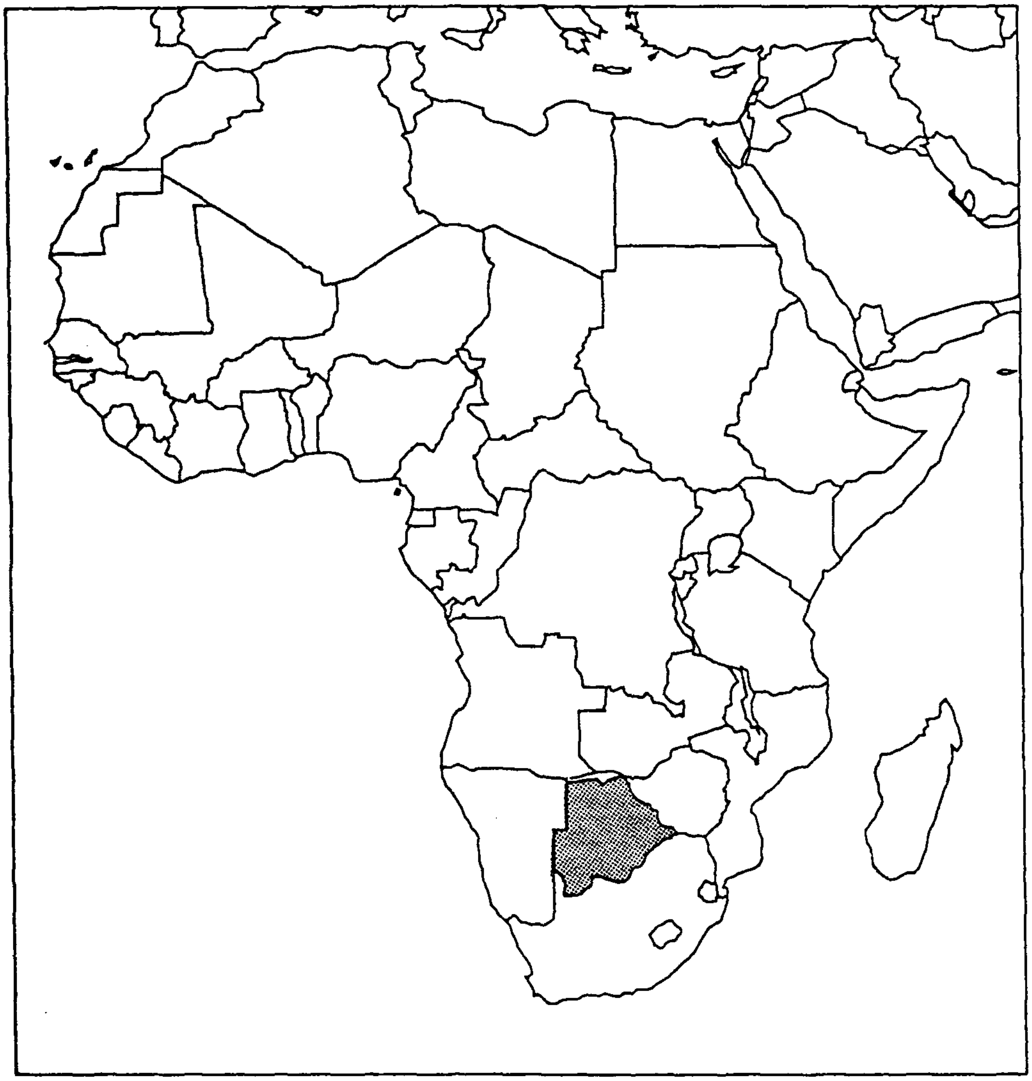

Figure 1: Location of Botswana in Africa.

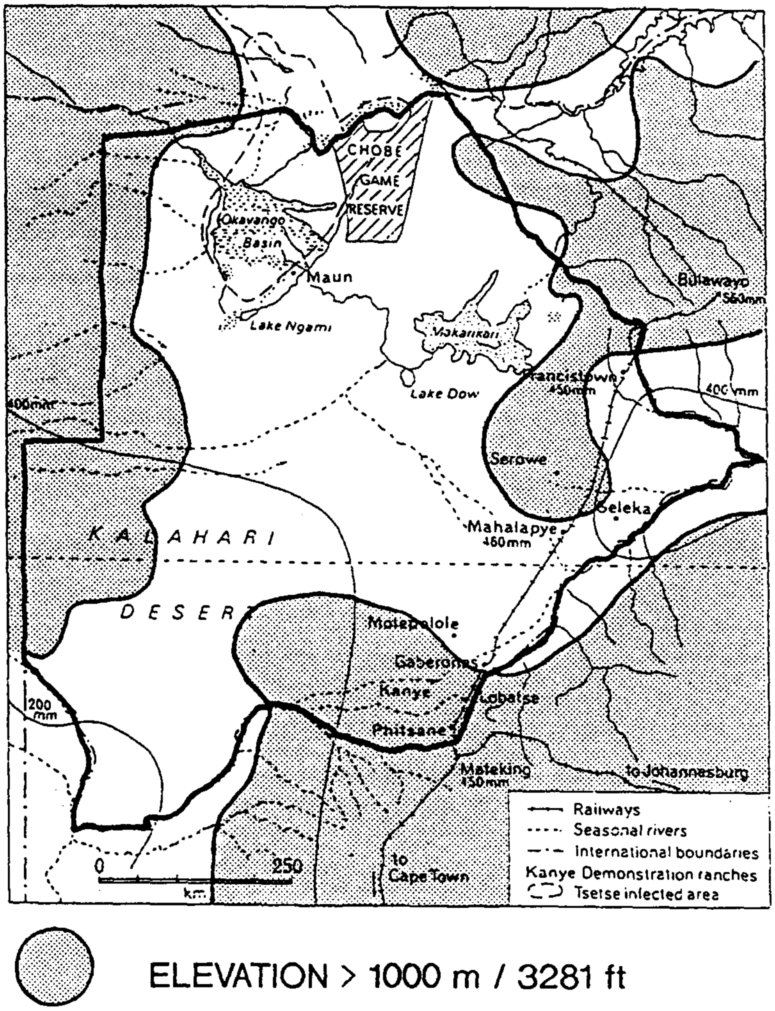

Figure 2: Main geographical features of Botswana (after White, 1978).

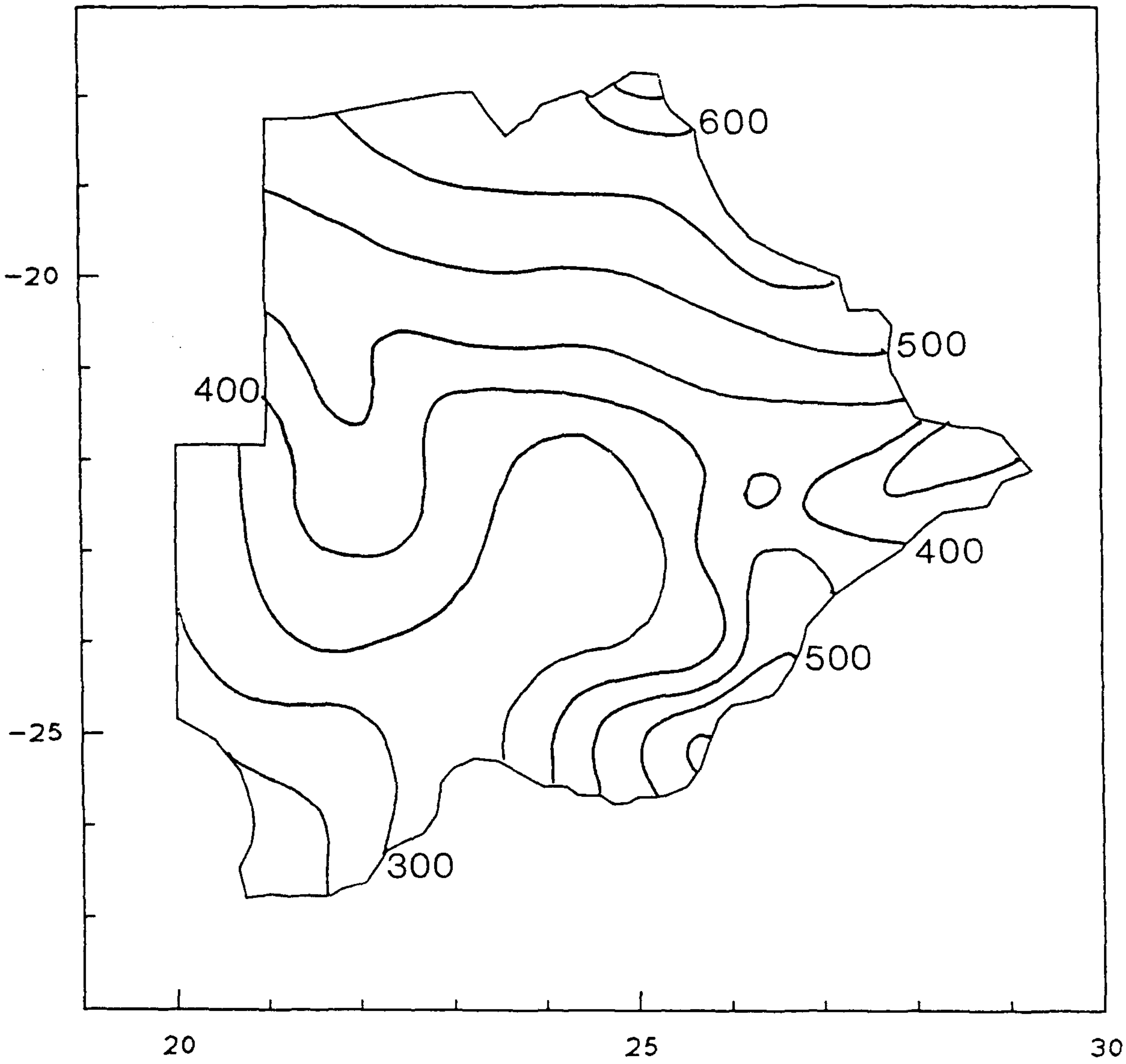

Figure 3: Mean annual rainfall (adapted from Director of Meteorological Services, 1984).

during earlier pluvial periods. Today, recharge to ground water encompasses only 1% of annual total rainfall. The only major region of irrigation is Tuli Block, which utilizes water from the Limpopo River (Campbell, 1983).

Roughly 80% of the rural population in Botswana depends on agriculture for a living. In 1983, agriculture accounted for only 12% of the gross national income, with 80% of that production in livestock. The grasslands are highly susceptible to overgrazing: moreover most areas are not conducive to crop growth because of highly variable rainfall, high temperatures, and sandy soils that are low in nutrients. Only about 7% of Botswana is ideally suited for agriculture (Campbell, 1983).

1.2 Remote Sensing of Vegetation

Satellite remote sensing has many applications in atmospheric and earth sciences. Methods have been developed to examine the energy balance cycle of the earth-atmosphere system and to measure surface characteristics such as albedo, temperature, and vegetation cover. Techniques for vegetation monitoring are based on the unique spectral and physiological characteristics of plant life.

An understanding of vegetation physiology will help clarify how biophysical processes are related to spectral properties of green vegetation. Figure 4 shows the process of photosynthesis within a plant leaf. The photosynthetic reaction occurs in the chloroplasts, which absorb photosynthetically active radiation (PAR) in the wavelengths of $0.4 - 0.7\mu m$ to drive the reaction:

$$CO_2 + H_2O \longrightarrow (light\ energy) \longrightarrow [CH_2O] + O_2 \qquad (1)$$

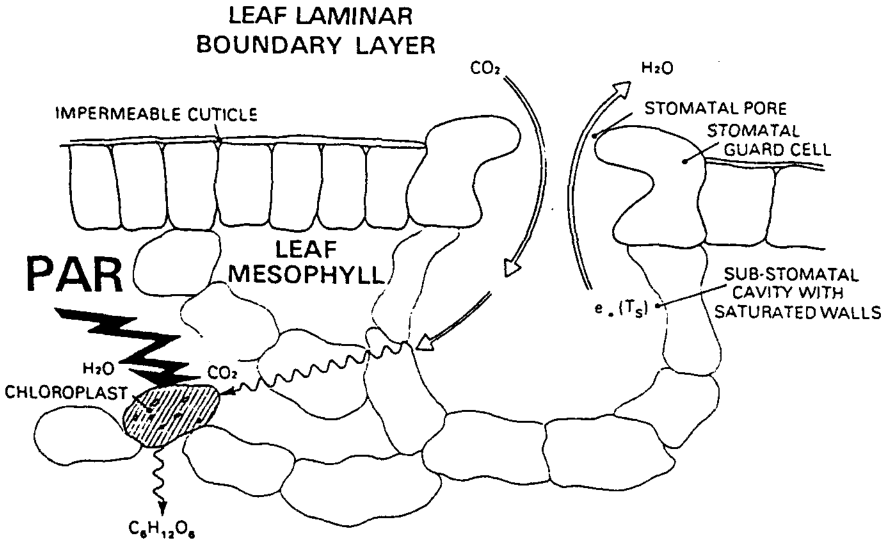

Figure 4: The process of photosynthesis (from Tucker and Sellers, 1986).

Quantitative knowledge of red and near-infrared (NIR) radiances provides insight into the plant surface chlorophyll density by indicating the amount of PAR that is absorbed by the chloroplasts. Since this is related to the rate at which CO_2 and H_2O are converted into carbohydrates, it ultimately provides information about the photosynthetic capacity of the canopy.

Within the leaf structure itself exists a complex arrangement of intercellular air spaces along with the internal components. Only 2-3% of the PAR incident on the surface of the leaf is reflected and the remainder is transmitted into the leaf (Tucker and Sellers, 1986). Inside the leaf, the radiation is either scattered or absorbed by various components of the internal structure. The degree of scattering or absorption is determined by the wavelength of the radiation. Since wavelengths in the 0.4-0.7 μm region drive photosynthesis, there is a high level of absorption and correspondingly low reflectance by the vegetation in that interval. In the 0.7-1.3 μm interval, absorption is low and reflectance is high, while in the 1.3-2.5 μm region, absorption is again high and reflectance low. Thus, these three intervals provide various details concerning the vegetation's biophysical processes. The first region gives information about plant pigments and chlorophyll absorption, the second provides data about the projected green leaf density and reflectance, and the last gives information related to the liquid water content in the canopy.

Differential reflection of vegetation in visible and infrared wavelengths (see Figure 5) forms the basis for remote sensing of vegetation (Tucker and Sellers, 1986). As evident in the above discussion, green vegetation absorbs strongly in the infrared wavelengths (0.6 - 0.7 μm) and reflects strongly in the near-infrared (0.75 - 1.1 μm). Tucker *et al.* (1983, 1985a, 1985b) developed a vegetation index, the Normalized Difference Vegetation Index (NDVI), using a ratio combination of measured radiances in these intervals. Observed values of the NDVI are routinely obtained via measurements from the NOAA Advanced Very High Resolution Radiometer (AVHRR) channels 1 (.58-.68 μm) and 2 (.725-1.1 μm). The formula for the index using measured radiances is as follows:

$$NDVI = \frac{C_2 - C_1}{C_2 + C_1} \tag{2}$$

where C_1 and C_2 are the radiances for each respective channel. NDVI values can range from -1.0 to +1.0. Generally, greener vegetation results in higher NDVI values due to the higher photosynthetic activity, which leads to a lower measured radiance in channel 1. NDVI values over water and clouds are small due to high reflectivities. Tucker and Sellers (1986) concluded that NDVI is a good estimator of instantaneous canopy biophysical rates, such as gross productivity and evapotranspiration, since it directly represents absorption of PAR and consequently measures photosynthetic capacity and canopy resistance to water vapor transfer.

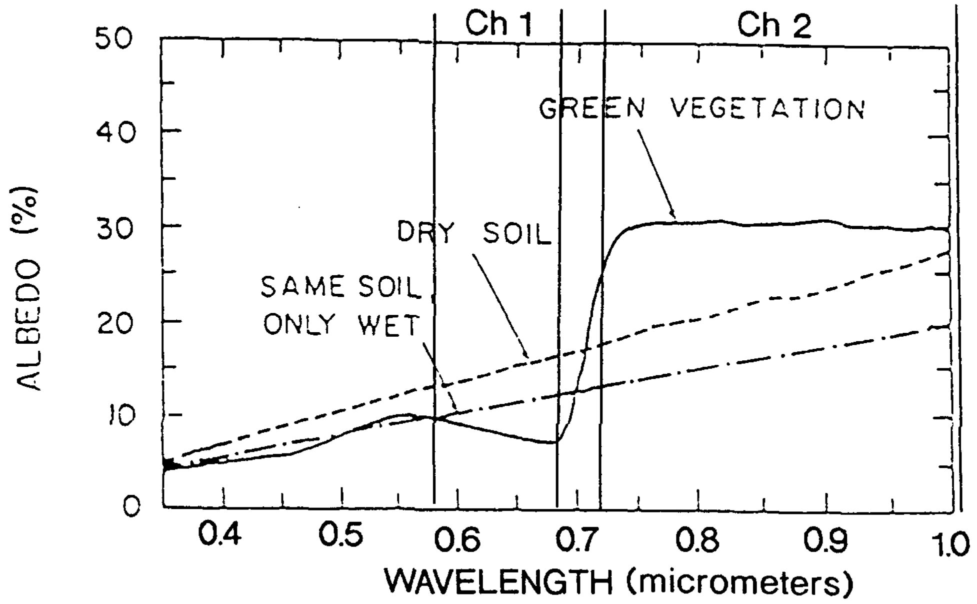

Figure 5: Spectral reflectance curve for green vegetation, and dry and wet soil (after Tucker and Miller, 1977).

The application of NDVI is limited by several inherent problems. The NDVI data must be calibrated by ground sampling of the vegetation, a difficult task in remote areas. It is affected by sun-target-sensor geometry and also by the atmosphere through which sensing is taking place. Factors such as off-nadir viewing, varying sun angle, atmospheric clouds and aerosols all act to reduce the indices (Tucker and Sellers, 1986), though the definition of NDVI as a ratio somewhat minimizes the effects of varying sun angle and topography. It does not, however, eliminate the additive effects of atmospheric attenuation (Justice *et al*, 1985). The presence of dead leaves in the canopy also lowers NDVI values.

In addition, in semi-arid and arid regions where vegetation cover is sparse, the index is dependent upon the type of soil background the vegetation is viewed against due to varying soil reflectances. Huete *et al* (1985) found a "significant" soil brightness effect for a normalized difference type of greeness measure. Greeness values decreased with increasing soil brightness for constant vegetation cover amount. In fact, NDVI was found to be independent of soil background influences for only 75% and greater plant areal coverage. While this is not a problem in many locations, in deserts it results in indices that are slightly biased. Hence, in these regions, the index must be used cautiously. Another related problem is the effect of soil moisture on background reflectance. Wetter soils have lower reflectances than do dry ones, as shown in Figure 4. Ultimately, discrimination of vegetation from soil background is a function of radiance contrasts (Tucker, 1979). Certain wavelength regions provide a better contrast and hence prove more useful (see Figure 4).

Jackson (1983) concluded that a comparison of greeness measures over different soil types would best be accomplished by first calculating the indices for bare soil, then subtracting that value from all measured greeness measures for that particular soil type. Since the soil and plant spectra interact, normalizing to a bare soil is only a "first step" in removing the soil effect (Huete *et al.*, 1985). Indeed, no large-scale soil corrections have been attempted as yet on NDVI data.

Chapter 2

Evapoclimatonomy

Previous studies (Nicholson *et al.*,1990; Malo and Nicholson, 1989; and Davenport and Nicholson, 1991) have examined vegetation response to rainfall variability. However, any study of vegetation dynamics in response to moisture variations should also include a study of soil moisture effects. (Assuming that all other environmental effects are kept constant, increased soil moisture generally results in increased plant growth.) As noted by Pinker and Corio (1987), conventional meteorological observations are not adequate to monitor the surface water balance for large-scale regions, especially in desert areas such as those in Africa. Large-scale inputs into general circulation models (GCMs) are normally derived from extrapolation of point observations which vary widely over microscale areas. In addition, current satellite methods for determining surface water balance features need further development.

In an attempt to quantify the study of climate, specifically surface energy and hydrologic balance, Lettau (1969) developed the "*climatonomy*" model. He described "*climatonomy*"

Table 1: Climatonomy model characteristics (from Lettau and Lettau, 1975).

Submodel	Forcing Function	Response/Output
Shortwave Radiation	Irradiance, I′(top of atmosphere)	Top/planetary albedo, $A*$ Absorption by submedium, $(1-a_s)G*$
Evapoclimatonomy	Precipitation, P and Absorption by submedium, $(1-a_s)G*$	Soil moisture, m Runoff, N Evapotranspiration, E
Thermal Radiation	Absorption by submedium minus evapotranspiration, $(1-a_s)G*-E$	T_{air}, T_{sfc} Surface fluxes Net radiation, R_{net}

as a "...study of man's physical environment that is significantly more numerically and theoretically oriented than conventional climatology." The basic model formulation is simple. A forcing function of the time series of solar irradiance received at the top of the atmosphere, supplemented by advected heat and moisture, is applied to a model algorithm. This involves the parameterization of mass and energy balance processes (to include storage and delay terms), as well as the solution of one-dimensional differential equations for continuity and balance requirements. The model output (the response function) consists of the time series of surface and instrument level temperature, exchangeable soil moisture, net radiation, evaporation and runoff, and latent and sensible heat fluxes.

For practicality, the model is broken up into three sub-models: *shortwave*, *evapo-*, and *thermo-*. The model characteristics in terms of forcing and response functions are shown in Table 1.

In normal usage, output from the first submodel is used as input for the second, which in turn passes its output as well as that of the first submodel to the third. For the purpose of this research, however, only the *evapoclimatonomy* submodel will be used. Input is simply observed global radiation at the surface, as well as ground albedo. Ground absorbed solar radiation is then calculated using these input values rather than having the first submodel determine it.

The model in use currently is that revised by Nicholson and Lare (1990, 1991). The *evapoclimatonomy* submodel is essentially a numerical solution to a simplified form of the hydrologic balance equation:

$$P = E + N + \frac{dm}{dt} \tag{3}$$

where P is precipitation, E is evapotransipration, N is runoff, and dm/dt is the change in soil moisture storage. It operates under the principle that surface water balance is primarily a function of incoming radiation and precipitation (the forcing functions).

Three assumptions are made in order to keep the model simple (Lare and Nicholson, 1990). First, for a continental region with a stable climate:

$$\frac{dm}{dt} = 0, \tag{4}$$

that is, there is no net storage of moisture over sufficiently long time periods (for example, one year). The larger the area and the longer the time scale considered, the better this assumption is. Therefore, rainfall goes either into evapotranspiration or runoff. In other words:

$$\overline{P} = \overline{E} + \overline{N}. \tag{5}$$

Secondly, the processes of runoff and evapotranspiration can be further subdivided into immediate ($'$) and delayed ($''$) parts. Thus:

$$E = E' + E'', \quad N = N' + N''. \tag{6}$$

Immediate processes are those that occur in the same month as the precipitation, while delayed implies processes that are associated with the rain which fell in previous months. Physically this separates temporal variations of runoff and evapotranspiration associated with concurrent rainfall from those due to subsurface moisture (Nicholson and Lare, 1990). Using this assumption, a quantity termed "reduced precipitation", P', is defined as:

$$P' = P - E' - N'. \tag{7}$$

Reduced precipitation is simply the rainfall that does not evaporate or runoff in the same month and is available for soil moisture storage. Therefore, the hydrologic balance equation may now be written as:

$$\frac{dm}{dt} = P' - (N'' + E''). \tag{8}$$

The final assumption of the *evapoclimatonomy* submodel is that the delayed processes vary directly in proportion to soil moisture according to:

$$N''(t) = \frac{\overline{N''}m(t)}{\overline{m}}, \quad E''(t) = \frac{\overline{E''}m(t)}{\overline{m}}. \tag{9}$$

where $\overline{N''}$ and $\overline{E''}$ are the mean quantities of delayed runoff and evapotranspiration. These quantities are combined in such a way as to yield a parameter known as "*residence time*", t^*:

$$N'' + E'' = \frac{m}{t^*}, \quad t^* = \frac{\overline{m}}{\overline{N''} + \overline{E''}}. \tag{10}$$

Residence time is the time required for a volume of water equal to the annual mean of exchangeable soil moisture to be depleted by the delayed processes of runoff and evapotranspiration. It is usually on the order of 2-3 months (Nicholson and Lare, 1990), though in some locations, it may be as low as one month or as high as one year. The actual value is a function of soil type and the potential evapotranspiration (PET), with higher PET values resulting in lower residence times. Residence time is calculated after Serafini and Sud (1987) as a function of the PET, the wilting point (the point at which the vegetation cannot absorb enough moisture to sustain itself and begins to wilt), and the maximum possible soil moisture storage. In determining residence times, the authors assume that neither precipitation nor irrigation adds moisture to the soil. Using equations (8) and (10), the hydrologic balance formula is then rewritten as:

$$P - E' - N' = \frac{m}{t^*} + \frac{dm}{dt}. \tag{11}$$

In order to calculate the immediate evapotransipration, another empirical concept, "*evaporivity*", e^*, is defined. Evaporivity is a non-dimensional measure of the land surface's ability to use part of the incoming solar radiation to evaporate the rainfall received in a given month (Lettau, 1969). It has been empirically determined that e^* generally falls between 0.4 and 0.8 (Lettau, 1971).

Runoff is calculated as a function of the gravitational drainage of existing soil water and surface runoff due to excess precipitation over infiltration rate (Warrilow, 1985). In determining gravitational drainage, it is assumed that there is a single layer of soil with spatially homogeneous soil moisture; that is, horizontal movements of water are neglected. Gravitational drainage varies with soil type, with larger values for coarser soils and smaller ones for fine grained soils. It also increases with increasing soil moisture. Surface runoff is calculated as a function of the surface infiltration rate and is affected by the spatial variability of rainfall. The use of a proportionality constant accounts for the fact that although the entire region may experience total rainfall that is below the threshold for runoff, a certain percentage of the area may receive amounts great enough to produce runoff in individual locations. Infiltration rate is determined as a function of sand and clay content according to Saxton *et al.* (1986). In general, infiltration rates are higher for soils with high sand content and lower for clay based soils. In addition to infiltration rate, gravitational drainage is calculated after Saxton *et al.* (1986).

The next step in the model is to subtract the annual means from each term in the new form of the hydrologic balance equation, resulting in an ordinary differential equation (ODE):

$$p'(t) = \frac{m - \bar{m}}{t^*} + \frac{d(m - \bar{m})}{dt} \tag{12}$$

where

$$p'(t) = P - E' - N' - (\overline{P - E' - N'}). \tag{13}$$

The ODE is solved as:

$$m - \overline{m} = e^{-t/t^*}\left[constant\ + \int e^{t/t^*} p' dt\right]. \tag{14}$$

Because of the initial assumption of climatic stability, the bracketed term must approach 0, thus determining the integration constant. The equation is solved via stepwise integration until the bracketed term equals 0—for practicality, until $| \ m_{13th\ month} - m_{initial\ month} \ |<$ 0.005.

This entire procedure is completed twice. Initially, the model is run as a diagnostic process for each station, using mean monthly values for rainfall and solar radiation to calculate mean annual values for soil moisture storage, total runoff and evapotranspiration. It is then run a second time as a prognostic tool using the mean values of soil moisture storage, and delayed runoff and evapotranspiration calculated during the first run. Observed values of precipitation are used as the forcing function. The final output is the time series of soil moisture storage, and runoff and evapotranspiration (both delayed and immediate).

The accuracy of climatonomic model output has not been rigorously verified outside of a handful of experiments. As previously stated, one problem is the lack of large-scale surface water measurements. However, Lettau (1969) applied the model to several areas in North America using observed data encompassing several years and found general agreement between monthly observed and calculated runoff, evapotranspiration, and soil moisture values. Lettau and Baradas (1973) applied the model to the Mabacan River watershed in the Philippines for a 12 year period. Annual averages of observed runoff were found to be correlated at the .89 level with calculations, and monthly evapotranspiration calculations also compared well with empirical data for the region. Corio and Pinker (1987) tested the validity of the model on shorter temporal and smaller spatial scales than the climatic scales associated with previous studies, conducting an experiment for the state of Kansas, as well as for several smaller individual watersheds. Calculated runoff compared well with observed values when the entire state was considered, resulting in phase differences of less than one month and similar amplitudes. The results were not as good, however, for the individual watersheds. The authors concluded that evapoclimatonomy is "realistic for testing parameterizations on large-scales." One is referred to the individual articles for details about these experiments.

Chapter 3

Data

This research uses monthly rainfall totals, monthly composited NDVI data, and the time series of monthly soil moisture calculated with the *evapoclimatonomy* model for the years 1982-1987. The monthly rainfall data were obtained from the archives of Dr. Sharon E. Nicholson, Department of Meteorology, Florida State University, which were obtained from African reporting stations and are described in Nicholson *et al.* (1988). Long-term mean annual rainfall and averages for the 6 years under study are given for the stations examined in Table 2. Table 3 shows the 6-yr means of annual rainfall, NDVI, and mean monthly soil moisture.

The NDVI data is calculated from NOAA AVHRR global area coverage (GAC) imagery with resolution of 3 × 5 km. The data was provided by Dr. C.J. Tucker of the NASA Goddard Space Flight Center (GSFC). During its processing, a cloud mask was applied with the AVHRR channel 5, labelling everything colder than 12°C as cloud. Monthly composite images are formed through a maximum-value procedure whereby the highest daily value of

Table 2: Rainfall data (mm/yr)

Station	Mean	1982	1983	1984	1985	1986	1987	6-Yr Mean
Tshabong *	293	246	365	75	141	391	292	268
Tshane *	353	279	365	173	202	403	343	294
Ghanzi *	430	392	340	164	385	309	302	315
Palapye Road *	410	209	288	397	146	444	448	322
Dibete *	381	383	239	395	300	279	412	335
Gweta *	440	211	360	263	386	420	399	340
Mahalapye *	471	407	234	465	245	426	226	334
Gaberones *	531	502	326	290	235	482	384	370
Baines Drift *	355	180	245	359	402	238	369	299
Francistown *	461	270	421	357	311	451	523	389
Maun *	473	288	400	262	341	397	230	320
Shakawe *	521	393	563	349	504	546	228	431
Lobatse *	565	442	317	379	356	376	549	403
Kanye *	522	580	360	253	479	393	556	437
Kasane *	673	377	543	389	715	553	467	507
Ramatlabama *	513	588	326	292	248	352	501	385
Masama	504	512	277	378	264	243	355	338
Serowe	459	333	317	223	284	436	520	352
Mochudi	500	482	292	351	288	617	301	389
Phitshane	464	370	204	107	259	281	423	274
Kalamare	448	404	360	379	290	380	386	367
Machaneng	420	604	152	290	405	261	283	333
Molepolole	503	352	244	211	153	347	307	269
Pandamatengo	569	294	639	410	333	755	546	496
Rakops	370	240	148	200	154	212	221	196

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* **Soil moisture was calculated for these stations**

Table 3: 6-year averages of rainfall (mm/yr), NDVI, and mean monthly soil moisture (mm/mo)

Station	Rainfall	NDVI	Soil Moisture
Tshabong	268	1.6	9.8
Tshane	294	1.7	14.6
Ghanzi	315	2.0	16.1
Palapye Road	322	1.6	13.8
Dibete	335	2.2	14.6
Gweta	340	1.8	17.1
Mahalapye	334	2.2	9.5
Gaberones	370	2.3	10.9
Baines Drift	299	2.5	10.7
Francistown	389	2.4	15.3
Maun	320	2.5	17.4
Shakawe	431	3.3	16.5
Lobatse	403	2.5	20.6
Kanye	437	2.5	21.3
Kasane	507	3.7	32.2
Ramatlabama	385	2.5	12.2

NDVI is retained for the compositing period. This compositing technique reduces the effect associated with atmospheric aerosols, scan angle, and cloud contamination (Tucker *et al.*, 1985b).

Figure 6 shows the density of reporting stations in Botswana; Figure 7 shows the 16 stations that were used in the analyses. Incomplete rainfall records primarily accounted for the fact that not all available stations were used, although a few were eliminated due to lack of other data such as detailed soil breakdowns.

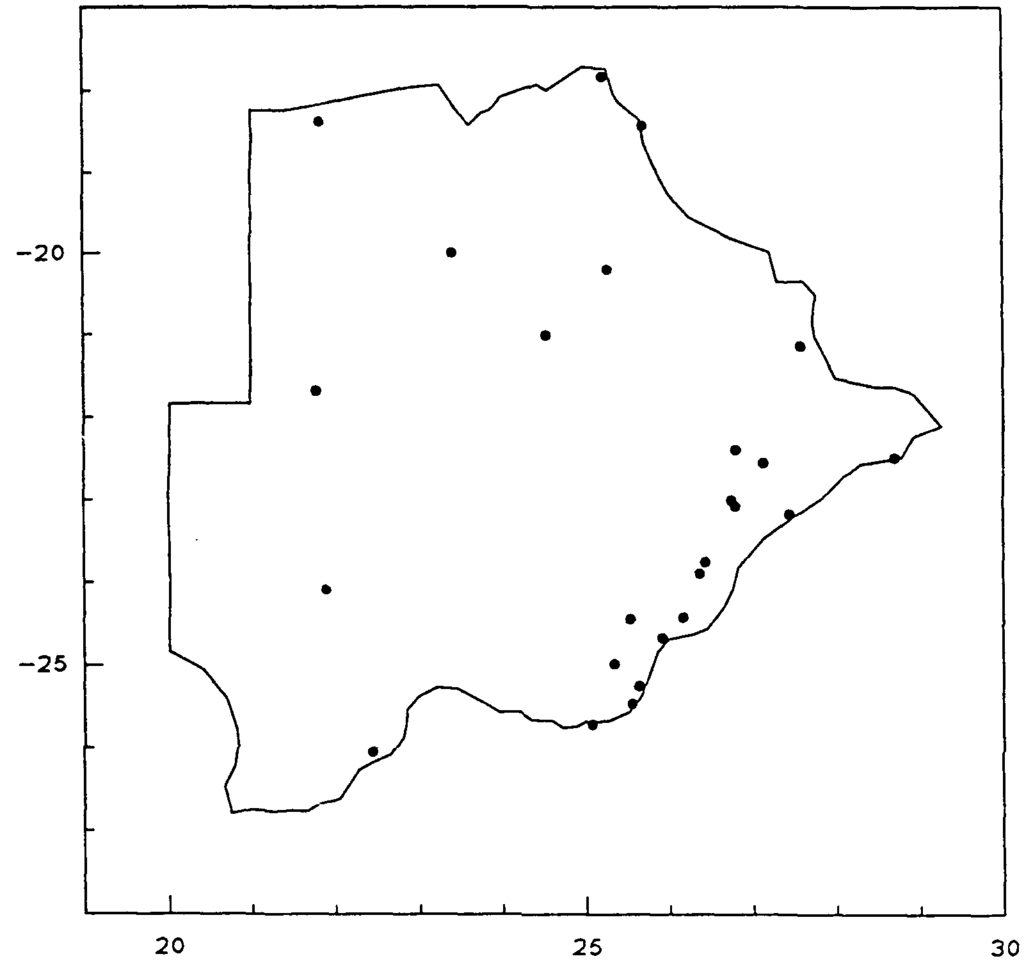


Figure 6: Density of Botswana reporting stations.

3.1 Vegetation Classification

Each of the stations used in the study were placed into one of three vegetation zones according to White (1983). Table 4 lists the vegetation classifications used, the number of stations in each zone, and typical stations in each type. The location of the vegetation zones are shown in Figure 8. A total of 7 separate formations are distinguished in White's

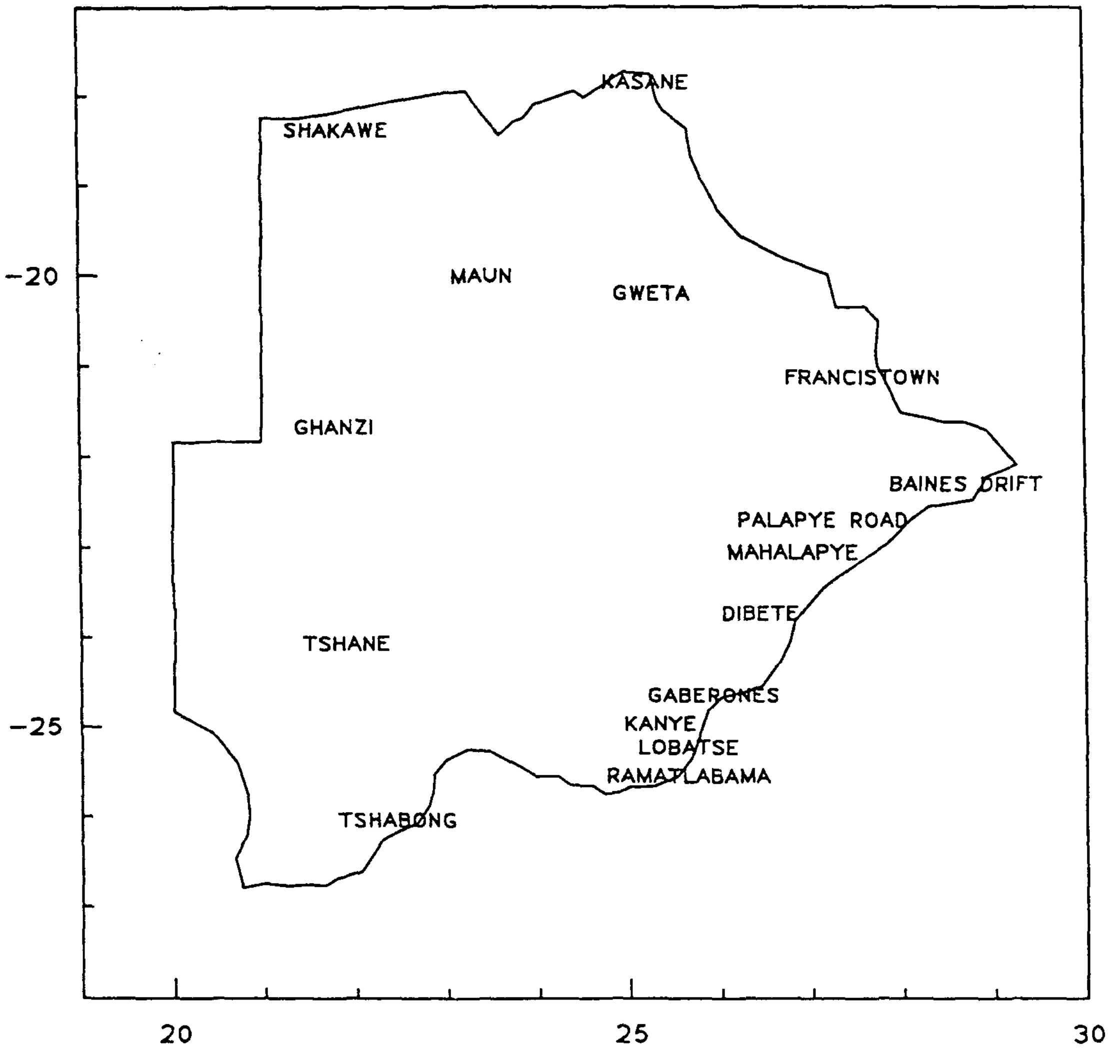


Figure 7: Stations used in this study.

Table 4: Vegetation classifications

UNESCO Vegetation formation	UNESCO number	Reference name in article	Number of stations	Typical stations
Zambezian *Mopane* Woodland and Scrub Woodland	28	*Mopane* woodland	6	Baines Drift Francistown Kasane Gweta Maun Shakawe
Kalahari thornveld	44	Kalahari thornveld	10	Lobatse Mahalapye Palapye Road Ramatlabama Tshabong Tshane
Transition to Zambezian broad-leaved woodland	35a	Transition zone	7	Dibete Gaberone Ghanzi Kanye

map. This study neglects four of these zones: those of swamp and aquatic vegetation in the Okavango Basin, the halophytic vegetation and drier Zambezian miombo woodland of the Makgadikgadi Pans and the Kalahari/Karoo-Namib transition zone in the southwest. These were neglected primarily because no reporting stations were available to be analyzed in these regions, but also because the northernmost regions are heavily influenced by the presence of exogeneous water, most of which originates in Angola. The three remaining zones consist of *Colophospermum mopane* woodland and scrub woodland, the Kalahari thornveld deciduous *Acacia* bushland and wooded grassland, and the transition zone to the Zambezian broadleaved woodland (White, 1983).

The *Colophospermum mopane* woodland and scrub woodland occur in mosaic in most

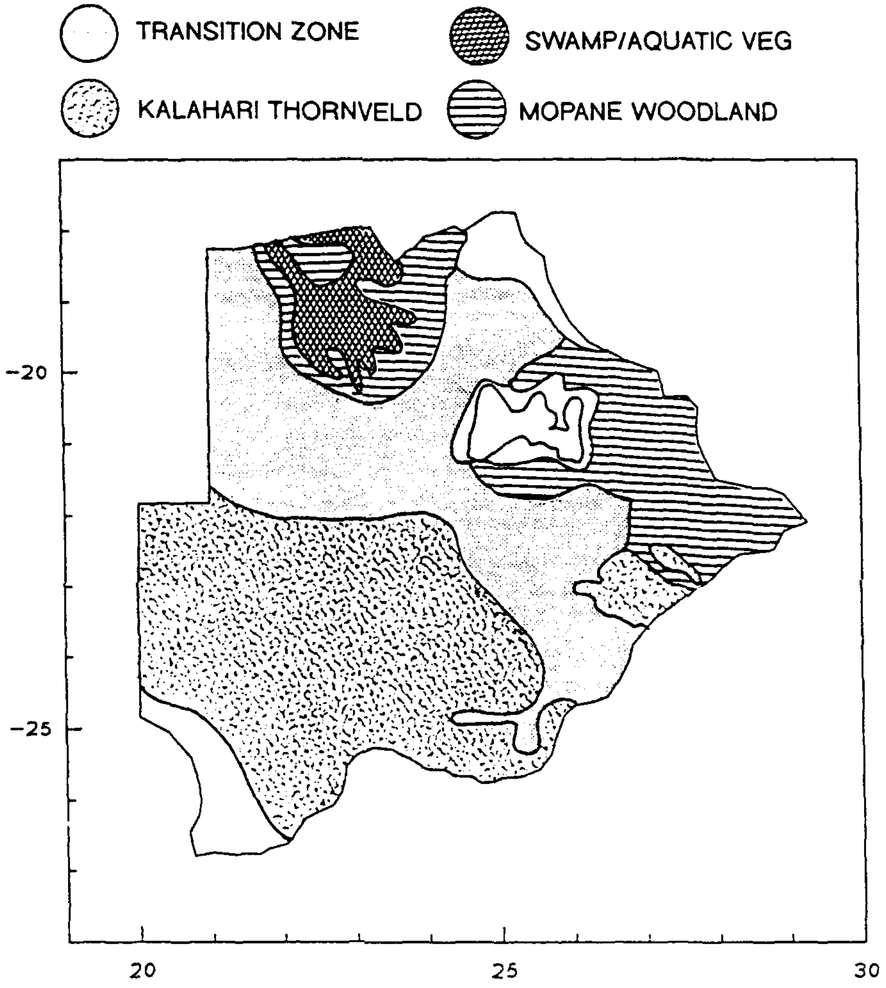


Figure 8: Vegetation zones (adapted from White, 1983).

locations. It is found in widespread areas in the Makgadikgadi and Okavango depressions in northeastern parts of the country, but does not exist farther south and west on Kalahari sand. *Mopane* woodlands are characterized by stands of trees 10-20 meters tall. The *mopane* itself is usually a single-stemmed tree with a crown of rigid, irregular ascending branches and butterfly shaped leaves (White, 1983).

Mopane's rainfall tolerance extends up only to about 800 mm/yr. Below 500 mm/yr, it grows on most types of soils, but above this limit, it is confined to shallow soils or those with heavy subsoils, usually with high sodium concentrations. Due to higher sodium levels, these *mopane* soils have low water storage capacity and are often not capable of absorbing all of the water they receive. In most parts of Botswana, *mopane* is deciduous for around 5 months. It has a shallow root system, concentrated in the top 25 cm of soil and grasses are virtually absent. However, in Botswana, *mopane* is largely maintained by human-induced fires, and is consequently converted to shrubby grasslands with burnt stems remaining in height of 0.3-1.6 m. Between the charred remains, grasses grow to equivalent heights (White, 1983).

Wooded grasslands, or savannas, are favored in regions where annual precipitation falls between 250-500 mm/yr and occurs in the summer months. In the remaining two vegetation zones, savanna is dominant and grasses generally grow to heights of less than 1 m. In the Kalahari, wooded grassland is characterized by grasslands with 10-40% coverage of woody plants, which may or may not occur as trees. The transition zone vegetation consists of more widespread broadleaved trees than the thornveld farther south, where *Acacia* species dominate. The trees in these regions average less than 7 m in height. On the Ghanzi ridge, where soils are shallow, grasses are less important and woody plants and shrubs dominate. However, on the Kalahari sand, overgrazing and anthropogenic effects have led to a degradation of the vegetation (White, 1983).

3.2 Soil Classificiations

Each of the stations in the study was also characterized by soil type according to the FAO/UNESCO Publication *Soil Map of the World* (1977). Three broad regions of soil types are distinguished in Botswana: two regions of sandy *arenosols*, and a higher clay content region of *luvisols* and *vertisols*. Each of these broad regions are subdivided into smaller, more detailed types. A total of 17 of these detailed regions are identified in Botswana (shown in Figure 9), and of these, 11 were used for the current research. The 11 subgroups were placed into one of 5 generalized types of soils: *arenosols*, *luvisols*, *fluvisols*, *cambisols*, or *vertisols*. Detailed soil analyses were available for the *arenosols* and two types of *luvisols*. Stations not in these regions were given the analysis for the broad region they fell into. The exception to this is Shakawe, which due to its proximity to the Okanvango River, was assigned to an alluvial soil rather than the broad regional analysis of *arenosols*. The soil breakouts and station classifications are given in Table 5. A discussion of the characteristics of each of the soils follows.

Arenosols are sandy, porous soils. Some classifications also refer to these soils as *aridisols*—soils that are dry 50% or more of the year without organic materials. In aridic soil regimes, potential evapotranspiration exceeds rainfall most of the year (Buol *et al.*, 1989).

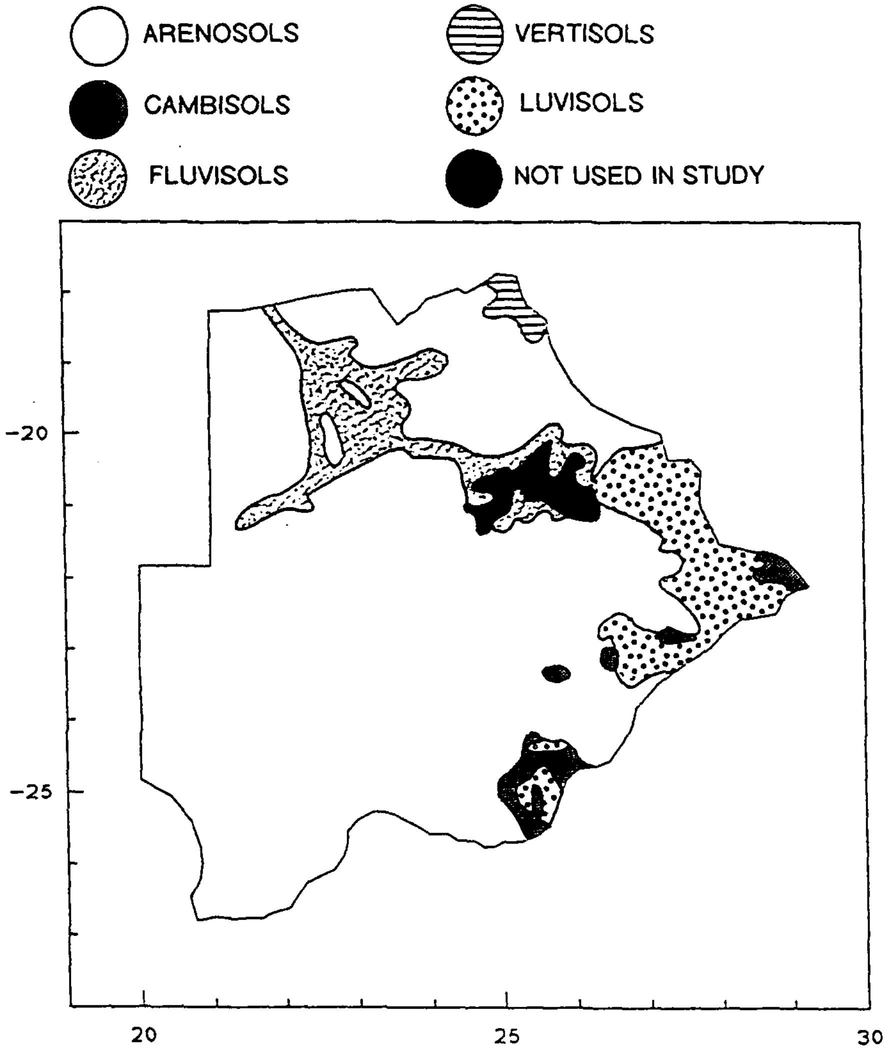


Figure 9: Soil types (adapted from FAO, 1977).

Table 5: Soil classifications

Soil Type	UNESCO Code	Sfc Sand	Sfc Clay	1 m Sand	1 m Clay	Stations Assigned
Arenosols	Qc/Qa	94.0	5.0	93.1	4.4	Tshabong Tshane Ghanzi Palapye Road Dibete Gweta
Luvisols						
Chromic Luvisol	Lc	56.0	38.0	48.1	41.1	Mahalapye Ramatlabama Gaberones
Calcic Luvisol	Lk	66.0	17.0	56.4	32.5	Baines Drift Francistown
Fluvisols *	Je					
Calcaric Fluvisol	Jc	37.0	40.0	58.6	31.2	Shakawe ‡ Maun †
Cambisols *	I-Bc					Lobatse † Kanye †
Vertisols *	V					Kasane †

*** No detailed compositional analysis available**

† Used compositional analysis for *arenosols*

‡ Alternate alluvial compositional analysis used...see text

Six of the stations examined in this study were classified as *arenosols*, with 5 falling into the subcategory of a *cambic arenosol. Cambic arenosols* are sub-arid, reddish-brown, and well-drained soils formed from sandstone (FAO, 1977). One station classified as an *arenosol* fell into the sub-category of *albic arenosols. Albic arenosols*—pale, sandy soils—are the result of very intense leaching in topographic depressions (FAO, 1977). For the purposes of this study, all *arenosols* are given the same detailed breakdown, that of a high sand and low clay content.

Luvisols are high base status soils with a dense clay illuvial horizon (that is, a lower soil layer to which materials are brought down from higher layers). *Luvisols* are also referred to as *alfisols* (Strahler and Strahler, 1987) and constitute the second largest group of stations in the study. Their clay content is greater than that of the *arenosols.* In this study, 5 of the stations were classified as either *chromic luvisols* or *calcic luvisols.* A *chromic luvisol* consists of generally dry, sandy-clay materials, slightly moist in lower layers. A *calcic luvisol* is one that has calcium or magnesium carbonates accumulated within it (Strahler and Strahler, 1987). In the analyses from FAO (1977), the *calcic luvisol* possesses slightly higher sand content than does the *chromic luvisol.*

Two stations were classified as *fluvisols*, also known as alluvial soils. They are formed of recent deposits near rivers which are often flooded and have phreatic water tables (ones from which springs or wells may exist) (Duchaufour, 1982). These water tables show seasonal variations in their levels, so the soils, while well supplied with water, are generally not waterlogged. Consequently, they are often "exceptionally favorable to vegetation" (Duchaufour, 1982). Alluvium material has properties of the soils that have been transported from other regions. They lack structure and are heterogeneous in texture (both horizontally and vertically) due to the wide variety of geological or geomorphological state of the lands they originated in. No detailed analyses were available for the *fluvisols.* As already noted, Shakawe was assigned an alluvial breakdown because of its proximity to the Okavango River, but Maun was given the soil breakdown of the broad region it is located in, that of the *arenosols.* Duchaufour (1982) states that *fluvisols* have high porosity and good surface aerations, so treating Maun as an *arenosol* is acceptable.

Cambisols are fine-grained soils that are characteristic of a recent stage of development (FAO, 1977). They are characterized by light brown color, and structure or consistency change due to the effects of weathering (Strahler and Strahler, 1987). They often have high potential fertility, but are generally not well suited for agriculture (Duchaufour, 1982). Two stations in this study fell into a region of *lithosol-chromic cambisol.* Detailed analyses for the *lithosols* and the *cambisols* were not available, and stations in this soil type were given the breakdown of the broad region they fell within, namely that of the *arenosols.*

The last soil type is that of the *vertisols*, a type of soil that is heavy, clay-based, and dark in color. It is very uniform in texture, but though often fertile, is difficult to work for farming because of waterlogging difficulties or hardening of the soil (induration) in the dry seasons (Duchaufour, 1983). *Vertisols are occasionally underwater due to floods* or rainwater accumulation in poorly drained depressions (FAO, 1977). However, *vertisols* are generally covered with savanna-type vegetation that is good for livestock. Because no detailed description of *vertisols* was available, stations where the map indicated *vertisols* were assigned to the general soil type of the region it fell within, the *arenosols.* It is likely that this resulted in errors in the calculation of soil moisture due to the fact that *arenosols* are low in clay content.

3.3 Evapoclimatonomy Model Input Data

Various sources were used to obtain the data required for input into the evapoclimatonomy model. Mean monthly values of rainfall, surface albedo, intercepted solar radiation, evaporivity, and potential evapotranspiration were required, as well as sand and clay content for the soil surface layer and top 1 meter. For the time series simulation, observed monthly rainfall was used. As previous mentioned, the precipitation data was obtained from Nicholson *et al.* (1988). The evaporivity values were empirically determined based on previous studies (Lettau, 1971, Pinker and Corio, 1987), and model simulations run for a test station in the semi-arid Sahel (Nicholson and Lare, 1990). Sand and clay contents were taken from FAO (1977). Ground intercepted solar radiation and potential evapotranspiration (PET) values were taken from FAO (1984). Surface albedo data was taken from global monthly fields derived by Dorman and Sellers (1989) using the Simple Biosphere Model (SiB) of Sellers *et al* (1986). Although the grid for these fields is extremely coarse (4° × 5°), sensitivity studies run on the model as part of this research indicated that albedo errors as large as ± 25% resulted in soil moisture differences of generally less than 4%.

For 8 of the 16 stations used in this study, radiation and PET data was not available. However, as noted in Lare and Nicholson (1991), the global radiation fields in the Kalahari are for the most part spatially homogeneous. For this reason, radiation and PET data for the nearest station with similar rainfall regimes were used for stations missing the values.

Chapter 4

Results and Discussion

The relationships between the greenness of the earth's surface and rainfall have been proven to be easily quantifiable (Nicholson *et al.*, 1990). This section will examine in depth the spatial and temporal aspects of the interrelationships between NDVI, rainfall, and exchangeable soil moisture as studied in Botswana. A discussion of NDVI patterns in the region, in both time and space, will begin the discussion. In the course of the analysis, the effect of varying soil type upon vegetation response in the region will be studied, and monthly data for the variables will be correlated for different time-lags between the onset of rainfall and soil moisture fluctuations and resulting responses of vegetation. The applicability of a vegetation mapping technique described in Nicholson *et al.* (1990) to Botswana will end the discussion.

4.1 NDVI Spatial and Temporal Characteristics

Upon examination, monthly and yearly NDVI patterns over Botswana show several interesting features. Monthly diagrams of NDVI are given in Figure 10, and annual data are shown in Figure 11. The annual data is calculated from Oct-Sep so as not to bisect the rainy seasons. Overall, the NDVI values over Botswana are low year-round (less than 0.2). Two exceptions to this are the northern and extreme southeastern parts of the country. These two regions correspond to the areas of highest mean annual rainfall. Monthly values of NDVI in the northeastern parts of the country average higher than 0.4 during the wet summer months, and are never less than 0.15 during the dry winter season. The *mopane* forest type vegetation that exists in this region is deciduous for approximately 5 months, and this is reflected in maximum NDVI values for the months of November - March. Along the Limpopo River in the southeast, minor maxima of greater than 0.25 during the rainy season are found. The presence of exogeneous water is evident around the Okavango Delta, with relatively higher values present year-round. This is also indicative of the more persistent swamp and aquatic species of vegetation found there. As mentioned in the geographical description of Botswana, the Makgadikgadi Pans are composed of bright soils with sparse vegetation cover. This shows up in the NDVI patterns as areas of values of less than 0.15 year-round, with minima of less than 0.1 found during the extreme dry season.

A seasonal cycle of vegetation growth in evident in the NDVI patterns. Green-up of the plants begins in November (a distinct response to the start of the rains), when NDVI values jump from around 0.15 to greater than 0.25 in northern regions, and from less than 0.15

to greater than 0.2 in portions of the southeast. Senesence begins first in the northeast in April (as the rainy season begins to come to an end), and lower NDVI values spread across the remainder of the country to reach minimum values during the months of September and October. Indeed, during the winter months, NDVI values of less than 0.1 cover a large portion of the country. Townshend and Justice (1986) stated that an NDVI value of 0.05 is the threshold for photosynthetic activity within a canopy, indicating that while some vegetation probably still exists during the dry months, most plant activity ceases over a great part of Botswana.

The annual NDVI patterns (shown in Figure 11) also show interesting features. Annual integrated values (a measure of total plant productivity) of generally less than 3.5 are found for each year. The largest annual values exist in a small section of the northeast, with a maximum of greater than 4.0 noted in the 1985-86 period. Persistently low values are found over the Makgadikgadi Pans. The presense of two regions of deciduous *mopane* woodland in the southeast is evident by interannual persistence of two areas of slightly higher NDVI values, while a small region of *acacia* dominated grassland between the *mopane* woodlands is evidenced by slightly lower values. Finally, low NDVI values persist in the southwest, indicative of the most arid conditions with brightest sandy soils and sparse vegetation cover.

Examination of the time series of NDVI at select stations also yields several interesting features. One station was arbitrarily chosen from each vegetation zone in the study. Tshabong is representative of the *acacia* dominant grassland, Francistown of the *mopane* woodland, and Gaberones of the transition zone between the two. Figure 12 shows the time series plots for these stations. Overall, the lowest NDVI values are found at Tshabong, due to the sparse vegetation cover, bright soil background, and probably lower annual rainfall. The effect of rainfall totals will be examined in the next section of this chapter. The largest interseasonal amplitude in NDVI values exists at Gaberones. This may be the result of higher annual rainfall totals (also to be examined in a subsequent section). Note that the maximum values of NDVI are similar at both Gaberones and Francistown, but that period of minimum values is shorter at Francistown, located in the deciduous *mopane* woodland. This is indicative of a longer growing season at Francistown than in the transition vegetation zone. In addition, the NDVI curves show broader peaks at Francistown than at the other two stations. This may be partially due to the wetter regime and slightly longer rainy season in the *mopane* woodland. In addition, slower senesence of trees in the woodland as opposed to the rapid death of grasses which are widespread in the transition zone likely influences the data as well.

Next, the NDVI time series for two stations within the same vegetation zone, but with different rainfall regimes was examined. Figure 12 shows the time series plots. Both Kalamare and Tshabong are located within the *acacia* dominated savanna and both have unimodal rainfall regimes, but Kalamare experiences a six-year mean of 367 mm/yr of rainfall compared to Tshabong with only 268 mm/yr. Though both stations show similar minimum

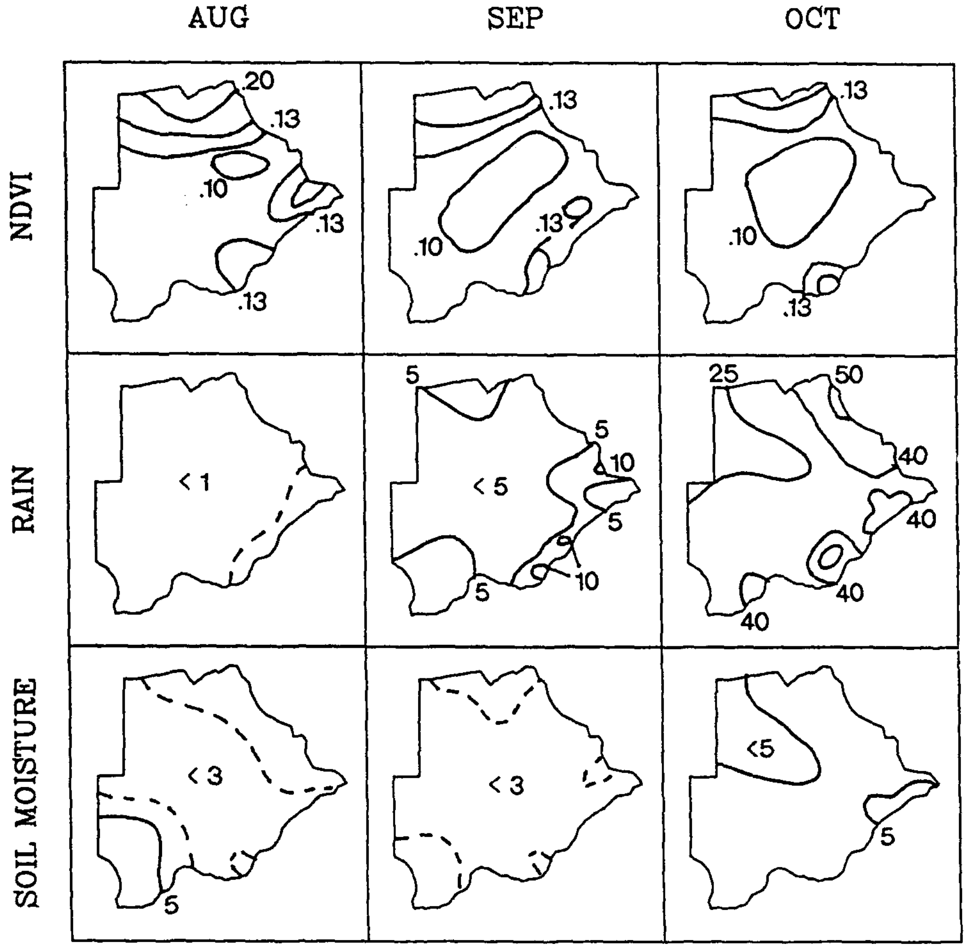
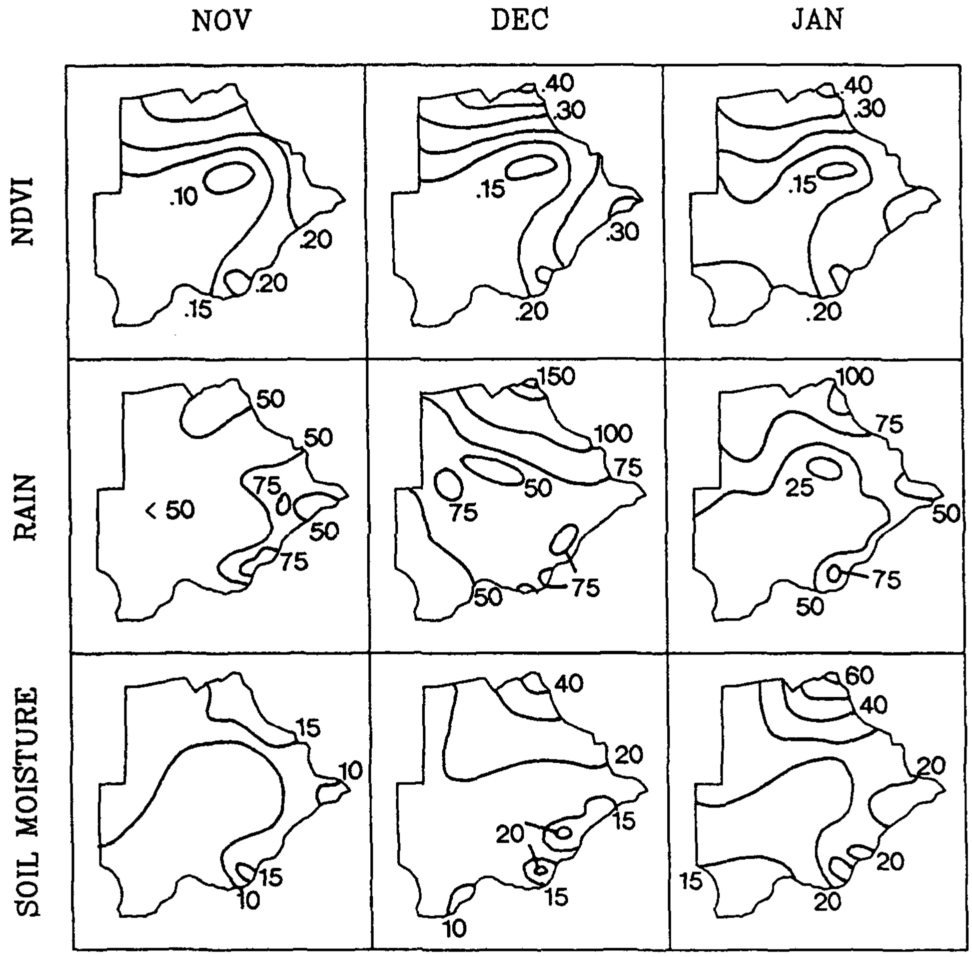


Figure 10: Monthly patterns of NDVI, rainfall(mm/mo) and soil moisture(mm/mo).



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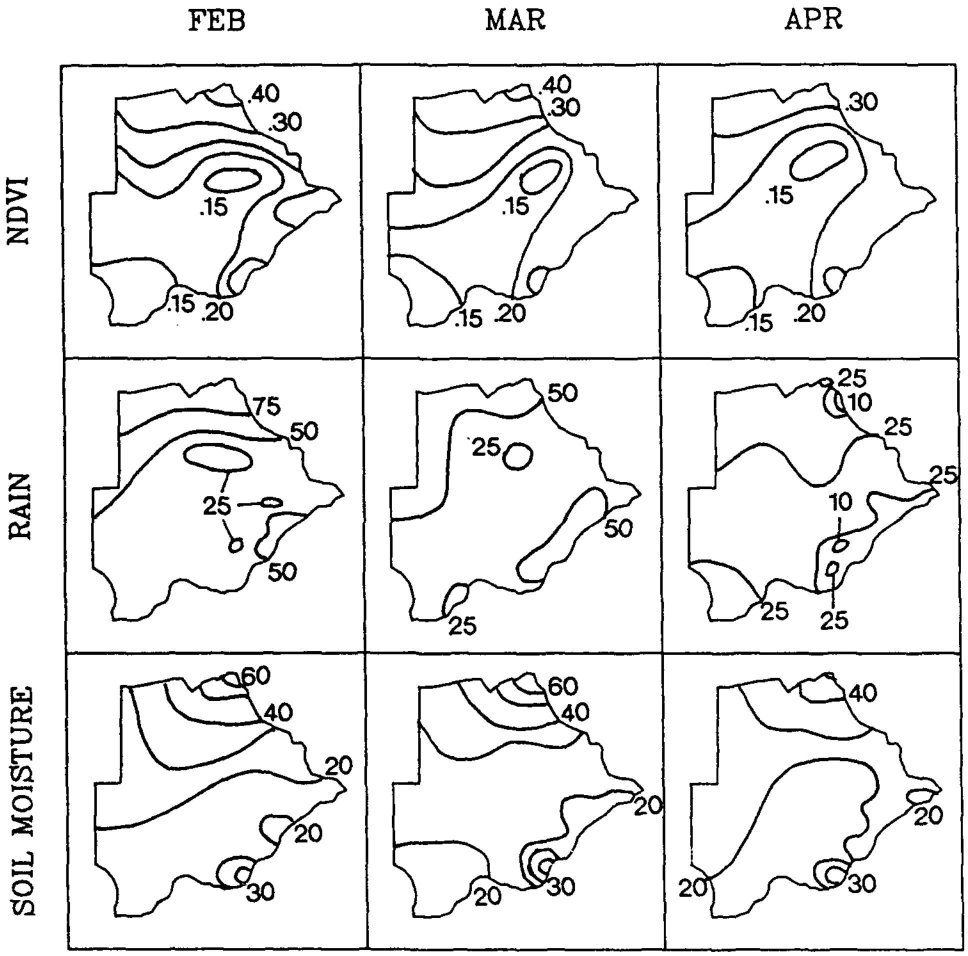

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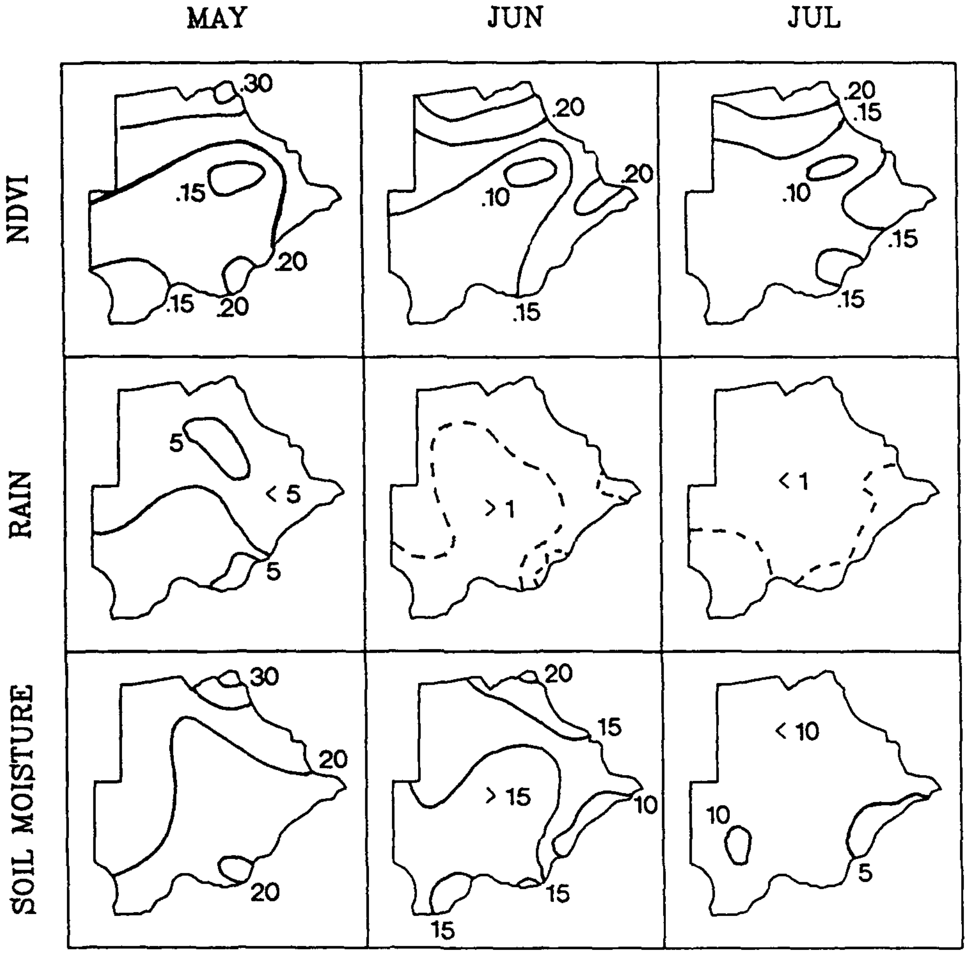

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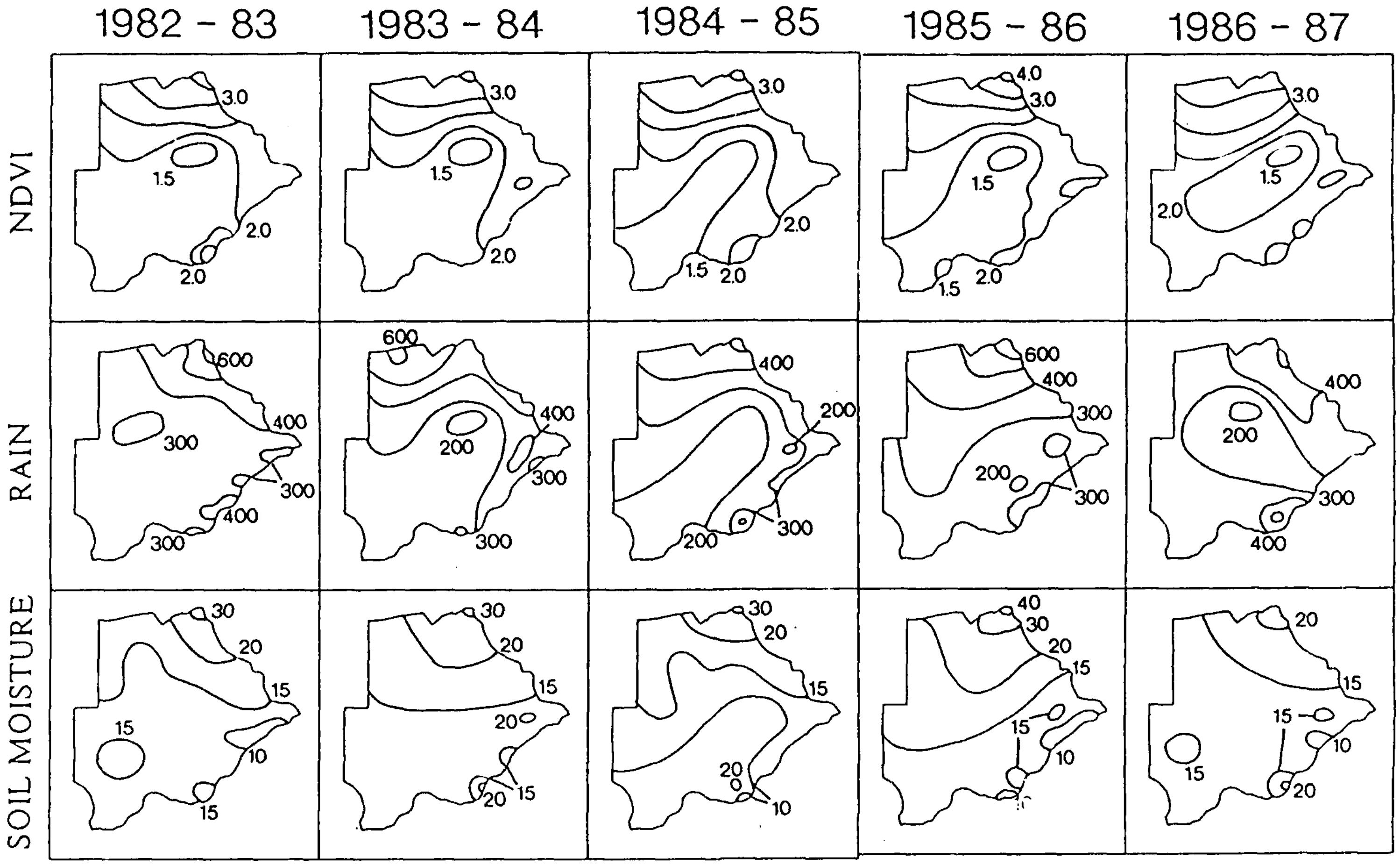

Figure 11: Annual spatial patterns of NDVI, rainfall (mm/yr), and mean monthly soil moisture (mm/mo) calculated October - September.

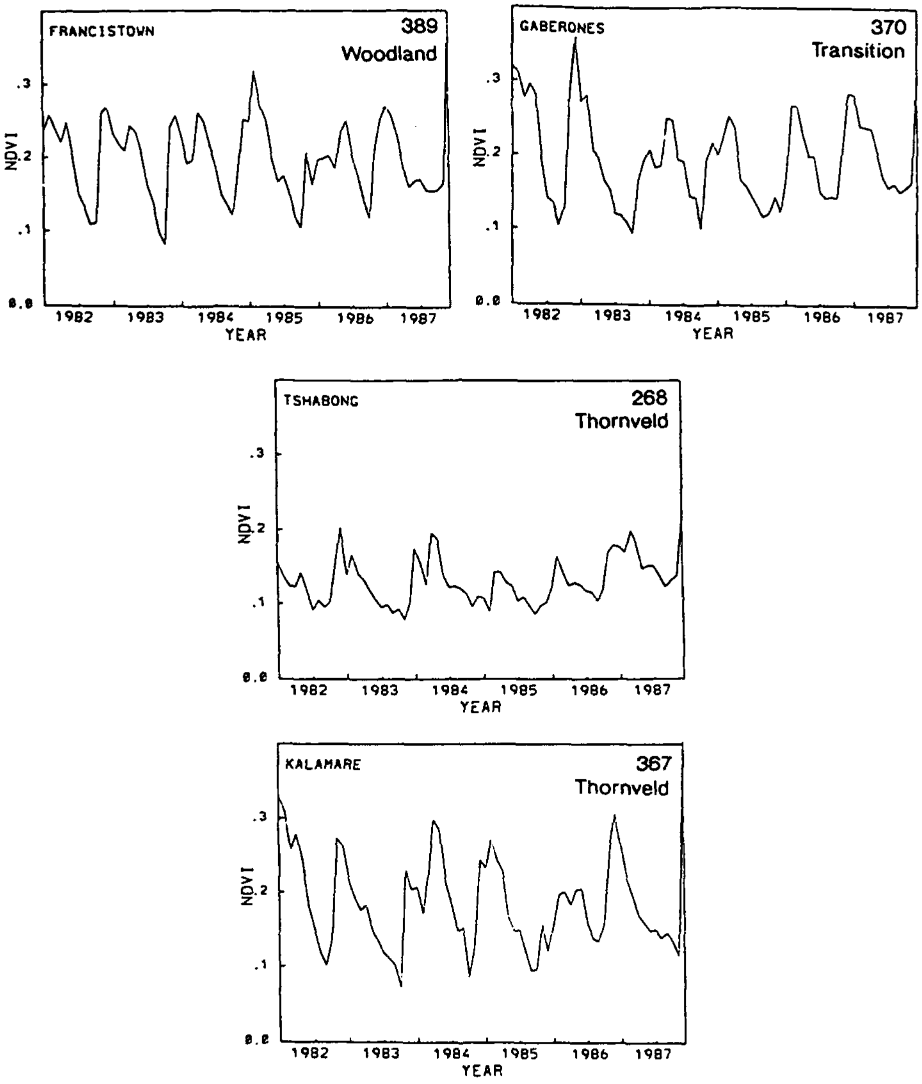

Figure 12: Time series plots of NDVI for select stations. 6-yr mean rainfall given in top right corner (mm/yr).

values of NDVI (on the order of less than 0.1 in most dry years), the seasonal amplitude is larger at Kalamare. This may be due in part to higher rainfall totals, but also may be the result of moisture entering the region via runoff from nearby highlands.

4.2 A Comparison of Mean Patterns of NDVI, Rainfall, and Soil Moisture

The spatial patterns of monthly and yearly rain and soil moisture are also shown in Figures 10 and 11. Monthly patterns of the variables will be examined first. Though it may be seen that the rains begin in the region during October and November, the NDVI values do not show a response until about one month later, with the largest increases occurring two months after the advent of the rains. On the other hand, a comparison of NDVI values with those of calculated exchangeable soil moisture indicate a closer relationship, with the largest increases in NDVI occurring almost immediately after the soil moisture values show an increase. Note that soil moisture increases seem to lag the start of the wet season by about 1-2 months, depending upon the location within the country. The rapidity at which soil moisture shows a response to rainfall is a function of soil type. Those regions that have soils that are largely sand based will show a more rapid response in soil moisture to rainfall due to the fact that immediate runoff is low for such soil compositions, while soils that are composed of more clay will take longer to show a soil moisture response to rainfall due to higher runoff values. Indeed, the areas where *arenosols* predominate (for the most part in the southwest and central parts of the country) show quicker responses to the beginning of the rains than do the clays. However, note also that these regions have overall lower soil moisture values than do the other soil types, due to the fact the soils with higher clay content have longer moisture retention times. Soil moisture values in the northeastern parts of Botswana reach peak values of greater than 50 mm/mo, while those in the southwest never exceed 20 mm/mo.

The cessation of the rains begins during the months of April and May. Again, the NDVI values appear to lag the rainfall variations by 1-2 months, while lagging the soil moisture decreases by no more than 1 month. The lowest rainfall amounts occur in July-August, the lowest soil moisture values during August-September, and the minimum NDVI values are obtained during September-October. Overall, these patterns seem to indicate a better relationship between NDVI and soil moisture than between NDVI and rainfall.

Annual diagrams of the three variables show good correspondence as well (Figure 11). On an annual basis, rainfall and soil moisture patterns are somewhat similar; however, this is not a surprise, since monthly rainfall is the forcing function for the model calculations of soil moisture. Because the 6 years examined were drier than normal, one expects the soil moisture to imitate the rainfall patterns. If, on the other hand, the years were relatively wet, some excess rainfall would go into runoff, and less correspondence would be evident in the soil moisture patterns.

All three quantities show maxima in the southeast and north for each period studied. In the southeastern areas, two persistent maxima in soil moisture correspond to areas of *luvisol*and *cambisol* type soils, which have a relatively high clay content, and therefore, a greater ability to retain the moisture. In between these two maxima lies a region of *arenosols*, which as previously mentioned, cannot retain water as long and which results in a minimum in soil moisture.

Good response of the NDVI to rainfall is evident annually. The patterns of the two sets of variables correspond well. For example, a relatively large area of rainfall 300-400 mm in 1985-86 is both represented as an increase in soil moisture and NDVI values. In addition, a relatively dry period in 1984-85 corresponds to lower NDVI values throughout the country. The poorest agreement in patterns is found for the driest period - 1986-87.

One quite fascinating feature is noted. Nicholson *et al.* (1990) found that in the Sahel, an annual integrated NDVI value of 2.0 roughly corresponded to a mean annual rainfall of 600 mm, while in East Africa, the same NDVI isopleth agreed more closely with rainfall of less than 500 mm/yr. A mean annual rainfall of 1000 mm/yr corresponded in East Africa to an annual integrated NDVI value of about 4.0 In Botswana, however, the NDVI 2.0 isopleth roughly follows the 300 mm/yr isohyet, while annual values of NDVI of 4.0 are found in regions of only 600-700 mm/yr rainfall. Thus, these differences will be explored more deeply in a later section.

4.3 Relationships Between NDVI, Rainfall, and Soil Moisture By Vegetation Type

The temporal relationships between NDVI, rainfall, and soil moisture will be examined first by vegetation zone, then by soil type to determine to what extent soil and vegetation differences affect the relationships. Figures 13-15 show the time series plots.

As similarly found by Nicholson *et al.* (1990), the NDVI cycle appears to lag that of rainfall by 1-2 months. However, while NDVI was generally found to be insensitive to rainfall fluctuations above 1000 mm/yr or 200 mm/mo in West and East Africa, only isolated evidence was found in this study to support this. This is primarily due to the fact that rainfall in Botswana seldom exceeds 200 mm/mo, and is never greater than 1000 mm/yr. The only indication that the same relationship holds in Botswana may be found in the time series for Malalapye. Note that the station received about 250 mm/mo during one month in 1984. Maximum NDVI values for Mahalapye still remained at about 0.3, the same as in years with lesser rainfall totals.

Examining the NDVI/rainfall and NDVI/soil moisture relationships by vegetation type yields many interesting results. The largest NDVI values are found in the *colosphermum mopane* woodland and scrub woodland, ranging for the most part from 0.3-0.4. Seldom do the NDVI values exceed 0.4 during the wet season, even with relatively high rainfall amounts. The highest NDVI values within this plant zone correspond to the stations with the highest rainfall amounts, a result also found by Nicholson *et al.* (1990). For example, maximum NDVI values run from 0.2-0.3 at Francistown (with a 6-year mean annual rainfall of 389 mm), while at Shakawe (6-year mean annual rainfall of 431 mm) the maximum NDVI values lie between 0.3 and 0.4. Minimum values of NDVI are just greater than 0.1 in the dry months, but never below about 0.08. Again, some indication of evergreen activity is present (Townshend and Justice, 1986). The number of months with low NDVI values is approximately the same from station to station, while the larger seasonal amplitudes seem to correspond to greater mean annual rainfall.

As noted in Nicholson *et al.* (1990), woodland stations show less erratic month-to-month variations than other vegetation types, with pronounced periods of NDVI values less than 0.2. Overall, the same result is obtained for the *colosphermum mopane* woodland in this study. For example, as may be seen in Figure 13, the annual integrated values (as evidenced by the areas under the NDVI curves) show little interannual fluctuations, despite interannual variations in rainfall. In addition, the time series plot for Shakawe shows that NDVI peaks at about 0.4 for 1986-87 (similar to other years), even though rainfall for that season peaked at roughly 75-100 mm/mo less than other years.

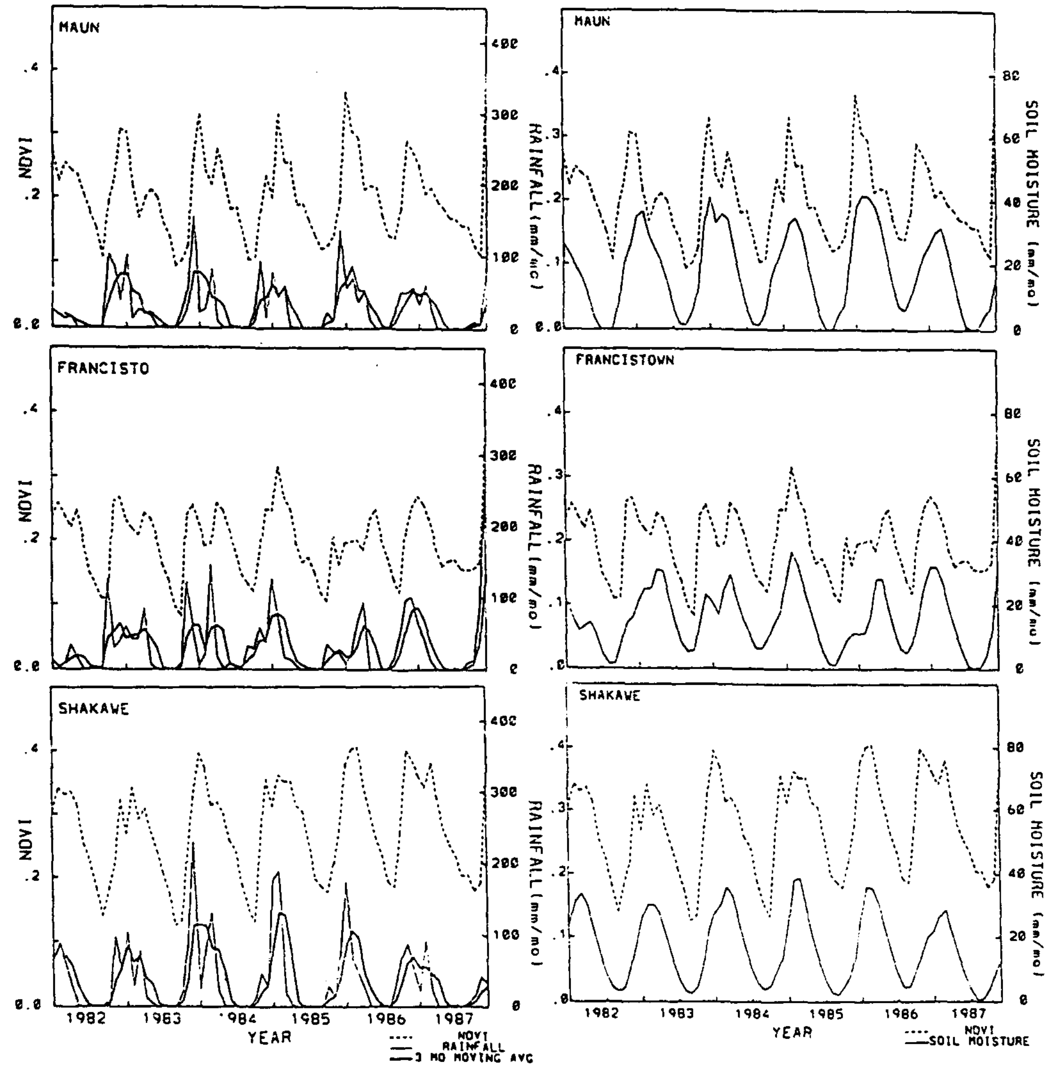

Figure 13: Time series of NDVI/rainfall and NDVI/soil moisture for select stations within the *Mopane* woodland .

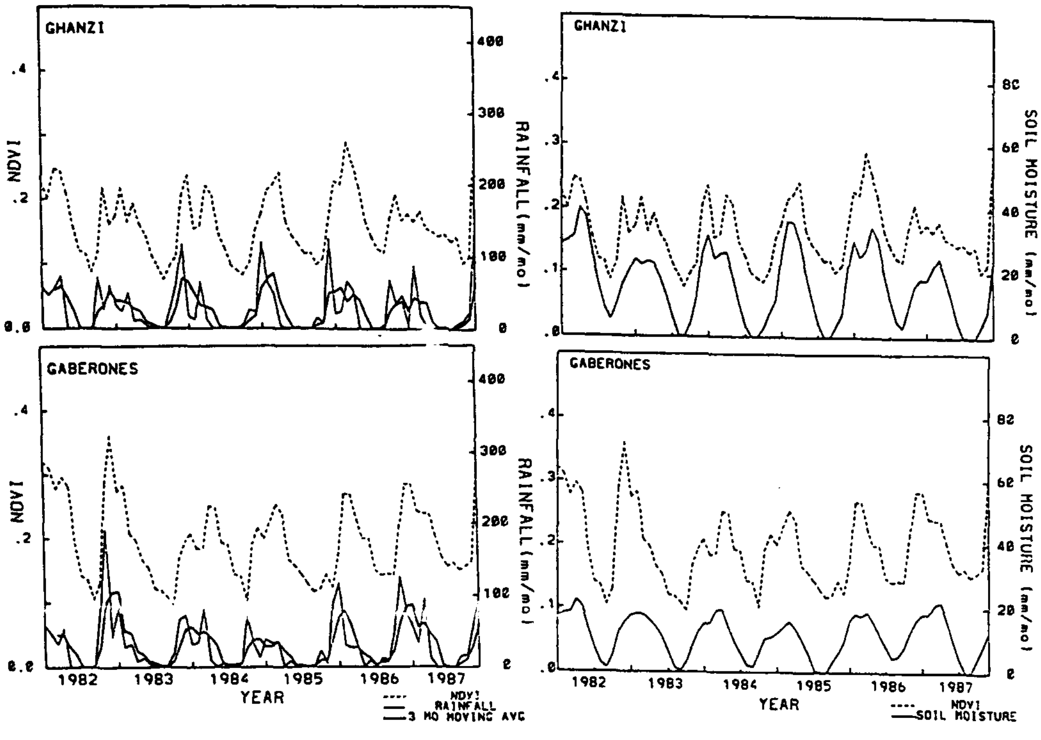

Figure 14: Time series of NDVI/rainfall and NDVI/soil moisture for select stations within the Transition zone.

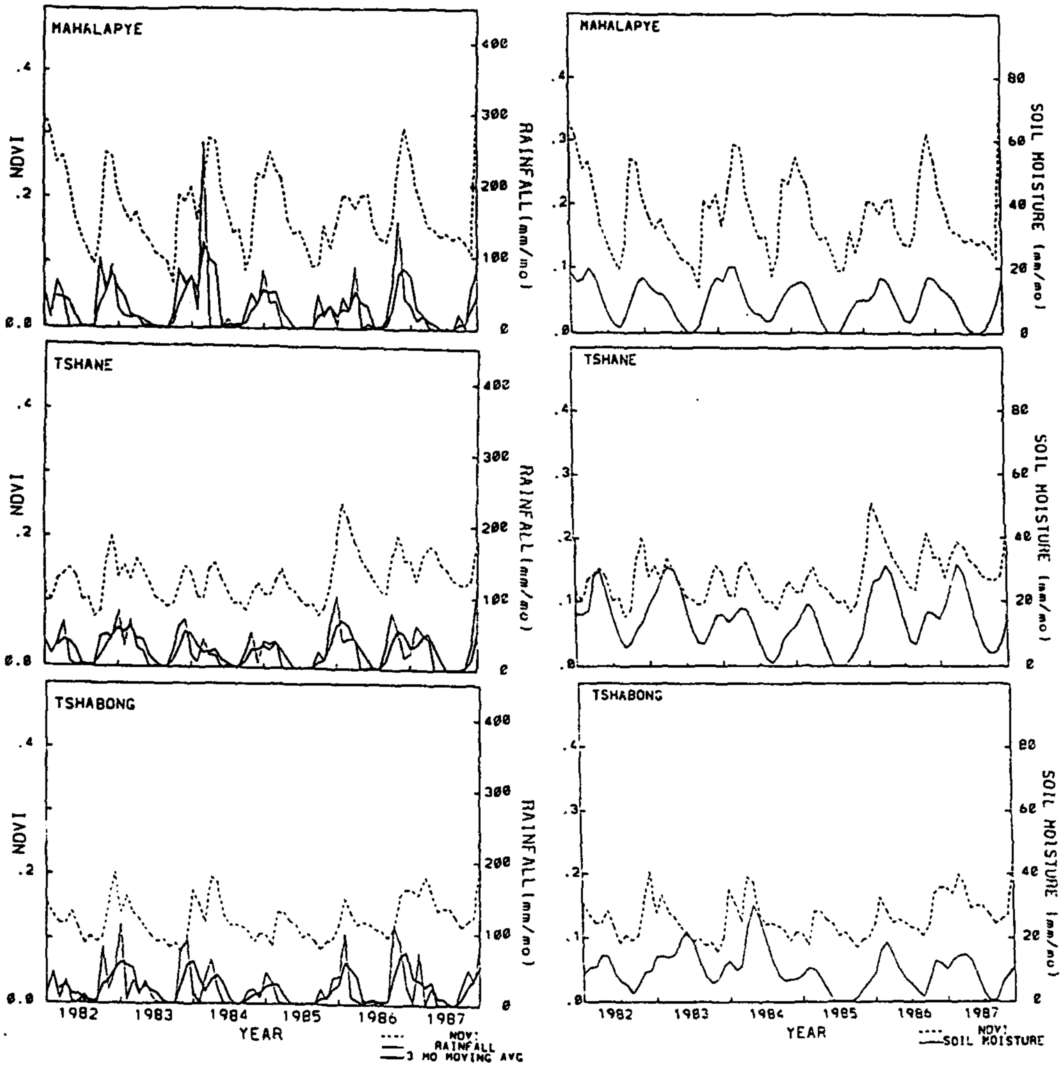

Figure 15: Time Series of NDVI/Rainfall and NDVI/Soil Moisture for Select Stations within the Kalahari thornveld.

However, some response to rainfall variability is still evident, especially in the drier regions. For example, the data at Maun shows that a peak in rainfall of 150 mm/mo in the 1983-84 season and a similar peak of 140 mm/mo in 1985-86 resulted in different NDVI values (up from 0.32 in 1983-84 to almost 0.4 in 1985-86). The NDVI curve seems most closely associated with the 3-month moving average of rainfall (the average of current plus previous two months). A similar effect occurs at Francistown. Despite a lower maximum peak in rainfall during 1984-85 summer (125 mm/mo as compared to nearly 150 mm/mo the previous summer), the NDVI maximum is actually higher during 1984-85. This is probably because a longer period of rainfall preceded the peak that year as compared to a sharper peak in other years. Less of the rain went into immediate runoff, the ground was better able to absorb the rainfall, and consequently more moisture was available for use by the plants. An examination of the NDVI and soil moisture time series for Francistown does show that soil moisture peaked higher during the 1984-85 season than in other years. However, the same effect is not evident in the soil moisture curve at Maun. This may be related to differences in soil types, a topic to be dealt with in the next section.

The NDVI curves in this particular vegetation type, Figure 13, have sharper peaks than do those of the other types under study. This in an indication that the *colosphermum mopane* woodland more rapidly converts available moisture to green phytomass, but decays more rapidly once moisture availability drops. Overall, the vegetation appears to respond best to variations in soil moisture rather than to those of rainfall, and the response seems almost immediate. It should be noted, however, that the timing of the vegetation response to soil moisture variations may be affected at Maun and Shakawe by the presence of exogeneous water from the Okavango River and Delta. NDVI values are probably larger than the calculated soil moisture would indicate (recall that the model does not account for outside sources of water.) In particular, sources of soil moisture other than rainfall likely account for NDVI peaks occuring prior to the calculated soil moisture peak values in several years, especially those that are relatively dry. In wetter years, the NDVI curve better reflects that of soil moisture.

Smaller seasonal amplitudes in the NDVI curves are noted in the transition zone broad-leaved vegetation (Figure 14), despite rainfall totals that are similar to those for the *mopane* woodland. However, overall NDVI values are smaller in the transition zone. This is likely indicative of the less dense tree coverage and the greater predominance of grasses in this vegetation zone. Interannually, the NDVI shows more variance in the transition zone than in the *mopane* woodland. It appears to respond more to rainfall fluctuations than those of soil moisture on a year-to-year basis. For example, soil moisture seems to have a maximum possible value at Gaberones, while the NDVI curve varies quite a bit interannually. The fact that soil moisture does not respond to greater rainfall totals is probably due to soil composition. In any case, a sharp peak in NDVI in 1982-83 corresponds to a greater rainfall amount that year, rather than a soil moisture variation. In addition, double and triple peaks in NDVI generally correspond to similar patterns in the rainfall plot. Finally, annual integrals in the NDVI data also show a distinct response to interannual rainfall fluctuations. These trends may be the result of the transition zone type vegetation having a greater potential for growth, given an adequate amount of rainfall. Note again that the 6 years under study were drier than normal. The plants probably retain the potential for growth even under dry conditions. Overall, however, the NDVI curves seem to show no lag behind those of soil moisture, but appear to lag rainfall variations by 1-2 months.

In the last vegetation type, the *acacia* dominated Kalahari thornveld, the lowest NDVI values in the country are found. Time series for this vegetation zone are shown in Figure 15. Maximum values are no more than 0.3, and for Tshabong and Tshane (the driest two stations shown), seldom exceed 0.2. It appears that these low NDVI values are the result of lower annual rainfall totals. Tshabong experienced a mean annual rainfall of only 268 mm/yr for the 6 years studied, while Tshane received only an average of 294 mm/yr. Mahalapye, on the other hand, averaged 334 mm/yr for the same time period. Smaller seasonal amplitudes at Tshabong and Tshane are likely the result of less total rainfall. Differences in vegetation type are seen to influence the NDVI/rainfall relationship if one considers Mahalapye and Shakawe. Even with similar peak monthly rainfall values of around 250 mm/mo, the NDVI values at Mahalapye never exceed 0.3, while those at Shakawe reach nearly 0.4. More sparse vegetation cover, more grasses, the presence of thorny *acacia* species as compared to broadleaved trees, and brighter soil backgrounds all act to reduce the indices in the Kalahari thornveld. However, even in the dry season, the NDVI values never drop below the 0.05 threshold of Townshend and Justice (1986).

Soil moisture values often approach 0 during the dry season, but not always. In 1985, low soil moisture values correspond to low rainfall that year. In addition, note that while the NDVI and soil moisture curves correspond well at Mahalapye, this is not the case at Tshabong and Tshane. At these stations, the vegetation seems to respond better and more rapidly to rainfall changes than those of soil moisture. This is the case even in dry years, indicating that when rainfall is below normal, the plants in the *acacia* thornveld retain the potential for growth. Good evidence of this is seen at Tshane. While the 6 years examined were drier than normal (268 mm/yr as compared to a long-term mean of 353 mm/yr), a larger peak of rain in the 1985-86 season resulted in an NDVI value of nearly 0.3, compared to other years with values of only 0.2. The plants have adapted to a location where soil moisture is low year-round, and utilize what is available most efficiently. To support this, Strahler and Strahler (1987) noted that in this particular vegetation type, the onset of rains results in the quick "greening" of the vegetation (Strahler and Strahler, 1987).

Likewise, peak soil moisture is often obtained after the NDVI curve starts to decline, which in turn is after the rains begin to decline. The plants have probably begun to adapt to the drier conditions associated with the cessation of rains, and begun their dormant period, using less of the soil moisture present than previously. Thus, small amounts of precipitation received during the late part of the rainy season are stored rather than being used by plants immediately. Overall, the *acacia* thornveld displays the best response to interannual rainfall fluctuations.

4.4 Correlations/Regression Analyses by Vegetation Type

In order to quantify the trends noted above, standard linear correlations for various time lags were performed on the monthly NDVI, rainfall, and soil moisture data by vegetation type. The correlations for NDVI versus rainfall for various time lags are given in Table 6. For the NDVI/rainfall relationships, the best correlations were found for the multi-month rainfall averages, with NDVI lagging rainfall by 1-2 months. The highest correlations were obtained for either rainfall averages of current plus previous 2 months (0+1+2) or for the previous two months (1+2). Correlations for NDVI versus soil moisture are given in Table 7. NDVI consistently correlated best with soil moisture in the same month.

The best correlations between NDVI and rainfall and NDVI and soil moisture were found in the transition zone vegetation. This is probably because a large variety of plants exist in the zone, all with varying abilities to adapt to changing moisture conditions. The lowest correlations are for the *acacia* thornveld, the driest location. The small amounts of rain received are quickly evaporated and not available for use by the plants. The fact that the lowest soil moisture amounts correspond to this vegetation type suggest that evaporation is anomalously high here. Overall, the lowest correlations were at Tshabong, the driest station. Possible explanations are the highly variable rainfall regime or the sparse vegetation cover, a condition which produces a soil background effect on the NDVI values. Another distinct possibility is that the rainfall record may be inaccurate.

The scatterplots of monthly NDVI versus rainfall and NDVI versus soil moisture data for the best correlations given in Tables 6 and 7 are shown in Figures 16-18. These depict the relationships at individual stations and for each vegetation zone collectively. These plots show that the relationship between NDVI and the three-month moving average of rainfall is approximately linear. For the Sahel and East Africa, Nicholson *et al.* (1990) found a similar relationship up to a rainfall intensity threshold of about 200 mm/mo. The log-linear relationship they found above the 200 mm/mo threshold cannot be confirmed with the Botswana data because rainfall there does not exceed 200 mm/mo in the years

Table 6: NDVI/rain lag correlations by vegetation type

Veg Type/Station Name	0	1	2	0+1	1+2	0+1+2
All Kalahari Thornveld	.368	.563	.501	.574	.667	**.680**
Mahalapye	.423	.660	.485	.630	.727	**.740**
Tshane	.423	.703	.541	.658	.736	**.750**
Tshabong	.191	.473	.500	.427	**.627**	.593
Palapye Road	.318	.499	.465	.536	.648	**.666**
Lobatse	.419	.662	.607	.624	**.751**	.737
Ramatlabama	.513	.720	.661	.726	.827	**.839**
All Transition Zone	.406	.710	.603	.674	**.807**	.791
Ghanzi	.459	.674	.482	.707	.723	**.781**
Gaberones	.355	.740	.623	.644	**.815**	.773
Dibete	.386	.666	.569	.624	**.767**	.743
Kanye	.403	.748	.680	.709	**.891**	.849
All *Mopane* Woodland	.406	.605	.521	.611	.683	**.705**
Francistown	.408	.669	.526	.633	.749	**.777**
Maun	.424	.689	.469	.696	.717	**.738**
Shakawe	.401	.679	.605	.642	**.762**	.758
Gweta	.406	.578	.457	.632	.659	**.728**
Baines Drift	.499	.703	.533	.712	.736	**.775**
Kasane	.474	.671	.622	.698	.787	**.809**

studied.

A large amount of scatter is evident for all vegetation types, especially when all stations within a given plant zone are considered. The scatter of the data is greatest for the NDVI/soil moisture plots. This probably occurs because greater errors are associated with the calculation of soil moisture data than are associated with observed rainfall. Some of the scatter is also probably associated with differing plant physiologies and their widely varying responses to available soil moisture. For instance, some species of plants, especially trees, have root systems that extend beyond 1 meter in depth (the limit of calculation of

Table 7: NDVI/soil moisture lag correlations by vegetation type

Veg Type/Station Name	0	1	2	0+1	1+2	0+1+2
All Kalahari Thornveld	**.618**	.497	.269	.577	.394	.500
Mahalapye	**.806**	.642	.313	.754	.488	.645
Tshane	**.643**	.446	.117	.568	.296	.449
Tshabong	**.417**	.262	-.004	.356	.135	.251
Palapye Road	**.646**	.528	.276	.617	.420	.539
Lobatse	**.825**	.676	.374	.780	.540	.686
Ramatlabama	**.735**	.547	.216	.662	.389	.536
All Transition Zone	**.755**	.613	.309	.713	.479	.616
Ghanzi	**.836**	.645	.347	.772	.514	.671
Gaberones	**.795**	.650	.294	.751	.487	.636
Dibete	**.778**	.636	.289	.741	.480	.633
Kanye	**.863**	.693	.314	.815	.525	.693
All *Mopane* Woodland	**.735**	.633	.420	.709	.544	.648
Francistown	**.794**	.613	.248	.742	.448	.625
Maun	**.752**	.572	.270	.686	.436	.581
Shakawe	**.832**	.683	.350	.786	.535	.682
Gweta	**.743**	.598	.340	.708	.488	.627
Baines Drift	**.660**	.446	.084	.578	.275	.438
Kasane	**.865**	.743	.459	.837	.624	.762

the *evapoclimatonomy* model). So, even if the calculated soil moisture is below their wilting point, these plants thrive on water deeper than 1 meter.

Finally, Figure 19 shows a plot of the 6-year annual averages of NDVI versus rain for all stations. A correlation coefficient of 0.84 was obtained for the data, higher than that found by Nicholson *et al* (1990) for East Africa (r = 0.73), but lower than that found for the Sahel (r = 0.96). Thus, when considering the long-term NDVI/rainfall relationship, less variation is discovered in the Kalahari than East Africa, but greater variability exists than in the Sahel.

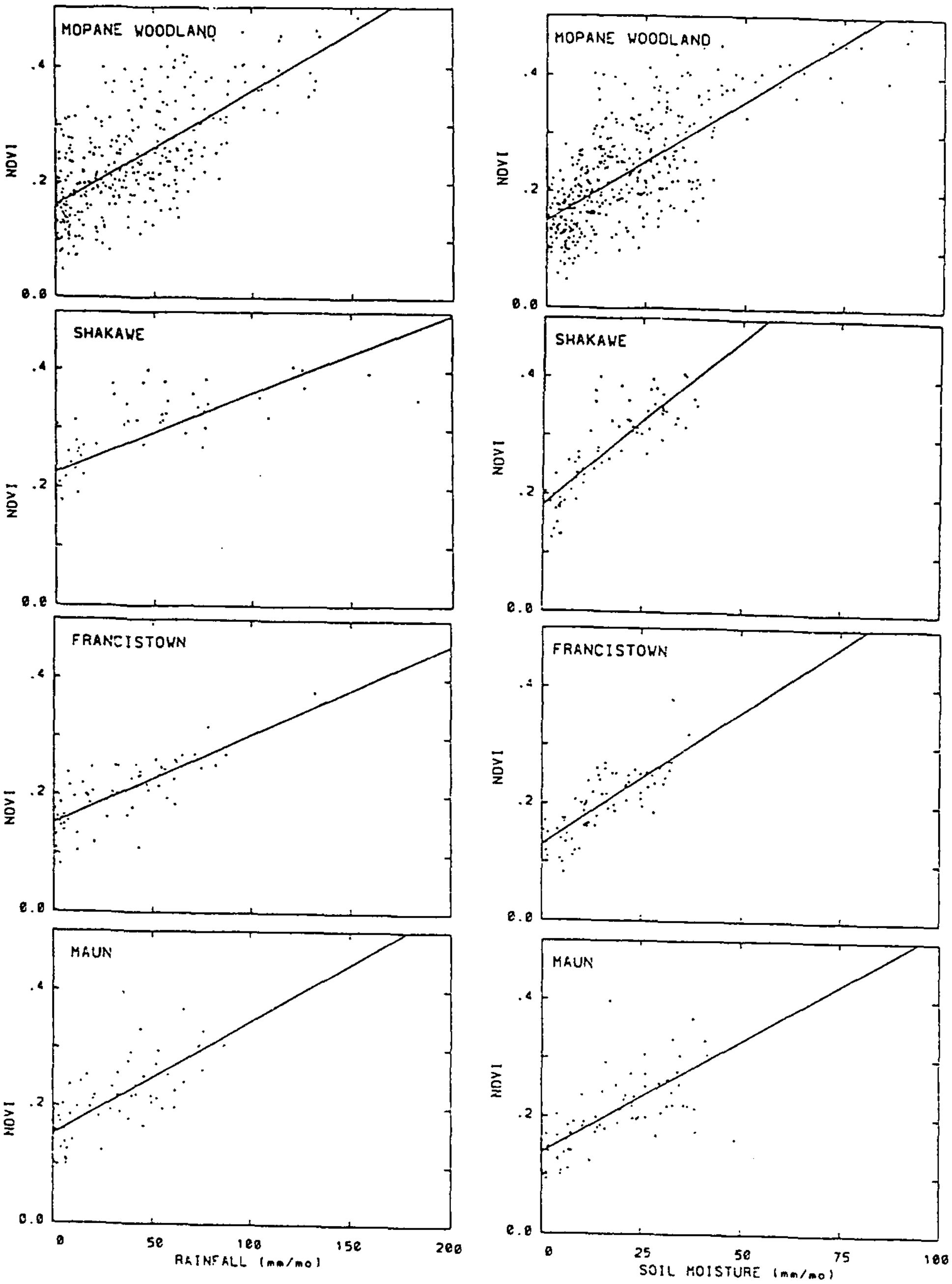

Figure 16: Scatterplots for NDVI/rainfall and NDVI/soil moisture monthly data for the *Mopane* woodland.

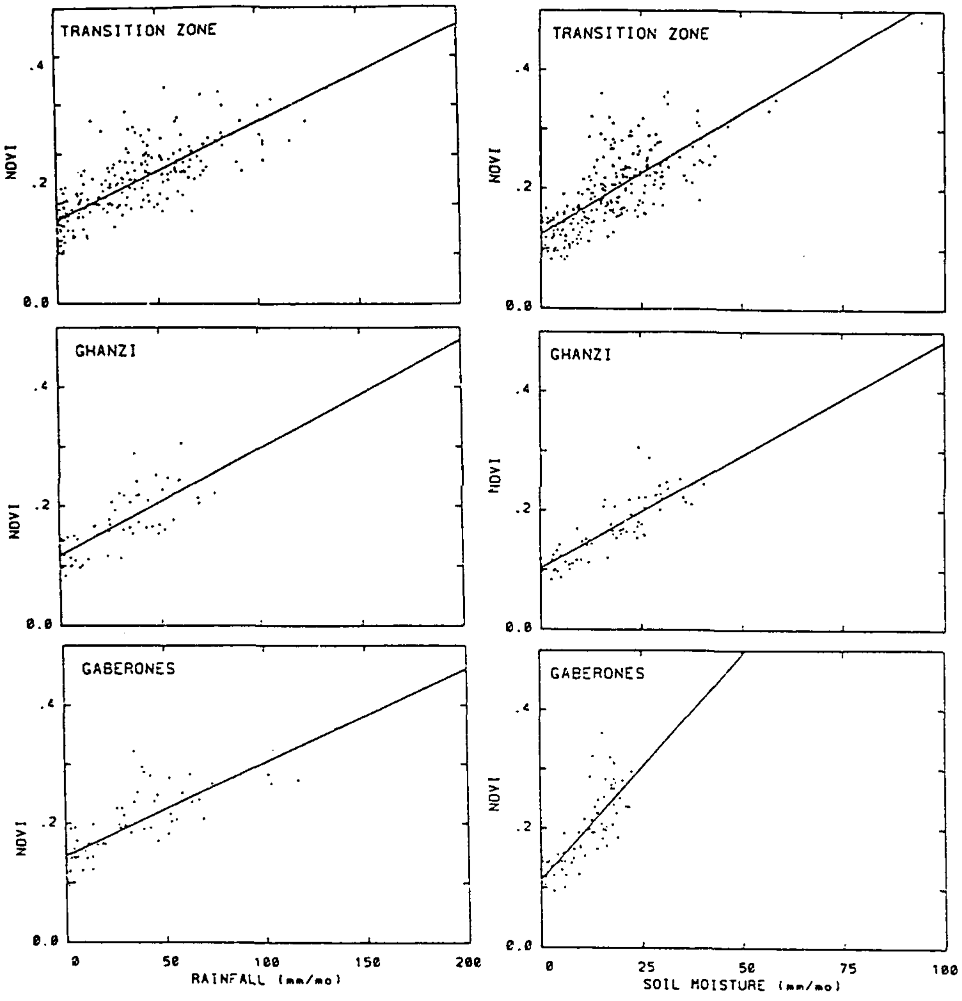

Figure 17: Scatterplots for NDVI/rainfall and NDVI/soil moisture monthly data for the Transition zone.

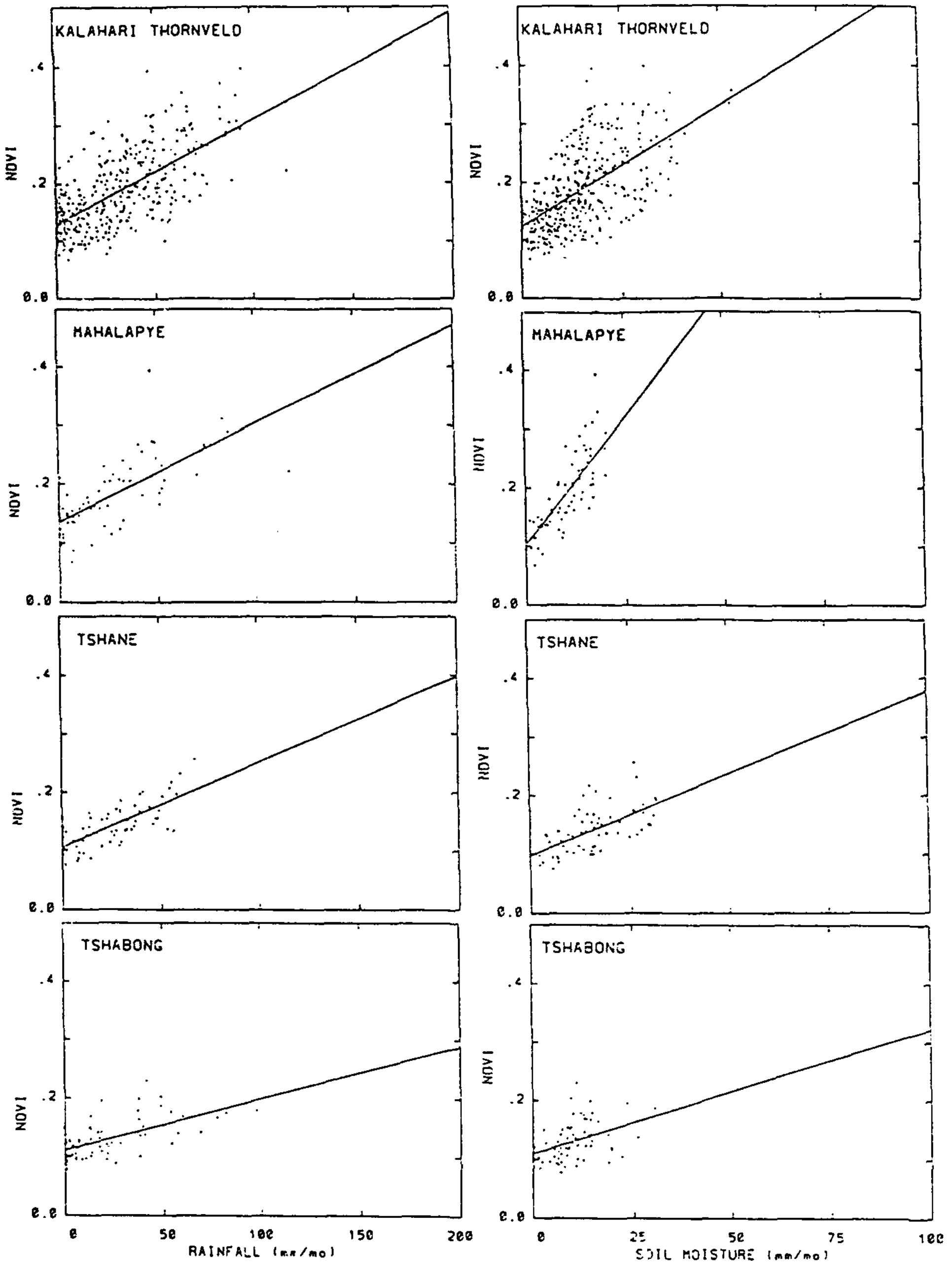

Figure 18: Scatterplots for NDVI/rainfall and NDVI/soil moisture monthly data for the Kalahari thornveld.

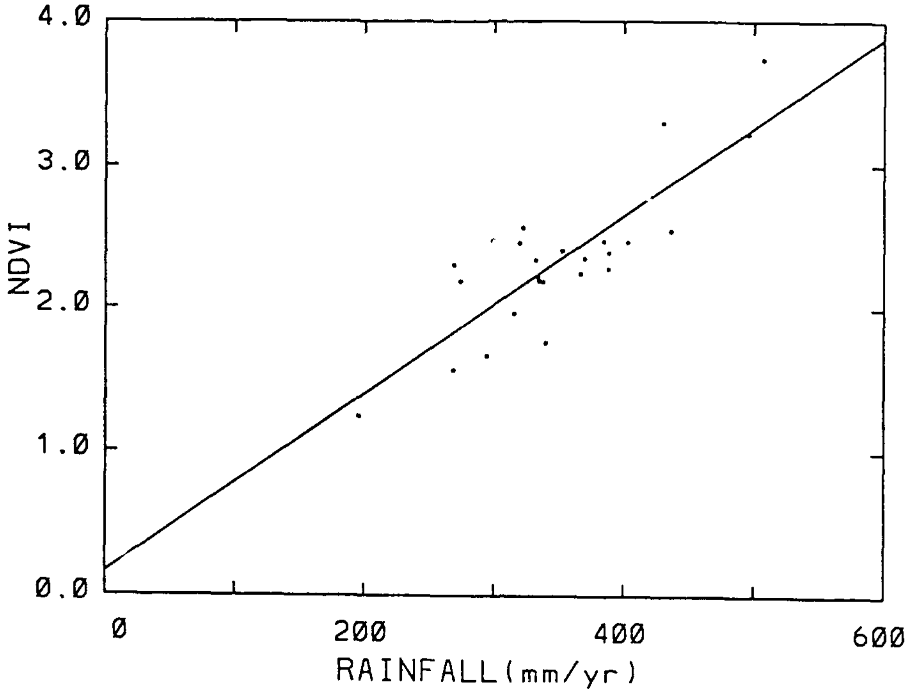

Figure 19: Six-year annual averages of NDVI versus rainfall for all stations.

4.5 Effects of Varying Soil Type on the NDVI/Rainfall and NDVI/Soil Moisture Relationships

As stated previously, the two primary goals of this study are to determine whether differences in "rain-use-efficiency" (LeHouérou, 1984; Nicholson *et al.*, 1990) are due to differences in the rate of soil moisture generation per unit rainfall, and to what degree soil type affects the efficiency of plant growth. In order to specifically answer these questions, the monthly data for NDVI, rainfall, and soil moisture were stratified according to soil type, as well as specific plant zones on each soil type. Analyses similar to those of the last section were performed on the data, as well as some additional ones.

Figures 20 - 23 show the time series of NDVI, rainfall and soil moisture for select stations within each soil type. Relationships between the three variables show some interesting differences when the various soils are examined. The time series show that soil moisture is most highly variable interannually on the *arenosol* soils. In addition, despite widely varying interannual rainfall totals, stations located on the *luvisols* have a fairly constant interannual cycle in their soil moisture. Much of the excess rainfall received in wet years for the *luvisols* likely goes into runoff, rather than being stored in the soil, because of their high clay content. It is also evident that certain stations have a greater generation of soil moisture per unit rainfall. Table 8 shows the ratios of mean monthly soil moisture to mean monthly rainfall. Kasane, located within a *vertisol* region, has the highest ratio of generated soil moisture per unit rainfall. The three of the *luvisols* stations, Gaberones, Ramatlabama and Mahalapye, have the lowest ratios; in fact they are lower than the *vertisols* by a factor of two.

Differences in the NDVI and rainfall relationship among soil types are evident as well, though in many instances the differences are slight. As noted in the previous section, all stations show a multi-month lag between rainfall and NDVI. The best correspondence between peaks of rainfall and those of NDVI occur for the stations located on the *arenosols*. Double and triple peaks correspond quite well in the rain and NDVI curves. The is due to the fact that high sand content results in rapid infiltration of the rainfall into the soil, where it can immediately be used by the plants. Correspondence between peaks is evident on the *luvisols*, where a direct relationship between the amount of rainfall and greenness values may be also seen. The *fluvisols* do not exhibit such a good relationship, probably

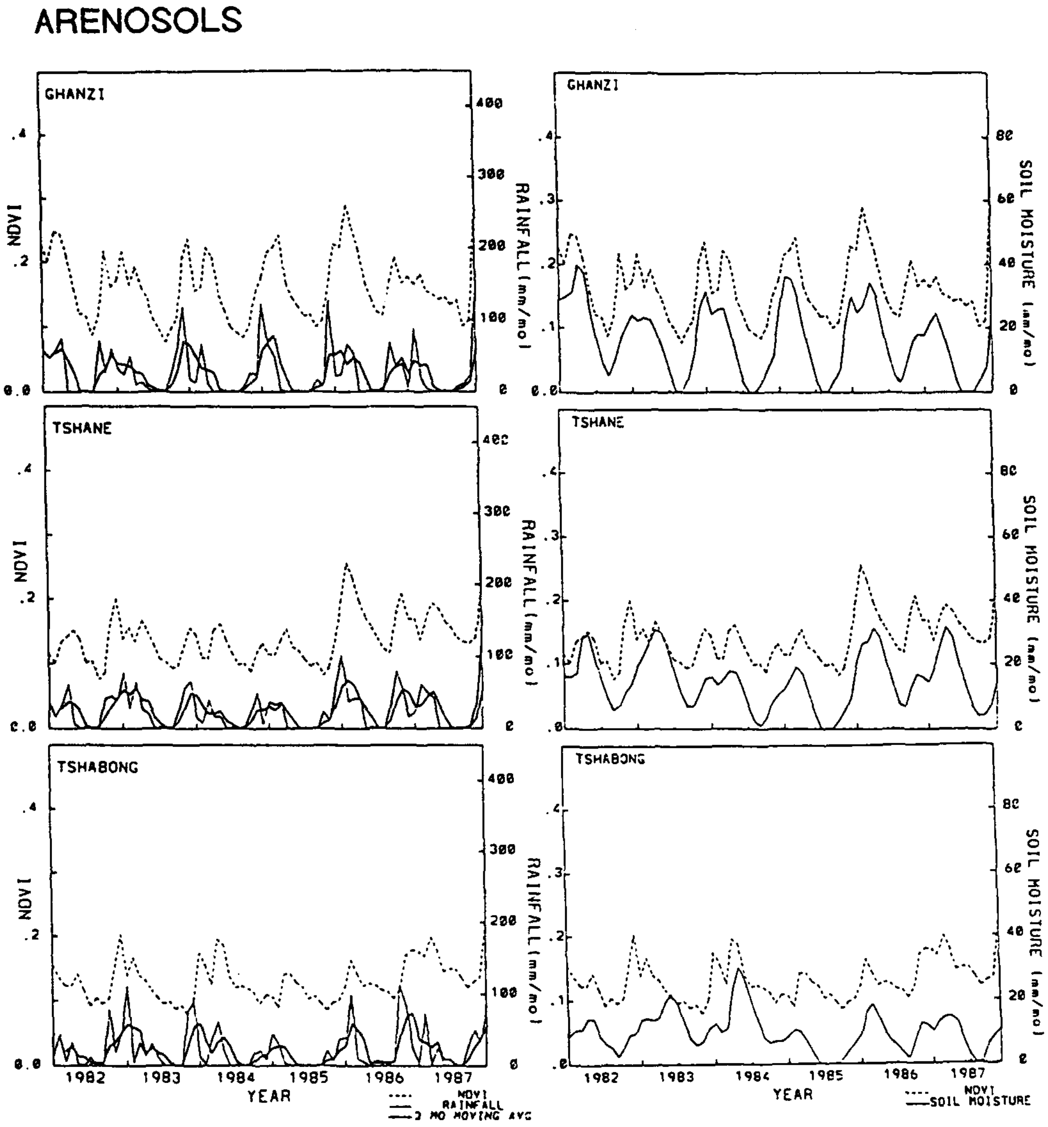

Figure 20: Time series of NDVI/rainfall and NDVI/soil moisture for *arenosols*.

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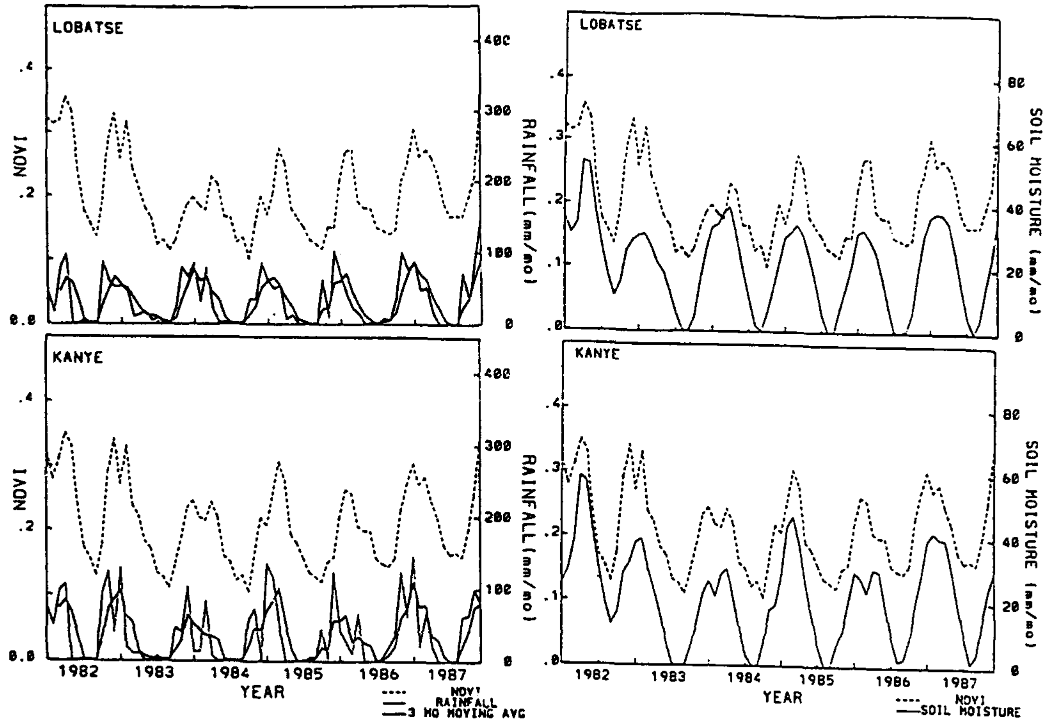

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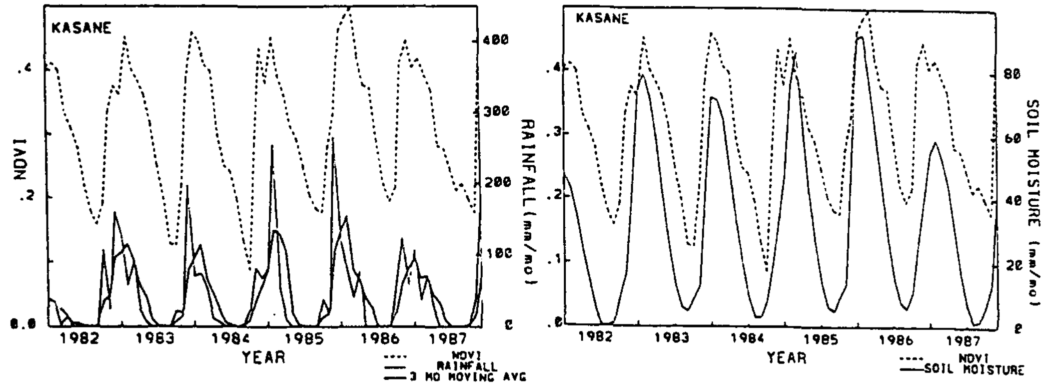


Figure 21: Time series of NDVI/rainfall and NDVI/soil moisture for *cambisols* and *vertisols*.

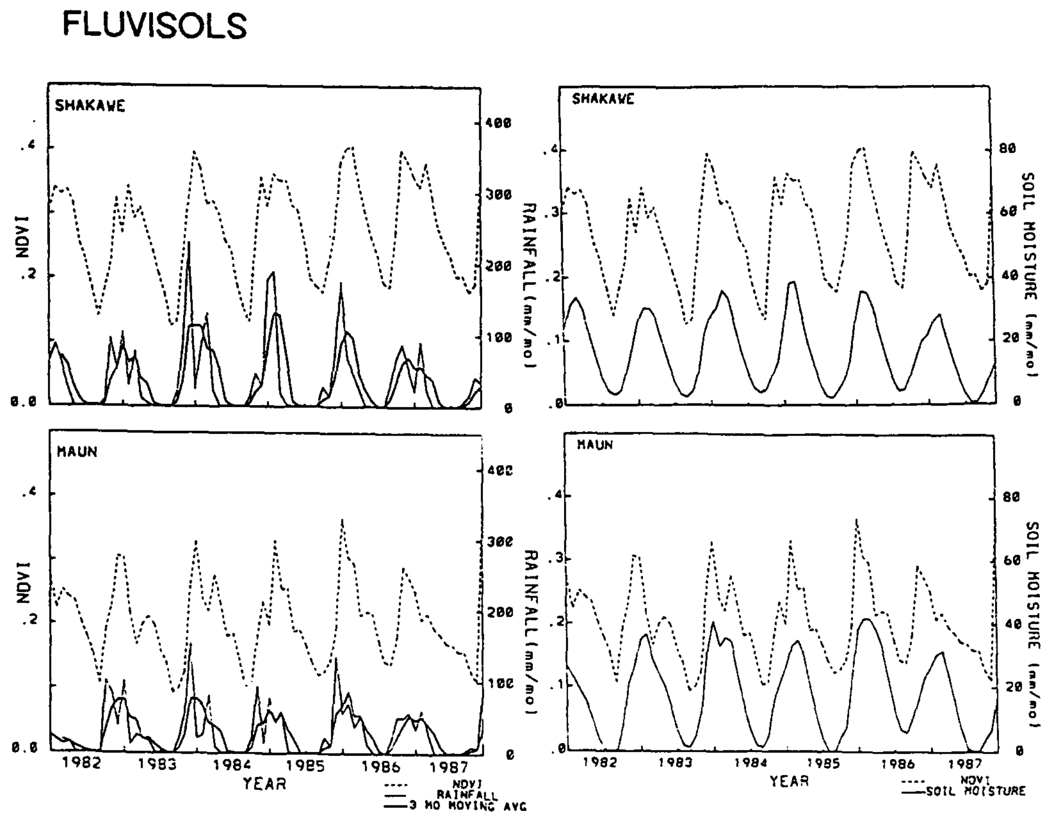


Figure 22: Time series of NDVI/rainfall and NDVI/soil moisture for *fluvisols*.

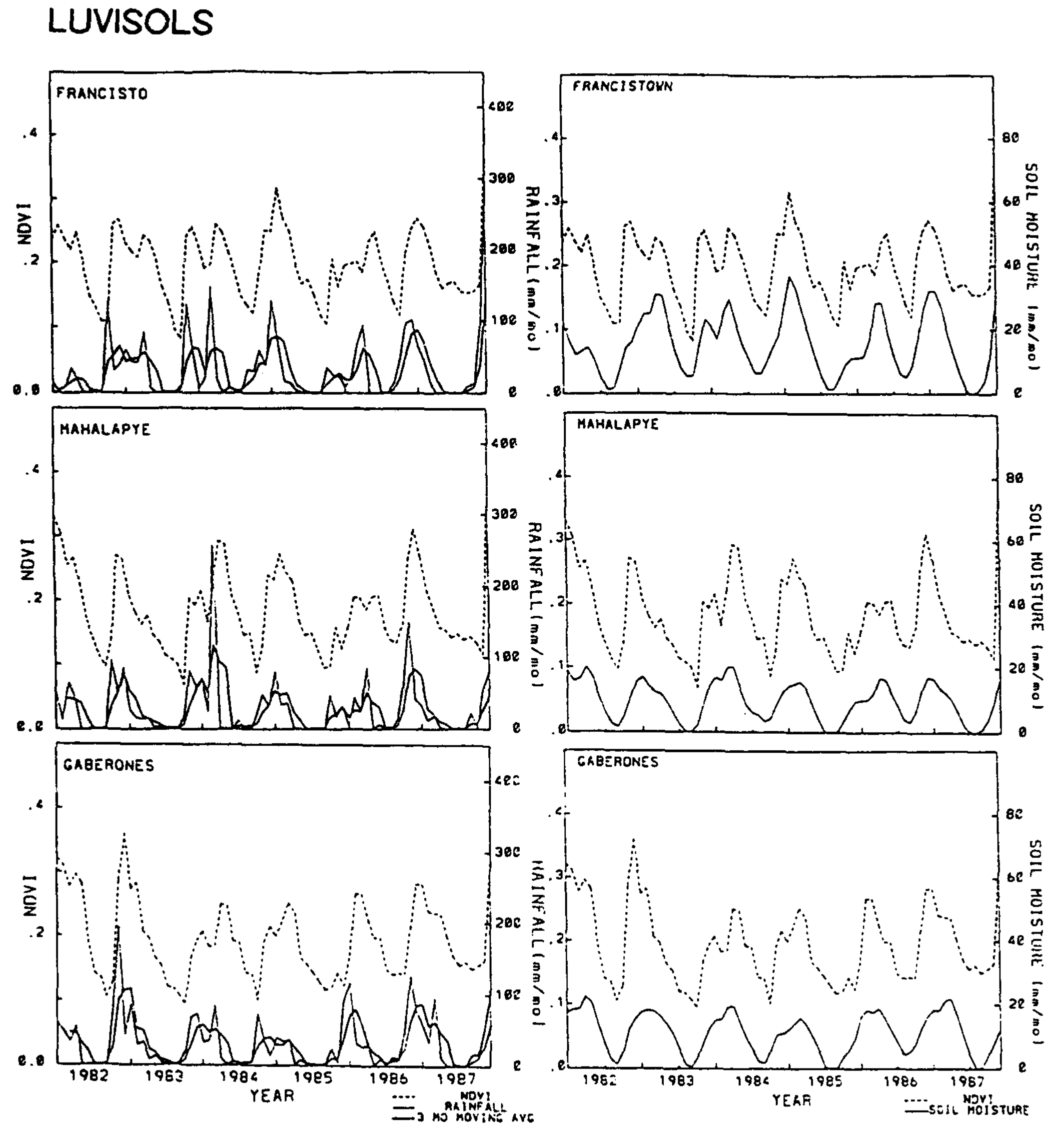


Figure 23: Time series of NDVI/rainfall and NDVI/soil moisture for *luvisols*.

Table 8: Ratios of mean monthly soil moisture to mean monthly rainfall.

Station	Soil Type	ratio
Tshabong	*arenosol*	0.44
Tshane	*arenosol*	0.60
Ghanzi	*arenosol*	0.61
Palapye Road	*arenosol*	0.52
Dibete	*arenosol*	0.52
Gweta	*arenosol*	0.60
Gaberones	*luvisol*	0.35
Mahalapye	*luvisol*	0.34
Ramatlabama	*luvisol*	0.38
Francistown	*luvisol*	0.47
Baines Drift	*luvisol*	0.43
Shakawe	*fluvisol*	0.46
Maun	*fluvisol*	0.65
Kanye	*cambisol*	0.58
Lobatse	*cambisol*	0.61
Kasane	*vertisol*	0.76

due to underlying water tables supplying the plants with moisture and increasing the NDVI values. Overall, the *cambisols* appear to show the greatest variability of NDVI values for the smallest variations in rainfall.

Another interesting feature can be noted in the NDVI and rainfall relationships on the *cambisols*. Note the great similarity between the NDVI curves at Lobatse and Kanye, despite differences in rainfall and vegetation types (Kanye is located in the Transition zone and Lobatse in the Kalahari thornveld). Carlsson *et al.* (1988) established "with some certainty" the existence of active ground water recharge in this region. The similarity in NDVI values with different rainfall amounts supports this theory. Scatter plots of NDVI versus NDVI and rainfall versus rainfall for these two stations are given in Figure 24. When monthly rainfall for the two stations are correlated, a coefficient of $r = 0.76$ results, while correlation of NDVI values gives a coefficient of $r = 0.97$. There is definitely an outside factor influencing the vegetation growth in this region.

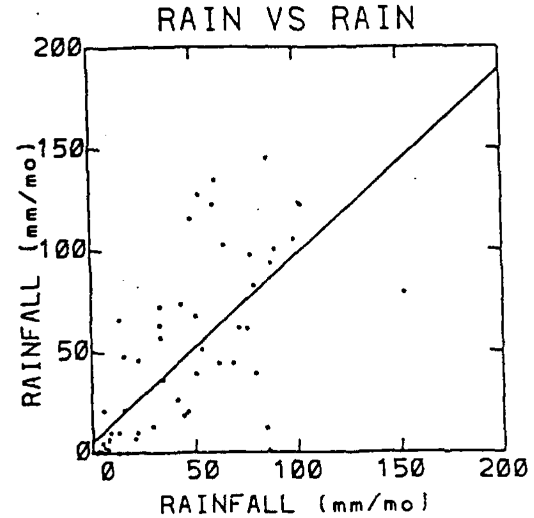


Figure 24: Scatter diagrams of monthly NDVI and rain for Lobatse and Kanye.

In order to quantify the trends noted above, linear regressions and correlations were done for the data stratified according to soil type, and also by vegetation type on each soil. The correlations are given in Table 9. The highest correlations between NDVI and rainfall are for the *vertisol* and *cambisol* soils. The *vertisols* correlated best when NDVI was compared to rainfall from the current plus previous two months, while the *cambisols* had the highest correlations when only the previous two months of rainfall were considered. The high correlations are probably due to greater moisture retention times for these types of soils, owing to their relatively high clay content. The more delayed response of the *cambisols* is likely the result of greater immediate runoff. The *arenosols* had the lowest correlations between monthly NDVI and rainfall, in addition to having the best correspondence between peaks in the two curves. This is because of the high sand content in the soil. There is more rapid infiltration of the rainfall into the soil, but high evaporation rates and the great porosity of the soils lead to short retention times.

Correlations of specific vegetation types on each soil also provide interesting information. The Kalahari thornveld, the vegetation of the driest locations, correlated best on the *luvisols*, the Transition zone vegetaton correlated highest on the *cambisols*, and the *Mopane* woodland zone correlated best on the *vertisols*. For all vegetation types, the lowest correlations were for the *arenosols*. The rainfall/NDVI relationship for all three vegetation types was, therefore, best on soils that are inherently fertile, with a good mix of sand and clay. The relationship was weakest on soils that have a high sand content.

In order to determine the plant productivity per unit rainfall, the slopes of the regression lines of the highest correlations were compared. Figure 25 shows scatter diagrams of NDVI and rainfall for the various soil types, and Figure 26 shows the plots for specific vegetation types within each soil zone. Calculated slopes for the regression lines are given in Table 10 (multiplied by 1000 to give a number that is easier to compare). The highest production rates are found for the plants located on the *vertisols*. The overall lowest production per unit rainfall are found on the *arenosols*, the soil that also had the lowest correlations between NDVI and rainfall.

On a long-term basis, differences among the soil types are evident in the NDVI/rainfall

Table 9: NDVI/rain lag correlations by soil type

Soil Type/Station Name	0	1	2	0+1	1+2	0+1+2
All *Arenosols*	.335	.525	.440	.538	.613	**.638**
Kalahari Thornveld	.274	.428	.394	.445	.529	**.547**
Transition Zone	.416	.664	.521	.657	.740	**.755**
Mopane Woodland	.406	.578	.457	.632	.659	**.728**
Tshabong	.191	.473	.500	.427	**.627**	.593
Tshane	.423	.703	.541	.658	.736	**.750**
Ghanzi	.459	.674	.482	.707	.723	**.781**
Palapye Road	.318	.499	.465	.536	.648	**.666**
Dibete	.386	.666	.569	.624	**.767**	.743
Gweta	.406	.578	.457	.632	.659	**.728**
All *Luvisols*	.411	.673	.552	.653	.756	**.764**
Kalahari Thornveld	.425	.657	.558	.675	.768	**.784**
Transition Zone	.355	.740	.623	.644	**.815**	.773
Mopane Woodland	.425	.670	.519	.645	.727	**.753**
Mahalapye	.423	.660	.485	.630	.727	**.740**
Ramatlabama	.513	.720	.661	.726	.827	**.839**
Gaberones	.355	.740	.623	.644	**.815**	.773
Baines Drift	.499	.703	.533	.712	.736	**.775**
Francistown	.408	.669	.526	.633	.749	**.777**
All *Fluvisols*	.410	.655	.541	.639	.716	**.724**
Mopane Woodland	410	.655	.541	.639	.716	**.724**
Maun	.424	.689	.469	.696	.717	**.738**
Shakawe	.401	.679	.605	.642	**.762**	.758
All *Cambisols*	.410	.706	.645	.669	**.826**	.797
Kalahari Thornveld	.419	.663	.608	.624	**.752**	.738
Transition Zone	.403	.748	.680	.709	**.891**	.849
Lobatse	.419	.662	.607	.624	**.751**	.737
Kanye	.403	.748	.680	.709	**.891**	.849
All *Vertisols*	.474	.671	.622	.698	.787	**.809**
Mopane Woodland	.474	.671	.622	.698	.787	**.809**
Kasane	.474	.671	.622	.698	.787	**.809**

relationship as well. Figure 26 shows a scatter plot of 6-year averages of annual integrated NDVI versus rainfall. The *fluvisols* and *cambisols* demonstrate the best long-term relationships between NDVI and rain, while the worst are found on the *arenosols* and *luvisols.*

Table 10: NDVI/rainfall regression slope comparisons for best correlations on Table 9

Soil/Vegetation	Slope
Arenosols	1.6
Thornveld	1.5
Transition	1.8
Woodland	1.5
Luvisols	1.8
Thornveld	1.9
Transition	1.6
Woodland	1.8
Fluvisols	1.8
Woodland	1.8
Cambisols	1.7
Thornveld	1.7
Transition	1.7
Vertisols	2.0
Woodland	2.0

The relationship between NDVI and soil moisture also shows differences among the various soil types. As may be seen in Figures 20-23, no lag between soil moisture fluctuations and NDVI is evident, and there seems to be a better correspondence than with the NDVI and rainfall curves. Soil moisture appears to be most variable at the two driest stations, Tshabong and Tshane. The worst correspondence between NDVI and soil moisture appears to be on the *arenosols* (as opposed to the good correspondence between NDVI and rainfall peaks on this soil). The *vertisols* and *cambisols* appear to have the best realtionship between NDVI and soil moisture maxima and minima. It is interesting to note that soil moisture appears to have a maximum value on the *luvisols.* These soils show a better correspondence between the height of the NDVI curve and that of rainfall.

Again, correlations and linear regression were done in order to quantify these trends. Table 11 gives the correlations calculated for the NDVI and soil moisture data. Figure 25 shows the scatter diagrams for the best correlations, and Figure 27 gives the scatter plots for vegetation zones within each soil type for the highest correlations. The highest correlation coefficients are found between NDVI and soil moisture in the same month, indicating that NDVI is a better indicator of given soil moisture conditions than of rainfall. The highest correlations are found for the *cambisols* and *vertisols*, while the lowest are found on the *arenosols* (similar to the NDVI/rain relationship). The *fluvisols* also have relatively low correlations, and this is likely due to the effects of underlying water tables and exogeneous water. The best overall relationships are again found for the most fertile soils with good balances of sand and clay.

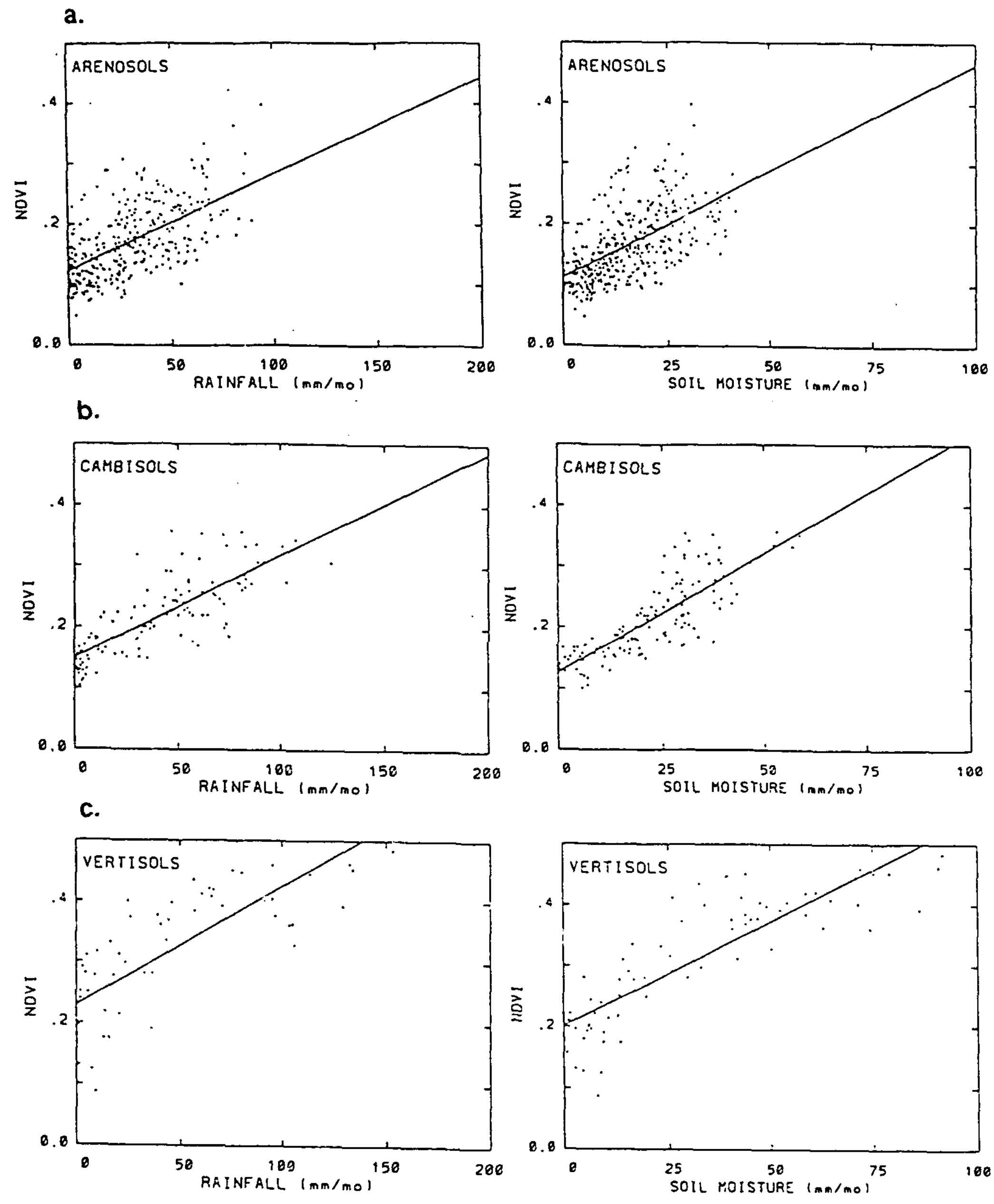
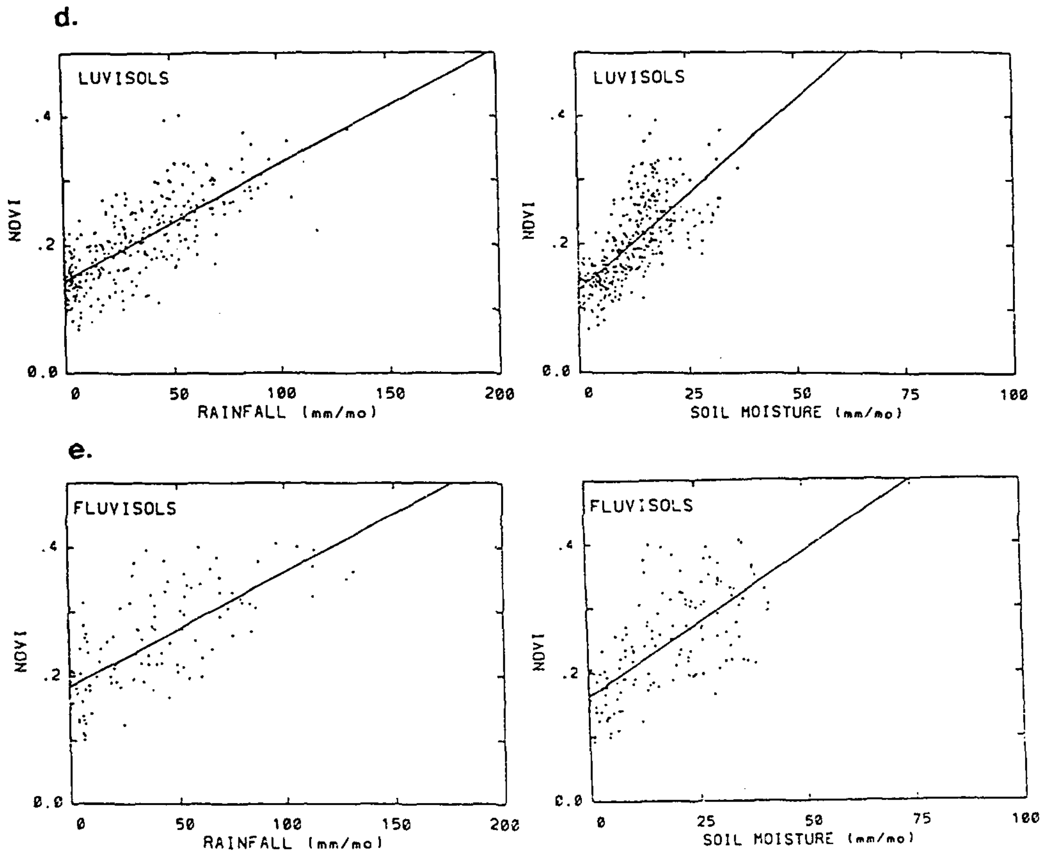


Figure 25: Scatter diagrams of monthly NDVI vs Rainfall and NDVI vs Soil Moisture According to Soil Type - a. *Arenosols*, b. *Cambisols*, c. *Vertisols*, d. *Luvisols*, e. *Fluvisols*.



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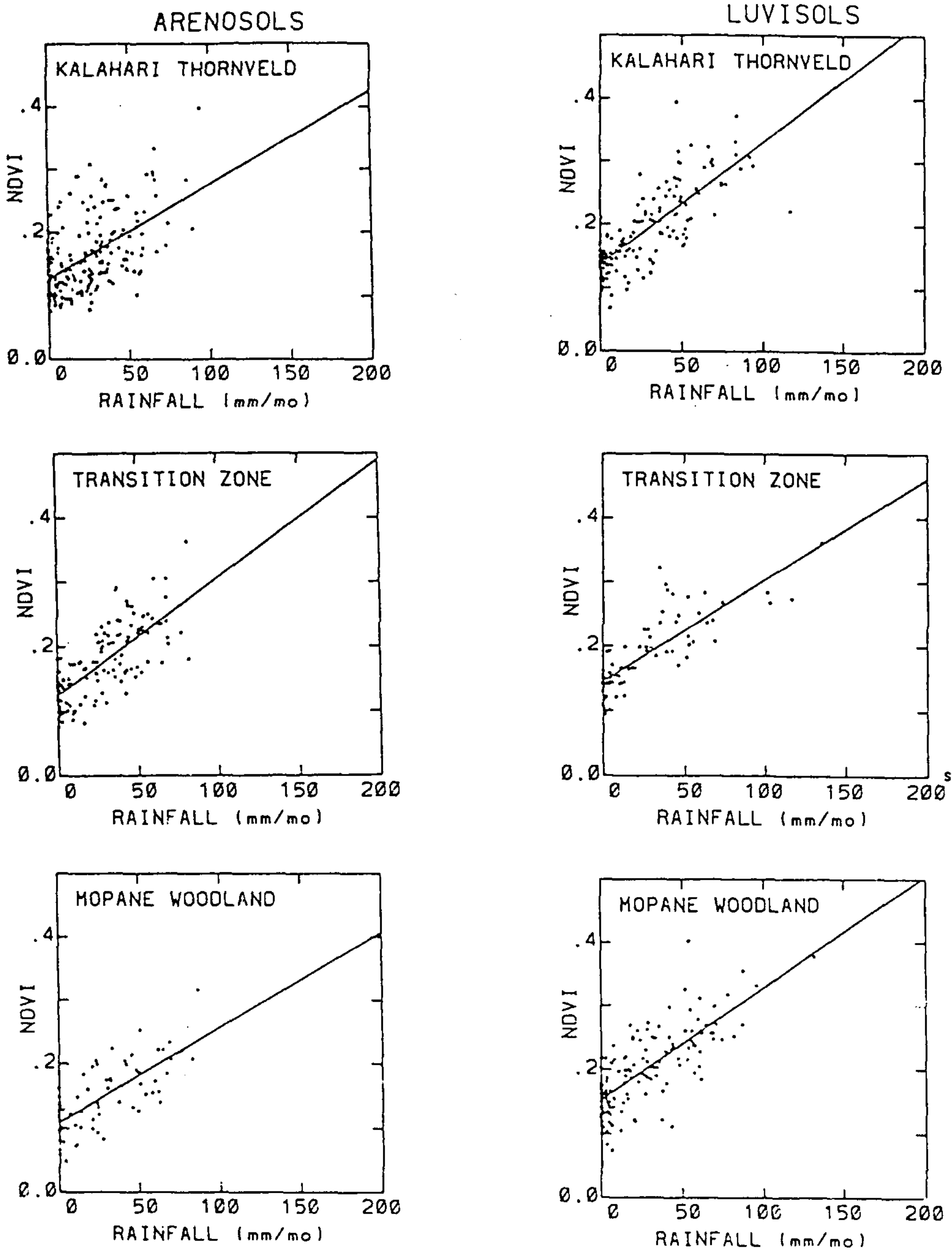
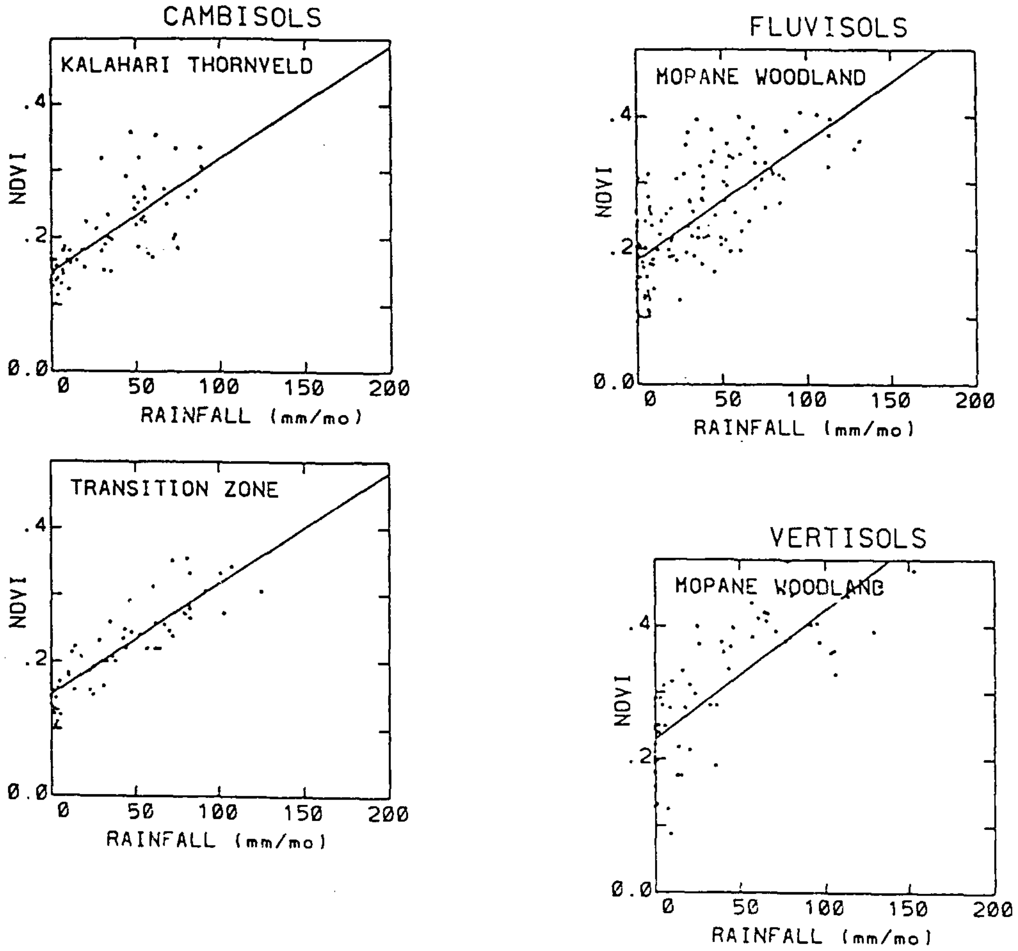


Figure 26: Scatterplots of monthly NDVI and rainfall data by vegetation and soil type.



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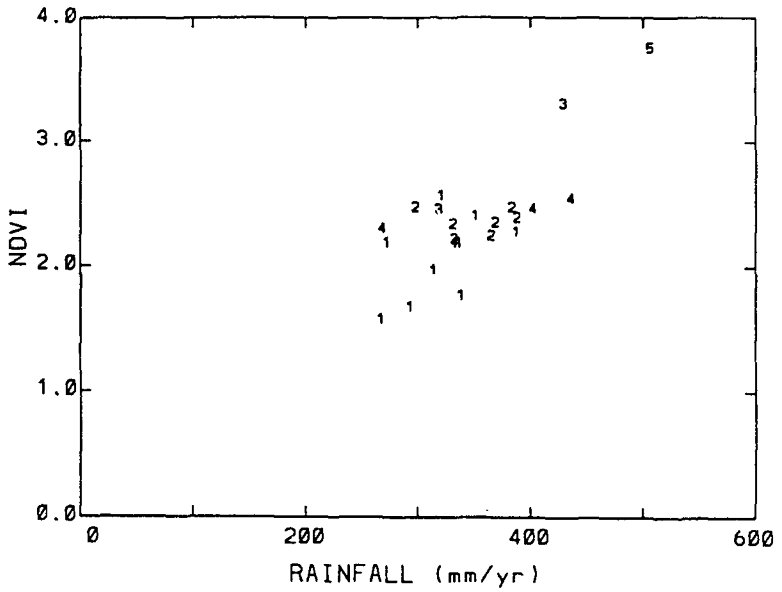


Figure 27: Scatter diagrams of six-year averages of annual NDVI versus rainfall by soil type - 1. *arenosols*, 2. *luvisols*, 3. *fluvisols*, 4. *cambisols*, 5. *vertisols*.

The three vegetation types exhibit varying responses on the different soils as well. All three types have the highest correlations between NDVI and soil moisture on the *cambisols*. The lowest coefficients are found on the *arenosols* for the Kalahari thornveld and the transition zone vegetation, while the woodland correlates lowest on the *luvisols* and *fluvisols*. In order to explain this, the efficiency of plant production per unit soil moisture must be examined.

Table 12 gives the calculated slopes for the regression lines of the highest correlations in the NDVI/soil moisture relationship. The most significant feature is that the *luvisols* have nearly twice as large vegetation production per unit soil moisture than the other soil types. However, as noted above, soil moisture appears to have a maximum value at these stations. Table 10 shows that *luvisols* show a relatively high rate of production per unit rainfall when compared to other soil types. The vegetation on this particular soil type, therefore, utilizes the limited soil moisture quite efficiently. Lower production rates per unit soil moisture are noted on the *arenosols*, probably due to low moisture retention times and high evaporation rates. The production rates are also relatively low on the *vertisols* and *cambisols*, despite higher correlations between the NDVI and soil moisture. This is probably more of a function of vegetation differences rather than soil composition differences.

Examination of the responses of different vegetation types on the various soils thus yields interesting features. All three vegetation types have the greatest production rates per unit soil moisture on the *luvisols*. Note however, that the rate of plant production on this soil is lower for the woodland vegetation than the other two zones. This is a clear indication that the vegetation of the drier regions (the transition zone and the Kalahari thornveld) have more efficient responses to moisture availability, and is in agreement with previous studies (Nicholson *et al.*,1990; Noy-Meir, 1985).

In summary, soils that are inherently fertile and which have a good mixture of sand and clay tend to produce the most efficient plant responses to moisture variations. Sandy soils, on the other hand, have the least efficient vegetation responses. In this study, the most efficient plant production per unit rainfall was found on the *vertisols*, and the most efficient

Table 11: NDVI/soil moisture lag correlations by soil type

Soil Type/Station Name	0	1	2	0+1	1+2	0+1+2
All *Arenosols*	**.621**	.491	.247	.583	.384	.504
Kalahari Thornveld	**.520**	.405	.200	.484	.317	.417
Transition Zone	**.775**	.613	.299	.726	.474	.626
Mopane Woodland	**.743**	.598	.340	.708	.488	.627
Tshabong	**.417**	.262	-.004	.356	.135	.251
Tshane	**.643**	.446	.117	.568	.296	.449
Ghanzi	**.836**	.645	.347	.772	.514	.671
Palapye Road	**.646**	.528	.276	.617	.420	.539
Dibete	**.778**	.636	.289	.741	.480	.633
Gweta	**.743**	.598	.340	.708	.488	.627
All *Luvisols*	**.718**	.554	.227	.664	.402	.550
Kalahari Thornveld	**.771**	.600	.282	.709	.450	.596
Transition Zone	**.795**	.650	.294	.751	.487	.636
Mopane Woodland	**.670**	.491	.149	.611	.333	.490
Mahalapye	**.806**	.642	.313	.754	.488	.645
Ramatlabama	**.735**	.547	.216	.662	.389	.536
Gaberones	**.795**	.650	.294	.751	.487	.636
Baines Drift	**.660**	.446	.084	.578	.275	.438
Francistown	**.794**	.613	.248	.742	.448	.625
All *Fluvisols*	**.684**	.539	.259	.634	.414	.541
Mopane Woodland	**.684**	.539	.259	.634	.414	.541
Maun	**.752**	.572	.270	.686	.436	.581
Shakawe	**.832**	.683	.350	.786	.535	.682
All *Cambisols*	**.844**	.685	.344	.798	.533	.690
Kalahari Thornveld	**.825**	.676	.374	.780	.540	.686
Transition Zone	**.863**	.693	.314	.815	.525	.693
Lobatse	**.825**	.676	.374	.780	.540	.686
Kanye	**.863**	.693	.314	.815	.525	.693
All *Vertisols*	**.865**	.743	.459	.837	.624	.762
Mopane Woodland	**.865**	.743	.459	.837	.624	.762
Kasane	**.865**	.743	.459	.837	.624	.762

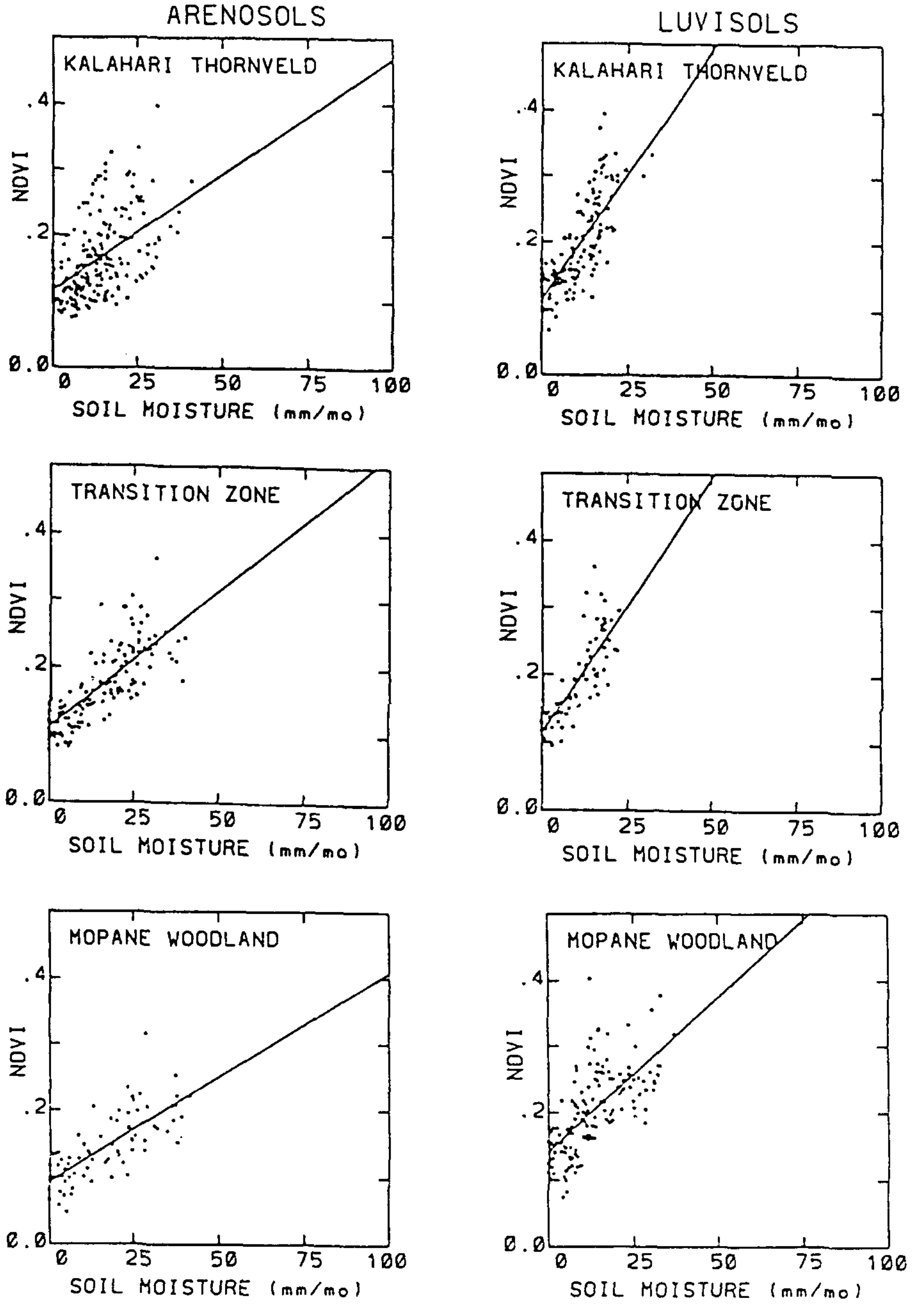


Figure 28: Scatterplots of monthly NDVI and soil moisture data by vegetation and soil type.

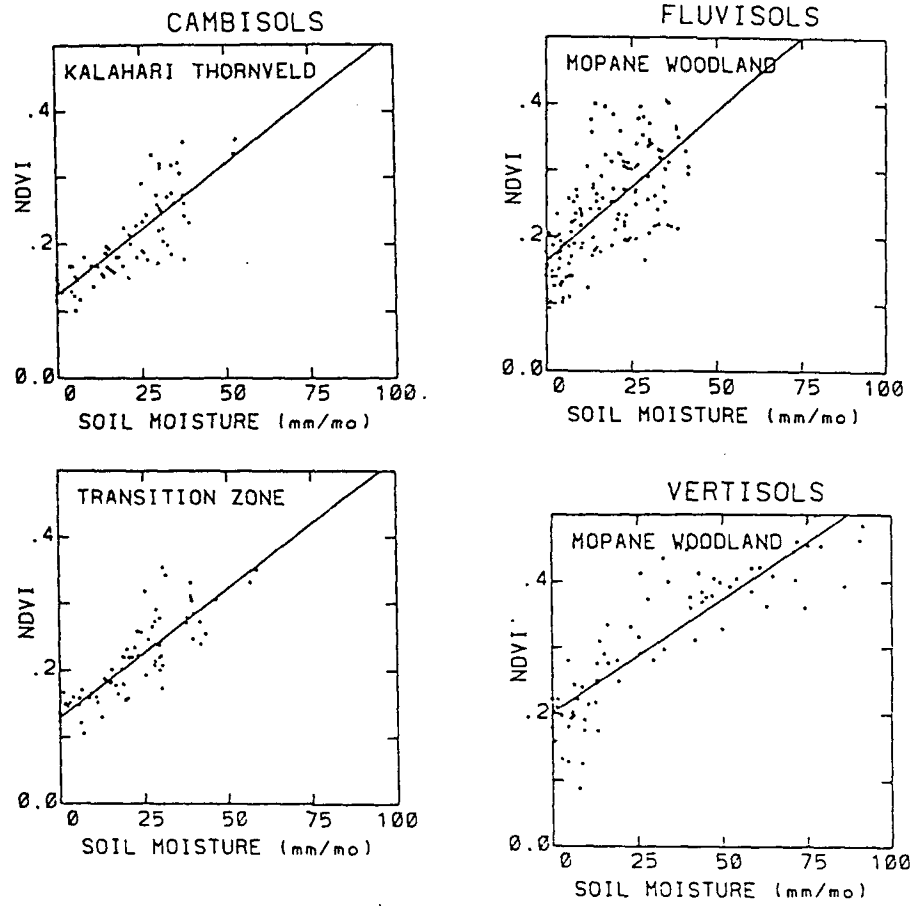


Figure 28: continued.

Table 12: NDVI/soil moisture regression slope comparisons for best correlations on Table 11

Soil/Vegetation	Slope
Arenosols	3.5
Thornveld	3.5
Transition	4.1
Woodland	3.2
Luvisols	5.9
Thornveld	7.5
Transition	7.6
Woodland	4.7
Fluvisols	4.5
Thornveld	4.5
Cambisols	3.9
Thornveld	3.9
Transition	3.9
Vertisols	3.4
Woodland	3.4

production per unit soil moisture was found on the *luvisols.*

Despite the fact that the *vertisols* have the highest rate of soil moisture generation per unit rainfall and the most efficient plant response to rainfall, the differences in rain-use efficiency among the soil types cannot be explained solely by differences in soil moisture generation. For example, while the *luvisols* have a fairly efficient response to rainfall, their soil moisture generation is the lowest of all soils considered. This indicates that the vegetation is being influenced factors other than the rate of soil moisture generation. The large degree of scatter in the rain/NDVI data can likely be explained by the same reason -

varying outside influences due to soil type differences. It is evident that the rainfall/NDVI relationship explored by Malo and Nicholson (1989), Davenport and Nicholson (1991), and Nicholson *et al.* (1990) and the soil moisture/NDVI relationship described here are indeed affected by variations in soil type.

4.6 Rain-Use Efficiency and Mapping of Vegetation

As noted by Tucker *et al.* (1985b), yearly integrated NDVI values have been shown to be related to the amount of accumulated above-ground green phytomass, or primary production. As described in Nicholson *et al.* (1990), vegetation formations differ in the rate of growth or primary productivity per unit rainfall. Le Houérou (1984) describes this as rain-use efficiency. Nicholson *et al.* (1990) utilized a "rain/greenness ratio" (RGR) to describe rain-use efficiency. The RGR is simply the ratio of mean annual integrated NDVI to that of mean annual rainfall multiplied by 1000 to yield a value greater than one. The authors found that a map of RGR over East Africa resembled the vegetation map of White (1983). Values of RGR ranged from 3.5-4.3 in the woodland zones examined, while in the dry grasslands, RGR values ran only about 3.5. This was surprising since growth efficiency in arid lands is generally considered to be higher than in wetter regions because of physiological adaptations in dry areas.

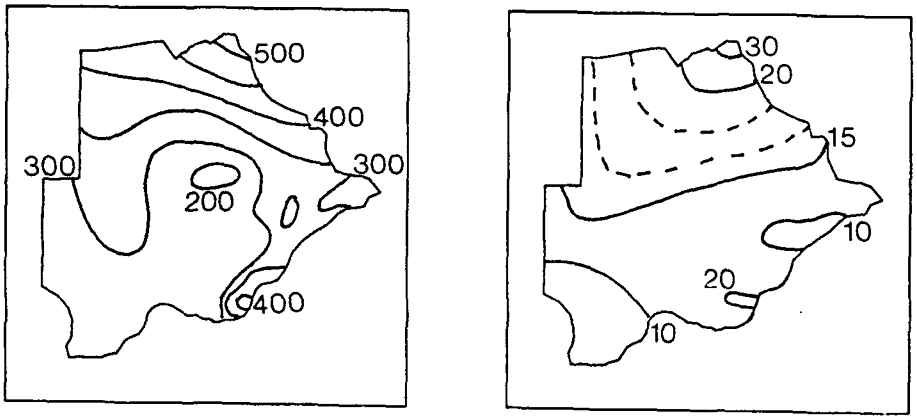
High noise level in the NDVI signal over the Sahel resulted in a poorer correspondence between RGR and White's map. However, the authors did find that the RGR decreased as rainfall did, and that the vegetation formations in the driest location had the most efficient responses to rainfall.

Figure 28 shows maps of mean annual rainfall, mean monthly soil moisture, mean annual integrated NDVI and RGR values over Botswana. Comparisons of the RGR map with that of rainfall and model calculated soil moisture show that some correspondence exists. Maximum in rainfall, calculated soil moisture, and NDVI values in the extreme northeast are somewhat reflected in the RGR values, though the RGR map picks up more on the presence of exogeneous water in the Okavango Delta. The lowest rainfall and calculated soil moisture regions in the southwest are reflected in an area of minimum RGR values. It is interesting to note that an area of minimum soil moisture storage and minimum rainfall in the easternmost portions of the country corresponds to a maximum area of RGR values. This corresponds to a region of active agricultural irrigation (Campbell, 1983).

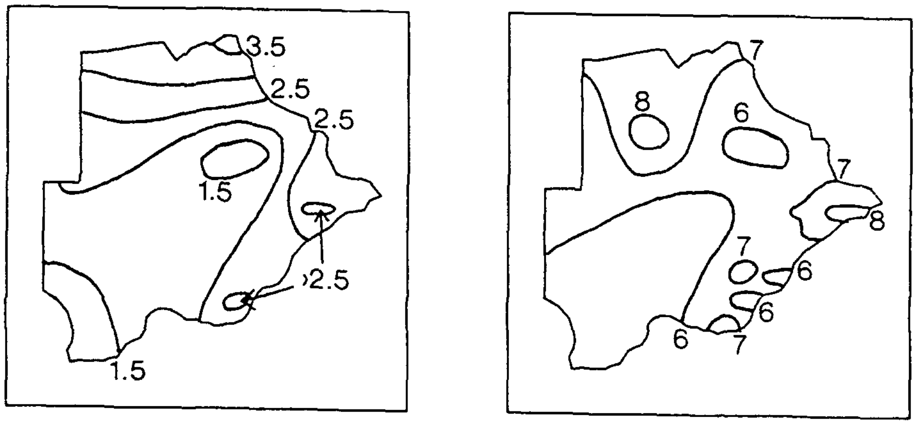
If one compares the RGR map of Figure 28 with White's vegetation map over Botswana (Figure 8), similarities are certainly evident. The large expanse of *acacia* dominant thornveld is reflected in a large region of RGR values less than 6. While one would expect higher values of rain-use efficiency over drier locations, and Figure 28 shows smaller values, one needs to bear in mind that these values are still almost twice that found for the driest locations in East Africa, and more on par with those found for the dry grassland in West Africa.

In addition, the location of swamp and aquatic vegetation in the Okavango Delta is, as already mentioned, clearly reflected in the RGR patterns. Likewise, the Makgadikgadi Pans show up as an area of lower RGR values. Along the Limpopo River in the southeast, complex vegetation patterns are evident in several areas of maximum and minimum RGR values. Indeed, it does seem promising as a method for vegetation mapping.

Values for RGR in various vegetation formations in the Sahel, East Africa and Botswana are given in Tables 13-15. Several extremely interesting and puzzling features are immediately apparent. The RGR values over Botswana are approximately twice that of those found in either the Sahel or East Africa. Additionally, in both the Sahel and East Africa, Nicholson *et al.* (1990) found a good correspondence between NDVI isopleths and rainfall isohyets. In the Sahel, an annual integrated NDVI value of 2.0 roughly corresponded to a mean annual rainfall of 600 mm, while in East Africa the same NDVI isopleth agreed more closely with rainfall of less than 500 mm/yr. A mean annual rainfall of 1000 mm/yr corresponded in East Africa to an annual integrated NDVI value of about 4.0 In Botswana, however, the NDVI 2.0 isopleth roughly follows the 300 mm/yr isohyet, while annual values of NDVI of 4.0 are found in regions of only 600-700 mm/yr rainfall. Clearly, there is a much higher rate of vegetation production per unit rainfall in Botswana than in the Sahel or East Africa.



MEAN ANNUAL RAIN (MM) MEAN MONTHLY SOIL MOISTURE (MM)



MEAN ANNUAL NDVI RAIN/GREENNESS RATIOS

Figure 29: Diagrams of mean annual rainfall (in mm), mean monthly soil moisture (in mm), mean annual integrated NDVI, and rain-greenness ratios (RGR) for 1982-87.

Table 13: Annual integrated NDVI (four-year mean), annual rainfall (four-year mean in mm), and rain-greenness ratio (RGR) for vegetation formations in East Africa (from Nicholson *et al.*, 1990).

Zone	Annual NDVI	Mean Annual Rainfall	RGR
Lowland Forest	4.3	1320	3.2
Coastal Mosaic	4.0	1014	3.9
Coastal Forest	5.2	1962	2.7
Upland Forest	4.3	1157	3.9
Wet Miombo	3.7	1102	3.5
Dry Miombo	3.8	948	4.3
Itigi Thicket	3.9	700	5.6
Shrub-thicket	2.5	546	5.1
Shrub-thicket Mosaic	3.3	803	4.6
Semi-desert Shrub	1.1	297	3.5

Table 14: Annual integrated NDVI(four-year mean), annual rainfall (four-year mean in mm), and rain-greenness ratio (RGR) for vegetation formations in West Africa (from Nicholson *et al.*, 1990).

Zone	Annual NDVI	Mean Annual Rainfall	RGR
Southern Woodland	2.6	951	2.8
Northern Woodland	1.5	460	3.5
Grassland/Woodland Transition	0.9	249	3.9
Grassland	0.6	110	5.7

Table 15: Annual integrated NDVI (six-year mean), annual rainfall (six-year mean in mm), and rain-greeness ratio (RGR) for vegetation formations in Botswana.

Zone	Annual NDVI	Mean Annual Rainfall	RGR
Mopane Woodland	2.7	381	7.0
Transition Zone	2.3	350	6.5
Kalahari Thornveld	2.2	333	6.6

Chapter 5

Discussion

The study presented here examined the relationships between rainfall, model calculated soil moisture and the Normalized Difference Vegetation Index for Botswana in southern Africa. The data were stratified according to both vegetation and soil type, then analyzed spatially and temporally with statistical analyses, including the evaluation of time series and linear regressions/correlations. The purpose of the research was to determine to what extent differences in soil type affected the efficiency of plant growth, and to determine whether the differences in plant productivity noted not only within Botswana, but among the Kalahari, the Sahelian region of West Africa and East Africa are merely reflections of differences in soil moisture generation per unit rainfall.

It was found that, on monthly and annual time scales, a good relationship exists between the NDVI, rainfall and soil moisture. Through analysis of monthly data, it was discovered that the NDVI cycle lagged that of rainfall by a multi-month average (either current plus previous two months or simply the previous two months). The vegetation index correlated best with soil moisture amounts in the same month. This indicates that not only does NDVI have the potential to be used in rainfall monitoring, but also that of existing soil moisture conditions.

The NDVI/rain and NDVI/soil moisture relationships were shown to be affected by variations in soil composition. Regions where soils are high in sand content typically have the lowest correlations among the variables. Although these soils have faster infiltration rates of rainfall into the soil (where it is immediately available for use by the plants), they also have the lowest retention times for the soil moisture. Soils overlying water tables also exhibit less correspondence than other types. The additional water source aids vegetation growth and results in larger greenness values, but is not reflected in the observed rainfall or model calculated soil moisture values. Soils with the highest clay amounts exhibited the best correlations, though the lag between the rainfall and NDVI cycles was more pronounced. Greater percentages of clay result in larger amounts of immediate runoff, and less immediate storage within the soil.

However, while the relationship between the vegetation index and rainfall is an observed one, soil moisture values were obtained with a surface hydrologic model. This may have introduced errors into the NDVI/soil moisture comparisons. The *evapoclimatonomy* model is sensitive to variations in soil sand and clay content. Sensitivity studies showed that variations in clay content of 25% resulted in percent differences of standard deviations of as high as 153.2% for monthly calculations, and 92.4% for annual calculations. If too high of a percentage of clay is input into the model for the region in question, soil moisture values not only are too high due to longer retention times, but runoff values are also unrealistically large. Thus, it is extremely important to obtain as accurate compositional analyses as possible when using the *evapoclimatonomy* model. The model also operates on time scales of one month, as do the observed data of rainfall and NDVI. Since vegetation exhibits responses to moisture changes on smaller time scales, faster variations in the vegetation could not be studied.

Rate of plant production per unit rainfall and soil moisture was examined. The most efficient plant responses were found to occur on soils composed of a relatively even mixture of sand and clay. The least efficient responses to moisture variations were found on sandy soils. When rates of soil moisture generation among the different soil types were examined, it was shown that the differences in productivity could not be explained as simply reflections of differences in soil moisture generations. While a greater soil moisture generation per unit rainfall resulted in higher productivities for some soil types, other soils had high productivities with relatively small amounts of soil moisture generation.

Another interesting finding is that productivities in the Kalahari were greater than those of East Africa and the Sahel region of West Africa. There are several possible explanations for this finding. Extensive irrigation, physiological differences among the plants of the various regions or greater soil fertility would all result in higher productivities in the Kalahari. In addition, differences in soil moisture generation rates and temperature regimes, or exogeneous water effects would produce higher vegetation productivities.

It was speculated (Malo and Nicholson, 1989; Davenport and Nicholson, 1991) that higher soil moisture generation rates per unit rainfall could explain the higher productivities in East Africa as compared to West Africa. This is also considered a possible explanation for the much higher productivities in the Kalahari. Table 16 shows a comparison of soil moisture generation rates for representative stations in the Sahel and the Kalahari. It is immediately evident that the generation of soil moisture is greater in the Sahel, not the Kalahari. Thus, differences in soil moisture generation do not explain the higher productivities.

Table 16: Comparison of soil moisture generation rates in the Sahel and the Kalahari

Kalahari Station	Generation Rate	Sahel Station	Generation Rate
Kasane	0.76	Gaya	0.90
Gaberones	0.35	Niamey	0.83
Dibete	0.52	Tahoua	0.58

Irrigation and variations in vegetation types are also not believed to cause the higher productivities in the Kalahari. Campbell (1983) states that the only area of irrigation is the Tuli Block region in extreme eastern parts of the country and White's (1983) descriptions of the plant zones indicate that any differences in vegetation compositions are minor. Additionally, Cole (1986) states that the "patterns and processes of the savanna are similar" in both West Africa and the Kalahari, and that the only major difference is that no *colosphermum mopane* trees are present in the Sahel woodlands. The dominant species in both regions is the *acacia* tree.

The remaining possibilities of more productive soils, temperature and exogeneous water effects are believed to produce the higher vegetation productivities in the Kalahari, though the exact extent of the effects of each are unclear at this time. For instance, Breman and de Wit (1983) state that both overgrazing by livestock and low soil fertilities are problems in the Sahel. Much of the Kalahari is natural vegetation, rather than agriculture, and anthropogenic effects are likely less. Thus, the possibility that soil productivity is higher in the Kalahari cannot be dismissed as a factor producing higher plant productivities.

Temperature plays a large role in regulating photosynthetic production in plants. Gross photosynthetic rate increases with temperature up to a certain maximum point, then levels off, while respiration rates increase with increasing temperature. Therefore, net photosynthesis occurs at some optimum temperature, which varies according to vegetation type. For example, Strahler and Strahler (1987) noted that a temperature of 20°C was the optimum temperature for a species of moss. Since temperatures in the Kalahari average 5 - 10 °C cooler than those of the Sahel (FAO, 1984a,b), it may be that the savannas in Botswana are closer to their particular optimum temperature, and are thus less stressed and more productive.

Finally, horizontal transport of water from outside the region into the Kalahari is believed to definitely play a role in causing higher plant efficiencies. The *evapoclimatonomy* model makes no account for exogeneous water effects. Evidence of this does exist for Botswana. As shown in Figure 3, much of Botswana is surrounded by highlands from which seasonal rivers flow into the country during the rainy season (Campbell, 1983). In addition, the findings of Carlsson *et al.* (1988) demonstrate the presence of active ground-water recharge in portions of south-east Botswana. The similarity of greeness values for much different rainfall regimes at two stations in the study (Figure 24) support this finding as well. Thus, exogeneous water likely also plays a part in producing high plant productivities in the Kalahari.

Chapter 6

Conclusions

This study showed that good and quantifiable relationships exist between a satellite-derived vegetation index (NDVI), rainfall and soil moisture. The NDVI cycle was found to lag that of rainfall by 1-2 months, but corresponded well with that of soil moisture in the same month. This indicates that NDVI might prove useful in monitoring both rainfall and soil moisture fluctuations.

Both the NDVI/rainfall and NDVI/soil moisture relationships were found to be affected by variations in soil composition. Best relationships exist on soils that are composed of a relatively even mixture of sand and clay. The relationships are poorest for regions having soils with a large percentage of sand. It is clear that if these relationships are to be utilized in climate or hydrological studies, account must be made of soil composition in order to accurately assess the results.

The hydrologic model used in this study was found to be highly sensitive to variations in clay content. Errors may have been introduced into the soil moisture calculations based on this, and consequently, some of the correlation values were biased unrealistically. If the *evapoclimatonomy* model is to be used operationally, great care must be taken to obtain accurate soil compositional analyses. Variations in plant water-use-efficiencies were found among the various soil and vegetation types in the Kalahari. Additionally, the overall productivities in Botswana were found to be as much as twice as high as those in either East Africa or the Sahel region of West Africa. It was shown that irrigation, vegetation variations, and soil moisture generation do not cause these higher efficiencies. They are due to a combination of temperature, soil fertility, and exogeneous water effects, the exact extent of which is unknown at this time.

The methods and results presented here have applications in several scientific areas. Since NDVI has applicability in rainfall and soil moisture monitoring, it thus has the potential for use in long-term climatic studies. In addition, it is possible to monitor anthropogenic effects and ecological changes to the land-surface through periodic examination of plant productivities for given rainfall amounts using the NDVI as an indicator of photosynthetic production. The relationships presented here also may have applicability to hydrologic and climate modeling.

The methods described are very dependent upon factors such as soil type. This, in addition to the magnitude of difference in plant productivities among East and West Africa and the Kalahari, indicate that any application of NDVI to rainfall or soil moisture studies must be conducted on a regional basis. Great care must be taken to obtain not only accurate soil compositional analyses, but to fully understand the vegetation and hydrologic characteristics of the region in question.

6.1 Recommendations for Future Study

The lack of data in Botswana often made analysis in this study difficult. Complete rainfall records were hard to obtain, and soil compositional analyses were weak in several areas. Only a small percentage of the data in the FAO/UNESCO soil publication is based on actual field measurements. Future study in this region should attempt to obtain rainfall records from additional reporting stations in surrounding countries, as well as actual soil compositional analyses.

In addition, field experiments to determine the accuracy of the *evapoclimatonomy* model are needed. Results presented here indicate that it is very sensitive to variations in soil clay content, and such field experiments would help quantify the exact nature of the sensitivity. It must also be noted that a time scale of one month is built into the model, as well as the observed rainfall and NDVI data. Since vegetation responds to moisture variations on smaller scales than one month, future studies should incorporate data obtained on smaller time scales, for example, one or two weeks. Examination of the relationships on seasonal time scales should also be attempted.

The causes of greater water-use-efficiencies in the Kalahari as compared to the Sahel are attributed to a combination of the effects of temperature, soil productivity, and exogeneous. The exact extent of these factors is unkown at this time, and should be examined in more detail in future studies.

References

Breman, H., and de Wit, C.T., 1983: Rangeland productivity and exploitation in the Sahel. *Science*, **221**, 1341-1347.

Buol, S.W., Hole, F.D., and McCracken, R.J., 1989: *Soil Genesis and Classification.* 3rd edition, Iowa State Univ. Press, Ames, 446pp.

Campbell, Alec, 1983: *The Guide to Botswana, Lesotho, and Swaziland, Book 1 - Botswana.* Winchester Press Ltd., Saxonwold, South Africa, 441pp.

Carlsson, L., Bromley, J., and Smellie, J., 1988: Ground water resource in a poorly transmissive sandstone in a semi-arid environment: 1. Estimation of recharge. *Proceedings of the Sahel Forum on the State of the Art of Hydrology and Hydrogeology in the Arid and Semi-Arid Areas of Africa.* November 7-12, 1988, Burkina Faso, 370-384.

Choudhury, B.J., and Tucker, C.J., 1987: Monitoring global vegetation using Nimbus-7 37 GHz data: Some empirical relations. *Int. J. remote Sensing*, **8**, 1085-1090.

Cole, Monica M., 1986: *The Savannas—Biogeography and Geobotany.* Academic Press, Inc., Orlando, Florida, 438 pp.

Davenport, M.L., and Nicholson, S.E., 1991: On the relationship between rainfall and the Normalized Difference Vegetation Index for diverse vegetation types in East Africa. *Int. J. remote Sensing* (in press).

Director of Meteorological Services, 1984: *Climatological Summaries for Botswana.* Dept. of Meteorological Services, Ministry of Works and Communications, Gaberone, Botswana.

Dorman, J.L., and Sellers, P.J., 1989: A global climatology of albedo, roughness length, and stomatal resistance for atmospheric general circulation models as represented by the Simple Biosphere Model (SiB). *J. of Appl. Met.*, **28**, 833-855.

Duchaufour, P., 1982: *Pedology.* Translated by T.R. Paton, George Allen and Unwin, London.

FAO, 1984a: *Agriclimatological Data for Africa. Vol. 1. Countries north of the equator.* FAO, Rome.

FAO, 1984b: *Agriclimatological Data for Africa. Vol. 2. Countries south of the equator.* FAO, Rome.

FAO/UNESCO, 1977: *Soil Map of the World. Vol. VI, Africa.* UNESCO, Paris.

Griffiths, J.F., 1972: *World Survey of Climatology, Vol. 10 — Climates of Africa.* American Elsevier Publishing Company, NY, 300pp.

Hielkema, J.U., Prince, S.D., and Astle, W.L., 1986: Rainfall and vegetation monitoring in the Savanna Zone of the Democratic Republic of Sudan using the NOAA Advanced Very High Resolution Radiometer. *Int. J. remote Sensing*, **7**, 1499-1513.

Huete, A.R., Jackson, R.D., and Post, D.F., 1985: Spectral response of a plant canopy with different soil backgrounds. *Remote Sensing Environ.*, **17**, 37-53.

Jackson, Ray D., 1983: Spectral indices in *n*–space. *Remote Sensing Environ.*, **13**, 409-421.

Justice, C.O., and Hiernaux, P.H.Y., 1986: Monitoring the grasslands of the Sahel using NOAA AVHRR data: Niger 1983. *Int. J. remote Sensing*, **7**, 1475-1497.

Justice, C.O., Holben, B.N., and Gwynne, M.D., 1986: Monitoring East African vegetation using AVHRR data. *Int. J. remote Sensing.* **7**, 1453-1474.

Justice, C.O., Townshend, J.R.G., Holben, B.N., and Tucker, C.J., 1985: Analysis of the phenology of global vegetation using meteorological satellite data. *Int. J. remote Sensing.* **6**, 1271-1318.

Lare, A.R., and Nicholson, S.E., 1990: A climatonomic description of the surface energy balance in the central Sahel. Part I: Shortwave radiation. *J. Appl. Met.*, **29**, 123-137.

Lare, A.R., and Nicholson, S.E., 1991: A comparison of surface energy and water balance in the Sahel and Kalahari regions of Africa: Implications for land surface-atmosphere feedback. *Proceedings of the 10th Conference on Biometeorology and Aerobiology, Sep. 10-13, 1991*, Salt Lake City, in print.

Le Houérou, H.N., 1984: Rain use efficiency: A unifying concept in arid-land ecology. *J. of Arid Environ.*, **7**, 213-247.

Lettau, H., 1969: Evapotranspiration climatonomy I: A new approach to numerical prediction of monthly evapotranspiration, runoff, and soil moisture storage. *Mon. Wea. Rev.* **97**, 691-699.

Lettau, H. and K., 1975: Regional climatonomy of tundra and boreal forests in Canada. Climate of the Artic. *Proceedings of the 17th Alaskan Science Conference*, Fairbanks, 209-221.

Lettau, H.H., and Baradas, M.W., 1973: Evapotranspiration climatonomy II: Refinement of parameterizations exemplified by application to the Mabacan River watershed. *Mon. Wea. Rev.*, **101**, 636-649.

Lettau, K., 1971: Radiation climate of New Dehli - Part II: Longwave radiation and energy budget. *Indian J. Meteor. Geophys.*, **22**, 529-540.

Malo, A.R., and Nicholson, S.E., 1990: A study of rainfall and vegetation dynamics in the African Sahel using Normalized Difference Vegetation Index. *J. Arid Envir.*, **19**, 1-24.

Nicholson, S.E., Davenport, M.L., and Malo, A.R., 1990: A comparison of the vegetation response to rainfall in the Sahel and East Africa using Normalized Difference Vegetation Index from NOAA AVHRR. *Clim. Change*, **17**, 209-241.

Nicholson, S.E., Kim, J., and Hoopingarner, J., 1988: *Atlas of African rainfall and its interannual variability*. Dept. of Met., Florida State Univ., Tallahassee, 237pp.

Nicholson, S.E., and Lare, A.R., 1990: A climatonomic description of the surface energy balance in the central Sahel. Part II: The evapoclimatonomy submodel. *J. Appl. Met.*, **29**, 138-146.

Noy-Meir, I.,1985: Desert ecosystem structure and function. In *Hot Deserts and Arid Shrublands. Ecosystems of the World, 12.* Elsevier, Amsterdam, pp 93-103.

Pinker, R.T., and Corio, L.A., 1987: Estimating monthly mean water and energy budgets over the central US Great Plains, Part I: Evapoclimatonomy model formulation. *Mon. Wea. Rev.*, **115**, 1140-1152.

Prince, S.D., and Astle, W.L., 1986: Satellite remote sensing of rangelands in Botswana. II. Landsatt MSS and herbaceous vegetation. *Int. J. remote Sensing*. **7**, 1533-1553.

Prince, S.D., and Tucker, C.J., 1986: Satellite remote sensing of rangelands in Botswana. II. NOAA AVHRR and herbaceous vegetation. *Int. J. remote Sensing*, **7**, 1555-1570.

Saxton, K.E., Rawls, W.J., Romberger, J.S., and Papendick, R.J., 1986: Estimating generalized soil-water characteristics from texture. *Soil Sci. Soc. Am. J.*, **50**, 1031-1036.

Sellers, P.J., Mintz, Y., Sud, Y.C., and Dalcher, A., 1986: A Simple Biosphere Model (SiB) for use within general circulation models. *J. of Appl. Met.*, **43**, 505-531.

Serafini, Y.V., and Sud, Y.C., 1987: The time scale of the soil hydrology using a simple water budget model. *J. of Clim.*, **7**, 585-591.

Strahler, A.N., and Strahler, A.H., 1987: *Modern Physical Geography*, 3rd edition, John Wiley and Sons, New York, 544pp.

Townshend, J.R.G., and Justice, C.O., 1986: Analysis of the Dynamics of African vegetation using the Normalized Difference Vegetation Index. *Int. J. Remote Sensing*, **7**, 1435-1446.

Tucker, Compton J., 1979: Red and photographic infrared linear combinations for monitoring vegetation. *Remote Sensing Environ.*, **8**, 127-150.

Tucker, C.J., and Miller, L.D., 1977: Contribution of the soil spectra to grass canopy spectral reflectance. *Photogrammetry Engineering and Remote Sensing*, **43**, 721-726.

Tucker, C.J., Vanpraet, C.L., Boerwinkel, E., and Gaston, A., 1983: Satellite remote sensing of total dry matter production in the Senegalese Sahel. *Remote Sensing Environ.*, **13**, 461-474.

Tucker, C.J., Vanpraet, C.L., Sharman, M.J., and Van Ittersum, G., 1985a: Satellite remote sensing of total herbaceous biomass production in the Senegalese Sahel: 1980-1984. *Remote Sensing Enviro.*, **17**, 233-249.

Tucker, C.J., Townshend, J.R.G., and Goff, T.E., 1985b: African land-cover classification using satellite data. *Science*, **227**, 369-375.

Tucker, C.J. and Sellers, P.J., 1986: Satellite remote sensing of primary production. *Int. J. Remote Sensing*, **7**, 1395-1416.

Warrilow, D.A., 1986: The sensitivity of the U.K. meteorological office atmospheric general circulation model to recent changes to the parameterization of hydrology. *Proceedings ISLSCP Conference, Dec 2-6, 1985*, Rome, Italy, ESA SP-248, 143-149.

White, F., 1983: *The vegetation of Africa.* UNESCO, Paris, 383pp.

White, R., 1978: *Africa - Geographical Studies.* Heinemann Educational Books, Ltd., London, England, 208 pp.

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