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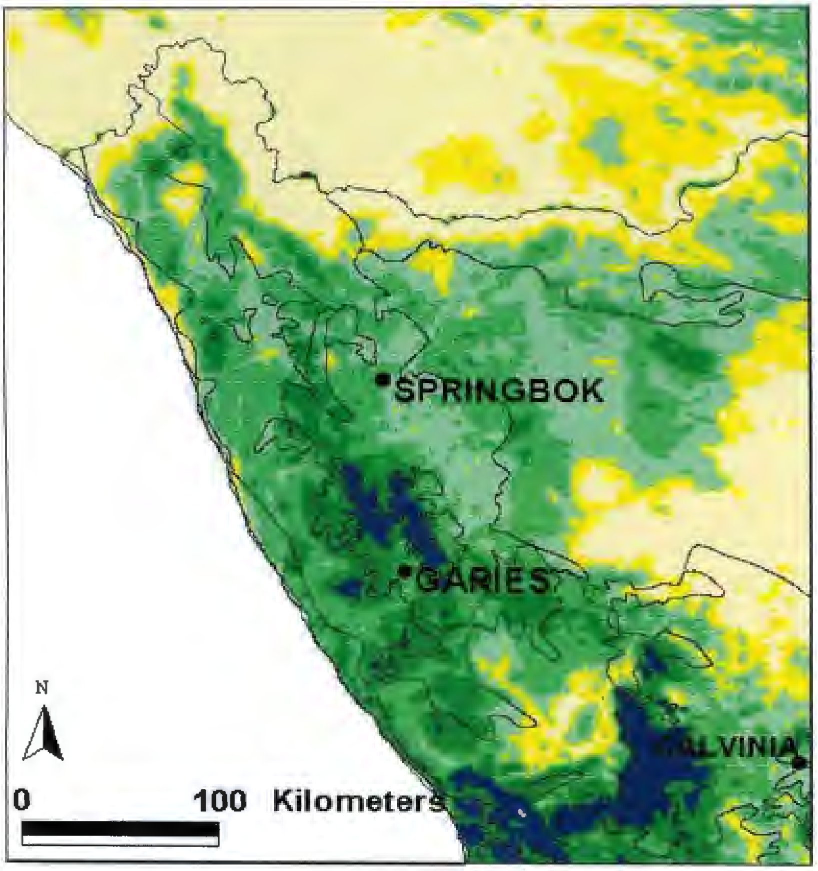
An analysis of vegetation pattern and its relationship to NDVI data in the Namaqualand area, South Africa.



Mean Annual NDVI in the greater Namaqualand area

By Sarah-Jane Caroline Fox

A project in partial fulfilment of the requirements for a B.Sc. Honours degree in Botany, University of Cape Town, 2003.

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Abstract

The Namaqualand area in the North Western Cape, South Africa is unique in comparison to other similar semi-arid areas of the world. It has a high biodiversity and endemism and is subsequently an area of interest for a growing number of conservation initiatives. Climate plays an important role in influencing the phenology and growth of the vegetation in the area. Remote sensing techniques were used to reveal the vegetation patterns in the greater Namaqualand area and to relate them to climatic variables. To do this we used the normalised difference vegetation index (NDVI) to relate biomass to altitude, rainfall and vegetation type. Each vegetation type in the area had a unique temporal signature and the climatic variables influencing the summer rainfall and winter rainfall vegetation types differed significantly from each other. Mean annual NDVI was significantly correlated to precipitation and potential evapotranspiration (PET) ($r = 0.60, -0.63$ respectively). A multiple regression model explained 52% of the variance when Mean Annual NDVI was related to climatic variables. Mean NDVI in August (the month of maximum NDVI in most of Namaqualand) was significantly related to PET and the current plus two previous months of precipitation ($r = -0.72$ and 0.74 respectively). A multiple regression model for mean NDVI in August and climatic variables explained 57% of the variance. The results suggest that NDVI can be used successfully as a measure of growth and phenology in the Namaqualand area and that NDVI could be used in climate models, drought prediction, desertification predictions and a number of other applications in the future.

Introduction

The Namaqualand area of the North Western Cape, South Africa is included in the Succulent Karoo Biome (Desmet & Cowling 1999a) and is an area of interest to a growing number of scientists. In comparison to other deserts of the world Namaqualand is exceptionally species rich at both the local and regional scales and has many unique features (Cowling *et al.* 1999). The region contains 4849 species of vascular plants 40% of which are endemic (Hilton Taylor 1996) yet there are very few protected areas in the region. Communal lands form more than 25% of the Namaqualand region and support 45% of the region's population (Hoffman *et al.* 1999). Livestock grazing is one of the major forms of land use and has been suggested as one of the major threats to biodiversity (Hilton-Taylor 1994, Cowling & Pierce 1999). A number of conservation initiatives such as the Succulent Karoo Ecosystem Plan (SKEP) have been undertaken along with socio-economic and grazing practice investigations in this area (Todd & Hoffman 1999, Scholes 1998). Consequently interest in this area has increased and much research has been undertaken.

Environmental and climatic cues have been related to phenological events in the Namaqualand area (Struck 1994, van Rooyen *et al.* 1979) and it is of particular interest to study arid regions where the overall influence of climatic factors on phenology would be more obvious than other areas (Struck 1994). Phenology is linked to biomass production (primary production), which can be "quantified as a result of the rain fed environmental status of a location" (Schulze 1997). Desmet & Cowling (1999) have stressed the importance of rainfall as one of the primary driving factors in determining vegetation patterns in southern Africa. Thus, climate has an important influence over phenology, biomass production and vegetation patterns. However, little work has used satellite imagery to study phenological patterns, vegetation patterns and environmental cues in Namaqualand or even in South Africa in general (Chidumayo 2001).

Remote sensing is one of the few sources of relatively long-term (10- 15 years) views of the Earth's surface (Weiss *et al.* 2001) and in recent years has been used in a number of studies to retrieve physical and biological information. NDVI data is frequently used in research on vegetation 'greeness' or productivity (Reed *et al.* 1994) and has been particularly useful in sparsely populated arid or semi-arid areas (Malo & Nicholson 1990).

Many of these studies have been based on the normalized difference vegetation index (NDVI) from the National Oceanic and Atmospheric Administration's (NOAA) Advanced Very High Resolution Radiometer (AVHRR). NDVI is defined as:

$$NDVI = (NIR - red)/(NIR + red)$$

where NIR is the near infrared channel (0.725 to 1.1 μm) and red is the visible channel (0.58 to 0.68 μm). The values can vary from –1 to +1 where water typically has values less than 0, bare soils have values between 0 and 0.1 and vegetation has values between 0.1 and 1 (White *et al.* 1997, Weiss *et al.* 2001). Daily images are rarely possible due to the fact that the invisible and near-infrared channels cannot penetrate cloud cover. The problem of cloudy days is overcome by creating maximum composite images. In the NOAA data set, images are created of 10 day (dekadel) composites and the maximum NDVI for each pixel is taken. This data is recorded with a 1 km x 1 km nominal spatial resolution and the NDVI value for a pixel is based on the composition of ground cover types within that pixel (Weiss *et al.* 2001). As vegetation grows, the NDVI values increase and as the vegetation dies back, the NDVI decreases (Weiss *et al.* 2001). Thus, the NDVI provides a measure of photosynthetic capacity such that the higher the NDVI value, the more photosynthetically active the vegetation (Sellars 1985). The changes in NDVI values therefore indicate the vegetation growth cycles in an area.

Remote sensing has been used in numerous vegetation studies around the world many of which have looked at NDVI signals for different vegetation types (Townshend & Justice 1986) and the relationship between NDVI and climatic variables. One of the few studies that have been done using NDVI in South Africa shows how NDVI can be used to asses the affects of different grazing practices on vegetation cover (Archer 2003). The relationship of NDVI to rainfall has been established in a number of studies (Tucker *et al.* 1985, Justice *et al.* 1986, Nicholsen *et al.* 1990). In some areas it has been found that NDVI closely reflects accumulated rainfall totals (i.e. rainfall in the concurrent plus two antecedent months) (Nicholsen *et al.* 1990). Not only does

NDVI correlate with rainfall but it also correlates with minimum and maximum temperatures (particularly in Savanna areas)(Lee *et al.* 2002, Chidumayo 2001) and with evapotranspiration (Justice *et al.* 1986).

Phenology and vegetation growth are influenced by the following environmental variables: Climate, soils, solar radiation, management practices and pest/disease infestation (Reed *et al.* 1994). It thus makes sense to look at these variables in relation to phenology, biomass and NDVI. This is particularly valid for the Namaqualand area where the predictability of seasonal rainfall is relatively high and therefore the phenology of the vegetation should be comparatively predictable (Hoffman & Cowling 1987). Ground surveys have shown a correlation between climatic variables and phenology (Van Rooyen *et al.* 1979, Struck 1994) and we therefore expect that NDVI will be correlated to climatic variables. We also expect that the different vegetation types will have different temporal NDVI signals, considering that the above ground biomass of Succulent Karoo differs from the vegetation types that surround it i.e. Fynbos, Renosterveld and Nama Karoo (Milton *et al.* 1997).

In this study we addressed the following:

1) What are the NDVI patterns in the greater Namaqualand area and how do they vary at different temporal scales (Annual, monthly and month of maximum)?
2) To what extent can NDVI be explained by climatic variables in the greater Namaqualand area?
3) How do the NDVI signals differ between different vegetation types?

Study Site

Namaqualand is formally defined as a magisterial district. However, in biogeographic terms it can be described as an area of winter rainfall in the Succulent Karoo biome, west of the Nama Karoo and extending from the Olifants River in the south to the Orange River mouth in the north (Cowling *et al.* 1999). Extreme temperatures in this region are made more temperate by the cold upwelled waters of the Benguela Current (Desmet & Cowling 1999). Rainfall is generally low (ranging from 50 mm in the North west to 400 mm per year in the central high lying areas) yet predictable- a unique feature when compared to other winter rainfall desert systems (Hoffman &

this reference not in ref list.

Cowling 1987). In the foothills rainfall is often supplemented by coastal fog (Desmet & Cowling 1999a), which occurs for about 75 days per year (Olivier 1985). The study area is, however, larger than just Namaqualand and also encompasses part of the Nama Karoo. We refer to the study area as the "greater Namaqualand area". The different vegetation types that occur within the study site are shown in Figure 1 and their main environmental attributes are summarized in Table 1.

Methods

The NOAA AVHRR NDVI data was synthesised for the period 1985 – 2001 and the conversion of data (a series of multitemporal georeferenced satellite data) into NDVI images in GIS format was done by David Hoare from the Institute for Range and Forage Science and made available for use in this project. Climatic data from the South African Atlas of Agrohrydrology and Climatology (Schulze 1997) was used in the analysis.

The methods of investigation entailed two major components. Firstly, an analysis of the phenological pattern was carried out. Secondly, I investigated the climatic variables that could potentially be determining this pattern.
The analysis of pattern entailed the combination of the 16 images for each year into

1) One mean annual NDVI image
2) 12 images (Jan-Dec) reflecting the monthly mean NDVI values and
3) An image showing month of maximum NDVI for each pixel.

All the maps were produced using ArcView GIS 3.2 and are presented with an overlay of Low and Rebelo (1996) vegetation types. The first two images required the combining of the 16 years of images into one. In each of the images the best colour scheme was assigned and this resulted in dividing the NDVI values from the value of zero to one into six categories. Using the Map Calculator the third image was compiled by comparing each of the months' mean NDVI values and identifying the month with the highest NDVI value. Each month was assigned a colour except August which was divided into three 10-day images.

In order to compare climatic variables with NDVI values a point theme was created in ArcView which contained 1225 random points. The random point theme was overlaid on the mean annual NDVI image and on the monthly mean images and the values at each point were extracted using Grid Analyst (ArcView GIS 3.2 extension). The random point theme was then overlaid and values extracted for vegetation types and the following climatic themes:

Mean precipitation, coefficient of variation of precipitation, monthly median rainfall, monthly potential evapotranspiration (PET), monthly solar radiation, mean annual temperature, monthly maximum temperature, monthly minimum temperature, monthly solar radiation.

From these data a number of different totals, averages and composites of monthly data were calculated for the final analysis. The analysis was carried out on

1) All the mean annual NDVI values of each of the points combined as one group as well as on each separate vegetation type.
2) The mean NDVI values in August of each of the points combined as one group as well as on each separate vegetation type.

The vegetation types were split up because of the inherent variance that would be caused by different geology, soil types, latitude, aspect etc.

Tests for correlations (Spearman Rank Correlation, Zar 1984) were done between the mean annual NDVI values of the vegetation types and the ten climatic variables. Climatic variables for mean NDVI in August were combinations of the concurrent plus two previous months.

Multiple regression models were developed using the Best Subsets Method in STATISTICA 6.1. This was done in order to examine how much of the variance in NDVI can be explained by climate.

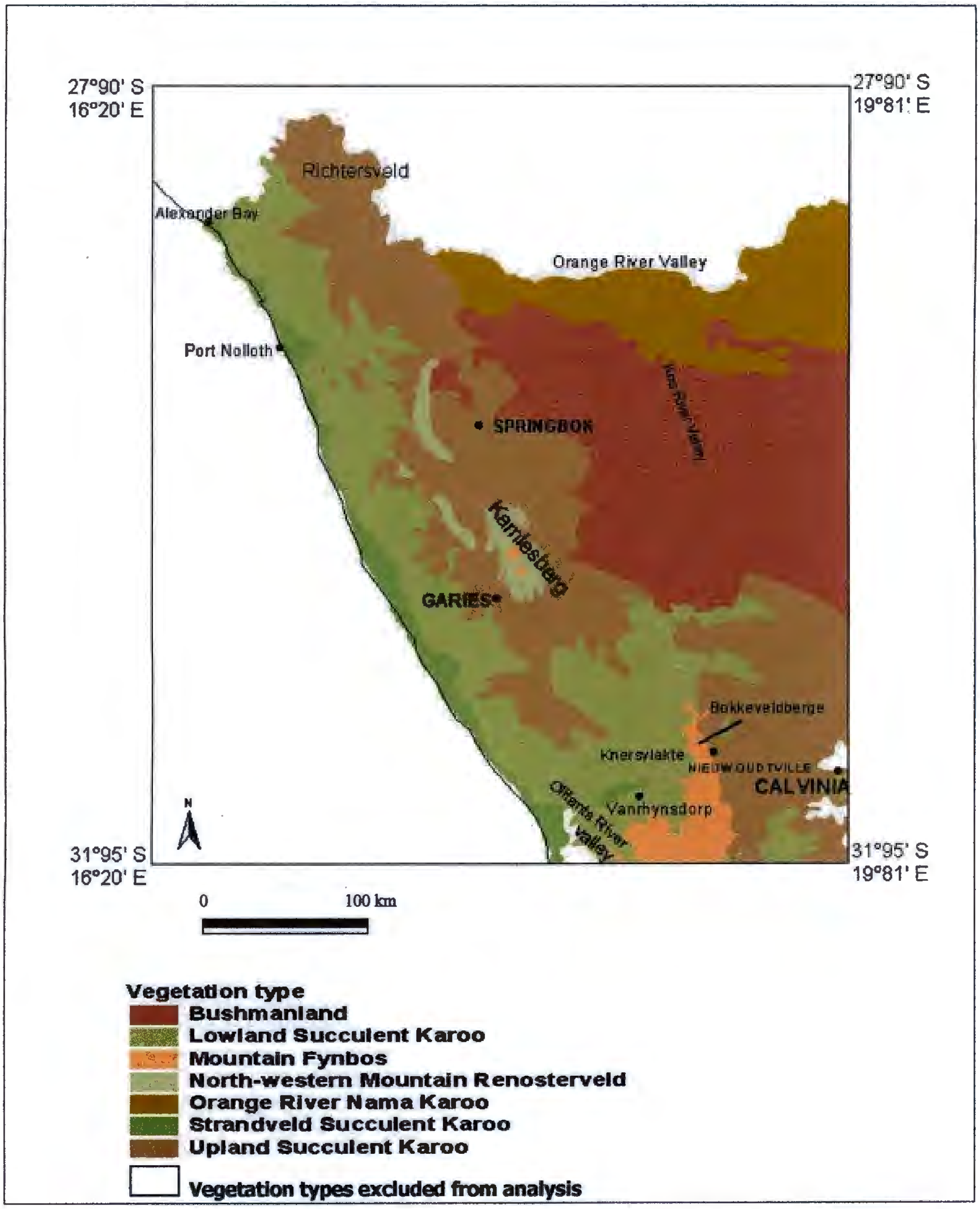


Figure 1: The greater Namaqualand area showing the main vegetation types (after Low & Rebelo (1996)) and important topographic features and place names used in the text.

Table 1: Summary of attributes of different vegetation types (Low & Rebelo 1996) in the greater Namaqualand area

Vegetation type (Low & Rebelo 1996)	Geology	Topography	Rainfall	Dominant vegetation	Land use
Strandveld Succulent Karoo	Calcareous soils, coastal Quaternary sands, poor in nutrients.	Low lying Coastal plains between the Berg River Mouth and Alexander Bay.	Winter rainfall ranging from 50mm in the north increasing to 300 mm per year in the south.	Dominated by low shrubs (particularly succulents) and trees.	Large areas subject to diamond mining, small stock farming.
Upland succulent Karoo	Soils are granites and gneisses and in the South there are Karoo sequence shales and sandstones.	Elevation ranges from 300 to 1700 m due to a series of mountain ranges (Kamiesberg, Hantamsberge and the Roggeveld).	Winter rainfall from 150 mm to 300 mm per year.	*Aloe dichotoma* is the characteristic species, many dominant dwarf shrubs. Also high number of annuals (Asteraceae and vygie family).	Stock farming with cropping in higher rainfall areas.
Lowland Succulent Karoo	On granites and gneisses and Karoo sequence shales and sandstones in the south-east.	Below the escarpment, between 0 m and 600 m above sea level.	Extremely arid, winter rainfall between 50 and 200 mm per year.	Heuweltjies (termite mounds) are characteristic. Wide range of succulents and the vygie family dominates. Annuals and geophytes are characteristic after good rains.	Mainly small stock farming (dorper sheep and Boer goats) although summer grazing is minimal.
North-western Mountain Renosterveld	Granites and gneisses, giving rise to deep, sandy loamy soils.	Confined to the Kamiesberg highlands around Leliefontein.	Rainfall between 250 and 400 mm per year mostly in winter with summer droughts.	*Elytropappus rhinocerotis* (Renosterbos) is dominant with *Eriocephalus africanus, Euryops lateriflorus* and *Nylandtia spinosa* occuring.	Stock farming with cropping in nutrient rich, higher rainfall areas.
Mountain fynbos	In the study area found on sandstones and granites.	Occurs on the peaks of the Kamiesberg above Renosterveld .	Rianfall varies from 200 to 400 mm per year.	Main families are Restionaceae, Ericaceae and Proteaceae.	Limited stock farming, because the vegetation is generally unpalatable and poor in nutrients.
Bushmanland Nama Karoo	Quaternary sands and Karoo sequence shales giving rise to structureless clay and sandy soils.	Topography is gereally flat, most of it lying at 900 m above sea level.	Rainfall is generally in autumn and ranges between 50 and 200 mm per year. Some patchy summer thunderstorms occur.	Dominated by annuals and non-succulent shrubs, has the highest proportion of annuals of all the Nama Karoo types.	Mostly small stock farming (Dorpers, Karakul sheep and Boer goats). Evidence of overgrazing in many areas.
Orange River Nama Karoo	Soils derived from granites and gneisses of the Namaqualand Mobile Belt.	Broken topography. Altitude about 250 m above sea level.	Rainfall between 150 and 350 mm per year, in late autumn.	Vegetation varies with the broken topography. Dominant species are *Aloe dichotoma, Euphorbia avasmontana, E.gregaria* on steep slopes. On pediments: *Acacia mellifera* and on the plains *Stipagrostis unilpumis* often dominates.	Mining is prevelant in the area. Small stock farming (Dorper sheep and Boer goats) as well as some irrigation farming in the more fertile areas along the Orange River.

Results:

Figure 2 shows the average amount of growth that occurs over one year. Lighter colours indicate lower NDVI values and a low amount of growth throughout the year. Darker colours, particularly blue, indicate higher NDVI values and higher growth or production throughout the year. Black lines are Low and Rebelo (1996) Vegetation types.

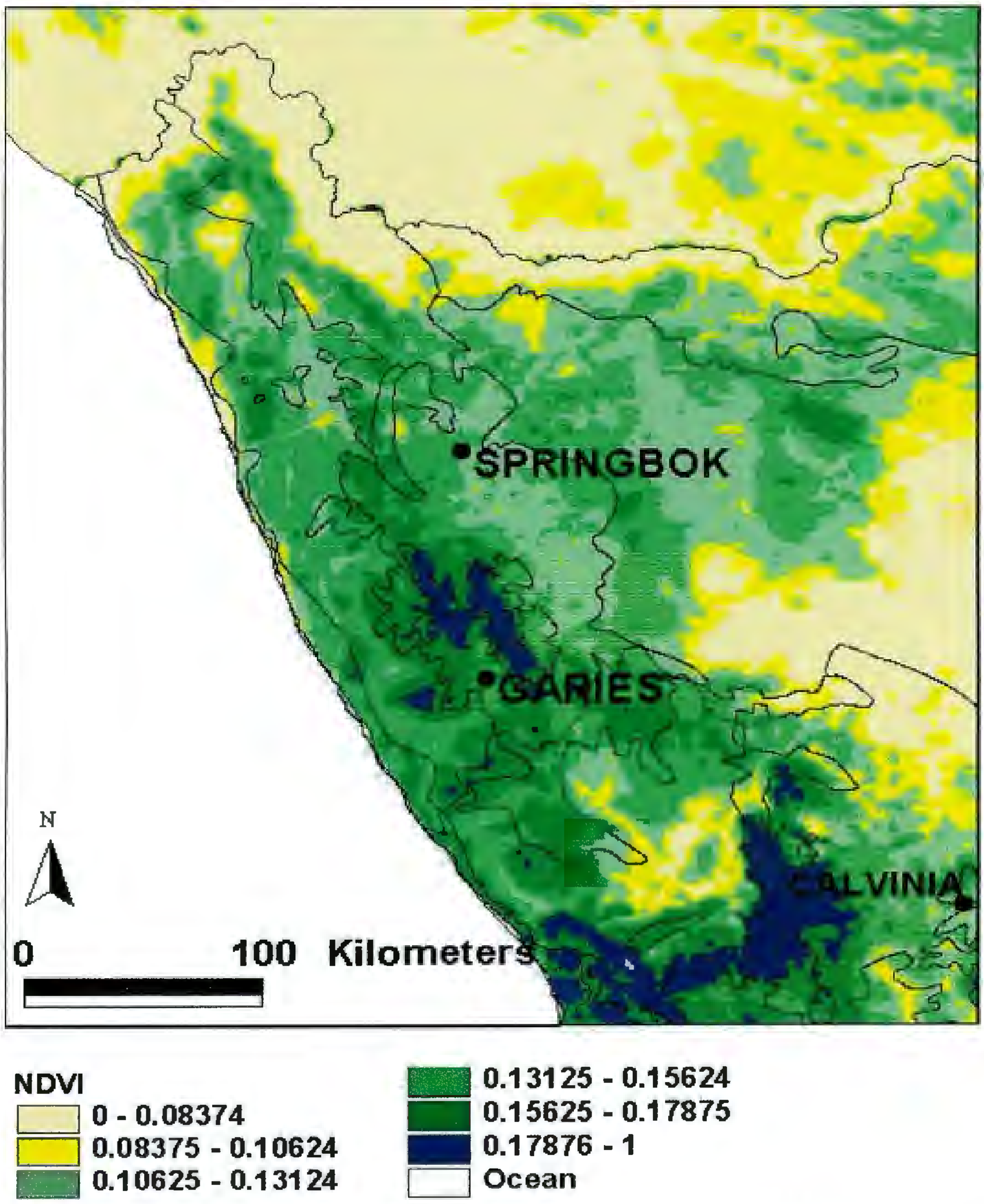


Fig 2. Mean Annual NDVI for the Greater Namaqualand Area for the period 1985 to 2001.

Areas with low vegetation cover and a high percentage of bare soil were the Knersvlakte, a large part of Bushmanland, parts of the Orange River Nama Karoo along the hot Orange river basin and the southern tip of the Southern Namib Desert between Alexander Bay and Port Nolloth. Areas with the highest NDVI values (0.17876 – 1) were generally areas at higher altitudes and with a higher biomass of vegetation. These areas included the Kamiesberg, the Bokkeveldberge west of Calvinia, the mountains (Hantamsberg) just north of Calvinia and most notably the Olifants River valley in the southern part of the image, which is used for irrigated agriculture (wine and vegetable production). Areas with an intermediate NDVI value (0.15625 – 0.17875) were usually also areas of higher elevation. They occurred in the Richtersveld near Alexander Bay (where a number of greener patches are mountain peaks) and along most of the Kamiesberg escarpment. Another notable feature is the Koa River valley, which has a higher NDVI than the surrounding vegetation.

Correlations between mean annual NDVI and climatic variables are shown in Table 2. Mean NDVI was generally most significantly correlated with mean precipitation, coefficient of variation of precipitation, total median rainfall, sum of rainfall in June, July and August total and annual PET. When Bushmanland and Orange River Nama Karoo were removed from the analysis the significance of the correlations increased, with a high increase for the sum of median rainfall in June, July and August. NDVI values for Bushmanland were not significantly correlated with any of the climatic variables while Orange River Nama Karoo was significantly correlated with mean annual temperature, mean maximum temperature, mean minimum temperature and total annual PET but not with any of the precipitation variables.

Mountain Fynbos had a small sample size and thus most of the correlations were not significant. Renosterveld also had a small sample size but most of the variables showed significant correlations except for minimum temperature. Strandveld Karoo and Upland Succulent Karoo were both significantly correlated with a range of climatic variables. Strandveld Succulent Karoo was not correlated with maximum temperature and mean solar radiation whilst Upland Succulent Karoo was not correlated with minimum temperature. Lowland succulent Karoo showed slightly weaker correlations than the other two succulent vegetation types but they were still significant except for mean minimum temperature.

Table 2: Correlation matrix of Mean Annual NDVI versus climatic variables. Correlations are given as r values (Spearman Rank Correlation). Significance values are given as: p<0.001=*, p<0.01=**, p<0.05=*.**

Mean NDVI vs:	All 7 Vegetation types N=1225	5 vegetation types[1] n=772	Mountain Fynbos n=20	North Western Mountain Renosterveld n=30	Upland Succulent Karoo n=378	Succulent Karoo n=300	Strandveld Succulent Karoo n=40	Bushmanland n=336	Orange River Nama Karoo n=114
Mean Precipitation	0.59***	0.60***	0.58***	0.76***	0.62***	0.43**	0.80***	0.17	0.33***
Coefficant of variation of Precipitation	-0.57***	-0.57***	-0.60***	-0.76***	-0.60***	-0.39**	-0.76***	-0.14	-0.26*
Total median Rainfall	0.58***	0.62***	0.62***	0.78***	0.63***	0.42**	0.82***	-0.22	0.20
Sum of Medain Rainfall in June, July and August	0.60***	0.67***	0.53**	0.79***	0.70***	0.46***	0.82***	-0.17	-0.05
Mean Annual Temperature	-0.34**	-0.41**	-0.28	-0.35*	-0.48***	-0.34**	-0.59***	-0.17	-0.66***
Mean Maximum Temperature	-0.47***	-0.47***	-0.40*	-0.47**	-0.59***	-0.39**	-0.06	-0.17	-0.66***
Mean Minimum Temperature	-0.06	-0.18	-0.43**	-0.21	-0.21	-0.05	-0.66***	-0.15	-0.65***
Total Annual PET	-0.63***	-0.68***	-0.44**	0.53**	-0.75***	-0.56***	-0.81***	-0.05	-0.61***
Mean Solar Radiation	-0.43***	-0.38**	-0.09	-0.66***	-0.61***	-0.34**	0.09	0.01	-0.19

[1] this analysis excludes Bushmanland and the Orange river Nama Karoo.

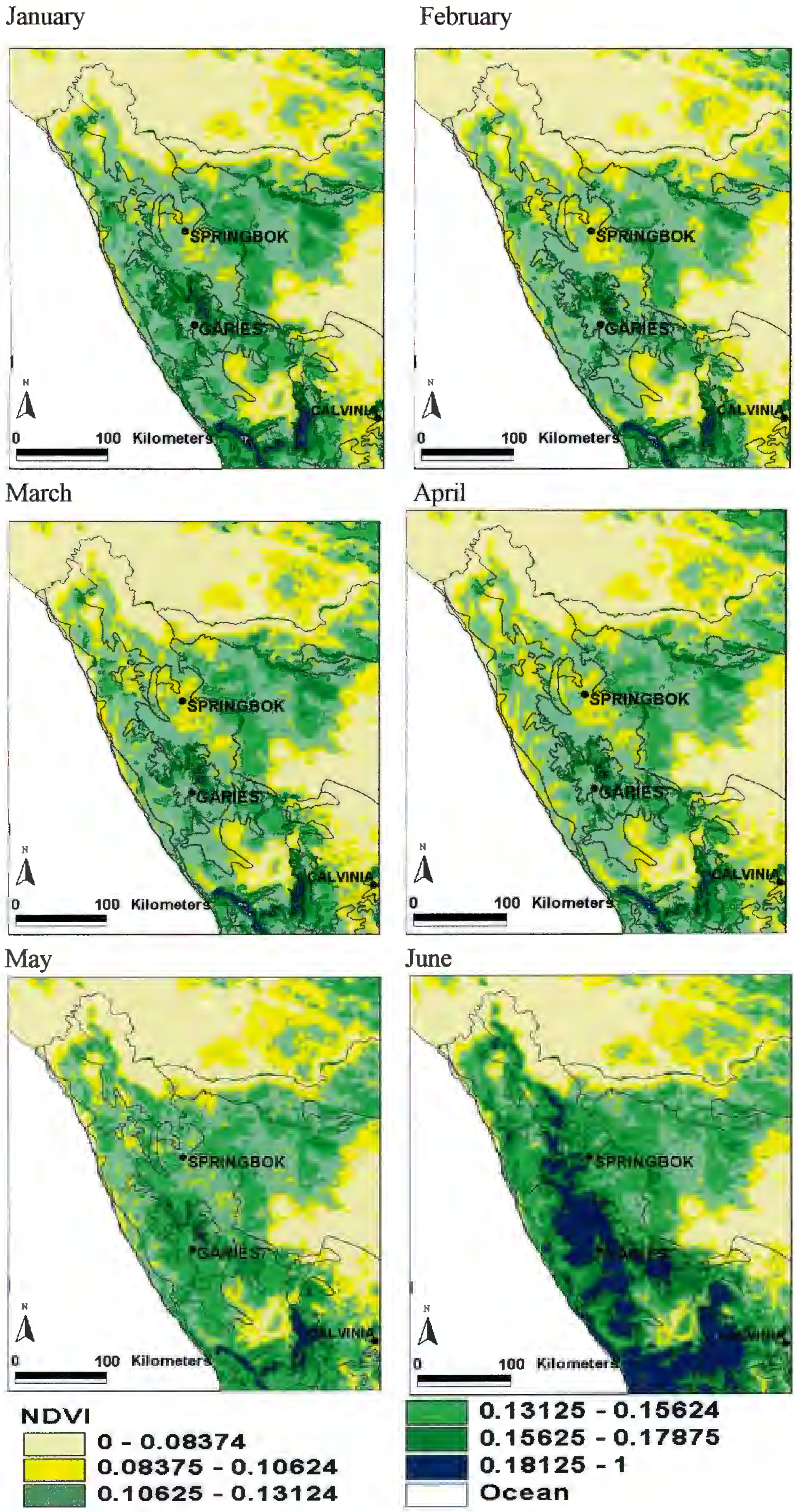
To relate NDVI to climate a multiple regression model was developed using the Best Subsets Method (STATISTICA 6.1) for mean NDVI of all the vegetation types. This provided the following equation ($n = 1225$, $df = 4$, Adjusted $R^2 = 0.4386$, $p < 0.001$):

Mean NDVI = 151.88 + 0.09* “Mean precipitation” – 1.72* “Mean maximum temperature” + 2.06* “Mean minimum temperature” –0.05* “Total annual PET”

When the Bushmanland and Orange River Nama Karoo vegetation types were taken out of the analysis a larger proportion of the variation was explained ($n = 772$, $df = 4$, Adjusted $R^2 = 0.522$, $p < 0.001$).

Figure 3 shows the changes in NDVI values from month to month and indicates the timing of ‘greening up’ and growth. Summer months showed low productivity in most areas with the first sign of an increase in growth in May in Lowland and Upland Succulent Karoo and a major change in June. Winter months showed higher productivity in the predominantly winter rainfall areas with the peak NDVI occurring in August. Spring still showed a high productivity with the major drop in NDVI occurring in November. The areas of highest elevation along the mountain ranges maintained a high NDVI year round. East of the Kamiesberg there appears to be a rain shadow with little change in NDVI throughout the year. The Knersvlakte also showed very little change in NDVI throughout the year in comparison to the surrounding vegetation. The summer rainfall areas seemed to follow the growth patterns of the winter rainfall areas but on a smaller scale.

seems odd! How does this compare with observed phenology of Nama Karoo plants?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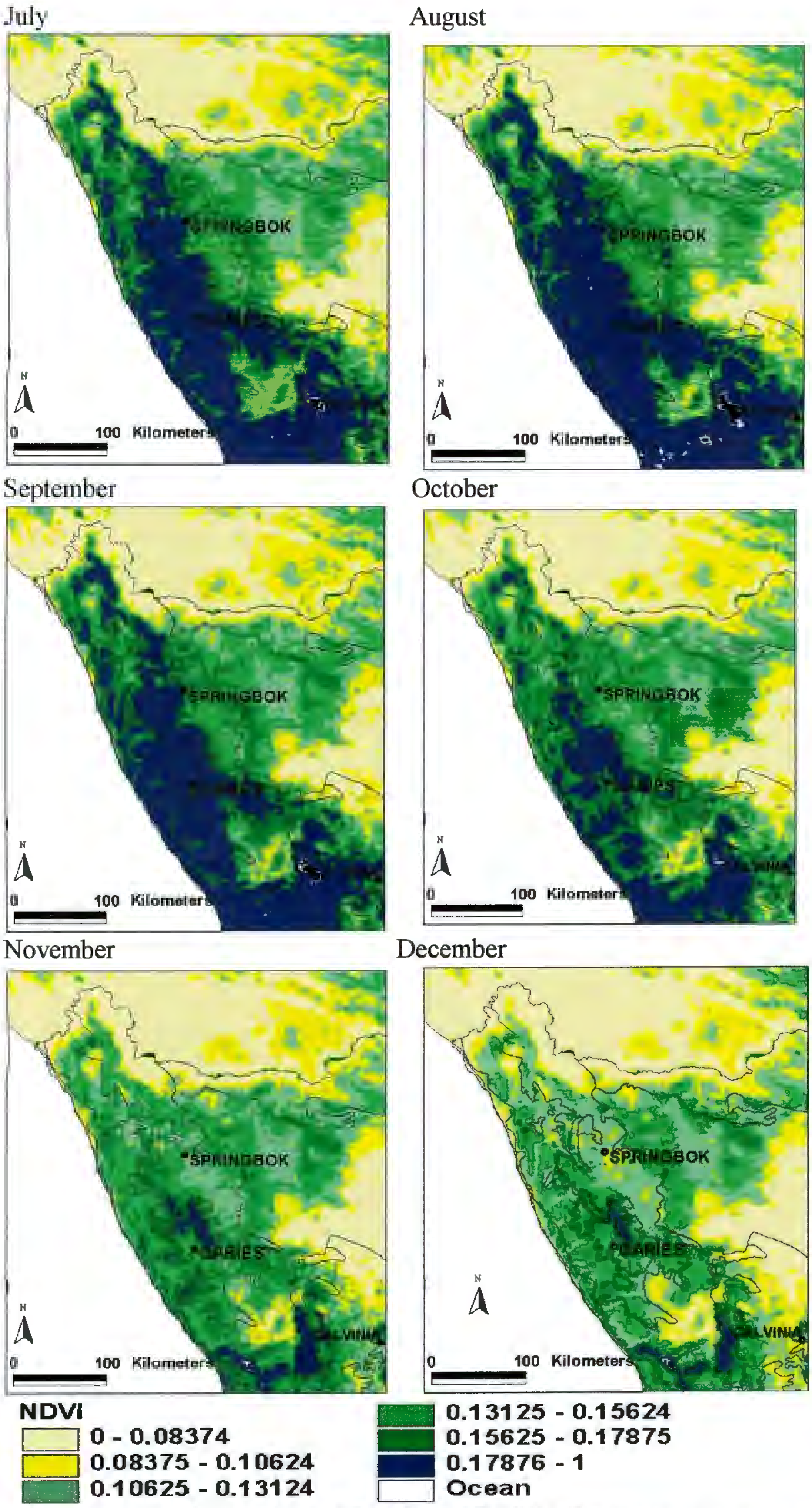

Fig 3. Monthly Composites of the Mean NDVI in the Greater Namaqualand Area for the period 1985 to 2001.

The seven different vegetation types found within the study area each had their own specific NDVI signal (Figure 4). Most of the vegetation types showed an increase in NDVI from May to August and a decline from September to April. Mountain Fynbos and North Western Mountain Renosterveld had the highest NDVI signals throughout the year. Upland Succulent Karoo, Lowland Succulent Karoo and Strandveld Succulent Karoo all had similar NDVI signals, except where Strandveld Succulent Karoo dropped below 0.1 in autumn. Bushmanland and Orange River Nama Karoo had fairly flat NDVI signals throughout the year, whilst Bushmanland was slightly higher.

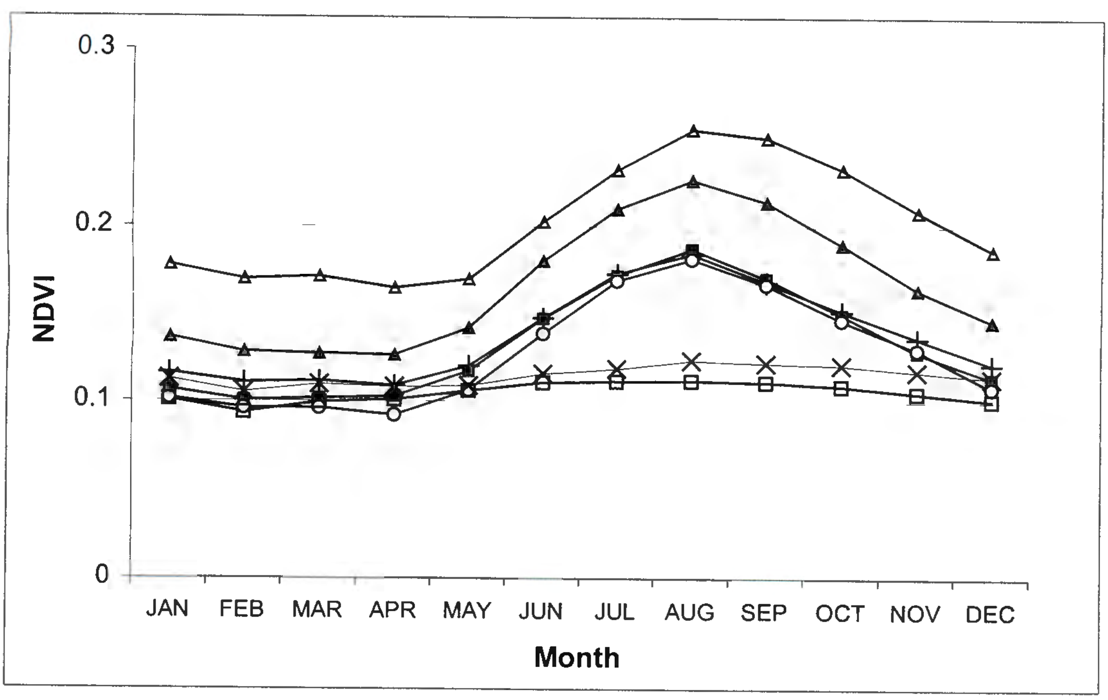

Fig 4. NDVI signals for the different vegetation types (Low and Rebelo) found in the Greater Namaqualand Area. (Δ= Mountain Fynbos, ▲= North Western Mountain Renosterveld, ■ = Upland Succulent Karoo, + = Lowland Succulent Karoo, ○ =Strandveld Succulent Karoo, × = Bushmanland, □ = Orange River Nama Karoo).

In Figure 5 each colour indicates a different month except for August, where the month is split into three, 10-day units. Yellows indicate summer months, browns indicate autumn months, blues and greys indicate winter months and greens indicate spring months. This figure explains when the maximum growth or productivity occurs.

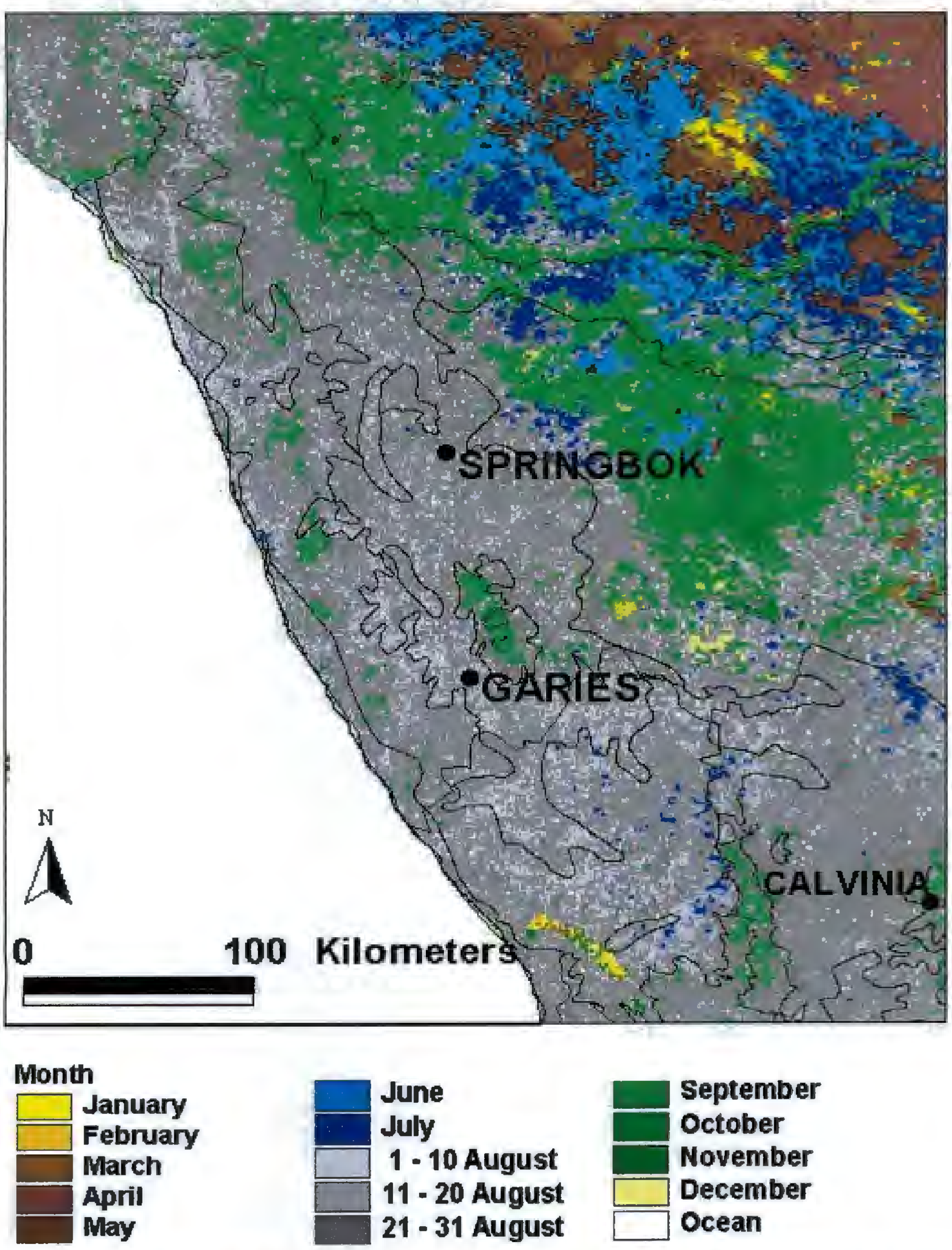

Fig 5. Month of Maximum NDVI for the Greater Namaqualand Area for the period 1985 to 2001.

The highest NDVI signal for the majority of Namaqualand was in August. The three mountain ranges, the Kamiesberg, Hantamsberg (directly north of Calvinia) and Bokkeveldberge all had patches that peak in spring. The Bushmanland area achieved its highest NDVI in spring. North of the Namibian border the NDVI peak occurred in winter (June/July) and further east into Namibia it occurred in autumn (March-May). Three of the river valleys stand out. The Koa River valley had its peak NDVI in November whilst the Orange River valley's peak NDVI occurred in spring (September). The Olifants River irrigation areas stood out with a peak in mid summer and in the beginning of autumn.

The analysis of correlations between month of peak NDVI (August) and climatic variables occurs in Table 3. In general, median rainfall in winter, PET in winter and solar radiation in winter showed the strongest significant relationships with NDVI. The strength of the correlation declined when Bushmanland and Orange River Nama Karoo were excluded. This was probably because Orange River Nama Karoo peaked in spring and it showed strong negative correlations with PET, solar radiation and temperature. Bushmanland, Renosterveld and Mountain Fynbos were generally poorly correlated with climatic variables. Strandveld Succulent Karoo was significantly correlated with most of the variables. Upland and Lowland Succulent Karoo both showed significant correlations between the variables and NDVI although Upland Succulent Karoo showed stronger relationships.

To relate month of maximum NDVI (chosen as August) to climate a multiple regression model was developed using the Best Subsets Method (STATISTICA 6.0) for all of the vegetation types (n=1225, df=4, adjusted R^2=0.5797, p<0.001):

Mean NDVI in August = 161.15 – 2.77 * "Maximum temperature in July" + 6.97* "Minimum temperature in July" – 1.62* "Sum of PET in June, July and August" + 5.53* "Sum of median rainfall in June, July and August"

Table 3: Correlation matrix of Mean NDVI in August versus climatic variables. Correlations are given as r values (Spearman Rank Correlation). Significance values are given as: p<0.001=*, p<0.01=**, p<0.05=*.**

August vs:	All 7 Vegetation types N=1225	5 vegetation types[1] n=772	Mountain Fynbos n=20	North Western Mountain Renosterveld n=30	Upland Succulent Karoo n=378	Lowland Succulent Karoo n=300	Strandveld Succulent Karoo n=40	Bushmanland n=336	Orange River Nama Karoo n=114
Median Rainfall (June+July+ August)	0.74***	0.66***	0.46**	0.31*	0.74***	0.53***	0.81***	0.03	0.03
PET(June+July+ August)	-0.72***	-0.67***	-0.26	-0.34*	-0.76***	-0.53***	-0.91***	0.04	-0.69***
Solar Radiation (June+July+ August)	-0.72***	-0.66***	-0.31	-0.29	-0.75***	-0.57***	0.84***	0.08	-0.47***
Maximum Temperature (July)	-0.15	-0.38**	-0.47*	0.13	-0.39**	-0.41**	-0.78***	-0.08	-0.67***
Minimum Temperature (July)	0.27*	-0.04	-0.06	0.35*	0.04	0.03	-0.64***	0.04	-0.63***

[1] this analysis excludes Bushmanland and the Orange river Nama Karoo.

Discussion

NDVI is a useful tool for detecting vegetation growth in arid and semi arid areas (Malo and Nicholson 1990) and the results in this study show that NDVI can be applied to areas such as the greater Namaqualand area. Elevation, rainfall seasonality and vegetation type seem to have a large influence on NDVI patterns in the greater Namaqualand area. However comparisons between surface measurements and satellite measurements could be important to do in order to establish the accuracy of satellite measurements in this area.

Each of the different vegetation types within the study area had different temporal NDVI signatures. Fynbos and Renosterveld had the highest NDVI signals while the two Succulent Karoo types and Strandveld grouped together with fairly similar signals throughout the year. In most of the Namaqualand winter rainfall area plant growth starts in May/June and maximum NDVI is achieved in August. This varies slightly from year to year with variation in the start of the rainy season. Most notable, were the flat temporal signatures of Bushmanland and Orange River Nama Karoo indicating very little growth and low biomass production throughout the year. The month of peak rainfall was in June for all the vegetation types except Bushmanland and Orange River Nama Karoo where the peak NDVI signal was in March.

The mountain ranges along the west coast separate the winter rainfall and summer rainfall areas and form an important barrier to the cyclonic westerlies that provide winter rainfall to the Namaqualand area (Desmet & Cowling 1999b, Cowling *et al.* 1999). Evidence of this is shown by the rain shadow directly east of the Kamiesberg Mountains. The difference in rainfall seasonality between The Succulent Karoo vegetation types and the Nama Karoo vegetation types should reveal a contrast in NDVI and growth. However, this does not appear on the images. The zone between the Succulent Karoo and the Nama Karoo is a mix of abrupt and gradual transitions (Rutherford 1997), which may explain the lack of a definite change between vegetation types. Further, the images show that the winter rainfall areas are greening up in much the same way as the summer rainfall areas only on a smaller scale. This could firstly be explained as coincident considering the extremely low annual NDVI values that the Nama Karoo has. Alternatively it could be explained by the fact that dew, which is more widespread than fog in the Karoo, occurs in autumn (April/May) (Desmet & Cowling 1999b) and thus prolongs the season for soil moisture. An unexplained pattern is the high NDVI area along the western edge of the Bushmanland area, which may be receiving some winter rainfall.

Mountain range peaks tend to have cooler temperatures and higher rainfall in the rainy season which influences the type of vegetation present (Fynbos and Renosterveld as apposed to Succulent Karoo types) (Low & Rebelo 1996). This results in high NDVI values year round. As elevation decreases there tends to be lower NDVI and lower biomass. An exception to this is in the low-lying Olifants River valley, which has very high NDVI values, and growth peaks in mid summer. This reflects the extensively irrigated crop farming and cultivation in the valley. The Orange River valley on the other hand is very dry except for patches where very localized irrigated crop farming occurs on fertile banks. The Koa River valley also stands out and has a higher NDVI than the surrounding vegetation of Bushmanland and the Orange River Nama Karoo. Directly next to the Koa River valley there is a patch of higher NDVI, which coincides with the occurrence of extensive Kalahari dune fields. Coastal fog may account for localized patches of higher NDVI values and an early peak of NDVI in the Lowland Succulent Karoo and Strandveld Succulent Karoo of the west coast.

Elevation and rainfall influence growth in different vegetation types and this is reflected in different NDVI values. This study has shown several significant relationships between NDVI and a range of climatic variables for both the entire study area and for specific vegetation types. Most climatic variables were significantly correlated with NDVI, the most significant of which were precipitation variables (mean precipitation, total median rainfall, the sum of median rainfall in June, July and August) and PET (which was negatively correlated to NDVI). Thus, in this region, NDVI increases with an increase in precipitation and a decrease in PET. Bushmanland and Orange River Nama Karoo are predominantly summer rainfall regions and this was reflected in their relationship to a slightly different suite of climatic variables. Orange River Nama Karoo was more significantly correlated with temperature and PET than with rainfall. This is probably due to the very hot and arid conditions in the Orange River valley and the very high annual evaporation of greater than 3000 mm (Schulze 1997). A similar result is found in the northern Sahel (the grazing lands of Gourma) where the NDVI-precipitation relationship becomes unpredictable below 250 mm of rainfall and a stronger relationship is found between NDVI and evapotranspiration (Milich & Weiss 2000a & b). Upland Succulent Karoo and Strandveld Succulent Karoo showed stronger relationships than Lowland Succulent Karoo, possibly because extra variables such as fog and patches of quartz fields may explain more of the variance.

Due to the fact that climate has a large role to play in vegetation dynamics the model of NDVI and climatic variables explained a large amount of the variance (R^2 = 0.4386) which increased to $R^2 = 0.522$ when the summer rainfall areas were removed from the analysis. Most of the variance in the model was explained by precipitation and PET. Including altitude, soil type and some sort of index of other water sources (fog and dew) may increase the explanation of variance in this model.

The month of maximum NDVI was in August in the winter rainfall areas, whilst the summer rainfall areas peak in spring (September) and in late autumn (April/May). Correlation analysis for the month of August showed similar trends to that for Mean Annual NDVI. For this analysis we experimented with multi-month integrals (e.g. June + July + August) as in a number of other studies (Malo & Nicholson 1990, Nicholson *et al.* 1990, Lee *et al.* 2002). We found high correlations between NDVI in August and the concurrent plus two previous months of Median rainfall and PET. The lag between rainfall and vegetation response could be due to vegetation responding to soil moisture rather than directly to rainfall as suggested by Malo & Nicholson (1990). This is supported by the idea that "competition for limited soil moisture is the overriding determinant of community structure in arid and semi-arid areas" (Cowling & Hilton-Talor 1999). The model for NDVI in August explained an even higher degree of variance than the model for Mean annual NDVI ($R^2 = 0.5797$), most of the variance was explained by precipitation and PET, which suggests that annual production is highly dependent on rainfall and temperature extremes.

Some of the limitations in these models are due to the databases we used in this project. One of the limitations of the data from the South African Atlas of Agrohydrology and Climatology (Schulze 1997) is that values at specific points were initially derived either by regression analysis or by other simulations. Thus values at a specific point may not be accurate unless they are near to weather stations where actual data was recorded (Schulze 1997). In terms of very arid areas such as Bushmanland where there is very little vegetation cover, it would be more useful to use coefficient of variation of NDVI as a measure of vegetation biomass (Weiss *et al.* 2001).

NDVI data have been used successfully to monitor regional to global scale vegetation patterns (Holben 1986) in many areas around the world. The results from this study show some clear patterns within the different vegetation types and the climatic variables that explain the variance within them. Further improvement on these models could prove very useful in a number of applications. Aside from what has been done in this project there are a number of applications that NDVI can be used for in the future in this area and in South Africa in general. NDVI measurements can be used to improve our understanding of plant-climate interactions (Sellers *et al.* 1996) and a useful application would be to try and use NDVI to determine links between growth and flower production for the use of the Namaqualand flower tourism industry.

NDVI measurements have been used to create large databases used in the generation of global climate models (Sellers *et al.* 1996). NDVI could potentially be used for identifying areas that are becoming desertified; although this may need higher resolution satellite data (Weiss *et al.* 2001) such as MODIS satellite data (Zhang 2003). NDVI can also be applied to the monitoring of drought conditions (Hellden & Eklundh 1988, Cited by Nicholsen *et al.* 1990) and could be used as an aid in setting grazing capacity guidelines for the Department of Agriculture, an example of which has been done in the eastern Karoo (Archer 2003). An interesting future application would be to compare the start of plant growth from year to year to see if a shift in timing or even if a shift in vegetation type is occurring. A number of studies have looked at interannual comparisons (Townshend & Justice 1986), which could be useful for looking at changes in vegetation over years and decades. This could be useful in arid areas where NDVI could be used to determine the extent of desertification as well as for drought early warning systems (Henrickson 1986, Hutchinson 1991).

Any number of these applications will be useful in conjunction with the many conservation initiatives such as the Succulent Karoo Ecosystem Plan (SKEP) that are underway in the greater Namaqualand area. Considering that current and future land use patterns are important factors determining the future conservation of the greater Namaqualand area (Todd & Hoffman 1999) it is important for conservationists to use as many tools as possible to solve problems that threaten ecosystems. NDVI is not just a tool that will provide us with interesting science but also a tool that can be used to help scientists in the on-going effort to better understand these unique vegetation types, as well as to conserve the numerous endemic species in this area and the general condition of the ecosystem at large.

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