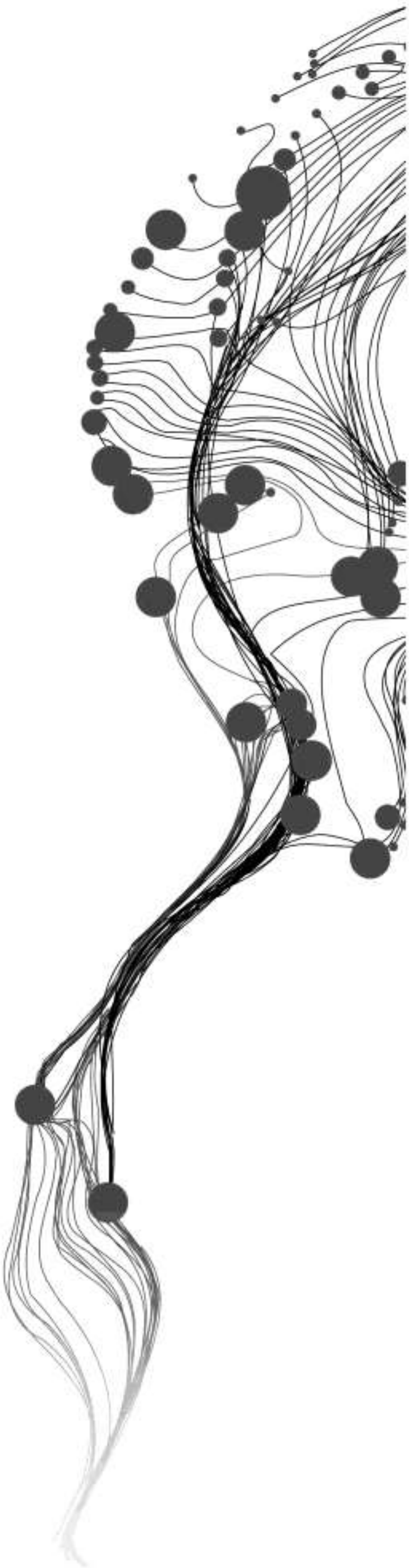
MAPPING OF VEGETATION TYPES AND BUSH ENCROACHMENT IN NAMIBIA

ANA PATRICIA RUIZ BELTRÁN
March, 2015

SUPERVISORS:
Drs. E. Westinga
Drs. Ir. A Vrieling



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ANA PATRICIA RUIZ BELTRÁN
Enschede, The Netherlands, March, 2015

Thesis submitted to the Faculty of Geo-Information Science and Earth Observation of the University of Twente in partial fulfilment of the requirements for the degree of Master of Science in Geo-information Science and Earth Observation.
Specialization: Natural Resources Management

SUPERVISORS:
Drs. E. Westinga
Dr. Ir. A Vrieling

THESIS ASSESSMENT BOARD:
Dr. Ir. C.A.J.M. de Bie (Chair)
Dr. J.F. Duivenvoorden (External Examine, UVA)

ABSTRACT

This thesis deals with vegetation types and bush encroachment in Namibia. Vegetation types are groups of plants that grow together in a certain area. Bush encroachment is the process where a grass-dominated ecosystem transforms into a tree-dominated ecosystem. The first objective of this thesis was to map the vegetation types in Namibia using SPOT VGT NDVI data of 15 years. The classification of the SPOT GVT NDVI data of 15 years was carried out using the Iterative Self-Organized unsupervised clustering algorithm (ISODATA). Based on separability statistics the number of optimum clusters was selected as 73. Based on the NDVI statistics of each cluster and environmental parameters, vegetation types were interpreted, reducing the number of clusters to 20 classes. SPOT-VGT NDVI time series from 15 years can be used to map vegetation types at a national level. The second objective was to explore the possibility to detect bush encroachment in Namibia with SPOT VGT NDVI time series profiles. As a proxy for ground observations historical (2002 – 2004) and recent Google Earth images were analyzed to assess changes in bush density and canopy cover, however, these changes were not detected.

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Ana Patricia Ruiz Beltrán

TABLE OF CONTENTS

1. Introduction 5
   - 1.1. Vegetation types 5
   - 1.2. Bush encroachment 5
   - 1.3. Structure of the thesis 7
2. Methodology 7
   - 2.1. Study area 7
   - 2.2. Datasets 8
   - 2.3. Research approach 10
3. Results 12
   - 3.1. Vegetation type map 12
   - 3.2. Bush encroachment detection 19
4. Discussion 23
   - 4.1. Vegetation type map 24
   - 4.2. Bush encroachment detection 25
5. Conclusions 26

LIST OF FIGURES

Figure 1 a) Location of Namibia in Africa b) Biomes present in Namibia.. 8
Figure 2 a) Average annual rainfall in mm b) Variation in annual rainfall by percent 10
Figure 3 a) Locations for which bush density was reported by De Klerk (2004). 12
Figure 4 Grouping of the 73 SPOT-VGT NDVI clusters into Vegetation types 13
Figure 5 Average and minimum separability between all pairs of clusters. With red is indicated the values for cluster 73. 14
Figure 6 NDVI temporal profiles from clusters 14, 31 and 68 from ISODATA classification from SPOT-VGT NDVI time series with 73 clusters... 14
Figure 7 ISODATA classification from SPOT-VGT NDVI time series with 73 clusters............................. 15
Figure 8 Standard deviation NDVI mean per cluster from the full cluster-averaged SPOT-VGT time series. The whiskers show the corresponding standard deviation... 16
Figure 9 NDVI mean per cluster from the full cluster-averaged SPOT-VGT time series. The whiskers show the corresponding annual standard deviation 16
Figure 10 Multiannual NDVI profiles for 4 different vegetation types 17
Figure 11 Left: Altitude derived from the STRM 4.1Right: 62 clusters from the ISODATA classification from SPOT-VGT NDVI time series with 73 clusters 17
Figure 12 Left: Soils group (A.S.G.C. stands for alluvial, sand, gravel, calcrete plains). Right: 15 clusters from the ISODATA classification from SPOT-VGT NDVI time series with 73 clusters that are related with soil groups.. 18
Figure 13 Left: Variation in annual rainfall in Namibia. Right: 62 clusters from the ISODATA classification from SPOT-VGT NDVI time series with 73 clusters 18
Figure 14 Example of the objects visible in the high resolution images provided by Google Earth 19
Figure 15 a) High resolution imager from the site visited b) Site visited, location: 21 55 21.25 S, 18 11 33.70 E c) High resolution imager from the site visited d) Site visited, location: 21 44 26.76 S, 18 10 2.17 E 20
Figure 16 Site visited and its corresponding Google Earth high resolution images for three different dates 21
Figure 17 High resolution images provided by Google Earth taken at different dates. Coordinates: site 5 22
Figure 18 High resolution images from site 4 and its NDVI profiles. The corresponding pixels to the NDVI time series profiles are indicated with the same colour. The black circles indicates the NDVI value when the image was taken.. 23
Figure 19 High resolution images from site 8 and its NDVI profiles. The corresponding pixels to the NDVI time series profiles are indicated with the same color. The black circles indicate the NDVI value when the high resolution image was taken.. 23

1. INTRODUCTION

This thesis deals with vegetation types and bush encroachment in Namibia. Vegetation types are groups of plants that grow together in a certain area. Mapping these vegetation types is important as such maps provide valuable information to land use planners, ecologists and others. Bush encroachment is the process where a grass-dominated ecosystem transforms into a tree-dominated ecosystem. This process changes the dominance of the plant species in a certain place, changing the species dominance of that area. The next subsections will introduce both concepts in more detail.

1.1. Vegetation types

The existing Vegetation Type map in Namibia was compiled by Antje Burke, Wynand du Plessis & Ben Strohbach was based on existing information available from diverse resources. The broad Vegetation Types present ecologically similar map units that are largely controlled by climate, topography and underlying substrate.

For this reason, it is necessary to map the vegetation maps in Namibia with a consistent source that also includes the temporal dimension to assess major accuracies.

The first research objective is thus: *to map the vegetation types in Namibia using SPOT VGT NDVI data of 15 years.*

1.2. Bush encroachment

Bush encroachment is often seen as one of the most extensive forms of degradation in rangelands. This phenomena is common in the arid and semi-arid biomes around the world (Eldridge et al., 2011; Skarpe, 1990). The accepted definition for bush encroachment in Namibia by De Klerk (2004) is the following: "Bush encroachment is the invasion and/or thickening of aggressive undesired woody species resulting in an imbalance of the grass: bush ratio, a decrease in biodiversity, a decrease in carrying capacity and concomitant economic losses".

Some of the causes related with bush encroachment are suppression of fire, overgrazing, nutrient availability and rainfall patterns (Kgosikoma & Mogotsi, 2013). Other authors claim that overgrazing and suppression of fire cannot be a direct cause of bush encroachment in areas without grazing or fires (Ward, 2005). Instead rainfall patterns may drive the bush encroachment rather than anthropogenic influence. Several encroacher species are found in the central north of Namibia: *Acacia mellifera, Acacia reficiens, Colosphospermum mopane, Dichrostachys cinerea, Terminalia prunoides* , *Terminalia sericea* ,among others (De Klerk, 2004; D. Joubert et al., 2013).

In Namibia, bush encroachment causes losses to the national economy. The area affected in 1999 was estimated in the order of 17.5 million hectare and by 2010 it was estimated to be in the order of 26 million (Moore, 2010). This is the cause of a decrease in carrying capacity of the rangeland (Bester, 1999) restricting severely the profitability of cattle farming (Lukomska et al., 2014). Bush encroachment reduces the carrying capacity in two ways: the first one is due to a loss of grass cover because this cannot grow under thick bush; the second one is that high bush densities do not allow grazing animals to penetrate the area to get to the grasses (Mendelsohn et al., 2002). Furthermore, bush encroachment decreases the diversity of habitat structure thereby influencing for example native savannah lizards (Meik et al., 2002) and some bird species (Sirami & Monadjem, 2012).

The costs of clearing are generally higher than the benefits in terms of increased carrying capacity (Sweet & Burke, 2006). There are some entrepreneur projects for obtaining extra benefits by clearing the bush: The CBEND Project (Combating Bush Encroachment for Namibia's Development) from the Desert Research Foundation of Namibia and the CCF Bush (PTY) Ltd from the Cheetah Conservation Found. The first one consists in a power plant for electricity that used bushes as fuel, however the pilot plant is not operational due to its inability to give sufficient power into the electrical power system. The second one manufactures wood fuel briquettes from remove thickened bush.

Aerial photo interpretation is the most frequently applied remote sensing technique used in bush encroachment studies (Oldeland et al., 2010). Van Vegten (1984) estimated with aerial photographs an increase from 1950 to 1975 of tree times more biomass in an area of 108 km^2 in Botswana. Hudak & Wessman (2001) made textural analyses of historical aerial photographs, quantifying a relative increase cover of over 30% in 41 years, between 1955 and 1996. Other studies have assessed the rate of expansion of Bush Encroachment with different approaches.

For thirteen sites in South Africa (Hottman & O'Connor, 1999) an increase in bush density was estimated using panoramic photographs from a mean of 21% in 1995 to 59% in 1998. It appears that bush densities have approximately doubled during the past century (Hudak & Wessman, 2001) assuming that bush encroachment is a linear process, yet it is not known whether BE is linear or nonlinear. Skarpe (1990) conducted a grazing experiment in Botswana for 5 years in paddocks between 0.50 and 1.25 km^2 finding that in the areas were grazing was taking place, the shrub density was higher than in those which didn't have. Nevertheless, it was considered that 5 years was a short period to study the dynamics in woody species

Blaser, (2013) using multi-temporal sequence of Landsat TM mapped spatial changes in shrub cover in an area of Lochinvar National Park, Zambia, estimating that woody cover increased from 26 to 45% and open areas decreased from 50 to 33% between 1986 and 2010.

Studies regarding to the process of Bush Encroachment have also been done. Hély et al., 2007 presented a regional fuel load model at a 1 km^2 resolution using multi-source remote sensing data. It was validated in Estosha National Park in Namibia, for canopy coverage from <5, 30 and 50%. This study describes actual vegetation patterns, such as bush encroachment. Joubert el al. (2008) described a conceptual model of bush encroachment by *Acacia mellifera,* in Namibia, identifying two main states of change: from grassy to bushy. Wu et al. (2013) founded a correlation between Landsat NDVI images and Canopy Cover (R^2=0.91) in tropical savannahs in Sudan. This relation may lose sensitivity when CC is below 5% or over 75%.

It is possible using hyper temporal data to map land cover and identify processes in natural and semi-natural landscapes (De Bie et al., 2010; Ali et al., 2014; De Bie et al., 2012). In Madagascar, NDVI MODIS time series were used to quantify and localize savannahs vegetation cover degradation (Jacquin et al., 2010). In the Kalahari, Namibia, it was possible to map vegetation type associations based on local scale in-situ botanical survey data with Landsat TM and NDVI-MODIS time series (Hüttich et al., 2009). Khan et al.(2010) mapped crop statistics for Andalucía in Spain developing a method using SPOT VGT NDVI images (1998-2006) and available existing data. The Bush Encroachment in Spain is related with the dry years, Estupiñan-Suarez, (2013) found a linear regression (R^2= 0.803, α= 0.05) between the minimum NDVI and evergreen perennial cover vegetation using time series analysis of MODIS. This was based on the assumption that in the summer the grasses and herbs are being colonized by bushes, and therefore it was likely to detect a minimum NDVI. Stellmes et al.(2013) identify the major land cover change processes, including bush encroachment, which occurred also in Spain between 1989 and 2004 using Mediterranean Extended Daily One Km AVHRR Data Set at a temporal resolution of 10 days.

Remote sensing approaches provide the capacity to cover large areas that will be impossible to achieve with other methods (Sannier et al., 2002). De Klerk (2004) developed a model using NOAA-AVHRR and SPOT-VGT to map bush density as a function of total seasonal biomass production. Unfortunately, the best fit had an $R^2=0.18$, a low value for extrapolating this to the entire area. It is therefore necessary to know where the encroached areas are and which main encroacher species (Colin Christian & Associates CC, 2010).

Given that no good spatial overview of bush encroachment exists for Namibia and past efforts to map it have had limited success, there is a need for a good national overview of areas suffering from bush encroachment.

The second research objective is thus: *to explore the possibility to detect bush encroachment in Namibia with SPOT VGT NDVI time series profiles*.

1.3. Structure of the thesis

This thesis is structure as follows. It continuously discusses vegetation types and bush encroachment separately throughout the thesis. It starts with describing the methodology: with a brief description of Namibia and the steps taken to collect and analyzed the data (Chapter 2). Chapter 3 presents the results of the first objective (Vegetation type map) and the second (Bush encroachment detection). These results are then discussed together with their limitations, and suggestions for future research are derived (Chapter 4). Finally, the thesis ends with the conclusions in Chapter 5.

2. METHODOLOGY

The previous section has provided an introduction to vegetation types and bush encroachment. It ended with the formulation of two research objectives. This section deals with the steps taken in attempting to reach these objectives. It discusses the datasets obtained and the approach taken, but first presents the study area: Namibia.

2.1. Study area

Namibia is a country located in southern Africa (Figure 1a). Namibia is bordering with Angola in the north, Zambia and Zimbabwe in the northeast, Botswana in the east and South Africa in the south. It has an area of 824 292 km² (Government of Namibia, 2014), which includes five biomes (Figure 1b): Lakes and Salt Pans, Nama Karoo, Namib Desert, Succulent Karoo and Tree-and-shrub Savannah (Mendelsohn et al., 2002). The rainfalls occur sporadically from September to February and its climate is generally arid. The use of natural resources for farming, mining, marine fishing and tourism are economical activities that provide the overall wealth in Namibia.

In this study the Caprivi was not considered.

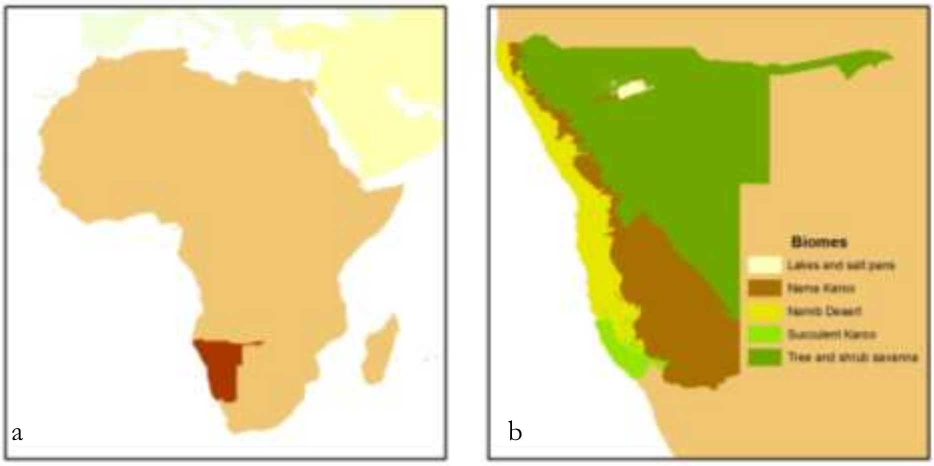

Figure 1 a) Location of Namibia in Africa b) Biomes present in Namibia

2.2. Datasets

In the following sections each dataset will be explained. SPOT VGT NDVI and High resolution imagery was used for aiming the two objectives. The Tree Atlas Project Database and Maps of environmental parameters were used for the Vegetation type map. The geo-located estimates of bush density were used for the Bush encroachment detection.

2.2.1. SPOT VGT NDVI

NDVI-images from the Satellite for observation of Earth (SPOT, in French "*Satellite Pour l'Observation de la Terre*") at 1km^2 resolution were used. The dataset extended from May 1998 until 31 December 2013 (564 images) and is available through the Flemish Institute for Technological Research (VITO: www.vgt.vito.be) as the S10 product. The SPOT VEGETATION (VGT) sensor has four spectral bands: Blue at 0.43-0.47 μm, red at 0.61–0.68 μm, near-infrared (NIR) at 0.78–0.89 μm, and middle infrared/short-wave infrared at 1.58–1.75 μm.

The NDVI was developed by Rouse et al.(1974) and uses the red and near infrared (NIR) spectral bands:

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

NDVI responds to variability in the amount of green biomass. Time series of NDVI allow for the monitoring of seasonal and inter-annual changes in vegetation growth and activity, and the rationing reduces many forms of noise that is present in multiple bands of multiple-date imagery like sun illumination differences, cloud shadows and topographic variations (Jensen, 2007).

While NDVI ranges between -1 (for water) to about 0 (bare soil) to 1 (green vegetation), VITO rescales the NDVI to 8-bit format, i.e. from 0 to 255. To translate these digital numbers (DN) to NDVI, the following equation should be applied: NDVI = 0.004*DN – 0.1. The S10 product is generated by using the best quality daily images of the Red and the NIR band over a 10-day period. Each month, three S10 products are composited.

SPOT-VGT NDVI images were de-clouded by removing pixel values considered to be invalid as determined by the supplied quality record. Only pixels with 'good' radiometric quality rating for red and NIR and without 'shadow,' 'cloud,' or 'uncertain' were kept. It was given a value of cero to the removed pixels. Finally, the adaptive Savitzky–Golay filter built in TIMESAT was used to remove short-duration impacts on cloud-affected pixel values of the SPOT NDVI datasets (Beltran-Abaunza, 2009; Jönson & Eklundh, 2004). No further data pre-processing was done. This data was process and provided by Dr. Ir. C.A.J.M. de Bie.

2.2.2. Geo-located estimates of bush density

Bush density data points from Mendelsohn and Coetzee (2003) were used. The map presents 1909 data points and has four categories of the number of bushes per hectare: Very high, with more than 3000; high from 2000 to 3000; medium from 1000 to 2000; and low, with bush densities minor to 1000. To use the information of the Bush density map, it was scanned from the book Bush Encroachment in Namibia by De Klerk (2004) and the sampling points were digitized. No more information could be obtained. The document is available at the libraries of the Ministry of Environment and Tourism and the Ministry of Agriculture, Water and Rural Development.

2.2.3. High resolution imagery

Two sources of high resolution imagery were used. The first was the satellite and aerial imagery with 1m or higher resolution from World Imagery online data layer, provided by ESRI[1].
The second was from the software Google Earth, which provided Historical (2002–2004) and recent (2012-2014) imagery provided by Digital Globe.

2.2.4. Maps of environmental parameters

Environmental parameters were used. All these layers were projected into the Plate Caree projection. When the images were obtain in a vector (shapefile) these were converted into raster, using the cell size as the SPOT VGT imagery. If they were from continues variables (for example altitude) the resampling technique used was cubic, if they were categorical the conversion was using maximum area.

The maps of soils, rainfall and vegetation types were provided by the Ministry of Environment and Tourism of Namibia and the Environmental Information Service – Namibia[2].

- Vegetation types: This map presents 26 classes. Is the current vegetation type map for Namibia. As it was obtained by the Atlas of Namibia (Mendelsohn et al., 2002) it is going to be referred from now to onwards as Mendelsohn's map.
- Rainfall: The annual rainfall data was originated by the Ministry of Agriculture, Water and Rural Development (Figure 2). The data was obtained for almost 300 stations across Namibia (Namibian Resources Consultants, 1999). The variation in annual rainfall is calculated as the standard deviation of annual totals as a percentage of average annual rainfall.
- Soils: This map was produced by the National Soil Survey 1998-2000. For this map 14 classes were used.
- Digital Elevation Model: was establish from the NASA Shuttle Radar Topographic Mission (STRM). Corresponds to the STRM data version 4.1 with a resolution of 90m (Jarvis et al., 2008)[3].

[1] See: http://www.arcgis.com/home/webmap/viewer.html?webmap=c1c2090ed8594e0193194b750d0d5f83
[2] See: http://www.uni-koeln.de/sfb389/e/e1/download/atlas_namibia/main_namibia_atlas.html
[3]See: http://srtm.csi.cgiar.org

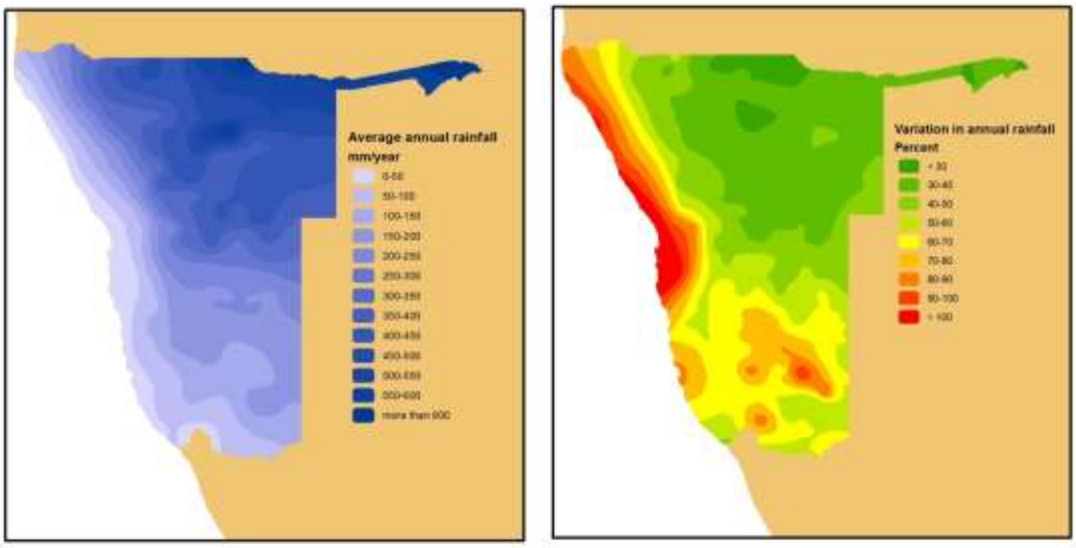

Figure 2 a) Average annual rainfall in mm b) Variation in annual rainfall by percent

2.3. Research approach

A method for each objective was done. The first method described in this section explains how a vegetation type map was created from SPOT-VGT time series. The second method explains the efforts made to evaluate if bush encroachment can be detected, both from high resolution imagery data and SPOT-VGT series.

2.3.1. Vegetation type map

Unsupervised classifications were carried out using the Iterative Self-Organized unsupervised clustering algorithm (ISODATA) of ERDAS Imagine software with the SPOT-VGT data. In the ISODATA classification the user predefines the number of clusters desired. A total of 90 classifications ranging from 10 to 100 clusters were performed. The algorithm selects a number of pixels randomly and calculates the cluster means. This number of pixels at the start of the iteration is equal to the number of clusters predefined. Using minimum distance techniques the remaining pixels are iteratively clustered into these initial pixels. The threshold value used for the classification was 1, which is the percentage of pixels that do not change classes between successive iterations and the maximum number of iteration was 50. The process finished until the number of pixels in each cluster change less than the selected threshold value or the maximum number of iterations is reached. Diagonal axis was used as statistical parameter. In the diagonal axis the means are computed to be along a diagonal vector and are evenly distributed within the scaling range for each band.

For each ISODATA classification divergence statistics were retrieved to use them as criteria to select the optimal number of clusters. The statistics used were average and minimum separability. The selection was based on compromise, where a clear peak of average separability was encountered and the minimum separability did not have a value that was not under the trend of this value in function of the clusters(Ali et al., 2013).

After selecting the classification with the considered optimum number of clusters, summary statistics for each cluster were calculated to better characterize each cluster. These statistics included the mean of the standard deviation of the pixel values within each cluster considering all the SPOT VGT time series and the mean of the NDVI values per each cluster considering also all the SPOT VGT time series. To reduce the information provided by each SPOT VGT NDVI cluster, for each the same 10-day period across all years were averaged, the profiles were reduce form 564 variables to 36. From these 36 variables which correspond to the dekads of the year, the maximum NDVI value was retrieved and that was considered the date with the maximum NDVI value. Also the standard deviation of the NDVI in this profile was calculated.

Environmental variables were used to interpret these clusters. Following the approach by De Bie et al. (2011), the use of existing maps, secondary data and the interpretation of high resolution imagery were used for the clusters interpretation. Annual rainfall, interannual variability of annual rainfall, altitude, soil groups and vegetation type map were compared to the resulting clusters. The Three Atlas Project databased was used to identify certain species that were common to abundant in certain clusters. Finally the clusters were grouped based on these parameters if they were spatially contiguous according to the NDVI annual profiles and the environmental variables.

2.3.2. Bush encroachment detection

To study the temporal NDVI profiles of bush encroachment over 15 years, areas with and without increase in bush density in the same period were selected. As a proxy for ground observations the change on historical and recent detailed images were investigated. Freely available images in Google Earth were used. In Google Earth areas were screened, where both historical and recent images were available within a difference of 9 years or more. A quick scan revealed no clear changes in bush density and canopy cover for most of these areas. Priority was therefore given to areas with reported bush densities (Mendelsohn & Coetzee, 2003). This is because of two reasons. First, this approach was less time-consuming for looking at places with high or medium bush densities. Second, this provided a valuable starting point for subsequent research steps.

These areas with reported bush densities were available as a map in the Bush Encroachment in Namibia report of De Klerk (2004). This map was scanned and georeferenced. The bush density data points were then digitized (Figure 3a). However, since the accuracy of the digitized bush density data points is unknown, an area of about 40 km^2 was investigated as a way to increase the likelihood to include the actual reported areas. However, not all these areas were in places were both historical and recent images were available. For these reasons, only 25 sites were incorporated in the study (Figure 3b).

Changes in bush density and bush canopy cover were interpreted for each pair of (historical and recent) high-resolution images and compared with the SPOT-VGT NDVI profiles. A rectangular grid was created to link the high resolution imagery to the temporal profiles of individual SPOT-VGT pixels. The grid definition and size was the same as for SPOT-VGT. The resolution of SPOT-VGT was about 1 km^2 (0.987 km^2). For consistent interpretation of the high-resolution imagery the scale on the monitor was fixed when assessing different areas. With an eye altitude of 2.85 km the entire SPOT VGT pixel area could be seen. At this scale density estimations were not always visible. More detail was therefore obtained by zooming to an eye altitude of 1.60 km as to interpret one quarter of a SPOT VGT pixel a time. The temporal NDVI profile of the corresponding SPOT VGT pixel was analyzed to investigate if the changes in canopy cover density were reflected in changes in the NDVI profile.

A field trip took place on 11 and 12 November 2014. A windshield survey was done on the roads Windhoek – Gobabis, M057, D1643 and M0070 in the provinces of Khomas, Otzjozondujpa and Omaheke. Windshield surveys are systematic observations made from a moving vehicle. Additionally, ground observations samples were taken. The criteria for selecting the sites to visit in the field were: 1) to have good quality in its recent high resolution image, this means that the bushes had to be clearly identifiable on the image; 2) the sites selected should show in their recent high resolution image a variety of bush densities between them to identify these differences on the ground; and 3) the sites should be accessible, the sites had to be along the roads as too many areas presented fences and therefore it was inaccessible. Visual estimation of ground cover was made in the selected sites for three layers: tree, shrub and grass. For each site, pictures were taken and the GPS location was recorded. Recognition of species was not done because the field trip took place during the dry season and most of the shrubs did not present leaves; for the time given, recognizing these species was not possible. The points visited and recorded on the ground were used to aid the visual interpretation of the high resolution imagery.

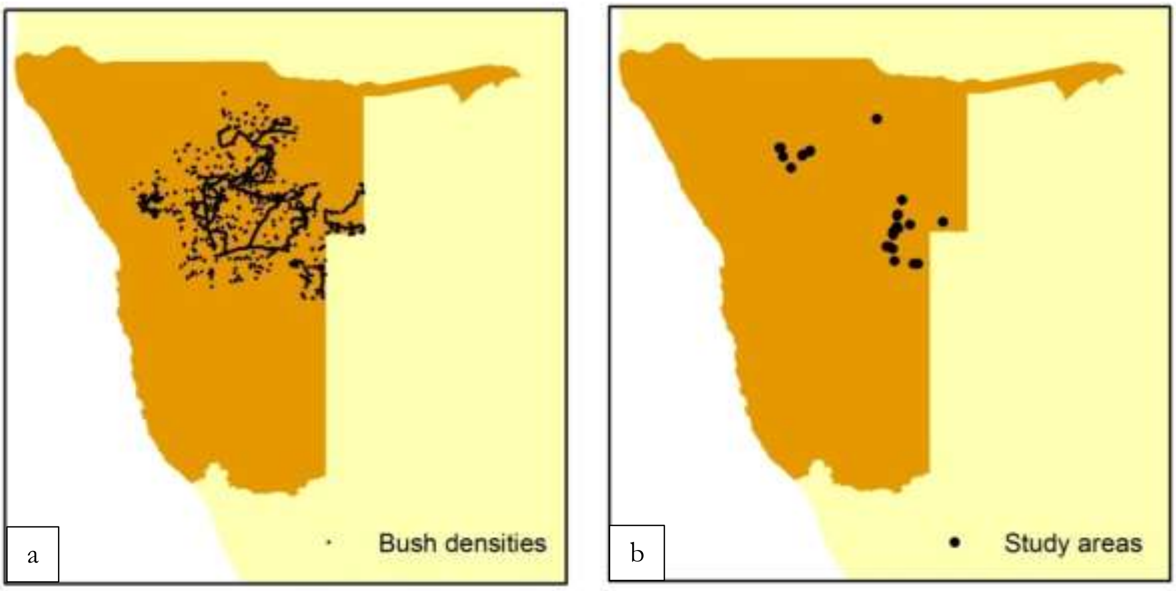

Figure 3 a) Locations for which bush density was reported by De Klerk (2004).
b) Study sites for which multi-temporal high-resolution imagery was examined to evaluate the occurrence of bush encroachment

3. RESULTS

The previous chapter discussed the methodology followed to collect and analyze data. Based on that, this chapter turns to presenting the findings of this study. As throughout the whole thesis, first the findings for the vegetation type map are presented and then of the bush encroachment detection.

3.1. Vegetation type map

This study explored the possibility to create a vegetation type map for Namibia using SPOT-VGT NDVI time series for 15 years. The time series were classified using the ISODATA clustering algorithm. Based on separability statisticss, 73 was selected as the optimum number of clusters. From these 73 clusters there was a reduction to 20 classes. The considerations to do this reduction were based on the cluster properties (NDVI profiles) and the environmental variables to produce finally a vegetation type map.

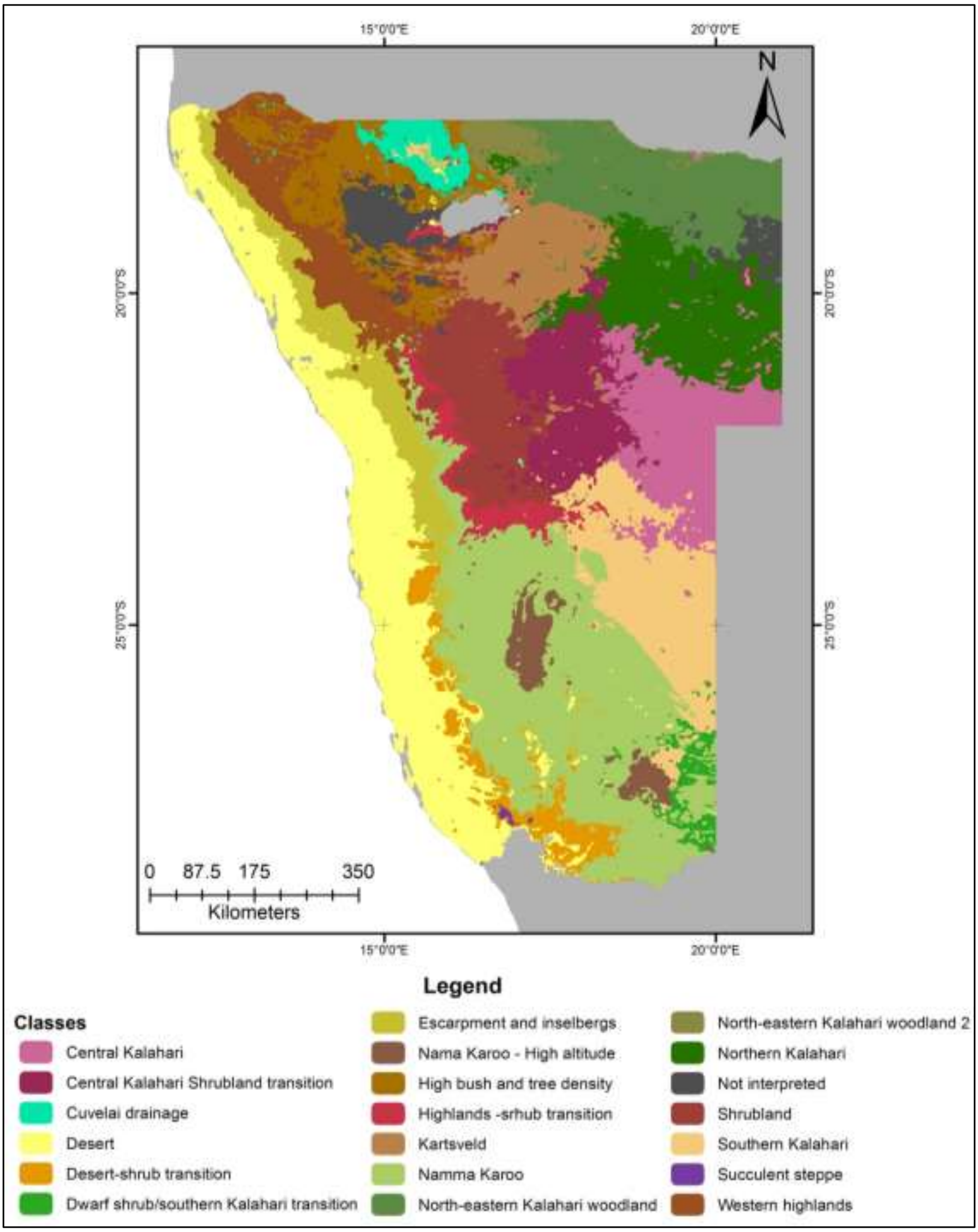

Figure 4 Grouping of the 73 SPOT-VGT NDVI clusters into Vegetation types

For the ISODATA clustering of the SPOT-VGT NDVI time series, the optimal number of clusters was 73. This was considered the best classification, because a clear peak existed for average separability and the minimum separability was above the tendency (Figure 5). With these classification temporal NDVI time series profiles were obtained for each cluster (Figure 6).

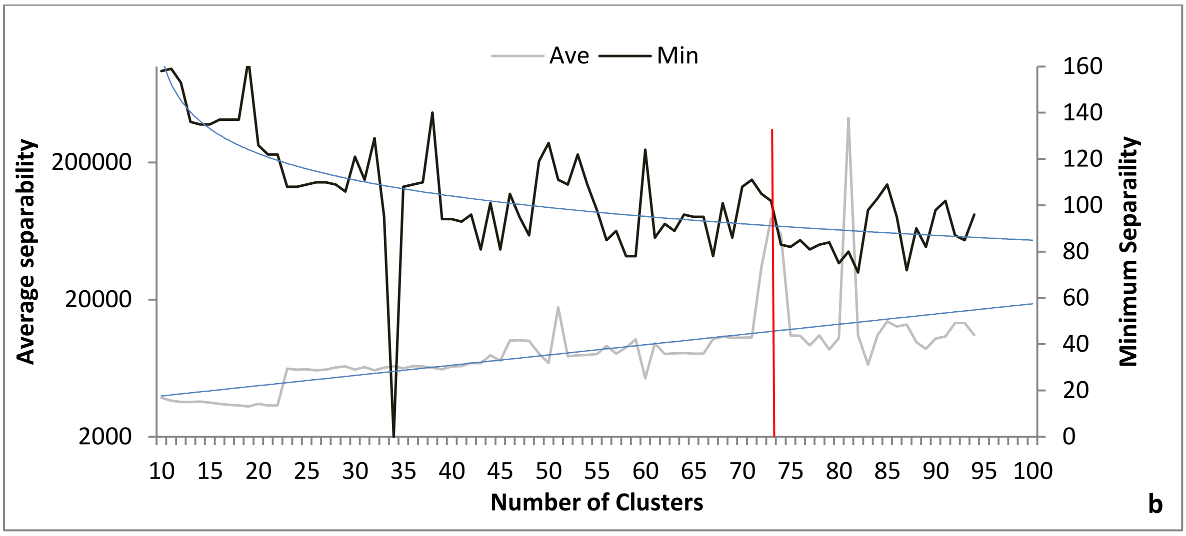

Figure 5 Average and minimum separability between all pairs of clusters. With red is indicated the values for cluster 73.

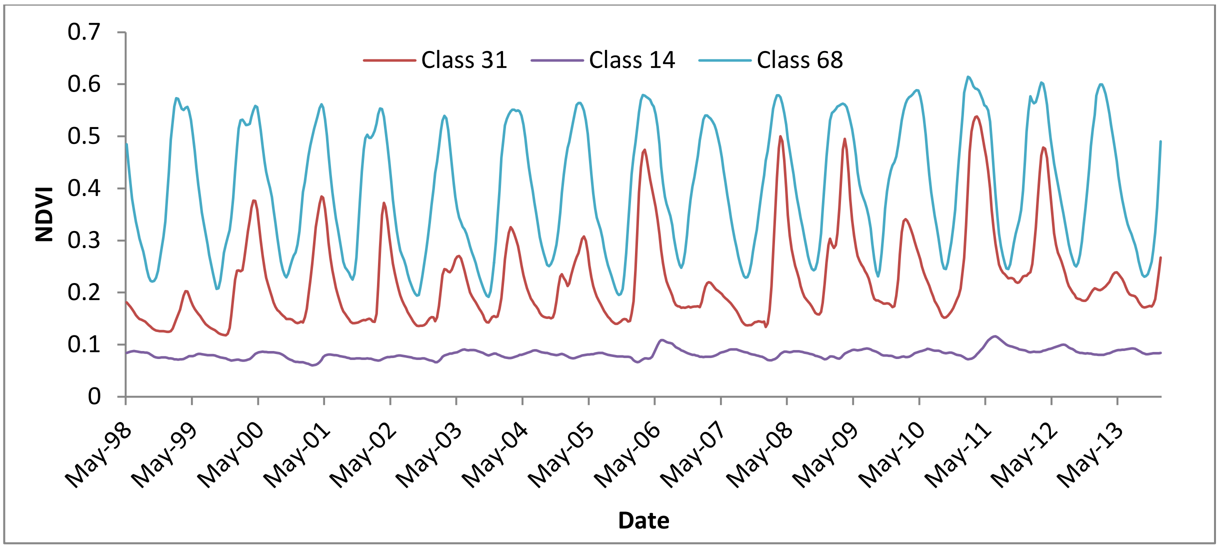

Figure 6 NDVI temporal profiles from clusters 14, 31 and 68 from ISODATA classification from SPOT-VGT NDVI time series with 73 clusters

When observing the general distribution of the 73 clusters in Namibia certain features can be recognized (Figure 7). The border between Angola and Namibia in the Cuvelai–Etosha basin can be seen with a straight line distinguishable between the cluster 40 in Namibia and the cluster 48 in Angola. The clusters with the lower NDVI values are in the coastal zone and the salt pan, while the clusters with higher NDVI values are in the northeast, approximately 400 km away from the coastal zone. The patterns of the biomes are also identifiable.

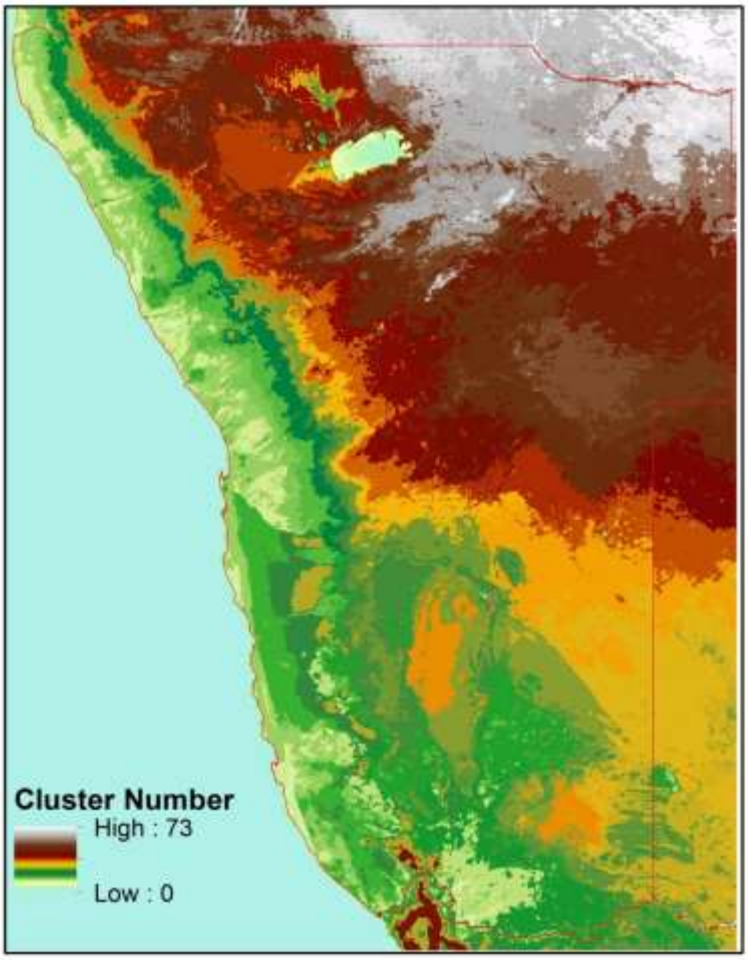

Figure 7 ISODATA classification from SPOT-VGT NDVI time series with 73 clusters

Not all the clusters were spatially connected (Figure 7). Cluster 5 and 7 were distributed in the foreshore and in the saltpan. Cluster 28 is distributed along the Central-western Plains but not spatially connected. Latitudinal the number of cluster increases from south to north and longitudinally increases from east to west. However, the cluster are not spatially grouped (from number 1 to 73 contiguously) since, for example, the cluster 44 is located in the southern part of Namibia (on the north of the Orange River) while the cluster 43 and 45 are located in the central part of the country, about 530 km north to the cluster 44.

The standard deviation of the multi-annual NDVI values was different for each cluster. Clusters 1 to 11 present a high standard deviation in comparison with clusters 12 to 22, indicating a higher variability of NDVI over time (Figure 8). Clusters 1 to 11 were eliminated from further analysis.

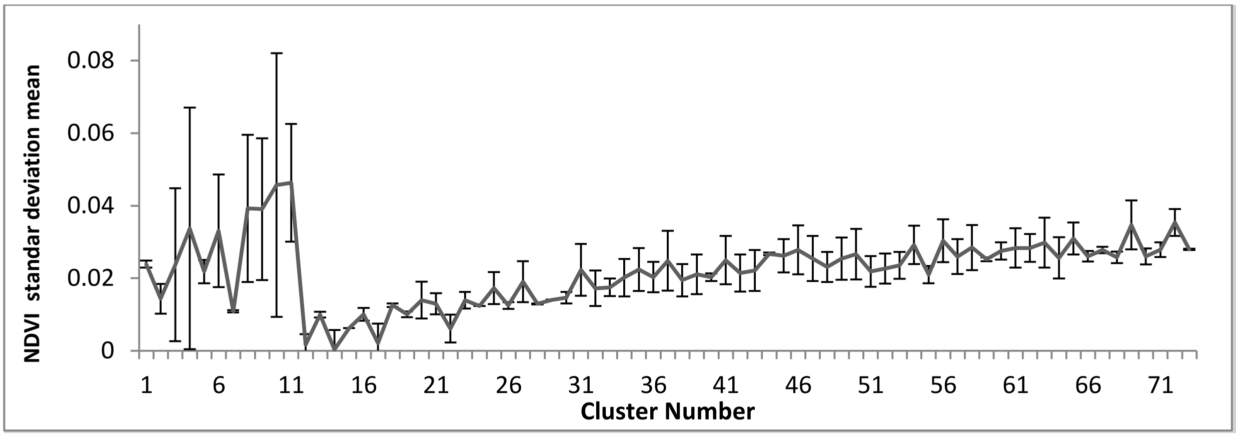

Figure 8 Standard deviation NDVI mean per cluster from the full cluster-averaged SPOT-VGT time series. The whiskers show the corresponding standard deviation

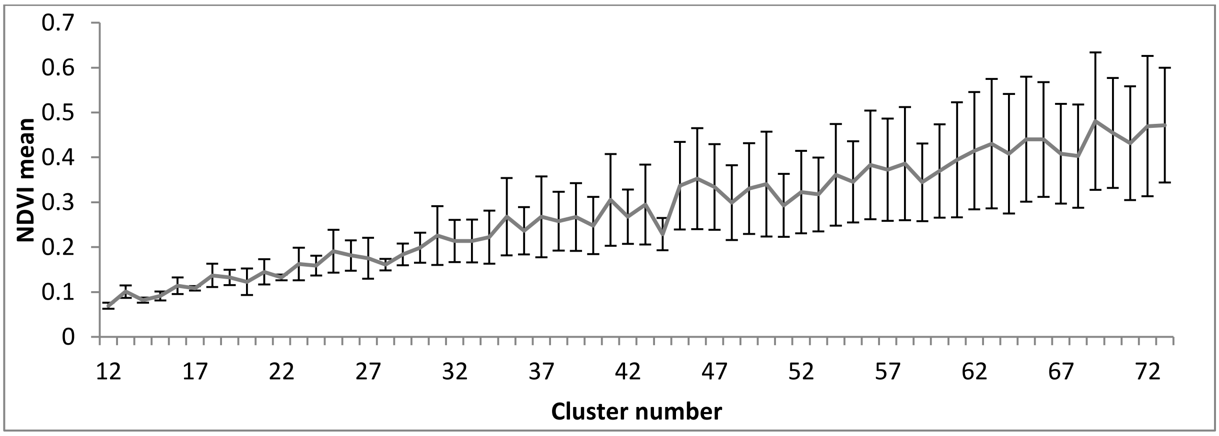

Figure 9 NDVI mean per cluster from the full cluster-averaged SPOT-VGT time series. The whiskers show the corresponding annual standard deviation

Following the creation of a multi-annual average NDVI profile per cluster, it was determined the standard deviation for each cluster within a year. From clusters 12 to 73 it can be seen that there is a tendency for the annual standard deviation to growth (Figure 9).

The spatial distribution of most clusters visually showed large similarity with a number of environmental variables. Clusters 32, 39, 42, 46, 47, 51, 62-67 and 70 were clearly explained by the vegetation type map Clusters from 12 to 24 were not explained by the vegetation type map. These clusters were explained better by environmental variables: altitude, mean annual rainfall and rainfall variability and some Tree Atlas Species. When grouping the clusters into vegetation types, the multiannual NDVI profiles were plotted (Figure 10).

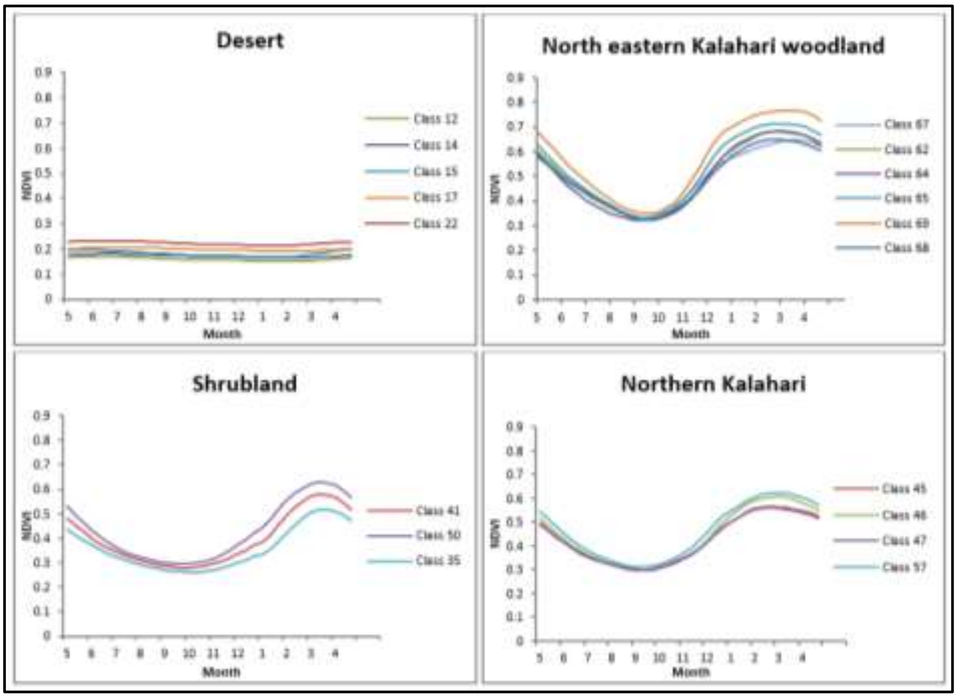

Figure 10 Multiannual NDVI profiles for 4 different vegetation types

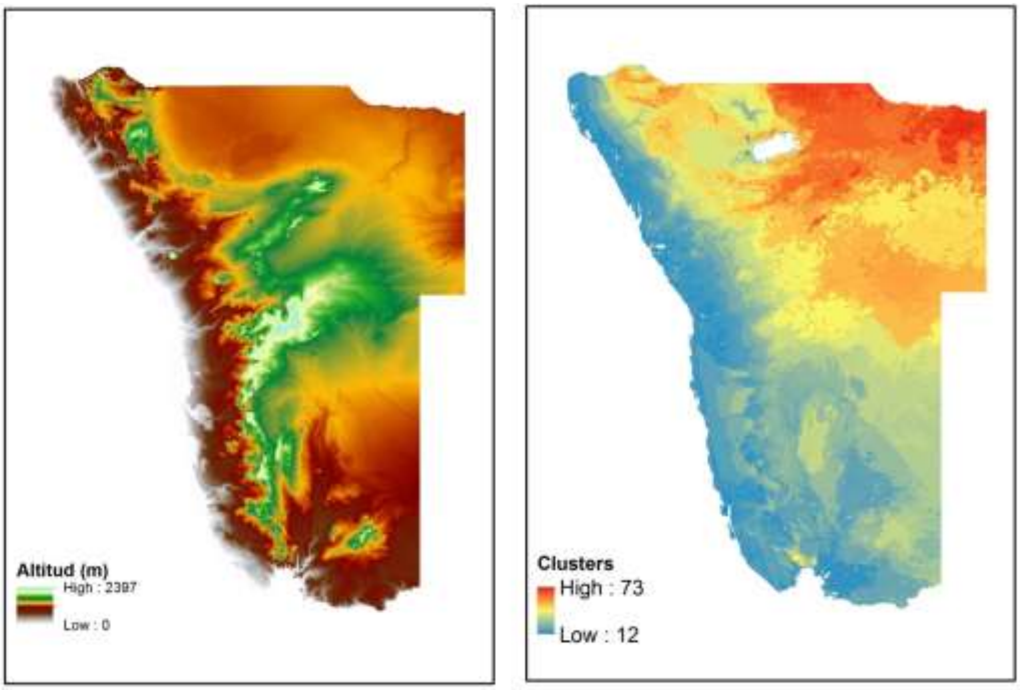

Figure 11 Left: Altitude derived from the STRM 4.1Right: 62 clusters from the ISODATA classification from SPOT-VGT NDVI time series with 73 clusters

In Figure 11 and Figure 13, similar patterns of altitude and the rainfall variability with the clusters can be seen. Class 33 is in the higher altitude zone in the southern part of Namibia. Class 62 is also in that area that is high in the southeast to Etosha with a low rainfall. Class 37 is in an area with high altitude. Class 44 is in areas with low rainfall variation in the southern part of Namibia. Areas with interannual rainfall variation were along the places with clusters with low NDVI values, and values with high rainfall were places with the highest NDVI mean values.

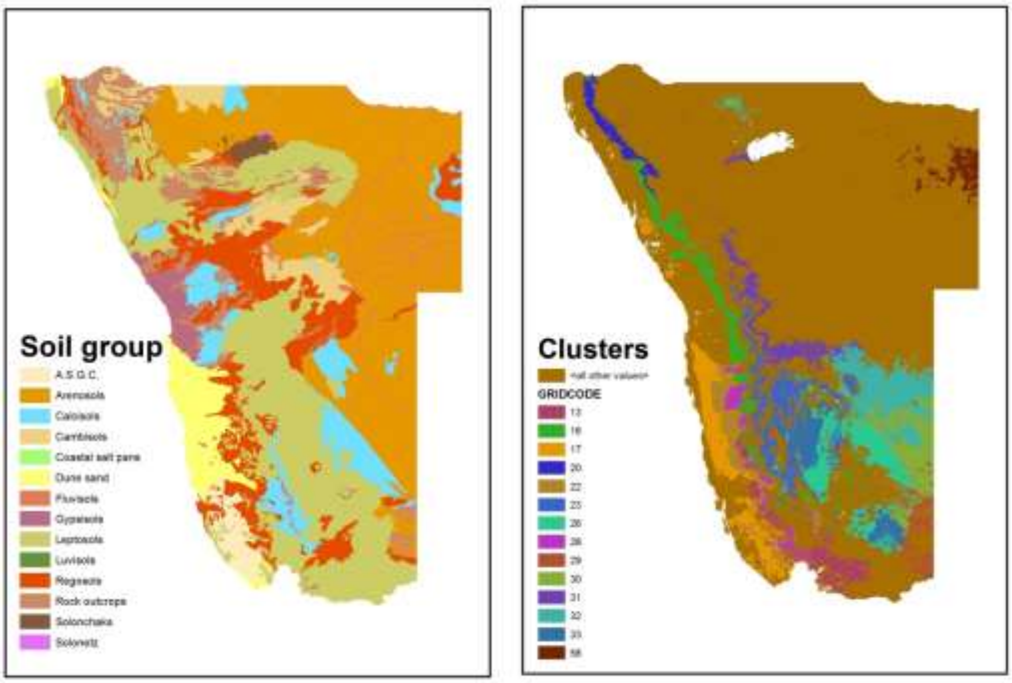

Figure 12 Left: Soils group (A.S.G.C. stands for alluvial, sand, gravel, calcrete plains). Right: 15 clusters from the ISODATA classification from SPOT-VGT NDVI time series with 73 clusters that are related with soil groups.

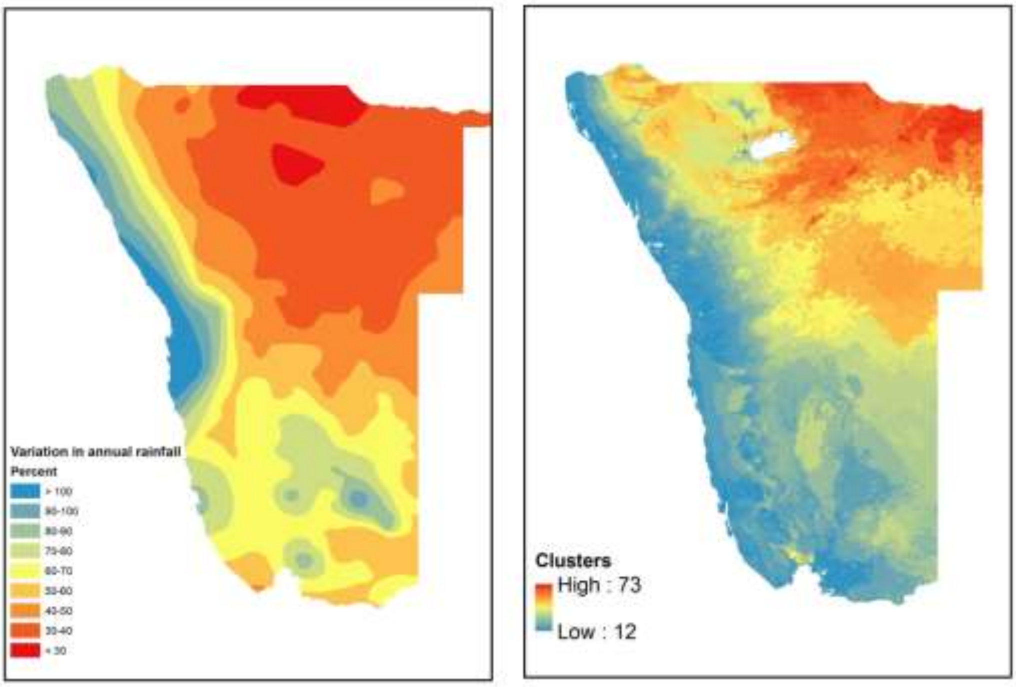

Figure 13 Left: Variation in annual rainfall in Namibia. Right: 62 clusters from the ISODATA classification from SPOT-VGT NDVI time series with 73 clusters

When comparing the clusters with the soil group distribution some patters were detected (Figure 12). Cluster 58 is distributed where regosols are found. Cluster 17 and 22 were distributed mainly in the sand dunes and the alluvium, sand, gravel, calcrete plains. Cluster 28 which contiguous with class 22, is also present in the salt dunes but a few pixels are in the regosols and leptosols. Other classes where along many groups of soils but show a pattern that they are not present in certain type of soil; cluster 23 is where regosols and leptosols are, but not in the arenosols. Also cluster 31 is not located in the aerosols.

3.2. Bush encroachment detection

This section will first explain how the high resolution images were interpreted: visual interpretation and relation with the areas in the field. Second, the main differences encountered between the images, and last the comparison between the high resolution imagery with the SPOT VGT NDVI profiles.

Different kinds of objects were recognized when interpreting the high resolution images (Figure 14). The roads can be distinguished as straight lines, generally with a lighter color than the rest of the elements due to the bare soil. The bushes can be seen as small dots that are darker than their surroundings. If they are tall enough, shadows can also be distinguished next to the bush with a darker color. The grasses can be visible in two different ways: when they are in a managed grassland area they appear with a homogeneous texture presenting a polygon shape with straight lines. The color inside this polygon is the same as the one that is in the space between the bushes and trees, which are grasses as well. Small human settlements could also be identified and generally were surrounded by grasses with low bush and tree density.

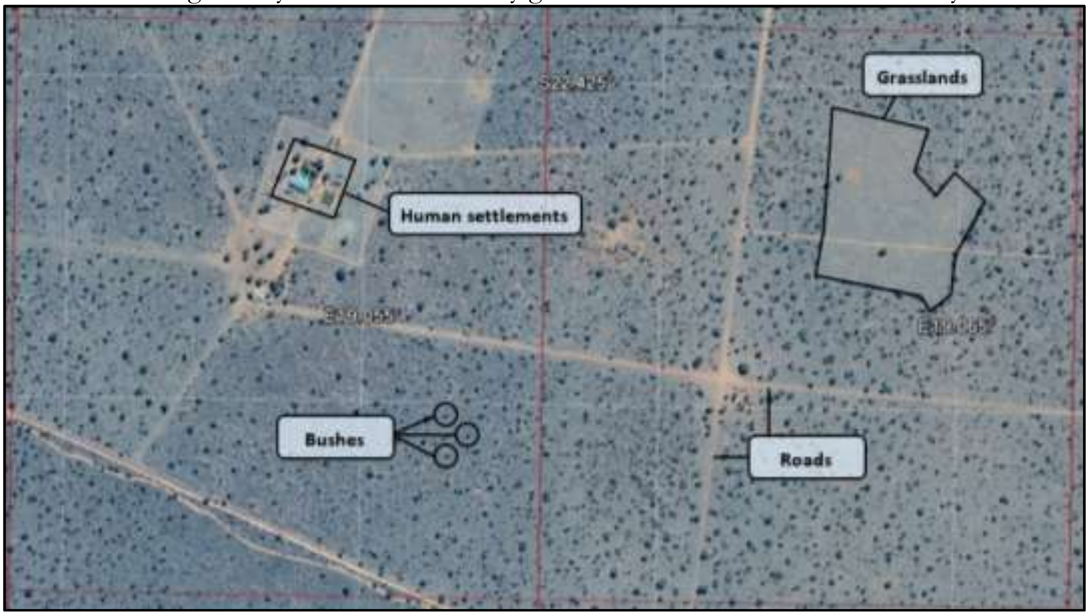

Figure 14 Example of the objects visible in the high resolution images provided by Google Earth

The area visited in Namibia was highly heterogeneous in terms of bush density and bush canopy cover. The state of the vegetation was different; some areas were green while others were still dry. Bush density areas ranged from 15% to 60% (without considering the grasslands). Bushes also differed in their heights, ranging up to about 5 m. Important attributes of the areas were heights and bush densities.

To achieve a better interpretation, it was thus necessary to compare these attributes with the high resolution images. When making such comparisons, more details can be detected in the high resolution images. Figure 15 and Figure 16 shows some examples of the recent high resolution images and its corresponding ground picture taken from the road. Different bush cover densities can be seen: 15% (Figure 15b), 40% (Figure 16d) and 60% (Figure 15d).

A few things can be noted when comparing the figures with the Google Earth high resolution images:

- When the bushes are not high enough (<1.5 m) these can be recognized as small dots with no shadows. Figure 15a and b are an example of this situation. When the site was visited the grasses were dry, while in the high resolution image they are presented with a bluish color.
- Figure 15d is an example of a plot with trees and bushes with a height between approximately 1.5 and 5 m. This can be recognized in the aerial imagery as dots with slightly shadow. However the dates of the images differ, while Figure 15c was taken in July (dry season), Figure 15d was taken in the wet season, making the bushes recognizable in the high resolution image with dark colors instead of greenish as it was seen in the field.

- Figure 16d shows an area with a visually-estimated bush cover of 40%. The grasses were dry when the image was taken and it can be appreciated with a brownish color in the ground. Three recent high resolution images were available from that site. Figure 16a corresponds to dry season, if it is observed; bushes can be seen as dark points. The color of the ground is from bluish to brownish. In the next image, the bushes are bigger, and some of them are present with a green color. The color of the ground, rather than blue is purple with brown. The third image corresponds with a non-dry season and the color is green. Note that in the three images the bare soil located down center remains with almost the same color for the three images.

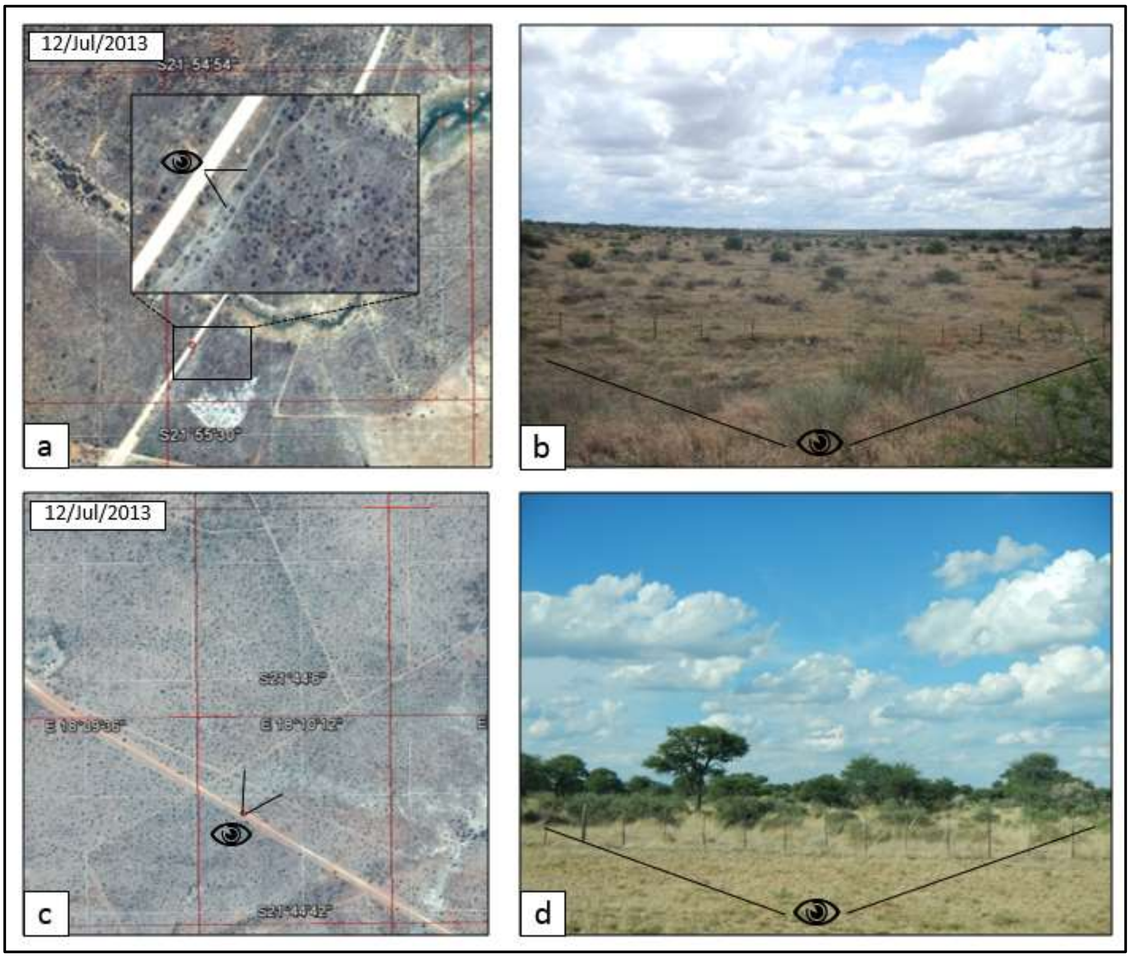

Figure 15 a) High resolution imager from the site visited b) Site visited, location: 21 55 21.25 S, 18 11 33.70 E c) High resolution imager from the site visited d) Site visited, location: 21 44 26.76 S, 18 10 2.17 E

From these comparisons, the following can be noted. The first is that the bush density can be estimated as the high resolution images provide sufficient detail for doing so. The second is that bush canopy differs annually according to the season (or rainfall events), which makes it difficult to assess canopy cover changes if one of the high resolution images was taken at the dry season. In the previous examples it was shown that high resolution imagery present a reasonable quality to detect these attributes, however, this was not always the case.

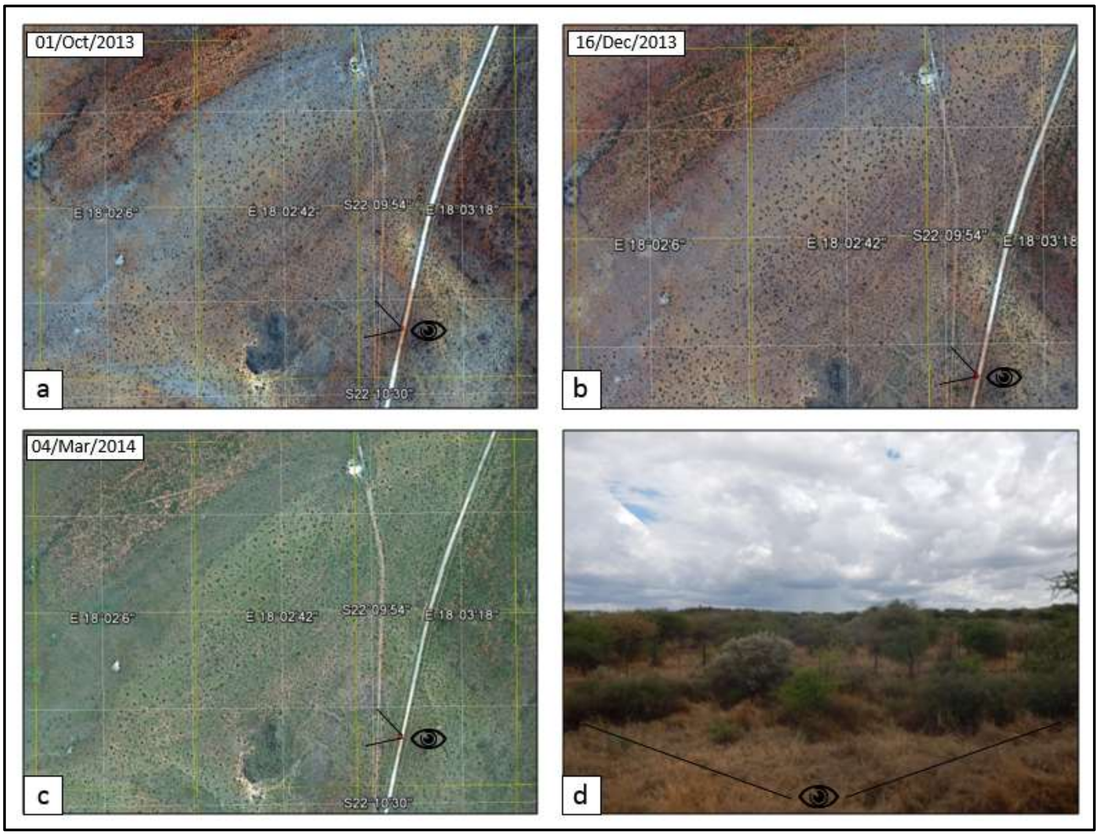

Figure 16 Site visited and its corresponding Google Earth high resolution images for three different dates

Images from the same site but taken at different dates present changes. The contrast, the sharpness and the colors were the three main differences found between the different images. Some of these differences correspond to the seasonality (Figure 16) and some others to the quality of the image. Figure 17a and b are presented with a green dominant color and figure g with a bluish color which corresponds to the dry season. Figure 17d and e have are considered to have poor quality. This consideration is based on: 1) The contrast of these images make the general color of the image to be presented in a tone that does not correspond to the seasonality of these images. Figure 17d is too dark, while Figure 17e is too light. 2) The sharpness is lower than in the other images. Features on the images are harder to recognize. The examples presented here are to visualize how the images can present different qualities and with these we can have two examples of the bad quality within the same area. Nevertheless, similar cases were found while looking for differences in bush canopy and bush density for one of the recent or historical images.

When analyzing high-resolution imagery, it is difficult to visually analyze changes with high accuracy, given the different seasonal-dependent scene characteristics. However, the comparison between the SPOT-VGT NDVI values and the high resolution imagery was done. Figure 18 shows an area of 8 km^2 approximately. The blue grid corresponds to the SPOT VGT pixels. The pixel corresponding to the Profile 2 shows less bush density than the others; its NDVI values are mainly higher than the rest of the pixels. The temporal behavior of NDVI was similar for all 4 pixels. In Figure 19, it can be seen that the pixel number four is the one that presents more bush density in the NDVI profile, but this value is not necessarily the highest in the whole profile. Profile no 3 shows that there was a process of bush cleaning, but cannot be recognized in the profile.

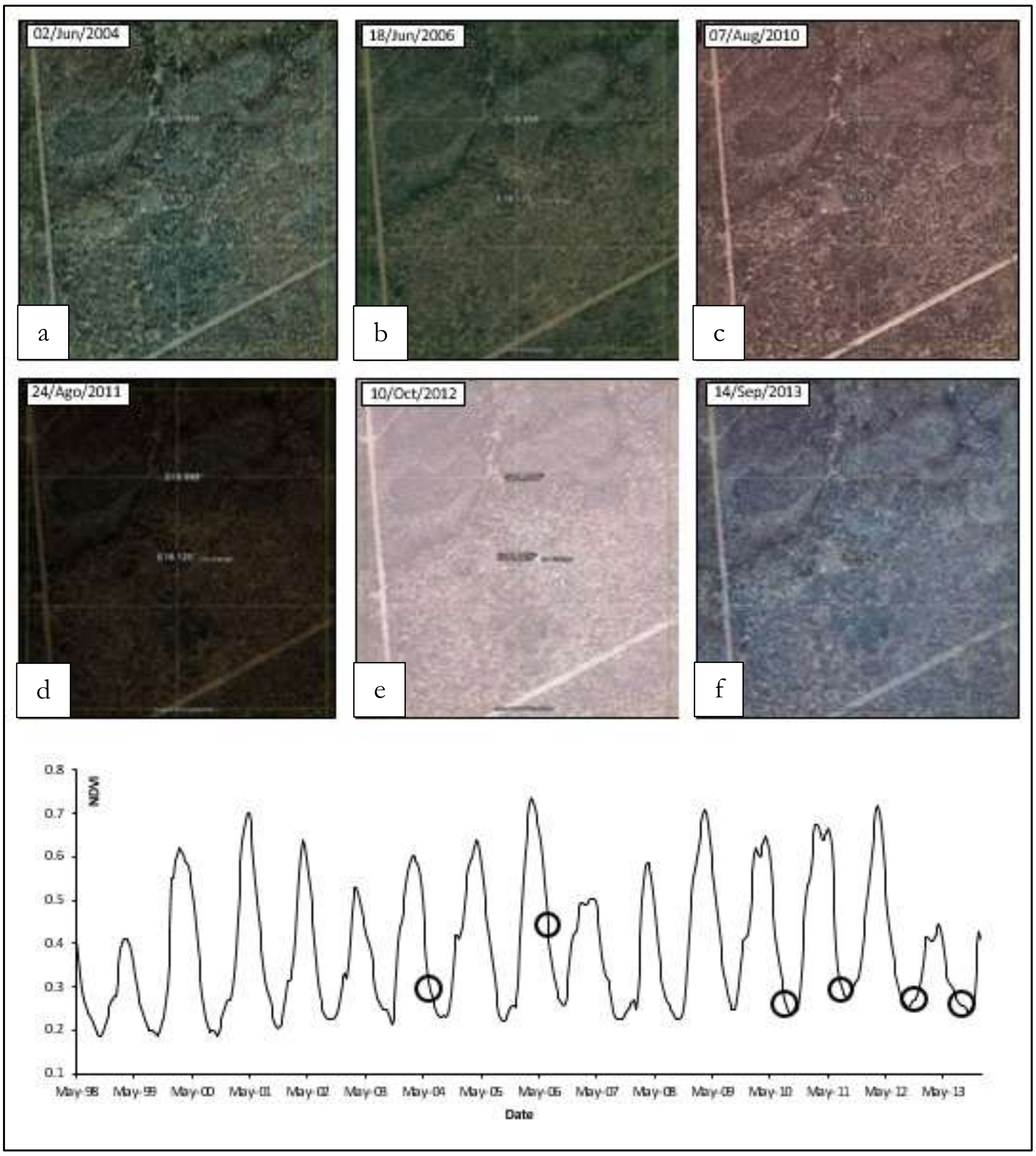

Figure 17 High resolution images provided by Google Earth taken at different dates. Coordinates: site 5

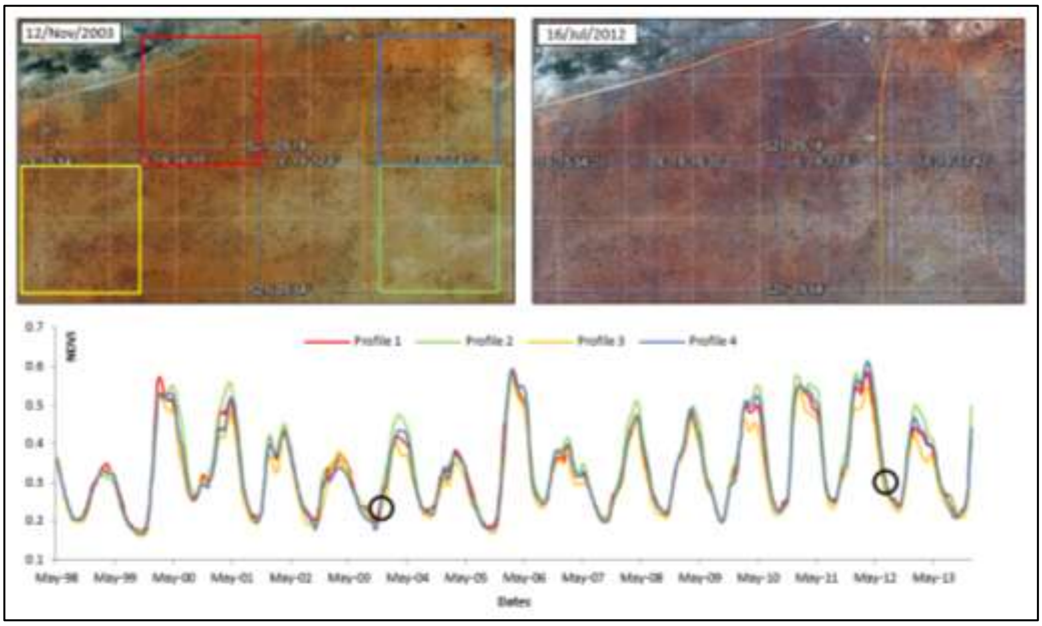

Figure 18 High resolution images from site 4 and its NDVI profiles. The corresponding pixels to the NDVI time series profiles are indicated with the same colour. The black circles indicates the NDVI value when the image was taken.

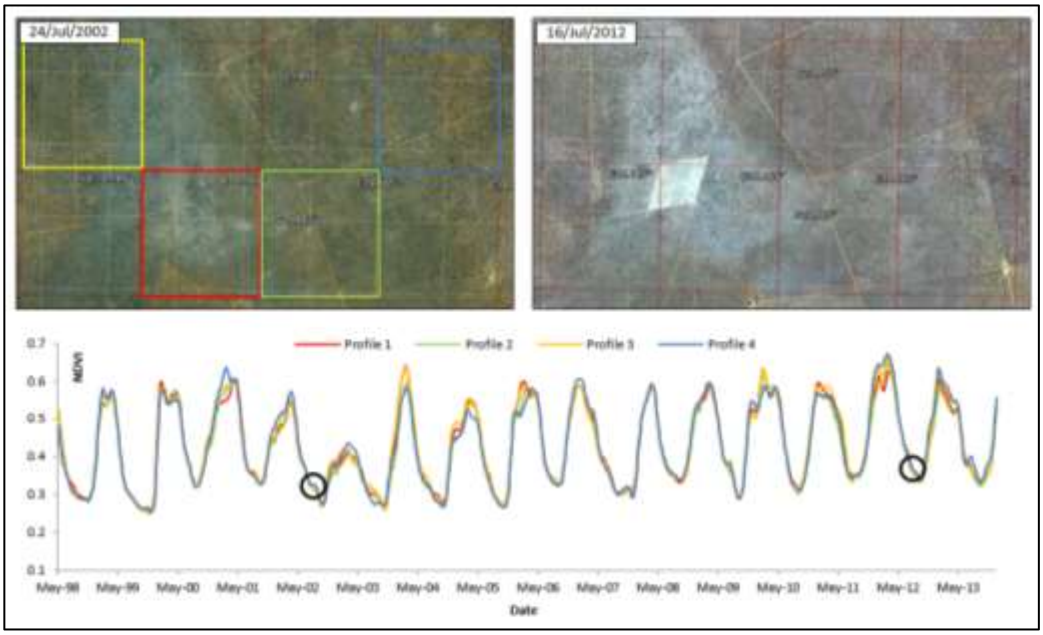

Figure 19 High resolution images from site 8 and its NDVI profiles. The corresponding pixels to the NDVI time series profiles are indicated with the same color. The black circles indicate the NDVI value when the high resolution image was taken.

4. DISCUSSION

Following the data collection and analysis procedures outlined above, the previous chapter has presented the findings of this research. These findings are subject to some caveats. This chapter discusses those and, based on that, formulates some suggestions for further research.

4.1. Vegetation type map

The number of clusters considered as the best classification for the SPOT-VGT NDVI profiles in Namibia was 73. The patterns in the statistics, where the average separability tends to increase and the minimum separability tends to reduce in function of the number of clusters are similar with the findings in the Korean Peninsula using SPOT-VGT NDVI MVC-Images from May 1998 to December 2009 (De Bie et al., 2011).

The high variability in the NDVI from the clusters 1 to 11 corresponded to their location. They presented occasionally negative values that suggest that these areas were sometimes flooded and/or near to the coastal zone. Class 2 does not present high variability as its pixels are located in the inshore. However, the clusters that are located in the foreshore present more variability, which can be attributed to changes in the tide. Clusters 3 and 4 are contiguous. They are located in the eastern area of the Etosha pan. The variations of this area correspond to certain anomalies presented in 2008 to 2009, 2009 to 2010 and 2011 to 2012. Some of these clusters have mixed pixels, which are pixels that encompass water and land (Pettorelli et al., 2005) and occur in the coastal zone or other areas with water in Namibia. For these reasons these clusters were eliminated for further analysis, besides they only represent 0.71% of the total study area.

Apart from these mentioned clusters that were easily identifiable other features could be recognized. For example, the border between Namibia and Angola in the Cuvelai Etosha basin was identified by the limits of two different clusters. These correspond to different managements between Namibia and Angola(Lira-Reyes, 1997). In the Cuvelai Etosha basin 1.2 million of people were living in 2012, of which 70% of them are living in Namibia (Mendelsohn et al., 2013). This makes that the land use is more intensive than in Angola territory.

Some of the NDVI cluster profiles can be related to vegetation structure. The annual NDVI variability of the clusters with a higher NDVI values (clusters 57-73) is due to the well-defined seasonality as can be seen in the profiles of Figure 6. These clusters are spatially connected and distributed in the northern part of Namibia which coincides with areas with low interannual rainfall variability. The rainfall is also higher in Namibia (>350mm/year). The minimum annual NDVI values are constant. On the other hand, clusters with medium NDVI means (30-34) present higher interannual variability (Figure 6). The minimum NDVI values from these clusters are not constant, neither the maximum NDVI. The NDVI clusters with higher values are located in areas with high bush and trees densities while the cluster with medium NDVI values are in the savannahs.

Not all the vegetation types from Mendelsohn coincide with the boundaries of the clusters. This could be for three reasons. First, the clusters are not spatially connected between each other. Second, these are gradients of vegetation the borders are not strictly defined. Third, due to Mendelsohn's map limitations described in section 2.2.5. Comparing the resulting map to the vegetation map of Mendelsohn the major differences are encountered in the Nama Karoo and the Namib Desert. Fourth, NDVI is not the best index map vegetation types in the desert; other index as Soil Adjusted Vegetation Index could have been better (Pettorelli et al., 2005) as it was observed that these clusters present a relation with the soil types.

In the current study, no attempt was made to quantitatively relate the NDVI-derived clusters to environmental variables. It is known that altitude and rainfall present a correlation in this area and vegetation types are largely controlled by climate, topography and substrate. A recommendation for future research is therefore to attempt statistically modelling how NDVI clusters relate to environmental variables, taking into account the collinearity between them to avoid erratic results. Apart from the environmental variables shown in this thesis, other variables may be included, such as maximum, minimum and average temperature, extreme rainfall events and relative humidity. In addition, for the variables that were included in this thesis, better data sources may exist.

Another suggestion for future research is to focus on the detection of the main dominant species for the smaller units mapped. The Tree Altas of Namibia seems to have valuable information to complement the information for understanding the vegetation types and include grasses species. With these a more accurate map can be created and can fill the areas that were not interpreted as the Nama Karoo. The distribution of certain species follow the patterns of these class as *Cadaba aphylla* , *Calicorema capitata*, *Aloe dichotomata*, among others.

4.2. Bush encroachment detection

This study explored the possibility to detect bush encroachment in Namibia with SPOT VGT time series profiles. 25 sites were visually analyzed to find evidence of bush encroachment using historical and recent high resolution imagery. From these 25 sites, the pixels in the series profiles have similar temporal behavior.

High resolution images provide sufficient detail to detect single bushes. These were encountered as small dots with a dark color presenting differences relying on their ground characteristics. For this reason, it is considered that high resolution images are good for estimating bush densities. It is not a coincidence that aerial photography has been the most common method in bush encroachment studies (Hudak & Wessman, 2001; O'Connor & Crow, 1999; Oldeland et al., 2010; Shanungu et al., 2013; van Vegten, 1984). However, these studies have a longer time period to detect changes.

The time period of this study is too short, which makes the detection of bush encroachment unreliable. There was no evidence found of bush encroachment in the aerial photographs, because 10 years are insufficient to notice a change, given that this ecological process is slow and nonlinear (Shekede et al., 2015). Depending on the species, the conditions for starting bush thickening are diverse. For *A. mellifera* this condition is presented 5 to 6 times per century when the seedlings are just established after exceptional rainfalls (more than 600 mm/year) (Joubert et al., 2008). The condition for *A. reficiens* to germinate and establish is documented as several rainfall events are needed (Wiegand et al., 2005). This situation was not present in the study areas from 1998 to 2004 (NOAA Climate Prediction Center, 2015), so the establishment of new seedlings was not expected.

The changes in these colors can lead to a misinterpretation of the images. They might suggest a possible change in bush density or bush canopy density. Such changes are not meaningful as they were not attributed to changes in the structure composition of vegetation, where bush encroachment could have been detected. An expert in bush encroachment from the Polytechnic of Namibia, Dave Francois Joubert, also argues that a time frame of more than 10 years is needed to be more confident that the possible change in density of two aerial images is valid and cannot be explained by an error (personal communication, November, 2014). He means that if we estimate the bush density and canopy for two images, it results in an error as in any interpretation and probably, the difference encountered between these two images will then just correspond to an error of the estimation.

Although the visual examination of two images separated in time sometimes gave the suggestion of changes in bush canopy cover, the different vegetation phenology at the time of observation did not allow drawing clear conclusions from this regarding bush encroachment. Most of the images corresponded to the dry season, where the bushes did not present leaves. Other images presented poor sharpness which also made the estimation of bush canopy cover unreliable. If images corresponded to the wet season, estimations of bush canopy density could have been made. However, if all the images acquired would have been from the same season, it is unlikely that this could have been achieved. That is, because the ratio of growth of the main encroacher bush species is very slow: measured mean annual stem diameter increments in *Acacia tortilis* and *A. raddiana* are as small as 0.39cm (Ward, 2005).

When comparing the pixels of the SPOT-VGT NDVI profiles with the corresponding area of the high resolution images from Google Earth, the pixels with more bush density did not necessarily correspond to higher NDVI values. This is because the NDVI values are not only the reflection of the bush densities but the whole biomass, including other species as grasses.

A better understanding could be achieved by studying these processes on a larger area and by studying a longer period of time. Bush encroachment can be seen as part of a cyclical succession between open savannah and woody dominance within the paradigm of patch-dynamic savannahs, and is a very slow process (Meyer, Wiegand, Ward, & Moustakas, 2007; Moustakas et al., 2009; Wiegand et al., 2005). In this study, the focus was not on the detection of bush encroachment with high resolution imagery but with the NDVI profiles, which had a limitation of 15 years. Given this, images that belong to this time-period were searched.

The study of bush encroachment should be studied on a bigger scale. Given that the process in bush encroachment was initially perceived by humans in situ, the perception in this small scale seems to be a problem for rangeland management as they rely on open extensions to their activity. However, modelling has been a useful tool to understand the dynamics between grass and bush in savannahs (Meyer et al., 2007; Moustakas et al., 2009).

The idea that bush encroachment is just a part of a cycle does not oppose Dave Joubert (2014), who claims that: "thickening has been rather modest and was in existence for much longer than currently thought". Part of this idea comes from that there is no quantitative data from where the bush encroachment was started being detected as a problem in the late 1950s / early 1960s and that the perceived relationship between the declines in cattle numbers in the commercial farming sector and bush encroachment is untested.

5. CONCLUSIONS

This study dealt with two research objectives. The first objective was to map the vegetation types in Namibia with the use of SPOT VGT NDVI data of 15 years. The second objective was to explore the possibility to detect bush encroachment in Namibia with SPOT VGT NVDI time series profiles.

Based on the findings, and taken the limitations above into account, it can now be concluded that:

- When analyzing the historical and recent Google Earth images there bush encroachment was not detected.
- SPOT-VGT NDVI time series from 15 years can be used to map vegetation types at a national level.

LIST OF REFERENCES

A., J., H.I., R., A., N., & E., G. (2008). Holefilled seamless SRTM data V4. International Centre for Tropical Agricultura.

Ali, A., de Bie, C. a. J. M., Skidmore, a. K., Scarrott, R. G., & Lymberakis, P. (2014). Mapping the heterogeneity of natural and semi-natural landscapes. *International Journal of Applied Earth Observation and Geoinformation*, *26*, 176–183. doi:10.1016/j.jag.2013.06.007

Ali, A., de Bie, C. A. J. M., Skidmore, A. K., Scarrott, R. G., Hamad, A., Venus, V., & Lymberakis, P. (2013). Mapping land cover gradients through analysis of hyper-temporal NDVI imagery. *International Journal of Applied Earth Observation and Geoinformation*, *23*, 301–312. doi:10.1016/j.jag.2012.10.001

Beltran-Abaunza, J. M. (2009). *Method Development to Process Hyper-Temporal Remote Sensing (RS) Images for Change Mapping*. University of Twente.

Bester, F. V. (1999). Major problem, bush species and densities in Namibia. *Agricola*, *10*, 1 – 3.

Bie, C. A. J. M. K. De, Venus, V., & Skidmore, A. K. (2011). Improved mapping and monitoring with hyper-temporal imagery. In *Proceedings of the internetional workshop on advanced use of satellite - and geo - information for agricultural and environmental intelligence* (pp. 122 – 133). Tsukuba.

Boschetti, M., Nutini, F., Brivio, P. A., Bartholomé, E., Stroppiana, D., & Hoscilo, A. (2013). Identification of environmental anomaly hot spots in West Africa from time series of NDVI and rainfall. *ISPRS Journal of Photogrammetry and Remote Sensing*, *78*, 26–40. doi:10.1016/j.isprsjprs.2013.01.003

Colin Christian & Associates CC. (2010). *The Effect of Bush Encroachment on Groundwater Resources in Namibia: a Desk Top Study* (p. 110). Windhoek.

Consultants, N. R. (1999). *Rainfall distribution in Namibia: Data analysis and mapping of spatial, temporal, and Southern Oscillation Index aspects.* Windhoek.

De Bie, C. a. J. M., Nguyen, T. T. H., Ali, A., Scarrott, R., & Skidmore, a. K. (2012). LaHMa: a landscape heterogeneity mapping method using hyper-temporal datasets. *International Journal of Geographical Information Science*, *26*(11), 2177–2192. doi:10.1080/13658816.2012.712126

De Klerk, J. N. (2004). *Bush Encroachment in Namibia. Report on phase 1 of the bush encroachment research, monitoring and management project* (p. 253). Windhoek.

Eldridge, D. J., Bowker, M. A., Maestre, F. T., Roger, E., Reynolds, J. F., & Whitford, W. G. (2011). Impacts of shrub encroachment on ecosystem structure and functioning: towards a global synthesis. *Ecology Letters*, *14*(7), 709–22. doi:10.1111/j.1461-0248.2011.01630.x

Estupiñan-Suarez, L. M. (2013). *Analysis of NDVI- Time Series to detect Bush Encroachment : A case study in Cadiz (Spain) assessing three different methods on the basis of minimum NDVI.*

Government of Namibia. (2014). Government of Namibia. *Overview*. Retrieved August 26, 2014, from http://www.gov.na/

Hély, C., Caylor, K. K., Dowty, P., Alleaume, S., Swap, R. J., Shugart, H. H., & Justice, C. O. (2007). A Temporally Explicit Production Efficiency Model for Fuel Load Allocation in Southern Africa. *Ecosystems*, *10*(7), 1116–1132. doi:10.1007/s10021-007-9082-3

Hottman, M. T., & O'Connor, T. G. (1999). Vegetation change over 40 years in the Weenen/Muden area, KwaZulu-Natal: evidence from photo-panoramas. *African Journal of Range & Forage Science*, *16*(2-3), 71–88. doi:10.2989/10220119909485721

Hudak, a. T., & Wessman, C. a. (2001). Textural analysis of high resolution imagery to quantify bush encroachment in Madikwe Game Reserve, South Africa, 1955-1996. *International Journal of Remote Sensing*, *22*(14), 2731–2740. doi:10.1080/01431160152518660

Hüttich, C., Gessner, U., Herold, M., Strohbach, B. J., Schmidt, M., Keil, M., & Dech, S. (2009). On the Suitability of MODIS Time Series Metrics to Map Vegetation Types in Dry Savanna Ecosystems: A Case Study in the Kalahari of NE Namibia. *Remote Sensing*, *1*(4), 620–643. doi:10.3390/rs1040620

J., M., A., J., & T., R. (2013). *A Profile and Atlas of the Cuvelai-Etosha Basin* (p. 170). Windhoek.

Jacquin, A., Sheeren, D., & Lacombe, J.-P. (2010). Vegetation cover degradation assessment in Madagascar savanna based on trend analysis of MODIS NDVI time series. *International Journal of Applied Earth Observation and Geoinformation*, *12*, S3–S10. doi:10.1016/j.jag.2009.11.004

Jensen, J. R. (2007). Remote Sensing of Vegetation. In *Remote Sensing of the Environment*.

Jönson, P., & Eklundh, L. (2004). TIMESAT - a Program for Analyzing Time-Series of Satellite Sensor Data Users Guide for TIMESAT 2 . 3. *Computers & Geosciences*, *30*, 833 –845.

Joubert, D. F. (2014). *The dynamics of bush thickening by Aciacia mellifera in the highland savanna of Namibia*. University of the Free State.

Joubert, D. F., Rothauge, A., & Smit, G. N. (2008). A conceptual model of vegetation dynamics in the semiarid Highland savanna of Namibia, with particular reference to bush thickening by Acacia mellifera. *Journal of Arid Environments*, *72*(12), 2201–2210. doi:10.1016/j.jaridenv.2008.07.004

Joubert, D., Zimmermann, I., Nathanael, N., & Hugh, P. (2013). *Baseline Study of Bush Encroachment and Available Management options for the Windhoek Green Belt Landscape* (p. 48).

Kgosikoma, O. E., & Mogotsi, K. (2013). Understanding the causes of bush encroachment in Africa : The key to effective management of savanna grasslands. *Tropical Grasslands*, *1*, 215–219.

Khan, M. R., de Bie, C. A. J. M., van Keulen, H., Smaling, E. M. A., & Real, R. (2010). Disaggregating and mapping crop statistics using hypertemporal remote sensing. *International Journal of Applied Earth Observation and Geoinformation*, *12*(1), 36–46. doi:10.1016/j.jag.2009.09.010

Lira-Reyes, G. (1997). *Spatial and seasonal variations along the U.S. - Mexico border: An analysis with Landsat Thematic Mapper Imagery*. *Arbor Ciencia Pensamiento Y Cultura*. University of Arizona.

Lukomska, N., Quaas, M. F., & Baumgärtner, S. (2014). Bush encroachment control and risk management in semi-arid rangelands. *Journal of Environmental Management*, *145C*, 24–34. doi:10.1016/j.jenvman.2014.06.005

Meik, J. M., Jeo, R. M., Mendelson III, J. R., & Jenks, K. E. (2002). Effects of bush encroachment on an assemblage of diurnal lizard species in central Namibia. *Biological Conservation*, *106*(1), 29–36. doi:10.1016/S0006-3207(01)00226-9

Mendelsohn, J., & Coetzee, J. & M. (2003). *Spatial analysis of bush densities and encroacher species data*. Windhoek.

Mendelsohn, J., Jarvis, A., Roberts, C., & Robertson, T. (2002). *Atlas of Namibia, a portrait of the land and its peple.* (p. 200). Cape Town: New African Books.

Meyer, K. M., Wiegand, K., Ward, D., & Moustakas, A. (2007). The rhythm of savanna patch dynamics. *Journal of Ecology*, *95*(0), 1306–1315. doi:10.1111/j.1365-2745.2007.01289.x

Moore, K. J. (2010). Bush Encroachment. *Converting Bush Encroachment Problem into Clean Energy*. Retrieved August 28, 2014, from http://www.bushencroachment.com/namibian-solution.html

Moustakas, A., Sakkos, K., Wiegand, K., Ward, D., Meyer, K. M., & Eisinger, D. (2009). Are savannas patch-dynamic systems? A landscape model. *Ecological Modelling*, *220*(24), 3576–3588. doi:10.1016/j.ecolmodel.2009.06.036

Munyati, C., Economon, E. B., & Malahlela, O. E. (2013). Effect of canopy cover and canopy background variables on spectral profiles of savanna rangeland bush encroachment species based on selected Acacia species (mellifera, tortilis, karroo) and Dichrostachys cinerea at Mokopane, South Africa. *Journal of Arid Environments*, *94*, 121–126. doi:10.1016/j.jaridenv.2013.02.010

O’Connor, T. G., & Crow, V. R. T. (1999). Rate and pattern of bush encroachment in Eastern Cape savanna and grassland. *African Journal of Range & Forage Science*, *16*(February 2015), 26–31. doi:10.2989/10220119909485715

Oldeland, J., Dorigo, W., Wesuls, D., & Jü, N. (2010). Mapping Bush Encroaching Species by Seasonal Differences in Hyperspectral Imagery Jens, 1416–1438. doi:10.3390/rs2061416

Pettorelli, N., Vik, J. O., Mysterud, A., Gaillard, J.-M., Tucker, C. J., & Stenseth, N. C. (2005). Using the satellite-derived NDVI to assess ecological responses to environmental change. *Trends in Ecology & Evolution*, *20*(9), 503–10. doi:10.1016/j.tree.2005.05.011

Rouse, J. W., Hass, R. H., Schell, J. A., Deering, D. W., & Harlan, J. C. (1974). *Monitoring the Vernal Advancement and Retrogradation (Greenway Effect) of Natural Vegetation* (p. 390).

Sannier, C. a. D., Taylor, J. C., & Plessis, W. Du. (2002). Real-time monitoring of vegetation biomass with NOAA-AVHRR in Etosha National Park, Namibia, for fire risk assessment. *International Journal of Remote Sensing*, *23*(1), 71–89. doi:10.1080/01431160010006863

Schröter, M., Jakobyb, O., & Olbricha, R. (2009). Remote sensing of bush encroachment on commercial cattle farms in semi-arid rangelands in Namibia by Matthias Schröter , Oliver Jakoby , Roland Olbrich , Marcus Eichhorn and Stefan Baumgärtner University of Lüneburg Working Paper Series in Economics, (131).

Shanungu, G. K., Blaser, W. J., Harms, J., Chabwela, H. N., Ellenbroek, G. A., Simukonda, C., … Venterink, H. O. (2013). Impact of shurb encroachment on the understoy vegetation differs among shurb species in the Kaufe Flats, Zambia. In *Impact of woody encroachment on soil-plant-berbivore interactions in the Kaufe Flats floodplain ecosystem* (pp. 75 – 104).

Shekede, M. D., Murwira, A., & Masocha, M. (2015). Wavelet-based detection of bush encroachment in a savanna using multi-temporal aerial photographs and satellite imagery. *International Journal of Applied Earth Observation and Geoinformation*, *35*, 209–216. doi:10.1016/j.jag.2014.08.019

Sirami, C., & Monadjem, A. (2012). Changes in bird communities in Swaziland savannas between 1998 and 2008 owing to shrub encroachment. *Diversity and Distributions*, *18*(4), 390–400. doi:10.1111/j.1472-4642.2011.00810.x

Skarpe, C. (1990). Shrub layer dynamics under different herbivore densities in an arid savanna, Botswana. *Journal of Applied Ecology*, *27*, 873–885.

Stellmes, M., Röder, A., Udelhoven, T., & Hill, J. (2013). Mapping syndromes of land change in Spain with remote sensing time series, demographic and climatic data. *Land Use Policy*, *30*(1), 685–702. doi:10.1016/j.landusepol.2012.05.007

Sweet, J., & Burke, A. (2006). *Country Pasture / Forage Resource Profiles: Namibia* (p. 16). Viale delle Terme di Caracalla.

Van Vegten, J. A. (1984). Thornbush invasion in a savanna ecosystem in eastern Botswana. *Vegetatio*, *56*(1), 3–7.

Ward, D. (2005). Do we understand the causes of bush encroachment in African savannas ? *African Journal of Range and Forage Science*, *22*(2), 101–105.

Wiegand, K., Ward, D., & Saltz, D. (2005). Multi-scale patterns and bush encroachment in an arid savanna with a shallow soil layer. *Journal of Vegetation Science*, *16*, 311–320. doi:10.1111/j.1654-1103.2005.tb02369.x

Wu, W., De Pauw, E., & Helldén, U. (2013). Assessing woody biomass in African tropical savannahs by multiscale remote sensing. *International Journal of Remote Sensing*, *34*(13), 4525–4549. doi:10.1080/01431161.2013.777487

APENDIX

Table I. Location of the sites where bush encroachment was searched and the dates of the high resolution imagery

No.	Coordinate X	Coordinate Y	Date 1	Date 2
1	16.32794	-20.30146	19-Jul-03	11-Jul-13
2	19.58925	-22.85797	5-Mar-03	13-Jul-13
3	19.70158	-22.85788	5-Mar-03	13-Jul-13
4	19.27669	-21.15294	12-Nov-03	16-Jul-12
5	19.17118	-21.54791	24-Jul-02	15-Jun-13
6	16.83501	-19.84075	9-Sep-03	25-Oct-12
7	16.83044	-19.86621	19-Aug-03	25-Oct-12
8	19.14865	-21.86294	24-Jul-02	16-Jul-12
9	18.86714	-22.39944	28-Apr-03	28-Oct-09
10	19.01218	-22.16095	24-Aug-02	4-Mar-14

11	19.04686	-22.08204	24-Aug-02	7-Apr-13
12	19.04734	-22.00047	6-Aug-02	1-Oct-12
13	16.64245	-19.95569	6-Sep-03	11-Jul-13
14	16.26648	-19.75731	14-Nov-03	25-Oct-12
15	16.63407	-19.98316	6-Sep-03	11-Jul-13
16	16.06338	-19.76797	1-Sep-03	24-Aug-12
17	16.02850	-19.77673	2-Sep-03	25-Aug-12
18	19.17843	-21.91420	6-Aug-02	16-Jul-12
19	19.16132	-21.58041	24-Jul-02	15-Jun-13
20	20.37184	-21.74231	15-Oct-03	9-Mar-13
21	18.92032	-22.39195	24-Aug-02	13-Jul-13
22	19.03643	-22.45493	25-Aug-02	14-Jul-13
23	19.49115	-21.81179	7-Nov-03	7-Jul-13
24	19.08909	-22.78515	17-Nov-02	13-Jul-13
25	16.12574	-20.00030	2-Jun-04	14-Sep-13