# Geospatial analysis of meteorological drought impacts on southern African biomes

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## Abstract

Within southern African biomes, droughts are recurrent with devastating impacts on ecological, economic and social security. As southern African rainfall continues to decline, there is a high risk of drought-induced vegetation decline. In this context, understanding drought impacts on vegetation are of extreme importance for effective mitigation measures. Information on the impacts of drought on natural vegetation at the biome level is scanty and remains poorly understood.Most studies on the impacts of drought on vegetation have focused on on crops, largely ignoring natural vegetation. The few existing studies on natural vegetation are based on experiments and measurements at individual tree level which are not representative of the biomes. In this study, we have analyzed and quantified the impacts of drought on southern African biomes using the vegetation condition index (VCI). The analysis was done at dekadal (every 10 days), monthly and seasonal (October-April) timescale. VCI was computed from SPOT VGT & Proba-V data for the period 1998-2017. VCI values range from 0 to 100, with VCI < 50 indicative of vegetative drought conditions and VCI<36 showing extreme drought. Our result showed a significant ($p<0.05$) decrease in both the drought impact intensity and the percentage area of vegetation affected by drought especially over the savanna biome over the last 20 years (1998-2017). A plausible hypothesis to explain the decreasing trend in drought impact on vegetation is that African savannas are greening up possibly due to an increase in the tree cover as more farmland is being abandoned due to decreased and erratic rainfall. The resultant tree dominated habitats that form after the abandonment of farmland show more resilience to drought than crops. However, this hypothesis needs to be tested and this calls for further studies on tree cover trends over southern African biomes. The results of this study provide crucial information on vegetation resilience and ecosystem conservation restoration programs.

Keywords: Drought, Southern Africa

## Introduction

Southern African biomes provide important ecological services, particularly to rural populations in the region. These biomes are however increasingly coming under pressure from climate change-induced droughts (Dai, 2011; Zribi, Dridi, Amri, & Lili-chabaane, 2016). A number of studies on drought trends e.g. (Rouault & Richard, 2005; Trenberth et al., 2013) have reported an increasing trend in drought occurrence over southern Africa. Simultaneously, the southern African countries are also experiencing rapid population growth (CARIAA, 2015) leading to increased pressure on the natural vegetation resources. In addition, the biomes of southern African support several wildlife national parks e.g. Central Kalahari Game Reserve in Botswana, Kruger National Park in South Africa, Etosha National Park in Namibia, Kafue National Park in Zambia, Luenge National Park in Angola, Gonarezhou National Park in Zimbabwe etc. As such monitoring, the spatial distribution of drought impacts on vegetation can provide the national park authorities with important information for drought early warning systems (Kusserow, 2017) which can help to minimize the drought impacts on the wildlife.

Drought occurrence is generally linked to precipitation deficits (meteorological drought) (Zargar, Sadiq, Naser, & Khan, 2011) and vegetative drought is identified based on soil moisture deficits. The determination of drought impacts  at subcontinental scales and over diverse landscapes is complex due to the difference in elevation, vegetation, climate and geology (F. N. Kogan, 1990). As such, these landscape differences should be removed in order to accurately assess drought i.e. weather impacts on vegetation (F. N. Kogan, 1990) This calls for robust drought indices which are invariant to the landscape and also standardized to enable the comparison of drought impact across the diverse vegetation landscapes.

Traditionally, most studies on drought impacts on vegetation are based on precipitation anomalies derived from meteorological ground stations. The resultant vegetative drought impact is viewed as proportional to the water deficit (Gouveia, Trigo, Sanatiago, & Vicente-Serrano, 2016). The most frequently used rainfall based drought indices include: (i) Standardized Precipitation Index (SPI); (ii) Palmer Drought Severity Index (PDSI); (iii) Aridity anomaly index (Leelaruban, Akyuz, Oduor, & Padmanabhan, 2009); and (iv) Standardized Precipitation Evapotranspiration Index (SPEI) (Vicente-Serrano, Beguería, & López-Moreno, 2010). The SPEI is the most robust as it incorporates the effects of evapotranspiration in drought assessment (Bento, Gouveia, Dacamara, & Trigo, 2018).

The meteorological drought indices are applicable for localized places with dense rainfall station network which permit the interpolation of drought conditions in areas without rainfall stations with small errors (Zribi et al., 2016). However, over large areas with a sparse network of rainfall stations as in southern African (Mutowo & Chikodzi, 2014), the spatial interpolation techniques can result in large errors. In addition, the general weakness of rainfall-based drought indices is that they provide indirect information about drought impact on vegetation based on the rainfall deficits.

The deficiency of meteorological drought indicators coupled with the availability of remotely sensed satellite data have given rise to a suite of vegetation based indices which provide direct information on vegetation health status (Zribi et al., 2016). Among the satellite-based vegetation indices, the Normalised Difference Vegetation Index (NDVI) is the most commonly used spectral index for monitoring vegetation conditions. NDVI measure the greenness of vegetation and is calculated as:

$$\mathrm{NDVI} = (\mathrm{NIR} - \mathrm{R})/(\mathrm{NIR} + \mathrm{R}) \qquad \text{(Eq.1)}$$

where NIR is the near-infrared reflectance and R is the red reflectance (Zribi et al., 2016). The NDVI values range from -1 to 1, with low NDVI values indicating a weak level of photosynthetic activity which translates to unhealthy vegetation (Theodore, Curtis, & Gamble, 2010). Thus, NDVI is useful for assessment of the intra-annual and inter-annual weather-related vegetation growth (Leelaruban et al., 2009). Several studies e.g. (Theodore, Curtis, & Gamble, 2010) have observed a strong positive linear relationship between NDVI and rainfall. This makes NDVI an ideal indicator for drought monitoring.

In drought monitoring studies, the current NDVI of a pixel is usually compared to long-term average statistics e.g. mean, maximum, standard deviation. This provides information on whether the current vegetation is either below or above average expected growth. The most commonly used drought indices are (i) Vegetation Anomaly Index (VAI); (ii) Drought Severity Index (DSI), combining the Vegetation Anomaly Index and evapotranspiration anomaly index; and (iii) Vegetation condition index (VCI) (Zribi et al., 2016).

The VCI compares the NDVI of a given period and pixel (NDVIt) with its minimum ($NDVILTmint$) and maximum (NDVI$LTmaxt$) and is calculated as:

$$\mathrm{VCI} = 100*(\mathrm{NDVIt} - \mathrm{NDVI}LTmint)/(\mathrm{NDVI}LTmaxt-\mathrm{NDVI}LTmint) \quad \mathrm{eq}\ldots.$$

The resultant VCI values range between 0 (unhealthy and stressed vegetation) and 100 (healthy and unstressed vegetation) (Felix N. Kogan, 2000). The concept of VCI is that maximum vegetation is associated with optimal weather i.e. warm and wet. On the other hand, minimum vegetation activity is associated with dry and hot weather (F. N. Kogan, 1990). Therefore, the maximum and minimum NDVI define the upper (favorable weather) and the lower (unfavorable weather) limits of the ecosystem resources in response to extreme weather conditions i.e. the pixel's "carrying capacity" (F. Kogan, 2002). VCI, therefore, provide a quick overview of how well the vegetation is growing and potential drought hotspots which might need further attention (F. Kogan, 2002).

VCI is ideal for vegetative drought impact studies as it captures the impact of weather conditions on vegetation across diverse vegetation landscapes (F.N Kogan, 1995). VCI has been tested in different parts of the globe (Africa, America, Europe, and Asia) for vegetative drought impact assessment (Zribi et al., 2016). VCI takes into account landscape composition in terms of fluctuations between prescribed maxima and minima of NDVI and is applicable in the semi-arid regions of southern Africa where water is the main limiting factor for vegetation growth (Bento et al., 2018).

Within the southern African region, most recent studies of drought on vegetation are localized and focus mainly on crops and largely ignore natural vegetation e.g. (Mutowo & Chikodzi, 2014).

There is no study to the best of our knowledge which analyzed drought impacts on natural vegetation for the entire southern African biomes. Consequently, the drought impacts on vegetation remain largely unknown for southern African biomes. Therefore, the main objectives of this study are to (i) analyse the spatial distribution of vegetative drought impacts across the southern African biomes over the last 20 years (1998-2017); (ii) analyse the space-time trends of vegetative drought impacts, and (iii) to determine biomes vegetative drought hotspots across the biomes, i.e. identification of biomes with high frequency of vegetative drought impacts.

## Method

### Study area

The study area covers southern African biomes and lies between latitude 6° N and -35° S and between Longitude 11° E and 41° E (Figure 1). The study area is covered by 9 main biomes (Figure 1) with the savanna covering greater part of the area. Greater parts of southern Africa, with the exception of the Cape province of South Africa receives rainfall mainly between October and April (Daron, 2014). The average annual rainfall for southern Africa is between 100 and 2500 mm. Southern African rainfall is highly variable and the region is frequently affected by drought with the recent 2015-16 being the most severe since the 1980s (Archer et al., 2017). One of the key phenomena regulating precipitation and the resultant droughts in southern Africa is the variations in the ocean temperatures (Morioka, Tozuka, & Yamagata, 2011; Reason, 2001), the so-called El Niño-Southern Oscillation (ENSO) (Lindesay, 1988).

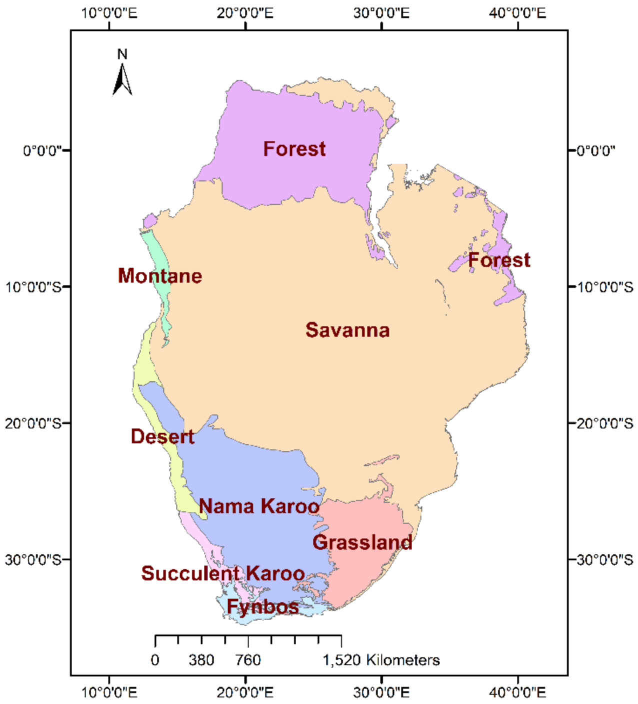


Figure 1: Study area showing southern African biomes.

## Remote sensing data

### 1) NDVI

We used SPOT & PROBA-Vegetation Normalized Difference Vegetation Index (NDVI) data from October 1998 to April 2017 available from Copernicus website (https://land.copernicus.eu/global/products/ndvi). The SPOT & PROBA-v is provided by VITO as a 10-day synthesis. Daily near-infrared bands (NIR) and red bands (R) are used to compute daily NDVI which is later aggregated at the end of 10 days (dekad) using the maximum value composite (MVC) technique. To reduce the impacts of cloud contamination, we first filtered the NDVI data using the Savitzky Golay algorithm using Timesat software (Jonsson & Eklundh, 2002). The filtered NDVI was then used to compute the VCI for vegetative drought impact assessment

### 2) Vegetation biomes

We analysed vegetative drought impact at biome level (Figure 1) as suggested by (Gouveia et al., 2016). We used the Terrestrial Ecoregions of the World data developed by (Olson et al., 2001) to analyse the drought impacts on vegetation. This data can be downloaded free from the WWF website (https://www.worldwildlife.org/publications/terrestrial-ecoregions-of-the-world). In order to simplify the biome data, we first re-classified the biome data into 8 main classes based on Rutherford biome classification method (Mucina & Rutherford, 2006). We then used the reclassified biomes data to extract the VCI for each biome and analyse the drought impacts on vegetation.

### Data Analysis

We analyzed vegetative drought impacts at dekadal (10 days), monthly and seasonal (October-April) timescales to capture both the intra-seasonal and inter-seasonal variability of drought impacts on vegetation. For monthly analysis, we only focused on the month of December and February. The month December is the midway of the growing season and is associated with rapid vegetation development with vegetation reaching the maximum production in February in Southern Africa. This way, we can evaluate the impact of early and late drought on vegetation which is critical for early warning systems and the development of mitigation measures.

### Vegetative drought impact assessment

For the purpose of mapping drought extent, we calculated 3-month SPI using the Software for the Processing and Interpretation of Remotely Sensed Image Time Series (SPIRITS). In order to accurately assess the drought impacts on vegetation, we calculated dekadal, monthly and seasonal VCI over the last 20 years (1998-2017). The VCI computation was done using the using the Monitoring for Environment and Security in Africa (MESA) Drought Monitoring Software (DMS) following (F.N Kogan, 1995):

$$\mathrm{VCI} = ((\mathrm{NDVIi} - \mathrm{NDVImin})/(\mathrm{NDVImax} - \mathrm{NDVImin})) \times 100\% \qquad \text{(Equation 2)}$$

Where; NDVI$i$ is the dekadal / monthly/seasonal NDVI value in the $i^{th}$ dekad / month/season and NDVImin and NDVImax are the minimum and maximum values of NDVI over the time series (1998-2017). The resulting VCI values are fixed in the range 0-100, with 50 representing mean vegetation conditions and 0 representing extremely dry vegetation conditions (F.N Kogan, 1995).

### Characterization of vegetative drought impacts intensity and areal extent

Several studies e.g. (Dutta, Kundu, Patel, Saha, & Siddiqui, 2015; Felix .N Kogan, 1997) have shown that VCI values of less than 50 are indicative of drought with values less than 36 showing extreme drought conditions. Based on this formulation, we re-classified the VCI maps into three classes as follows: (a) VCI < 36 – severe impact; (b) VCI >=36 & VCI< 50 - moderate impact; and VCI >50 – no impact.

In order to establish the biome with the most severe drought impacts, we computed histograms and boxplots showing the proportion of biomes with severe, moderate and no vegetative drought impact. For each vegetative drought impact class (severe impact, moderate impact, and no impact), we computed the percentage area of biome impacted by drought.

## Trends analysis

Intra-annual analysis

To understand the intra-annual variability of drought impacts, we extracted dekadal and monthly mean VCI values for each biome during the growing season (Oct- April) using the Software for the Processing and Interpretation of Remotely Sensed Image Time Series (SPIRITS). We then created a temporal matrix of VCI in order to show the dekadal trends of drought impacts on vegetation over the last 20 years (Figure 8).

## Inter-annual analysis

We computed a pixel-wise linear regression model in R software (Equation 3) on mean seasonal VCI values for each biome to establish the general trend in vegetative drought impacts across the study area using Equation 3:

$$y = \beta_1 + \beta_2 X + \epsilon \qquad \text{(Equation 3)}$$

Where y is the seasonal (October - April) VCI value from 1998 to 2017; x is the year (1998 to 2017); $\beta_1$ and $\beta 2$ are the intercept and slope of the seasonal VCI, respectively; and $\epsilon$ is the error term, the component of $y$ which is not accounted for by the regression model (Prabhakaran, 2018). In order to determine the VCI trend for each pixel, we calculated the slope using the least squares method (Equation4)

$$Slope = \frac{x\sum_{i=1} i * VCIi - \sum_{i=1} i \sum_{i=1} VCIi}{n * \sum_{i=1}^{n} i^{2} - \left( \sum_{i=1}^{n} i \right)} \qquad \text{(Equation 4)}$$

Where n is the number of years (20 years i.e. 1998-2017); and VCI*i* represents the seasonal mean VCI value in the $i^{th}$ year. When the slope>*i*, seasonal VCI is increasing, indicating a reduction in drought impact severity and when the slope <*i*, VCI is decreasing indicating the strengthening of drought impact on vegetation.).

To facilitate the comparison of VCI trends across the biomes, we calculated VCI z-score for each biome. The z-score defines the number of standard deviation (anomaly) from the mean. We computed the VCI z-score based on (Equation 5)

$$Z_{ij} = \frac{x_{ij} - \bar{x}_i}{\sigma_i} \qquad (5)$$

Where $Z_{ij}$ is the z-score; $x_{ij}$ is the raw value to be standardized i.e. the seasonal VCI; $\bar{x}_i$ is the mean of the population i.e. the mean seasonal VCI; and $\sigma_i$ is the standard deviation seasonal VCI. The resultant VCI z-score values are either positive or negative, indicating whether the VCI is above or below the average respectively.

## Vegetation drought impact frequency analysis

To analyse the vegetative drought impact frequency, we computed the number of dekads when the vegetation was: i) severely impacted by drought (VCI< 36); and ii) moderately impacted by drought (VCI >=36 & VCI< 50) during the growing season. The resultant frequencies were converted to percentages time to get the percentage time vegetation was under drought during the growing season

## Results

### Inter-annual vegetative drought impact spatial coverage and trends

The spatial variation of drought impacts over the past 20 growing seasons (1998-2017) is illustrated in Figures 2 & 3. Drought impact on vegetation is depicted using the red to yellow colours and the green colour indicate no drought impact on vegetation. We observed that drought impacts on vegetation mostly occur in December compared to February (Figure 3).

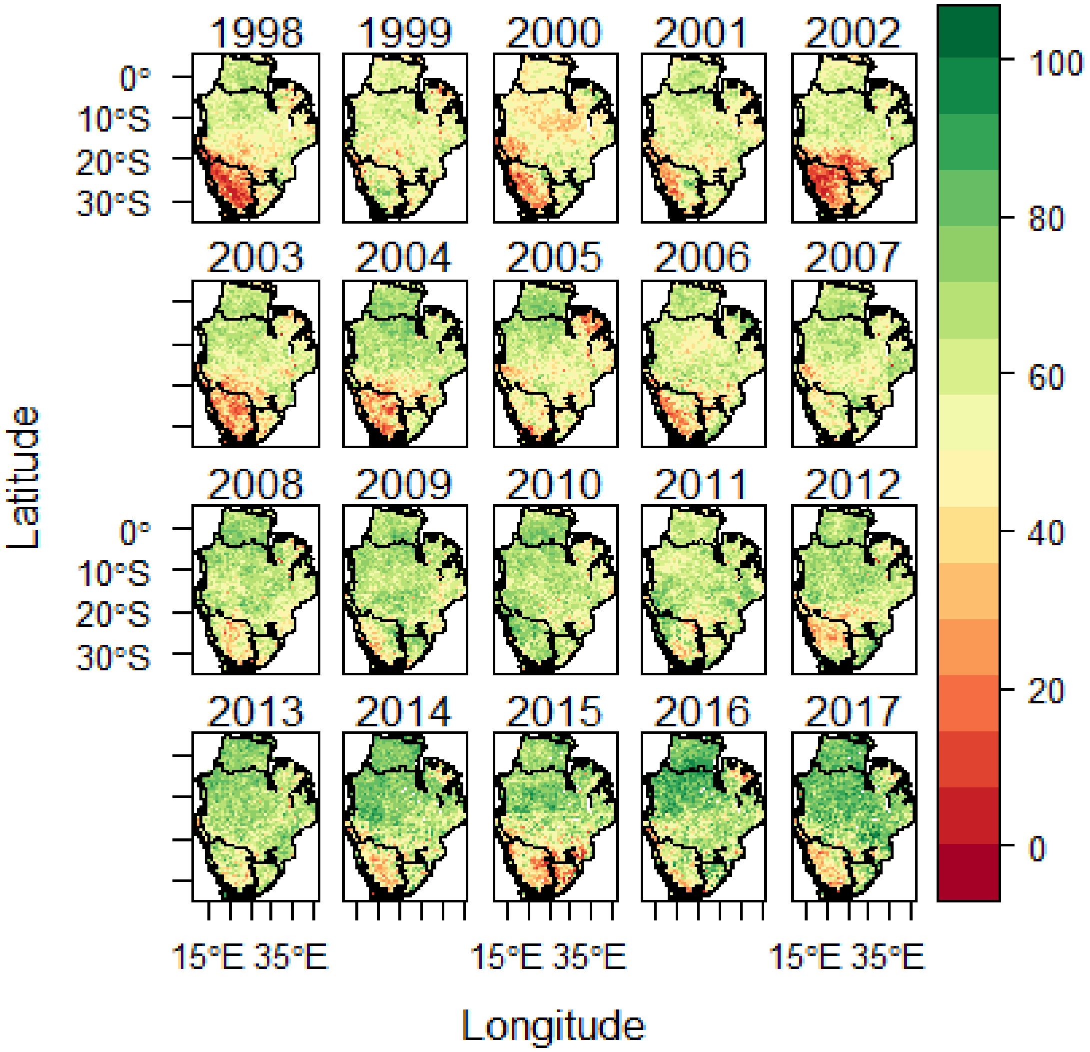
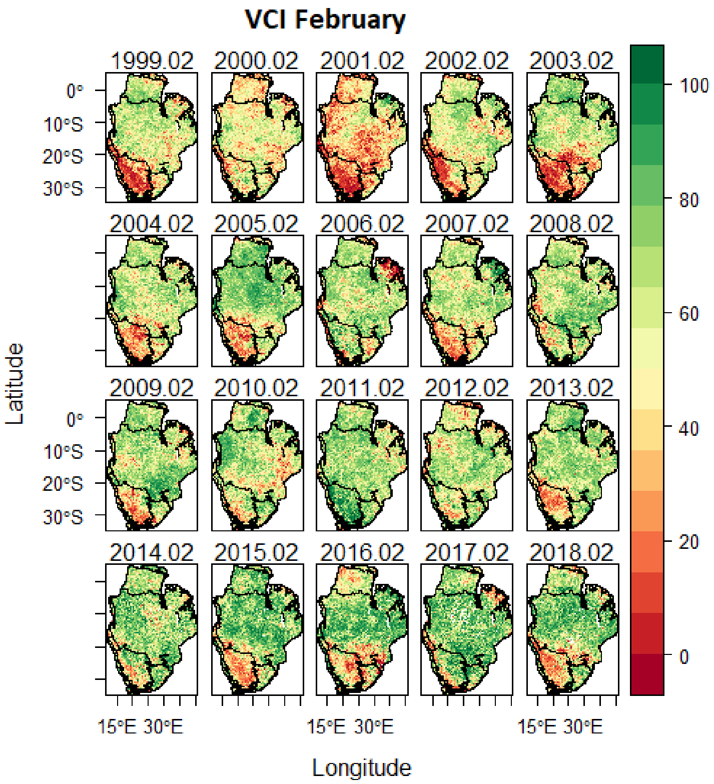


*Figure 2: Seasonal spatial trends of drought impacts on vegetation. Red -yellow colors indicate drought impact on vegetation and green color indicate no drought. Drought impacts have been decreasing over time. Note: the year indicates the start of the season e.g 1999 represents season 1999-2000.*


VCI February
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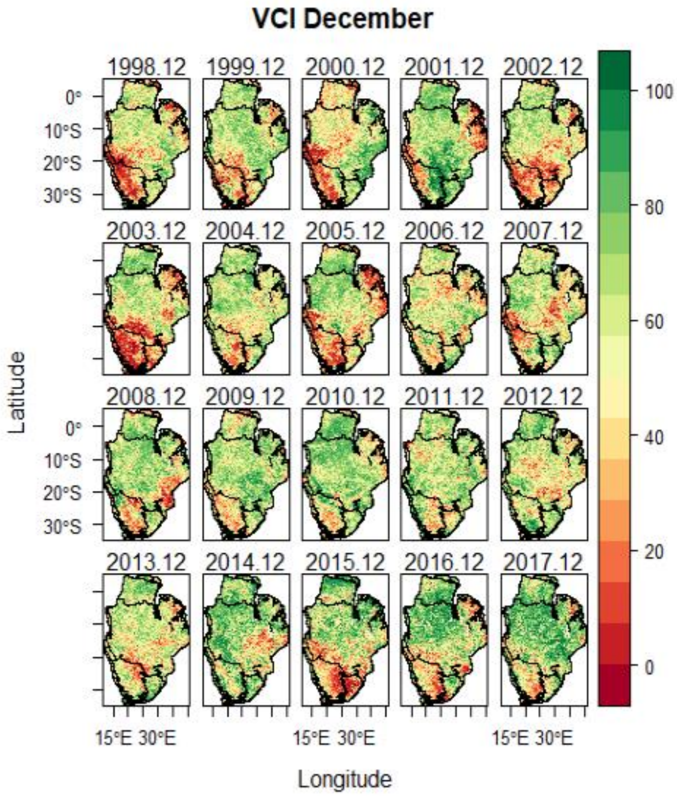
VCI December
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Latitude
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Longitude
100
80
60
40
20
0

*Figure 3: Monthly spatial trends of vegetative drought impacts. a) February b) December. Drought impact on vegetation generally occurs in December (rapid vegetation growth) than February (peak of vegetation development).*

From the VCI time-series images, the rainfall seasons 1998-1999, 2002-2003, 2003-2004 and recently the 2015-2016 season have more drought impacts on vegetation. This is also confirmed by the SPI maps which show the same seasons as among the driest seasons (Figure 4b).

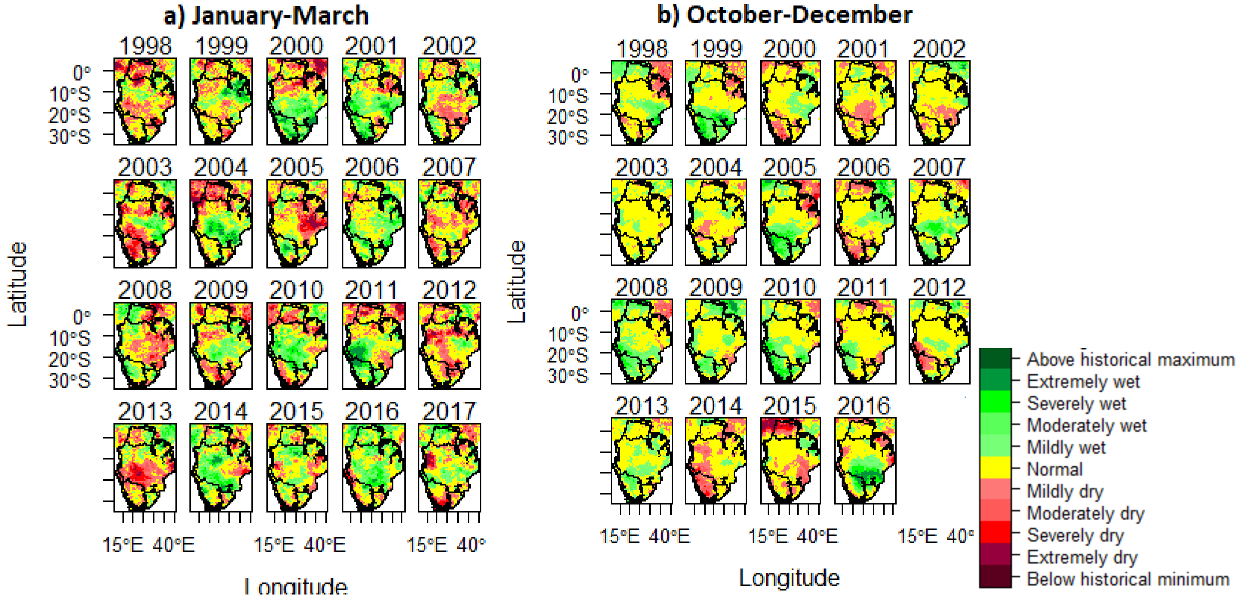

*Figure 4: 3-month SPI based on CHIRPS rainfall data. (a) January-March (b) October-December.*

Using the season 2015-2016 as an example, we found out that drought impact on vegetation generally increases with decreasing latitude (Figure 5). Most of the vegetative drought impacts are confined to biomes below latitude 20° South.

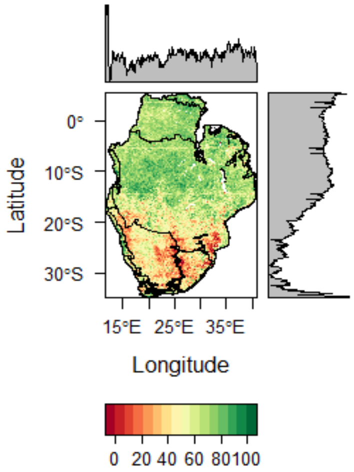

*Figure 5: Longitudinal & latitudinal variation of vegetative drought impacts during 2015-16 rainfall season.*

The latitudinal gradient exerts more control on vegetative drought impacts and this explains why the biomes at high latitudes e.g. Forest, Montane and northern parts of the savanna biome have a small area of vegetation impacted by drought (Figures 2 & 3).

**Drought intensity analysis**

Figure 6 shows the intensity and spatial extent of drought impacts on vegetation based on re-classification of the seasonal VCI (Figure 2) as follows; i) severe impact, VCI < 36; ii); moderate impact, VCI >=36 & VCI< 50; and iii) no impact, VCI >50). The reclassified VCI revealed that most of the drought impact on vegetation over the last 20 years falls in the severe impact category (Figure 6) and is confined to biomes below 20$^{o}$ latitude.

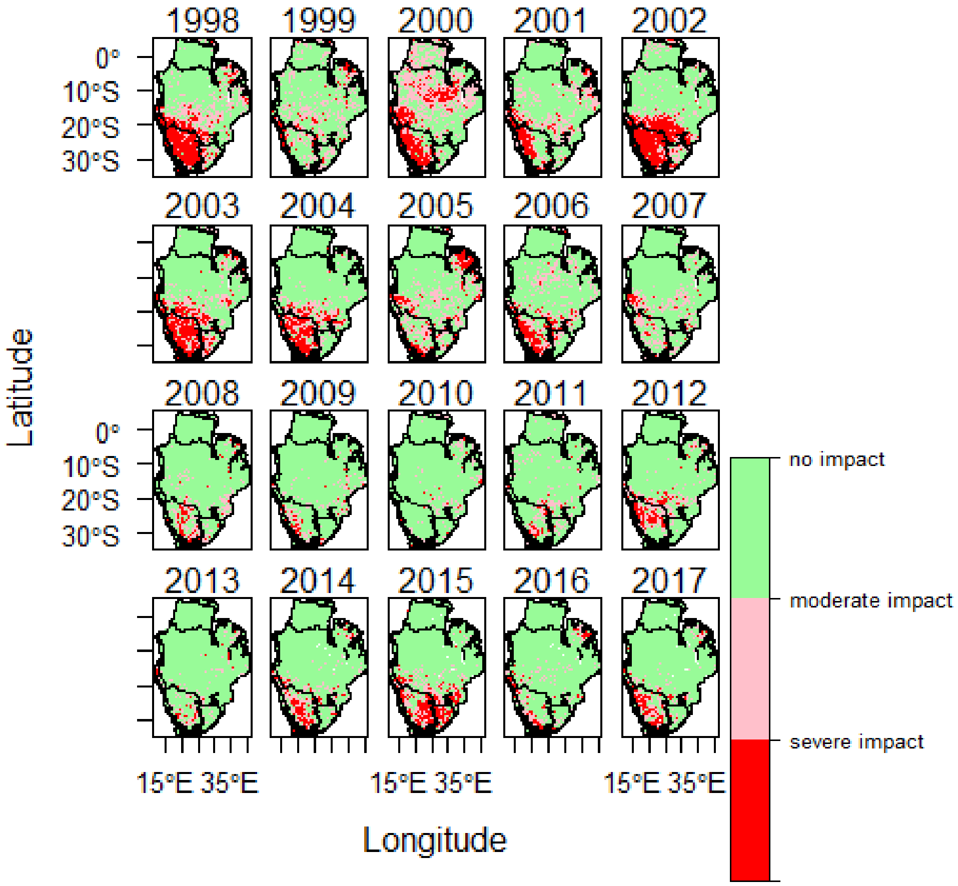

*Figure 6: Spatial trends of differential drought impacts on vegetation based on the re-classification of VCI (October - April)*

**The percentage area of vegetation affected by drought**

Figure 7 show boxplots of the mean percentage area of the biome with severe, moderate and no vegetative drought impact. Of all the biomes, the forest biome has the smallest mean area affected by drought over the last 20 years. The Nama Karoo biome has the highest proportion of vegetation pixels affected by drought with an average of 33 % of the biome's vegetation area affected by severe drought) every season (Figure 7). This is followed by the desert biome with an average of 24% of the biome's vegetation area affected by severe drought. The forest biome is least affected by severe drought impact.

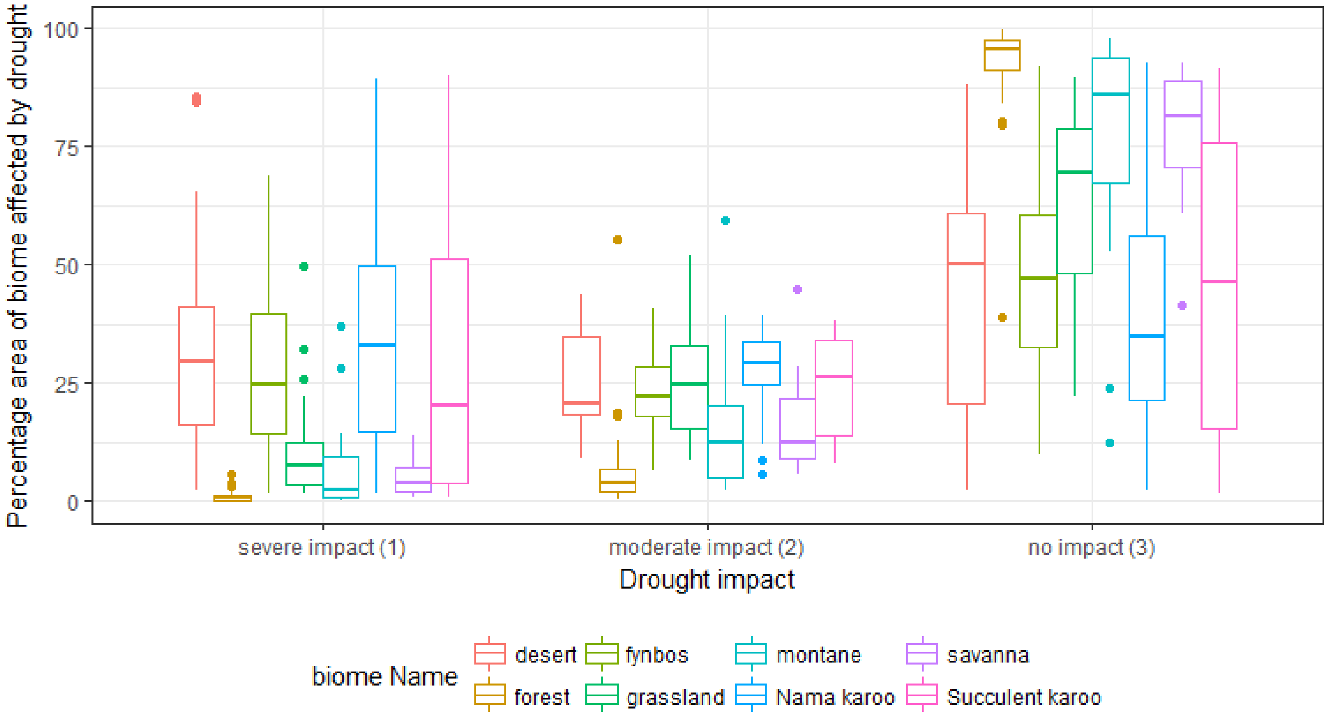

*Figure 7: Comparison of mean percentage area of the biome's vegetation area with severe (1), moderate (2), and no drought impact (3).*

## Temporal trends of vegetative drought impacts

### Intra-annual vegetative drought impact trends

The VCI matrix (Figure 8) shows the intra-annual trends of drought impacts on vegetation from 1998-2017 based on dekadal VCI data. A quick glance at the matrix show that the savanna and forest biomes are less affected by drought compared to other biomes. Even the most recent droughts of the 2014-15 and 2015-16 season are not pronounced in these two biomes (Figure 8). Severe vegetative drought conditions are mainly restricted to the Nama Karoo and desert biome (Figure 8)

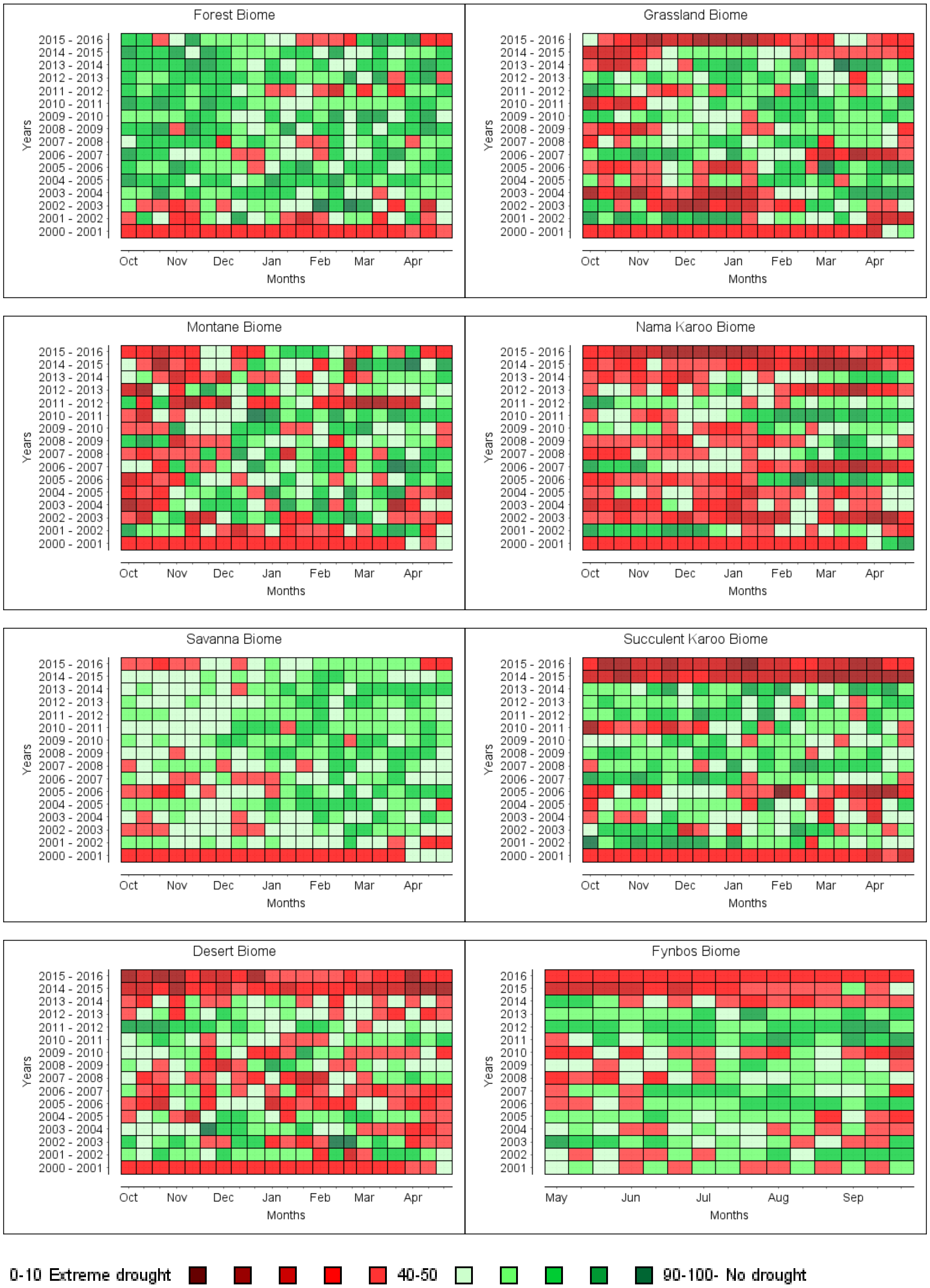

*Figure 8: Temporal variation of vegetative drought impacts. Severe drought impacts over the Nama Karoo and desert biome.*

## Inter-annual vegetative drought impact trends

Most studies suggest that the VCI cut-off for vegetative drought impact is 50 (Figure 9 black dotted line) with vegetation cover with VCI below 36 (Figure 9 red solid line) being the worst affected. Based on trend analysis, we observed a general increase in the mean seasonal VCI over time especially after the 2006-2007 season (Figures 9 & 10). The increase in VCI translates to a reduction in vegetative drought impacts. As observed during intra-annual vegetative drought impact trend analysis (Figure 8), the Karoo and desert biomes are also the worst affected at inter-annual time scale. On the other hand, the forest biome is the least affected by drought. This biome was only affected once during the 2000-2001 season when the VCI was 48.

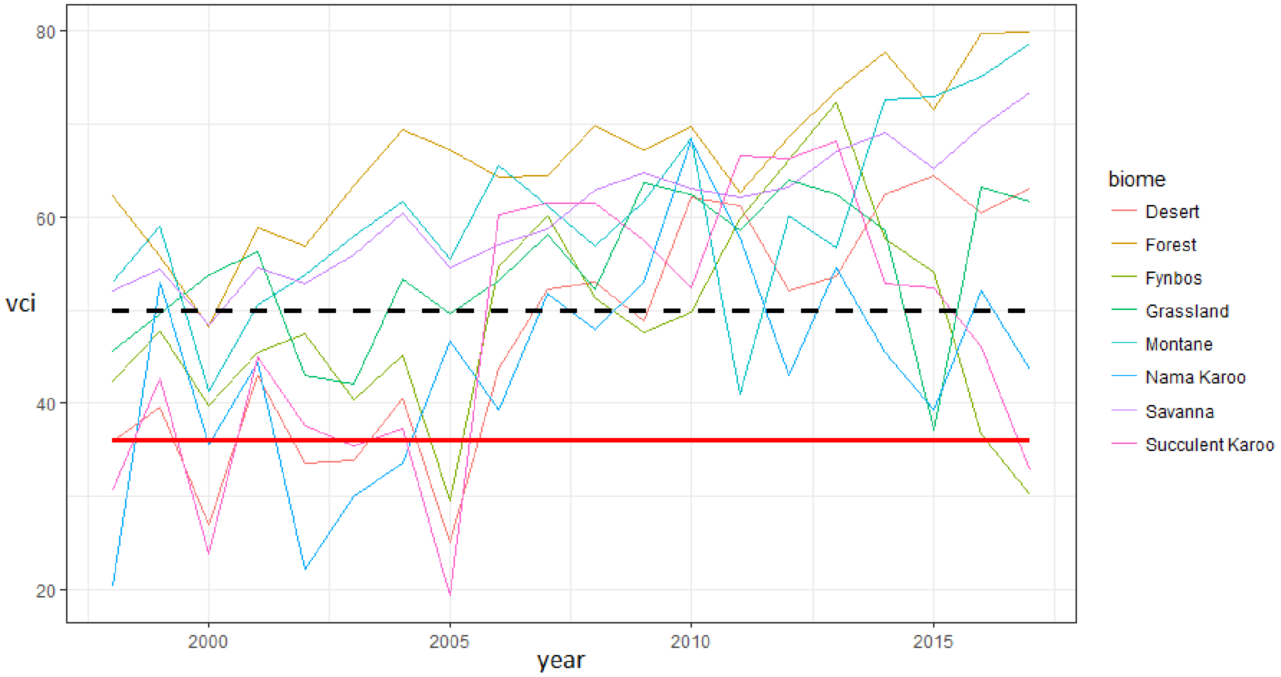

*Figure 9: VCI trends aggregated at biome level. There is a general increase in the vegetation condition index across all biomes indicative of the general decline of drought impacts on vegetation*

The results from the pixel-wise linear regression analysis generally showed a significant increase ($P< 0.05$) of VCI over the last 20 especially over the savanna biome (Figure 10b). We also observed a decreasing trend of VCI mostly around major cities (Figure 10b). However, this decreasing trend is not statistically significant (Figure 10a)

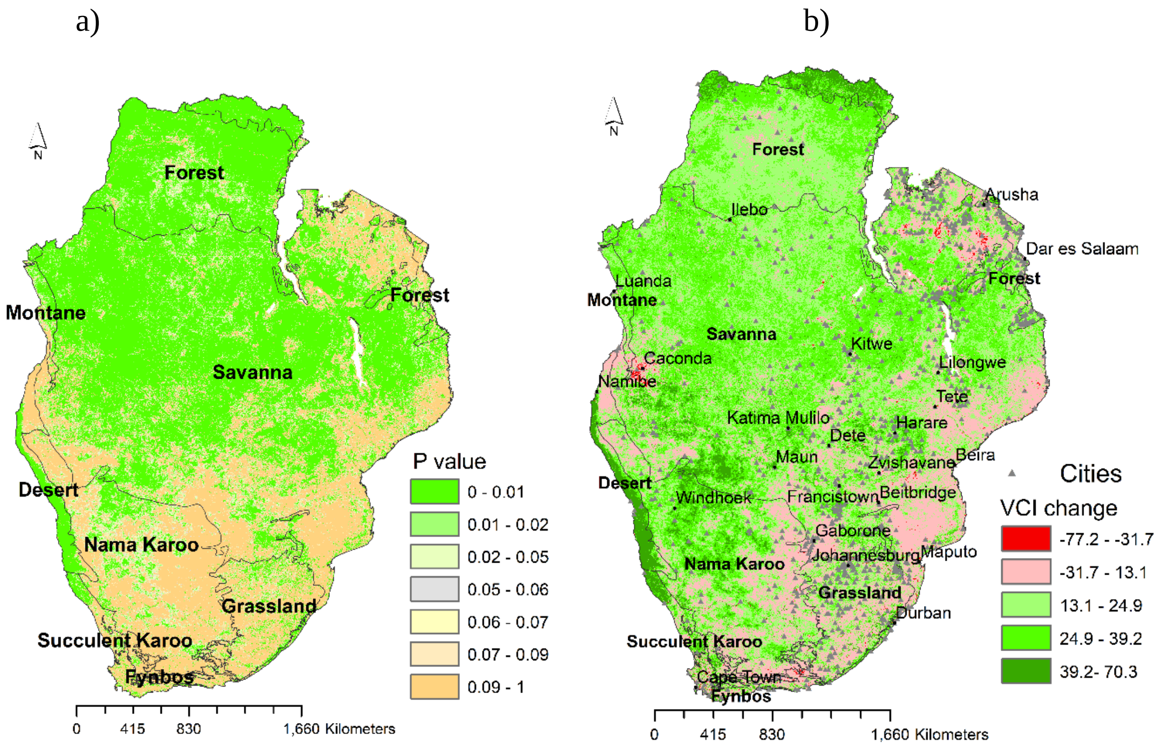

Figure 10: a) p values ($P<0.05$) b) Seasonal VCI (October- April) increase (+) or decrease (-)

The z-score trends analysis provides a summary of the average trends and vegetative drought impacts across the biomes (Figure 11). The savanna biome has the steepest positive trend and has the highest VCI z-score value of 2. This implies that drought impacts on vegetation have been declining over the savanna biome.

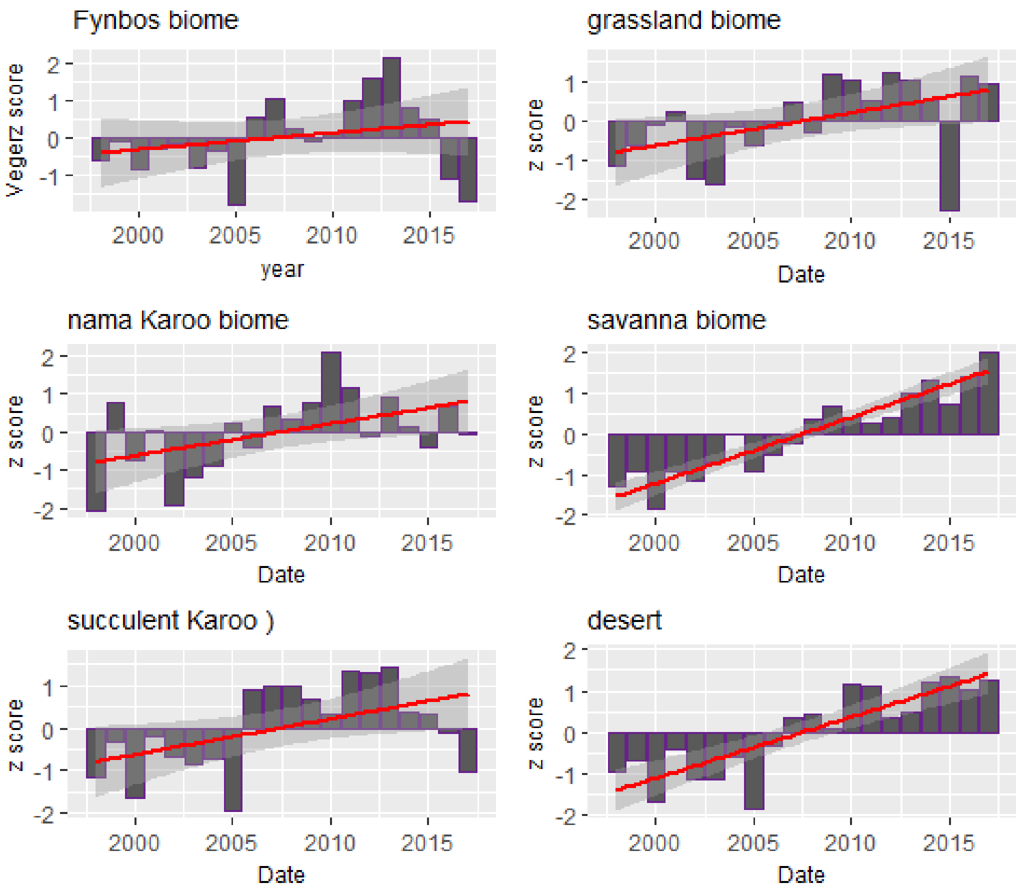

Figure 11: VCI z-score trends

## Vegetative drought impact frequency analysis

In this section, we present the results of the vegetation drought impact frequency analysis. Table 1 show vegetation drought impact frequency based on the percentage time a biome is affected by drought i.e. VCI <50 every 10 days during the growing season (October – April).

*Table 1: Vegetation drought impact frequency analysis based on the count of the dekads (10-day period) with VCI less than 50 during the growing season (October - April).*

| **year** | **Savanna** | **Nama karoo** | **Succulent Karoo** | **Montane** | **Grassland** | **Fynbos** | **Forest** | **desert** |
|---|---|---|---|---|---|---|---|---|
| 2001 | 3 | 5 | 1 | 10 | 4 | 6 | 8 | 3 |
| 2002 | 5 | 19 | 5 | 10 | 13 | 4 | 7 | 8 |
| 2003 | 2 | 15 | 5 | 7 | 15 | 3 | 1 | 5 |
| 2004 | 1 | 14 | 6 | 7 | 6 | 6 | 0 | 6 |
| 2005 | 6 | 11 | 15 | 7 | 10 | 3 | 1 | 14 |
| 2006 | 5 | 13 | 2 | 4 | 8 | 3 | 2 | 14 |
| 2007 | 3 | 8 | 2 | 9 | 4 | 3 | 4 | 10 |
| 2008 | 1 | 14 | 1 | 6 | 7 | 5 | 1 | 5 |
| 2009 | 1 | 6 | 3 | 6 | 1 | 3 | 0 | 10 |
| 2010 | 1 | 4 | 10 | 6 | 4 | 10 | 0 | 4 |
| 2011 | 0 | 2 | 1 | 14 | 7 | 1 | 6 | 1 |
| 2012 | 0 | 2 | 2 | 4 | 1 | 0 | 2 | 7 |
| 2013 | 1 | 9 | 0 | 10 | 5 | 0 | 0 | 10 |
| 2014 | 0 | 20 | 21 | 7 | 13 | 10 | 0 | 21 |
| 2015 | 6 | 21 | 21 | 10 | 18 | 13 | 5 | 21 |
| Average dekads VCI<50 | 2 | 11 | 6 | 8 | 8 | 5 | 2 | 9 |
| Total dekads season | 21 | 21 | 21 | 21 | 21 | 21 | 21 | 21 |
| **Percent dekads with VCI<50** | **11** | **52** | **30** | **37** | **37** | **22** | **12** | **44** |

Based on the frequency analysis (Table 1), we observed that the Nama karoo biome has the highest frequency of vegetative drought impact. In this biome vegetation is affected by drought approximately 52% of the time during the growing season (October - April) i.e. in 11 out of 21 dekads, vegetation is affected by drought every season. The forest and savanna biomes have the least vegetative drought frequency of 10% and 12 % respectively.

## Discussion and Conclusions

The Vegetation Condition Index (VCI) has been widely applied in vegetative drought monitoring studies worldwide. Unlike other meteorological drought indices, VCI provides a direct measurement of drought impact based on the vegetation's photosynthetic activity. VCI was successfully used for drought mapping in different parts of the world (Africa, Asia, and Europe). The main advantage of VCI is its ability to characterize drought conditions across diverse landscapes.

The novelty of our study lies in its regional aspect i.e. covering the whole of southern African biomes**.** The analysis of VCI trends across southern African biomes reveals an increasing trend of VCI especially over the savanna biome over the last 20 years, translating to a reduction in the intensity of drought impacts (Figure 12). A plausible hypothesis to explain this is that the proportions of tree cover in the savanna biome have been increasing over time as more agricultural land is left fallow due to erratic and declining rainfall (Malvern et al., 2012). Even under drought conditions, trees always green up in anticipation of the rainfall season (Chidumayo, 2001; Cho, Ramoelo, & Dziba, 2017) and have deep root system which can sustain the plants during extended drought periods. This possibly explains the increase in the VCI. We, however, recommend that future research studies focus more on tree cover trend analysis over southern African biomes.

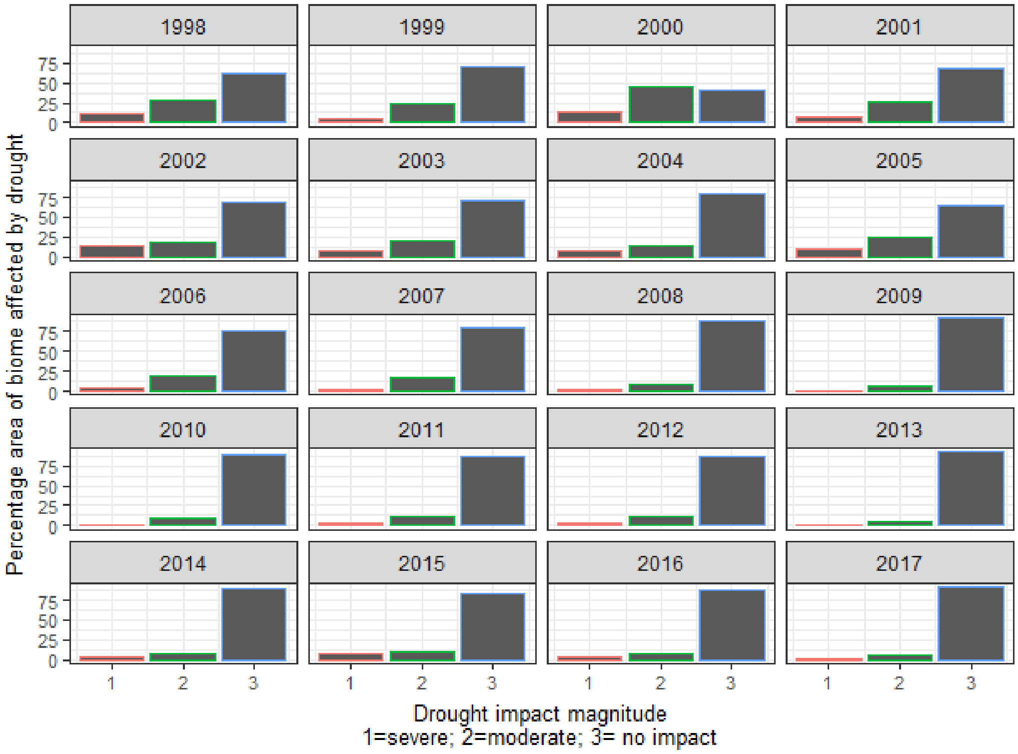

*Figure 12: Savanna biome trends in percentage area of vegetation with; (1) severe; (2) moderate; and (3) no drought impact. The percentage area with drought impacts has been increasing over time from approximately 60 % in 1998 to 80 % in 2018*

We also found out that drought impact mainly varies along the latitudinal and longitudinal gradient. Drought impacts generally decrease with increasing latitude. This explains why the forest biome which is located at higher latitude is less affected by drought. This is largely due to the fact that higher latitude areas in Southern Africa are closer to the Inter-Tropical Convergence Zone (ITCZ), which controls rainfall over the Southern African region (REF). This implies that biomes at higher latitudes i.e. closer to the ITCZ get more rainfall compared to low latitude biomes e.g. Karoo, desert and grassland biomes. Consequently, biomes at low latitudes are severely affected by drought as they quickly react to water stress (Gouveia et al., 2016).

In terms of drought frequency for all the biomes combined we found out that on average about 30% of the time during the growing season i.e. in 6 out of 21 dekads vegetation is generally affected by drought (VCI <50). The highest contribution of the drought impact on vegetation comes from the Nama karoo biome where vegetation is affected 52% of the time during the growing season. The forest and savanna biome has the lowest contribution of drought impact on vegetation with approximately 11 % of the dekads affected by drought during the growing season. This could be possibly be explained the higher evapotranspiration rates for example in the Nama karoo biome  (Daron, 2014).

Our results provide the baseline information and framework for vegetative drought mitigation and ecological restoration programs. Future studies should focus on drought impacts on landscape phenology as well as the vegetation response to droughts at different time scales

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