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The Utility of NOAA AVHRR Data for Vegetation Studies in Semi-arid Regions

- A Minor Field Study in the Hoanib Catchment of Namibia

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Abstract

The relationship between field measurements of vegetation in a semi arid region and NDVI from the 1 km NOAA AVHRR was investigated within this study. The Hoanib catchment in the northwestern Namibia was chosen as study area. The field measurements were carried out during the month of February 1999. Different NDVI values and combinations of NDVI were used and it was found that the integrated NDVI until the time of the field measurements correlated best to the grass vegetation. No significant correlations were found with the woody vegetation.

The utility of non-destructive measurements of vegetation was also examined. Since destructive measurements of woody vegetation are both time-consuming and harmful to the environment, two different non-destructive methods were compared. It was found that the result of the two methods differed considerably for species and growth forms that were not recorded in the areas where the equations were established. The relationship between NDVI and grass measured with destructive or non-destructive methods was also compared. It was found that a non-destructive method returned almost as high correlation values as the destructive method.

The relationship between NDVI and vegetation for all plots (with a large precipitation gradient) were compared to the relationship for the most easterly plots (with a small precipitation gradient) to draw attention to the fact that a trend in the data set improves the correlation values. This was also the case in the study.

Finally, a Monte Carlo simulation was used to study the sensitivity of the calculated net primary production, using the Monteith equation, to variations in the ε, a and b parameters. It was found that the NPP was very sensitive to variations in ε but less sensitive to variations in a and b.

Minor Field Study

This study has been carried out within the framework of the Minor Field Study (MFS) Scholarship Program, funded by the Swedish International Development Co-operation Agency (Sida).

The MFS Scholarship Program gives the Swedish university students the opportunity to carry out field work in a Third World country. The extent of the fieldwork corresponds to BA or Master's dissertations, or similar in-depths studies. The studies focus on areas and issues of relevance for development problems, and are conducted in countries supported by Swedish development assistance.

Sida's main purpose with the MFS Scholarship Program is to stimulate the students' interest in, and increase their knowledge about, as well as their understanding for, developing countries and development issues. The MFS scholarships provide the students with practical experiences of the conditions of development. One further aim for Sida is to widen the personnel resources for recruitment in the field of development co-operation.

The department of Social and Economic Geography at Lund University is one of the departments, which administers MFS Program funds. Studies conducted by students granted scholarships by this department focus on spatial aspects of different development issues.

Key Words
Namibia, Hoanib, Remote Sensing, GIS, Vegetation, Net Primary Production

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Aim

The overall aim of the study is to see if it exists any relationships between the field measurements of the vegetation and NDVI from 1 km NOAA AVHRR in a semi-arid region with a great spatial variation in species composition, cover and height. The study also focuses on the following issues:

- The possibility to combine the NDVI values in different ways as well as using single values when investigating the relationships with the field measurements.
- The utility of non-destructive field measurements, which are not as time-consuming and harmful to the environment as destructive methods.
- To draw attention to the fact that a trend in the data set might increase the correlation values.
- The sensitivity of the Net Primary Production calculations by Montieth in concern to variations of ε, a and b parameters.

1 Introduction

The majority of the African livestock and 30 million people dependent on livestock live in the arid and semi-arid regions of Africa (Kruger & Kressirer, 1996). It is important to draw attention to this part of the world, where the population depends strongly on its resources in an unpredictable climate.

This study concentrates on the resources of the grass and the woody dry weight. The grass dry weight produced during the rainy season by the annual grasses in semi-arid regions provides an indication of resource availability for livestock for the following dry season. Additionally the resource of firewood from trees and shrubs is the primary household energy source for the majority of the people.

To study these resources in a vast region would require a dense network of ground measurements. To avoid this dense network, the method of remote sensing is useful. NOAA AVHRR has been used to quantify and characterize vegetation since the beginning of the nineteen eighties. The aim was first to monitor and achieve a better understanding of the Sahelien environment after the droughts in the late sixties and seventies. Today one objective is to estimate crop yields in the support of food security and economic planning as well as natural resource management at a national level (Rasmussen, 1996). When studying the relationships between vegetation characteristics, measured in situ, and the Normalized Differential Vegetation Index (NDVI) as measured with the NOAA AVHRR sensor, the fact that dry aboveground net primary production correlates well with NDVI integrated during the rainy season (Rasmussen, 1996) is applied. Much research has been carried out to assess the dry weight in photosyntetically homogenous vegetation such as agricultural crops, natural grasslands and dense forests (Franklin & Hiernaux, 1991), but extensive research considering heterogeneous vegetation covers has not been carried out.

Most studies have been carried out in the Sahel, but another region with similar conditions is Namibia; the driest country south of the Sahel. Approximately 60% of the population lives in rural parts of the country where livestock production is the main economic activity (Kruger & Kressirer, 1996).

The Hoanib river catchment in northwestern Namibia was chosen for the study. The catchment is a particularly good representative of western Namibia, because the population is steadily increasing along with the number of tourists, while the natural resources remain the same. The Hoanib is also undergoing additional stress since the independence of the country in 1990. The stress is caused by the intensification of livestock, as the people of Hereros are moving back into the area after being dislocated since the 1950's (Directorate of Planning, 1998).

The project was carried out to achieve a master in physical geography at Lund University of Sweden. It is addressed to anyone with an interest in relationships between vegetation and NDVI in semi-arid regions. A wide knowledge of neither the conditions of Namibia nor remote sensing is necessary.

2 The study area

Namibia as a country and the Hoanib catchment are described to give an idea of the physical geography as well as the interaction between the local people and the environment.

2.1 The country of Namibia

Namibia, former South West Africa, gained its independence only in 1990 making it one of the youngest countries in Africa. It is a large country of 824 269 km^2 (figure 1) with a population of only 1.6 million people. The population is increasing with 3.3% per year, which makes it is the fastest growing population of Africa (Jacobson *et al*, 1995). The population consists of 11 main groups of people.

Figure 1. Namibia's location in Africa.

Namibia is considered economically advanced compared to the other countries of southern Africa, even if the economical resources are unevenly distributed. After South Africa, Namibia is the country in the region with the highest rate of income per capita. The main economic sectors, in the order of economic importance, are mining, agriculture, fishery and tourism (Jacobson *et al*, 1995). Even if agriculture only is the second largest economic sector, it employs 50% of the workforce and is livestock dominated. Tourism, which today is forth in the order of economical importance, has the potential of becoming the second most important sector by the year of 2002 (Jacobson *et al*, 1995).

Located mainly in the desert, one of the countries major problems is the lack of fresh water. Permanent rivers are found only at the northern and the southern borders of the country, whereas there are several ephermal rivers, flowing only a few days each year after localized rains. The Hoanib is one of these ephermal rivers.

2.2 The Hoanib catchment

The Hoanib catchment is located in northwest of Namibia (figure 2). The size of the catchment is 17 200 km^2 (Directorate of Planning, 1998).

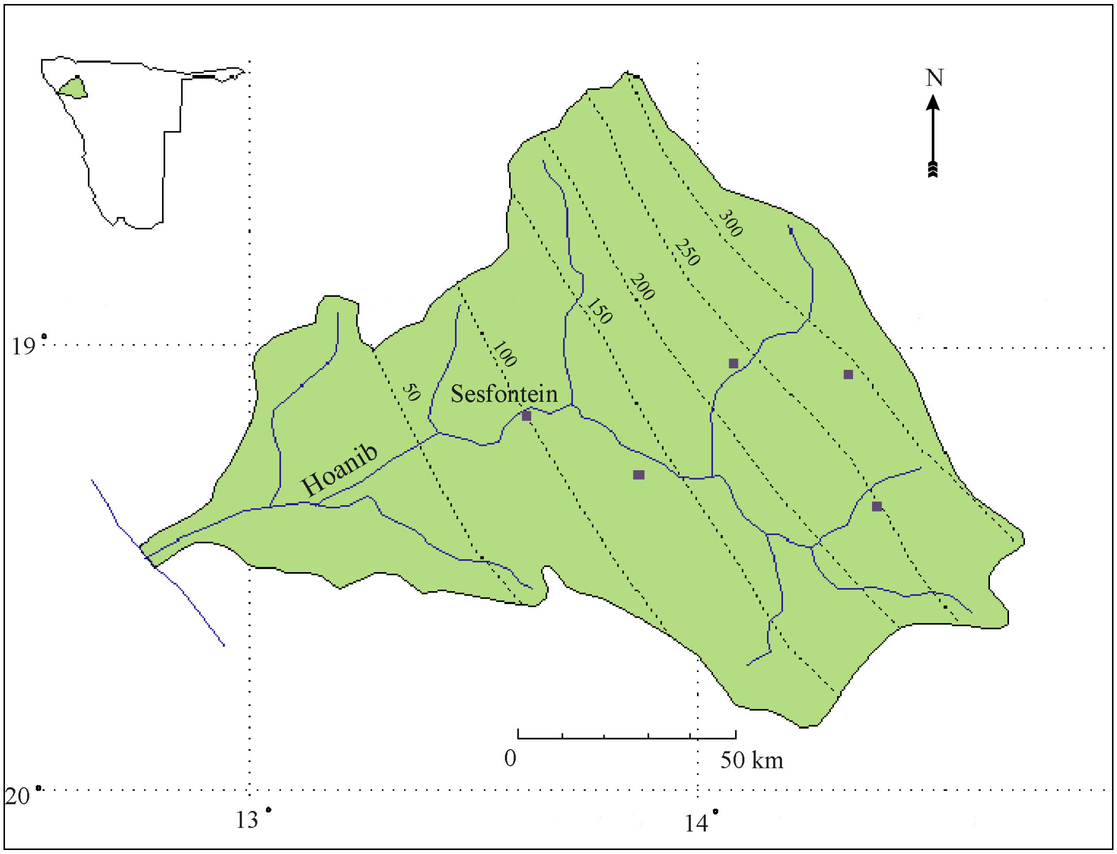

Figure 2. The Hoanib catchment and its location in Namibia (modified after Jacobson et al, 1995). The main community Sesfontein is marked as well as the isohythes (see "Climate" below).

2.2.1 Climate

The catchment is a semi-arid region and experiences very low precipitation. The mean precipitation ranges from 0 mm in the west to 325 mm in the east (Jacobson *et al*, 1995) (figure 2). The variability of the precipitation is as high 50-70% above or below the mean[1] (Rhode, 1994). The first rains fall in October to November, although the main rains begin in January and fall all through April (Shell Namibia Ltd, 1996).

During the days in the summer, the temperatures often rise above 35°C, but are sometimes as low as 14°C. The winters are cooler with temperatures of 5-26°C during the days (Shell Namibia Ltd, 1994). The high temperatures lead to a high evapotranspiration.

[1] This variability is true for Damaraland, which is the former region south of the Hoanib river.

2.2.2 Vegetation

The precipitation is the main controlling factor for the vegetation in the region; therefore the steep precipitation gradient coincides with a gradual change from desert in the west to savannah and woodlands in the east (Hall-Martin *et al*, 1988). In the catchment 87% is classified as Mopane savannah (Jacobson *et al*, 1995), consisting mostly of *Colophospermum mopane* in the form of tree or shrub. The rest is classified as the northern Namib vegetation class, consisting of a desert flora. Except from *Colophospermum mopane*, different species of Accacia are also common in the region.

The riparian forests are a main characteristic of the region. With their big trees compared to the surrounding environment they form linear oases in the landscape. The trees usually have a deep root system to enable the use of subsurface water, as the occasional floods are not sufficient for their survival.

The following photos are some examples of the vegetation in the Hoanib catchment. The first two (figure 3a and b) are both from the vicinity of Sesfontein (see figure 2 for location) before the growing season has started. These areas are dominated by *Colophospermum mopane*. The third photo (figure 3c) is taken in the eastern part of the catchment at the beginning of the growing season and is dominated by different Accacia species.

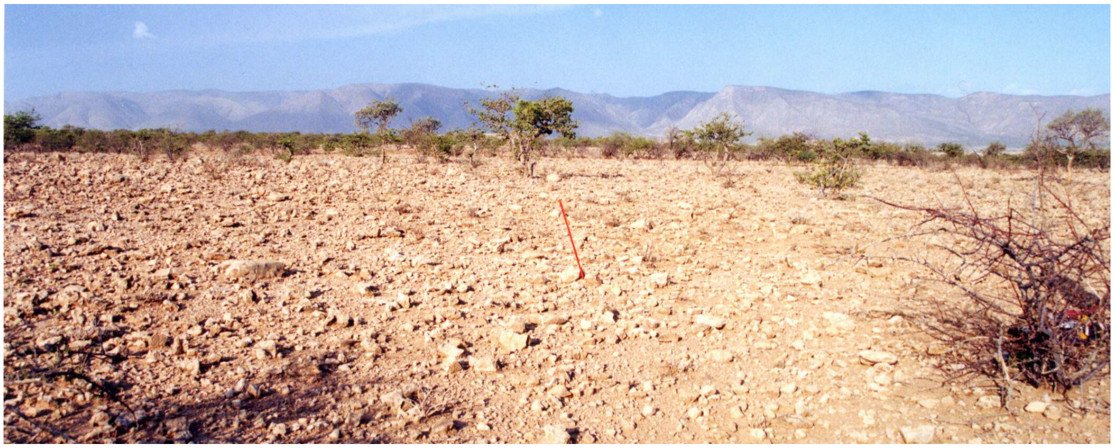

Figure 3a. The Sesfontein region (see figure 2 for location) where there was a very low canopy cover. Figure 3b. The Sesfontein region with a relatively higher tree cover than in figure 3a. The dominant species in figure 3a and b was Colophospermum Mopane. For both the photos the herbaceous cover was non-existing (the growing season had not yet started).
Figure 3c. The eastern part of the catchment dominated by different Accacia species and with an existing grass cover. The red stick seen in photo a and b was one meter long (note: in photo b the stick is placed in the tree).

2.2.3 Geology and topography

On its way to the Atlantic Ocean the Hoanib passes through an area with rugged terrain of dolomite hills (Owen-Smith, 1970), steep canyons and plains. Near Sesfontein the river valley widens and forms large plains. Further to the west the plains are ended by the escarpment mountains, which run parallel to the coast. Before entering the ocean the river crosses the coast desert with its vast sand fields and dunes.

As a result of the slow process of weathering in this arid area, the soils are fairly thin and poorly developed. The wind picks up easily in the wide plain and has the potential of carrying away large amounts of its fine-grained alluvial soil.

2.2.4 The people and their interaction with the environment

Even if there is a high urbanization rate in the country, the population is still increasing in the catchment with a population of almost 8000 (Jacobson *et al*, 1995). The population growth is as high as for the rest of the country (Warden, 1997). The population is not only increasing because of a high fertility and a reduced mortality, but because many people are resettling in the region. These people had to leave their land during the 1950's, because of the creation of the Etosha National Park. After Independence in 1990 when the Homelands Policy is no longer valid and the borders of Etosha National Park are again changed, covering a much smaller part of the catchment, the region experiences a high and increasing population pressure

(Directorate of Planning, 1998). The main community in the catchment is Sesfontein with a population of just above 600 (Warden, 1997).

The main group of people in the catchment is the Hereroes. They are pastoralists and relay strongly on their livestock for their living. The Hereroes lived a life of nomads for a long period of time. Thus after the influence of European settlers the Hereroes have become more sedentary. They have mostly settled in the vicinity of boreholes and natural springs. The livestock, consisting mainly of cattle and goats play an important role for the people in many different aspects i.e. for milk and meat, ploughing, ceremonial purposes, symbol of status, dung for buildings and for selling.

Except livestock, other activities are becoming more and more important, such as tourism and agriculture. The former being the only one with a potential growth considering the limited agricultural potential in this semi-arid environment (Jacobson *et al*, 1995). Since 1990 there has been a great increase of tourism in the catchment. Between the years of 1994-1996 the region experienced an increase of 35%[2] (Humavindu & Nekwiyu, 1996).

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[2] Several estimations were done since for some places the data were rough and there were many gaps. However the number works as an indication of the increasing tourist number.

3 Theory

To understand why the technique of remote sensing has been chosen instead of ground observations this chapter describes how the vegetation may be compared to measurements from remote sensing. Aspects treated are the spectral signature of objects, the vegetation index NDVI, the remote sensing sensor NOAA AVHRR and the principals for integrating NDVI during a vegetation season to achieve information about the total above-ground biomass produced. Finally the advantages and the disadvantages of remote sensing are reviewed.

3.1 Spectral signatures

When radiation from the Sun hits an object on the Earth, the radiation is absorbed, transmitted or reflected. Different features of the object decide how the radiation behaves in concern to these three ways. The features are for example color, chemical composition, humidity and the structure of the surface (Nämden för skoglig fjärranalys, 1993). Remote sensing uses the fact that objects may be separated from each other by the intensity of the different wavelengths reflected. In other words, objects are recognized by their so-called spectral signature.

The spectral signature of vegetation is distinguished by a reflection maximum in the green spectra and an even greater maximum in the near infrared spectra (figure 4). Reflection minimums are found in the blue and red parts of the spectrum. The chlorophyll absorbs in the blue and red parts of the spectrum and the water vapor absorbs some of the wavelength of the middle and high infrared. The large difference in the reflectance of red and near-infrared radiation is typical for vegetation and not found for any other surface.

The soil on the other hand has a more even curve representing its spectral signature (figure 4). The reflectance increases evenly in the visible and in the near infrared part of the spectra, to more or less level off in the middle infrared part of the spectra. Figure 4 also shows the spectral signature for water.

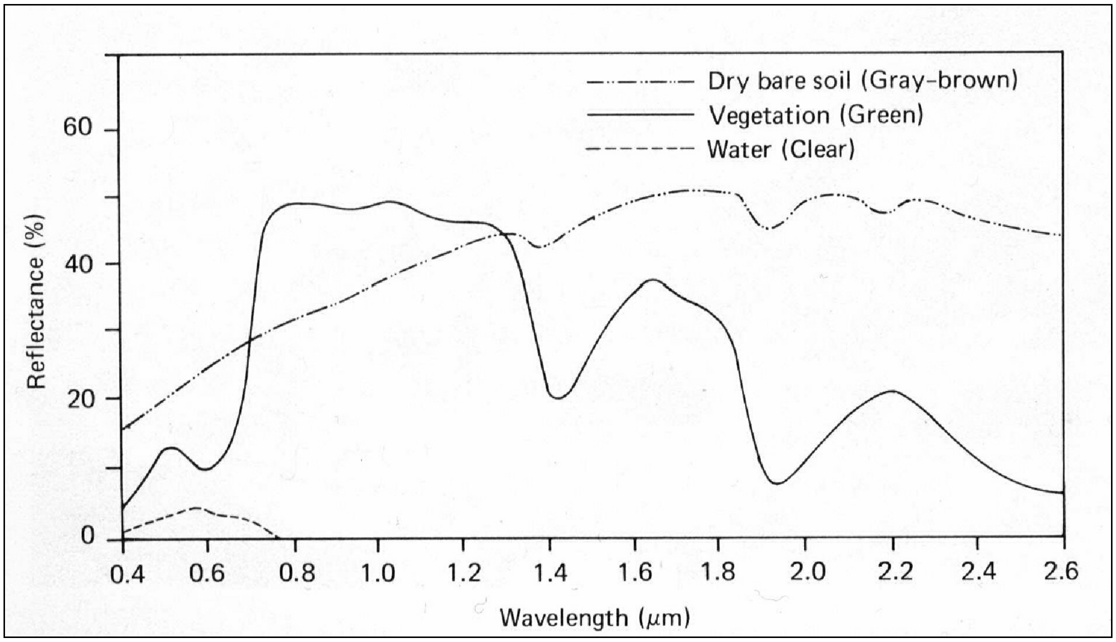


Figure 4. Typical spectral signature curves for vegetation, soil and water (Lillesand & Kiefer, 1979).

3.2 Normalized Differential Vegetation Index

Different vegetation indices have been constructed to avoid one of the fundamental problems of remote sensing; to separate the signal from the vegetation to that of the soil. The most widely used index is the Normalized Differential Vegetation Index (NDVI) (Olsson & Pilesjö, 1999). The index is constructed by the wavelengths band of the near infrared (NIR) and the red (RED) parts of the spectra according to the following formula:

$$NDVI = \frac{(NIR - RED)}{(NIR + RED)} \qquad \text{(Equation 1)}$$

The ratio varies from -1 to 1, where the higher the ratio, the higher amount of green biomass is included in that particular pixel. The ratio for green vegetation ranges from 0.1 to 0.6, depending on its health and quantity (Eriksson, 1999).

The ratio differ from the simpler ratio of NIR/R by the means that NDVI compensates for the variations caused by atmospheric effects and different sun angles (Eriksson, 1999).

3.3 Advanced Very High Resolution Radiometer

Many different sensors register red and near-infrared wavelengths and may therefore construct the vegetation index NDVI. One of the sensors is the Advanced Very High Resolution Radiometer, AVHHR, carried by the National Oceanic and Atmospheric Administration, NOAA. A great advantage with this satellite is the high temporal resolution of twice a day. This increases the chances of acquiring cloud free images, which is otherwise a high limitation to the use of remote sensing. The disadvantage is the low spatial resolution of 1.1 km at nadir (Nämden för skoglig fjärranlys, 1993).

The registration occurs in different wavelength bands (table 1), where as mentioned the red and near infrared wavelengths are used to create the vegetation index NDVI.

Table 1. The different wavelength band of AVHRR (Campbell, 1996).

Nr	Wavelength (µm)	Description
1	0.58-0.68	Visible (RED)
2	0.72-1.10	Near infrared (NIR)
3	3.55-3.93	Thermal infrared
4	10.30-11.30	Thermal infrared

3.4 The Net Primary Production

The amount of radiation active in the photosynthesis is used to estimate the amount of aboveground biomass production during a growing season. This radiation is called the absorbed photosynthetically active radiation (APAR). The photosynthetically active radiation (PAR) corresponds to the amount of radiation in the visible region of the spectra (0.4-0.7 µm), whereas the APAR corresponds to the amount of this radiation actually being absorbed by the vegetation and used in the photosynthesis.

The radiation in the visible spectra is the only radiation being absorbed by the chlorophyll and consequently the most interesting part of the spectra for biomass calculations. PAR is dependent on latitude, time of the year and cloudiness. Direct measurements of PAR above the canopy are preferred but if this is not possible, PAR is often approximated to 50% of the incoming radiation on the ground (Gower *et al*, 1999).

The integral of the APAR during one vegetation season equals the net primary production, NPP, for the vegetation season as described in the following equation (Olsson & Pilesjö, 1999), where ε stands for the photosynthetic efficiency factor (ε is explained further down).

$$NPP = \sum_{i=1}^{365} \varepsilon_i \cdot APAR_i \qquad \text{(Equation 2)}$$

However APAR is a difficult parameter to measure. This is solved by another parameter that has been found linearly to NDVI; fractional absorbed photosynthetically active radiation (fAPAR) (equation 3a). Dividing APAR by PAR forms this fraction. Table 2 shows how the a and b values may vary from different studies (Lind & Fensholt, 1998). The linear relationship between FAPAR and NDVI is valid as long as leaf area index does not exceed 2.0 (Olsson & Pilesjö, 1999).

$$fAPAR = a * NDVI + b \qquad \text{(Equation 3)}$$

Table 2. Different a and b values used for equation 3 (Lind & Fensholt, 1998).

Authors	a	b
Begue	1.39	-0.125
Asrar	1.25	0.11
Hatfield	1.21	-0.19
Prince & Goward	1.67	0.08
Pinter	1.41	0.40

The linear relationship between FAPAR and NDVI was initially illustrated by Monteith in 1972 and it has been widely used to estimate the NPP for terrestrial biomes since then (Gower *et al*, 1999). This relationship makes it possible to estimate the biomass production with remote sensing. Therefore equation 3 can be expressed as equation 4 where the product of FAPAR and PAR substitutes APAR.

$$fAPAR = APAR/PAR \Rightarrow APAR = fAPAR * PAR \Rightarrow APAR = (a * NDVI + b) * PAR$$

The following equation[2] is often referred to as the Monteith equation.

$$NPP = \sum_{i=1}^{365} \varepsilon_i \cdot (a \cdot NDVI_i + b) \cdot PAR_i \qquad \text{(Equation 4)}$$

As mentioned before, ε is the photosynthetic conversion factor (sometimes referred to as the biological efficiency factor, since factors independent of photosynthesis also influence ε. See Discussion). This is a coefficient describing the conversion of light to organic matter by plants (g/J) (Gower *et al*, 1999).

Field measurements of ε show that experimental values lay between 0,2 and 4,8 g/MJ (Prince, 1991) but some studies have found values as low as 0,07 g/MJ for desert areas (Gower *et al*, 1999). Theoretical maximum of ε is found to be 7,6 g/MJ (Prince, 1991). Table 3 shows some ε values from different studies (Gower *et al, 1999*).

[2] This equation includes above ground biomass only and does not take into account respiratory losses. Additionally it is valid under no water stress.

Table 3. ε values (g/MJ) for different vegetation types (Gower et al, 1999)

Vegetation type	ε (g/MJ)
Agriculture C3	1.02 – 3.37
Agriculture C4	2.3 – 3.9
Grasslands	0.07 – 0.13 (desert) 0.24 – 0.8 (short) 0.53 – 2.0 (mixed) 0.8 – 1.33 (tall)
Temperate evergreen	0.19 – 1.14
Temperate deciduous	0.64 – 1.58
Woodland	0.2
Tropical evergreen	0.24 – 1.06

3.5 Advantages and disadvantages of remote sensing

One of the main advantages of remote sensing is the possibility to frequently cover a vast area at a relatively low cost.

One of the main difficulties with remote sensing is the influence of the atmosphere. There exists always a certain amount of particles influencing the pathway like, dust, and water vapor and other aerosols. Also cloud shadows influence the pathway. Another problem is the difficulty to separate the signal of the green vegetation from other surfaces such as the soil. This is especially true in semi-arid areas where the vegetation cover is low. When studying the vegetation, the shadows of trees is also a problem since it lowers the reflectance in all wavelengths.

4 Method and Material

The following chapter describes the choice and processing of satellite images and NDVI. It also describes the field measurements and the calculations of woody and grass parameters from these measurements. Additionally the method used to study the sensitivity of the ε, a and b parameters in the Monteith equation of NPP is presented. Finally the statistical preprocessing of data is explained.

4.1 Images from the NOAA AVHRR sensor and NDVI

The choice and processing of NOAA AVHRR images are described below. When studying the correlation between field measurements of vegetation and NDVI, different parameters (single values or combinations of NDVI) can be used. The choice of NDVI parameters is therefore also explained below.

4.1.1 NOAA AVHRR images

To obtain a vegetation index from satellite images the NOAA AVHRR sensor was chosen, because it enables the creation of time series. The images were received from the Etosha Ecological Institute in Namibia and were 10 days mosaics with each pixel showing the maximum NDVI value during these 10 days (maximum value composite). Each month is therefore divided into three dekads with one image representing the period from day 1 until day 10 of that month, the second day 11 until day 20 and the third day 21 until the last day of the month. This way the risk of getting cloud covered pixels is lowered. In total 22 images were received from the last dekad of September to the last dekad of May.

4.1.2 Image processing

Processing of images includes converting DN values into NDVI and to extract pixel values from the images at the same location as the sampling plots in field. It also includes altering NDVI values that are influenced by atmosphere, subtracting background values and creating complete time series of NDVI. The following steps were used to process data:

4.1.2.1 Converting Digital Number values to NDVI

The original NOAA AVHRR images were received in Ida format and were converted to Idrisi format. A vector file consisting of the 30 plots of field measurements was created. This vector file was used together with the images and a program that extract the Digital Number (DN) value of a pixel corresponding to a particular point in a vector file. This results in 30 DN values for each image.

To simplify the work with the values a program was used to convert an Idrisi vector file to a plain xyz file. Finally the values were analyzed in Excel.

The DN values in each pixel were transformed to actual NDVI values according to the following formula received from the Etosha Ecological Institute:

NDVI = (DN – 82) / 256 (Equation 5)

4.1.2.2 Creating data due to missing images

Since three images were missing from the first dekad of September to the last dekad of May, NDVI values for these dekads were created to receive a complete time series.

When creating data, only the period of the growing season was taken into account, since this is the only period, which was actually used in the comparisons with the field measurements. The NDVI curve for each plot was studied visually and the start of the growing season was defined as the first dekad with a distinct and continuous increase in NDVI. It was assumed that from the first dekad of the growing season to the dekad of maximum NDVI, the slope of the curve should be positive. It was also assumed that the slope should be negative from the dekad of maximum NDVI to the end of the growing season. In the case of a missing image a new value was formed by calculating the average from the dekad before and after the missing dekad.

4.1.2.3 Altering data due to atmospheric influence

As mentioned it was assumed that the slope of the NDVI curve should be positive from the beginning of the growing season until the maximum NDVI. When this was not the case the atmospheric influence was decided not to be acceptable. A new value was formed in the same way as for the creation of data above. In total 47 pixels from different dekads were altered (appendix 2). Figure 5 shows an example of data before and after alteration.

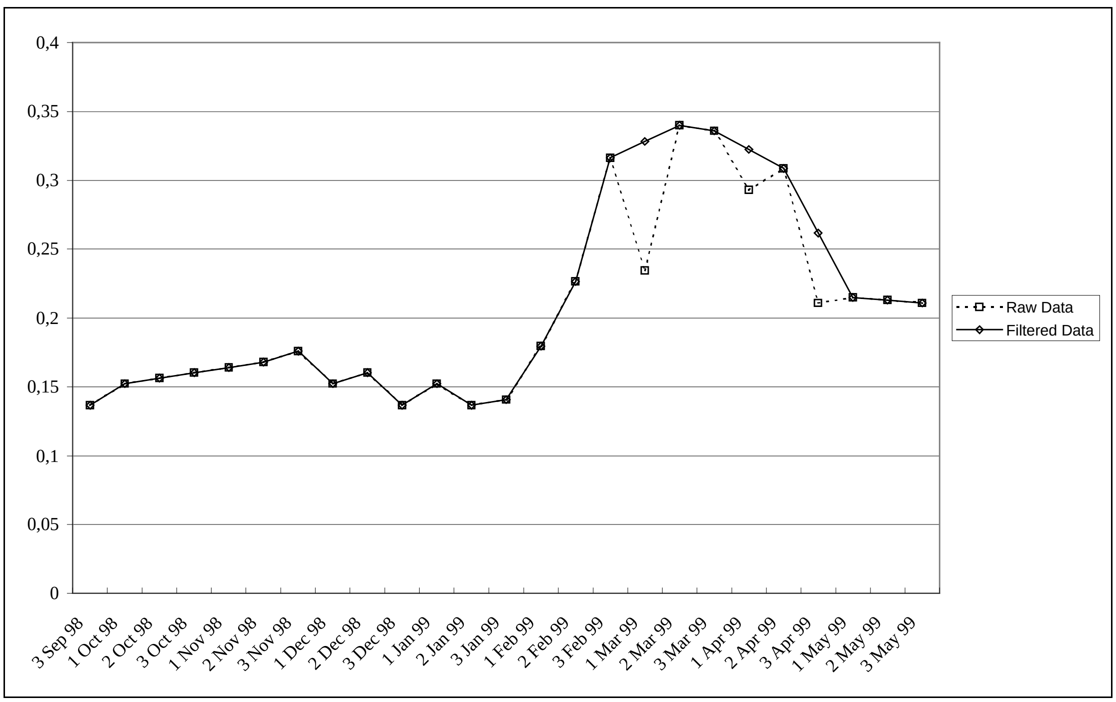


Figure 5. Raw and filtered data for plot number 24.

4.1.2.4 Subtracting background values

When using the NDVI, it has to be taken into account that the background may influence the signal (Rasmussen, 1996). The background is composed of the reflectance from for example the soil and litter and varies with the soil type, water content and degree of trampling by cattle.

For these reasons the background value of each plot was determined and subtracted from the values of each dekad (Rasmussen, 1996). The first dekad of November was chosen as the background value[2] since vegetation from the precedent growing season was thought to be at a minimum at this time. This dekad coincides with the time just before the beginning of the rainy season, which means that the variation in the amount of aerosols, water vapor and dust in the atmosphere might influence the NDVI. Performing the subtractions therefore leads to negative NDVI values in some cases. All the negative numbers were set to the value of 0.

4.1.3 NDVI parameters

Five different NDVI parameters (single values or combinations of NDVI) were chosen to study the relationship between NDVI and the field measurements (table 4). For the grass measurements the sum, sum field, sum decrease and max were studied, whereas concerning the tree measurements the max and the background were used.

Table 4. Description of the five different NDVI parameters.

NDVI parameters	Description
Max	The maximum NDVI value during the growing season.
Sum field	The sum of NDVI values from the beginning of the growing season until the dekad of field measurements. The field measurements coincide with the second (Khowarib and Sesfontein) and third dekad of February 1999 (Hobatere, Omuramba and Otjikovares).
Sum	The sum of NDVI values from the beginning to the end of the growing season. The last dekad of May was assumed to correspond to the end of the growing season.
Sum decrease	The sum of NDVI values until a considerable decrease in NDVI occurs after the maximum value (this dekad is decided visually).
Background	The value of the first dekad of November.

Figure 6 visualizes the definition of the parameters described in table 4.

[2] The first dekad of November was chosen as background value even though it sometimes rains during this period. This is possible since it was clear that no rain fell during this period in 1998.

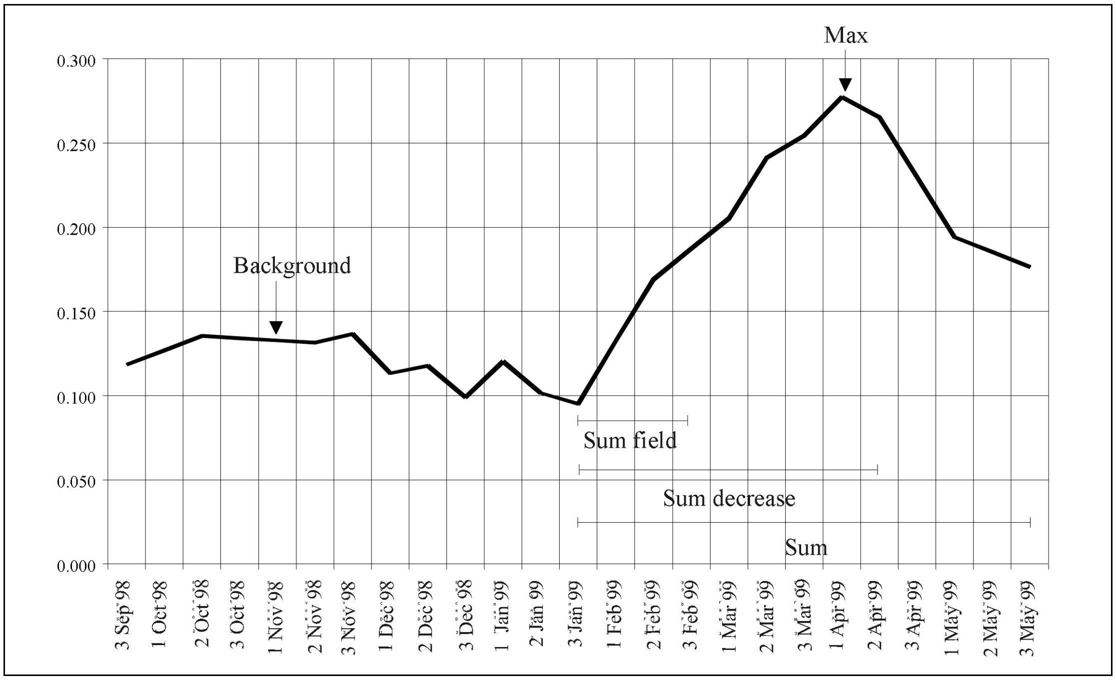


Figure 6. The definition of the NDVI parameters chosen.

4.2 Field measurements

The field measurements were carried out in the month of February 1999. The following five areas were chosen as sampling areas; Khowarib, Sesfontein, Omuramba, Otjikowares and Hobatere (figure 7). The objective when choosing the five areas was to distribute the areas spatially in the catchment (even though the plots tend to be concentrated in the eastern part of the catchment due to the low vegetation cover in the western parts). The accessibility by car and the route of the accompanying researchers also determined the location of the five sampling areas. The borders of the study were set to the ones of the Hoanib catchment, to follow the project carried out by the DRFN.

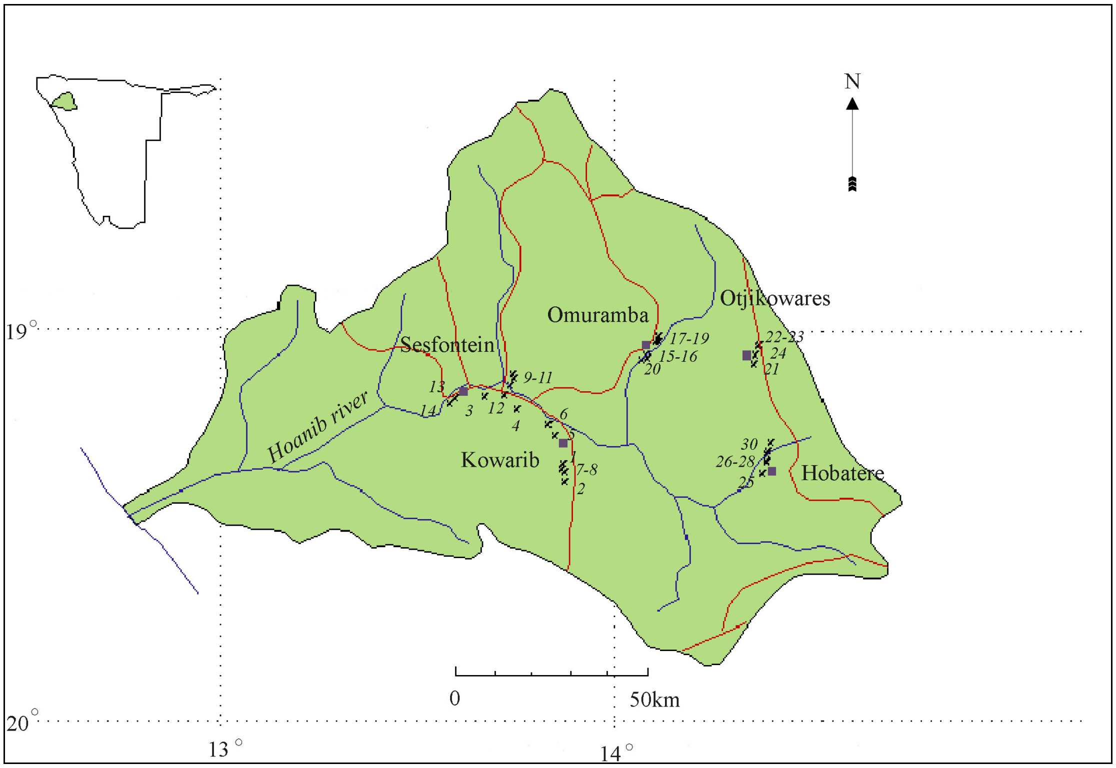


Figure 7. The Hoanib catchment with the 30 plots of field measurements marked. The communities in vicinity to the plots are used to refer to the plots in the text. Also the main roads were marked.

4.2.1 Sampling method for localizing the 30 plots

Four to eight 50 times 50 m plots were randomly selected in the five areas. The procedure below was followed when deciding the location of the 30 plots:

- The localization of each plot was carried out using the roads as base lines.
- A number between 1 and 5 was randomized to represent the numbers of kilometers to be traveled along the road.
- The left or right side of the road was randomized.
- To minimize the influence of roads 500 meters were walked perpendicular to the road.
- Before determining the exact location of the plot a final number between 1 and 100 was randomized to represent the number of meters to walk before reaching the corner of the plot.

The corners of the 50 times 50 meters square were marked with red sticks. A compass was used to make sure that the sides of the plot always were in accordance with four cardinal points to avoid a subjective placement of the plot. Before measuring the vegetation the surrounding area was studied visually and it was determined if the vegetation in the plot was a good representative for the vegetation in the surrounding 1 times 1 km area. If not, a new location of the plot was chosen according to the procedure described above.

4.2.2 Field measurements in each plot

The following data was collected in each plot:

Coordinates
The coordinates, both in WGS84 and Schwarz, in the center of the 50 times 50-meter plot were noted with the help of a GPS.

Tree sampling
The plot was initially studied visually to get an overview of the species composition and density and height of vegetation. When overlooking the area one average tree (tree also refers to shrubs) of each species was chosen. This average tree was chosen according to height and canopy width, branching and number of stems. If one species had two or more distinct subgroup, according to height and canopy width, one average tree from each subgroup was chosen. The average tree represented all individuals of that species or subgroup and all the measurements were only carried out on this tree. This procedure was recommended by the Desert Research Foundation of Namibia to make measurements less time consuming and to simplify comparison of results from their studies if necessary. The total number of each species or subgroup was counted. Individual trees or shrubs located on the border of the plot were included. Shrubs less than 50 cm in height were included in the grass measurements.

The measurements carried out on each average tree were tree height, canopy diameter, stem circumference and the number of stems (for multi-stemmed trees branching below breast height). The stem circumference was measured at breast height. If the tree had several stems, all the stems were counted but only the diameter of the largest and the smallest stem was measured. From this the average stem circumference was calculated. The circumferences of the other stems were assumed equally distributed between the smallest and the largest stem.

Finally the cover in percent of each species or subgroup was estimated according to the scale in table 5. This scale was chosen because it was generally used for estimating vegetation cover at the Desert Research Foundation of Namibia.

Table 5. The scale used to classify the vegetation cover.

Scale	Cover (%)
R	Very few individuals scattered in the area
+	Present but covering less than 1 % of the area
1	Covering 1-5% of the area
2a	Covering 5–12.5% of the area
2b	Covering 12.5–25% of the area
3	Covering 25–50% of the area
4	Covering 50–75% of the area
5	Covering 75–100% of the area

Grass sampling
The measurements of the grass (including herbs) weight and cover were carried out in five randomly chosen 1 times 1-meter squares inside each 50 times 50-meter plot. These five squares were assumed to be representative for the grass in the entire plot. The procedure when localizing the five grass squares inside the plot was as follows. The southeast corner of the plot was used as starting point. Two numbers between 1 and 50 were randomized. The first number determined the number of meters to walk from the southeast corner, in a westward direction, along the plot border. The second number determined the number of meters to walk northward in the plot.

In each grass plot the height and cover of perennial and annual grasses were estimated respectively according to the scale in table 5. The perennial and annual grasses were cut and placed in two separate paper bags. Finally the grasses were dried and weighed. The average dry weight (sometimes referred to as weight) and cover of the five 1 x 1 m squares were calculated to represent the entire plot.

Photo
A photo was taken from the first corner stick covering as much as possible of the plot. This was done to simplify the comparison between plots when analyzing the results.

Only the measurements used in this study are explained in this section. Additional data about for example phenology, browse line and soil type were also collected as a part of "Environmental Issues Investigation Project-Hoanib River Catchment study" and to simplify future analyzes of the results within this study if necessary.

4.3 Calculations from field measurements

The two different methods to calculate woody dry weight from field measurements are described below. Additionally the methods to calculate the total woody dry weight and cover in each plot are presented as well as the method to calculate dry weight, cover and volume of the grass.

4.3.1 Woody dry weight calculations using two different methods

The destructive measurements from two studies were used for calculating dry weight from the field measurements. One study was carried out by the Namibian Department of Forestry in Bushmanland, northwestern Namibia (Burke *et al*, 1996) and the other was carried out by K Olsson in an area in western Kordofan, Sudan (Olsson, 1985). They were both carried out in semi-arid areas with similar temperature, rainfall, vegetation type and species composition as in the Hoanib catchment. In both Olsson's and Dep of Forestry's study several trees were felled and weighed to establish the relationship between the non-destructive parameter and the tree weight. Different non-destructive parameters were used in the two studies, Olsson used the crown diameter and Dep of Forestry used the stem diameter in breast height.

Since no destructive measurements were included in this study it was assumed that the non-destructive measurements of the woody dry weight was acceptable if the two methods gave similar results.

To simplify further analyses a brief description of the two studies follows.

4.3.1.1 K Olsson's method

The study area was located in the Sahel zone, in western Kordofan, Sudan. The rainfall varied in a north-southward direction between 100 and 600 mm/year. Two main vegetation zones, semi-desert and woodland savannah with different species of *Acacia*, dominated in the area.

The aim of the study was to estimate the woody dry weight with the help of remote sensing. K Olsson used crown diameter as non-destructive parameter since there is a direct relationship between crown diameter and NDVI values measured with remote sensing. Field measurements and aerial photos were used to estimate the crown cover in the study area.

To minimize the influence of the grass vegetation, the study was carried out when most trees had shed their leaves. After the trees were cut down the branches and the stem were weighed. A number of 39 trees and shrubs of 12 different species were included in the destructive measurements. The linear relationship between crown diameter and the wet weight is described by the following equation (correlation 0.94):

$$Y = 0.19 + 1.28 * X \qquad \text{(Equation 6)}$$

Y = log wet weight
X = log (crown diameter)^2

To compare the result with the Dep of Forestry's the dry weight had to be calculated from the wet weight. Out of the 39 trees that were felled and weighed within K Olsson's study, 19 trees were also dried and the dry weight was measured. The dry weight for these 19 trees was plotted against their wet weight (these calculations were carried out by Elmqvist & Lundström) and the regression was found as (with a correlation value of 0.99):

$$\text{Dry weight} = 0.685 * \text{wet weight} \qquad \text{(Equation 7)}$$

All trees were then converted to dry weight using this equation.

4.3.1.2 Dep of Forestry's method

The study area was located in Bushmanland in northern Namibia. The rainfall varied in a east-westward gradient from 300 to 400 mm/year. Additional sampling was performed in the Caprivi district in the northern strip of Namibia to increase the number of samples and the variation of species. The main vegetation types were forest and woodland savanna. Dominant species were *Burcea africana*, *Pterocarpus anglosensis*, *Combretum collinum*, *Terminalia sericea*, *Lonchocarpus nelsii* and *Colosphermum mopane*.

The aim of the study was to carry out an inventory of the woody resources in northeastern Namibia. The stem diameter at breast height was used as the non-destructive parameter. Most trees were single stemmed and branched above breast height.

During the project, 148 trees from six different species were measured at breast height, felled and weighed. Each of the six species represented one group and all other species found in the area were also recorded and classified into one of the six groups. The trees were dried and weighed again and volume functions (equation 8 and 9) were established for the six species (the correlation value was not presented in the Dep of Forestry's report). The constants a and b are species dependent (see explanation below) and d is the stem diameter in breast height. Equation 8 was found to describe the relationship between volume and diameter at breast height for *Burkea africana* and *Terminalia sericea*. For *Combretum collinum, Lonchocarpus nelsii, Pterocarpus anglosensis* and *Colosphermum mopane*, equation 9 was found to best describe the relationship. Two equations were used to make it easier to distinguish between variations in densities, water content and growth form for different species. The diameters of the felled trees ranged between 5–75 cm so equation 8 and 9 were only valid for these diameters.

Apart from using different equations for different species, each of the six species had different a and b constants to use in the equations. Table 6 shows the six different species and the constants used in the equations 8 and 9.

Burkea africana and *Terminalia sericea*:

$$V = e^{(a_0 + a_1 / d)} \quad (dm^3) \qquad \text{(Equation 8)}$$

Combretum collinum, Lonchocarpus nelsii, Pterocarpus anglosensis and *Colosphermum mopane*:

$$V = (a_0 + a_1 \cdot d + a_2 \cdot d^2) \cdot d^2 \quad (dm^3) \qquad \text{(Equation 9)}$$

Table 6. Volume constants used in equation 8 and 9 for the six different species. Some groups do not require a_2 constants[1].

Group	Species	a_0	A_1	A_2
1	Burkea africana	8.607856	-58.71163	-
2	Combretum collinum	0.131382	0.0180767	-0.0000905
3	Lonchocarpus nelsii	0.396588	0.0077865	-
4	Pterocarpus anglosensis	0.667061	-0.008408	0.0002143
5	Terminalia sericea	7.158742	-39.232256	-
6	Colosphermum mopane	0.246675	0.01826	-0.0002

The volume was converted to dry weight by multiplying with the basic density. Table 7 shows the basic densities for the six different species.

[1] The significant numbers of the constants are questionable.

Table 7. Basic densities (kg/dm^3) for converting volume (dm^3) into dry weight (kg). For diameters less than the limits multiply volume with B1, otherwise use B2.

Group	Species	Basic density, B1	Limit for using B1	Basic density, B2
1	Burkea africana	0.805	D < 30 cm	0.770
2	Combretum collinum	0.881	D < 25 cm	0.770
3	Lonchocarpus nelsii	0.977	D < 25 cm	0.854
4	Pterocarpus anglosensis	0.598	D < 30 cm	0.525
5	Terminalia sericea	0.754	D < 20 cm	0.616
6	Colospherum mopane	0.803	D < 26 cm	0.707

4.3.2 Total woody dry weight

To investigate the relationship between woody dry weights measured in field and different NDVI values, the total woody dry weight in each plot had to be calculated. This was done using K Olsson's and Dep of Forestry's equations described above.

K Olsson's equation could be applied to all trees but since Dep of Forestry's equations only were applicable to species with stem diameters between 5 and 75 cm, the dry weight of trees with other stem diameters could not be calculated. Instead they were calculated with equations established in another project. This study was carried out in the Otjiwarongo district in central Namibia (Erkkilä & Siiskonen, 1992). The woody dry weight in 13 ha of woodland was examined and a relationship between stem diameter and dry weight was established for the four species *Terminalia sericea, Burkea africana, Combretum psidoides* and *Ochna pulchra*.

The equation for *Terminalia sericea* (equation 10) is valid for stem diameters between 1 and 26 cm. Since *Terminalia sericea* belongs to group 5 (in the Dep of Forestry's study), equation 10 was applied to all group 5 species with stem diameters less than 5 cm that were found in the Hoanib region. The equation for *Combretum psidoides* (equation 11) was valid for stem diameters between 1 and 9.3 cm. *Combretum psidoides* belongs to group 2 (according to the Dep of Forestry's study) so the dry weight for all group 2 species with stem diameter less than 5 cm were calculated with equation 11.

Terminalia sericea:

$$V = -1{,}2586 + 0{,}51309 \cdot d + 0{,}29737 \cdot d^2 \qquad (1\text{ cm} < d < 26\text{ cm}) \qquad \text{(Equation 10)}$$

Combretum psidioides:

$$V = 0{,}03701 \cdot d^{2{,}48634} \qquad (1\text{ cm} < d < 9{,}3\text{ cm}) \qquad \text{(Equation 11)}$$

4.3.3 Canopy cover

The canopy cover is the total coverage in percent of trees in one plot seen from above and is calculated from the measurements of canopy diameter of the individual trees. The shape of the trees was assumed to be circular.

4.3.4 Grass parameters

To study the relationship between the NDVI and the grass measurements, three different parameters were used. The weight, formed by a destructive method, represented the total dry weight of the annual and perennial grass. The two other parameters, the cover and the volume, were non-destructive. The former represented the total cover of the annual and perennial grass and the later was formed by the cover and the height of the grass according to equation 12 below. The annuals were separated from the perennials in the equation since they were measured separately in field even though this was not taken into consideration when investigating the correlation values with NDVI.

(Equation 12)

$$\text{Volume } (m^3/ha) = (\text{cover } (m^2/ha) * \text{height } (m))_{(annual)} + (\text{cover } (m^2/ha) * \text{height } (m))_{(perennial)}$$

4.4 Sensitivity test of the ε, a and b parameters in the Monteith equation

A sensitivity test of the Montieth equation (equation 4) to variations of the ε, a and b parameters were carried out with a Monte-Carlo simulation. This means that NPP was calculated with the Monteith equation several times and for each calculation a number for ε, a or b was randomized. The ε, a and b parameters were randomized between the maximum and minimum value found for each parameter in literature (see Theory, *Net Primary Production*) (table 8). The total number of calculations can be set to any value but 100 calculations were chosen for this study.

Table 8. Minimum and maximum values for ε, a and b

Parameter	Minimum	Maximum
ε	0.07	3.9
A	1.21	1.67
B	-0.19	0.4

Three different options were tried to test the sensitivity:

1. ε, a and b were varied
2. Only e varied and a and b were held constant
3. A and b varied and e was held constant

The average of the values found in literature was used for the parameters that were held constant.

PAR was approximated to 50% of the incoming radiation and calculated according to appendix 1. Incoming radiation depends on latitude, time of the year and cloudiness. The cloudiness was not taken into consideration since there was no access to cloud data for the time of the field measurements. To simplify calculations of PAR and later NPP, an average latitude (–19.00.00), longitude (13.00.00) and day of the year (16^{th} of February) was chosen.

The Monte Carlo simulation was carried out for plot number 22 only. This plot was randomly chosen out of the 22 plots with a distinct growing season. The average, minimum and maximum NPP were calculated as well as the standard deviation.

4.5 Statistical preprocessing

For statistical purposes the population and the sample must be normally distributed (Shaw & Wheeler, 1997). Therefore the normal distributions for all the parameters used in the comparisons were studied initially. If no normal distribution existed, the data was transformed (for example 10^{th} logaritm or square root). If this improved the distribution the transformed data was used for the analysis. If no clear evidence of improved normal distribution was found after transformation, raw data was used for the analyses. All these decision were taken on a subjective basis by visually studying histograms.

Another factor that has to be kept in mind is the presence of a trend in the data. As mentioned the vegetation is affected by the east-westerly precipitation gradient. The annual precipitation is three times as high in the most easterly plots compared to the most westerly plots (300 mm and 100 mm respectively). The great rainfall variability of 50-70% also has to be kept in mind. This precipitation gradient influences the vegetation to a great extent, since the precipitation is the major controlling factor of the vegetation in the region.

To investigate the effect of a trend in the data on the correlation values, not only the total number of plots was studied, but also a smaller statistical population representing the eastern areas (the 16 plots in Otjikowares, Omuramba and Hobatere) with a less varied annual precipitation and therefore also a more similar vegetation type.

A third factor is the one of spatial and temporal autocorrelation. Spatial autocorrelation is expected because several plots are located very close and should be influenced by each other. The temporal autocorrelation is due to the fact that the NDVI value for one dekad is dependent on the NDVI value for the preceding dekad. Nothing was done to test this problem, but it has to be kept in mind.

With the restrictions mentioned above in mind, along with the caution needed for small samples, the relationship between the NDVI and vegetation parameters measured in the field were studied.

5 Results

The results of the measurements and calculations of woody and grass parameters are described in this chapter. The time series of NDVI are also presented as well as the correlation between the woody and grass parameters with NDVI. Finally the result of the sensitivity test of ε, a and b parameters in the Monteith equation is presented.

Before studying these relationships, the normal distribution of data was examined.

5.1 Normal distribution of data

From the visual interpretation of data it was found that the normal distribution of some parameters was not satisfying. When transforming data only the grass volume was improved when transformed into the 10^{th} logarithm. The logarithmic volume of grass will therefore be used with the correlations to NDVI. Since the normal distributions of the other parameters were not significantly improved after transformation, raw data was used.

5.2 Time series of NDVI during the growing season 98/99

The period of available images, the last dekad of September to the last dekad of May, was divided into three time periods to simplify the description of the variation of the NDVI values. The lengths of the three time periods varied for the different areas, but lasted approximately from the end of September to November, from December to January and finally from February to May (figure 8).

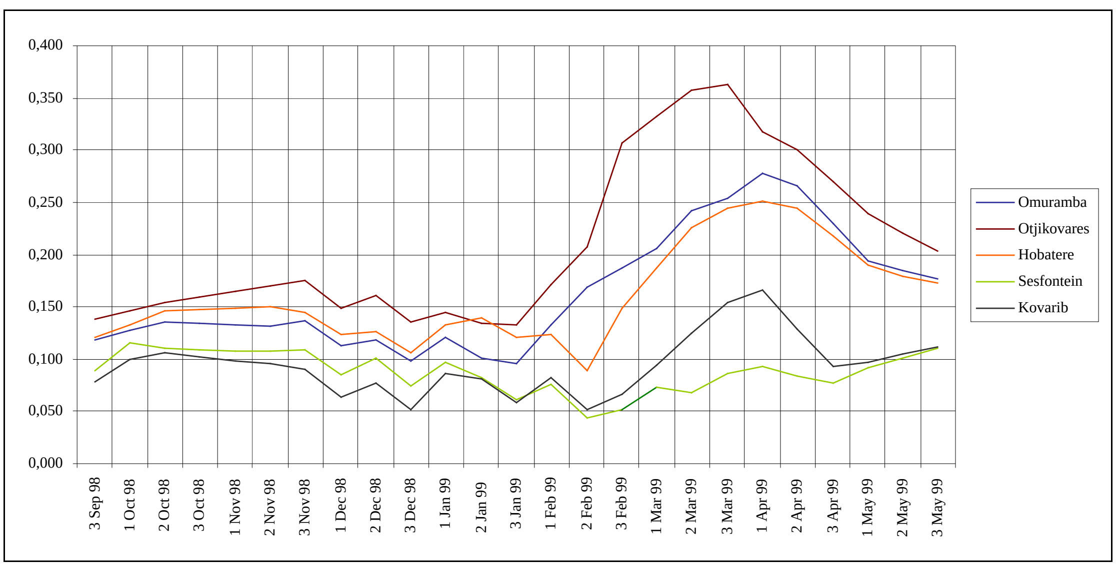


Figure 8. The variation of NDVI from the last dekad of September to the last dekad of May for the five different areas (some of the dekads during the growing season were either altered or created: see Method and Material, Altering data due to atmospheric influence). The field measurements were carried out during the second dekad of February in the Sesfontein and Khowarib areas and during the third dekad of February for the areas: Omuramba, Otjikovares and Hobatere.

The end of September to November was characterized by flat NDVI curves for all areas, with values ranging from about 0.1 in Khowarib to just above 0.15 in Otjikovares. For all regions except Otjikovares there was a slight decrease or constant levels of NDVI during the time period.

When entering the second time period, December to January, an increased variation in NDVI was noted for all areas as well as an overall decrease. The change in atmospheric constitution from dry to humid probably caused this decrease of NDVI at the beginning of the rainy season (Rasmussen, 1996). The increased amounts of clouds were likely to have caused the drops in NDVI for some dekads.

The third time period, February to May, coincided with the growing season. The start was represented by a sudden increase in NDVI. Omurumba and Otjikovares were the regions where the growing season first was noted, which occurred during the first dekad of February. The differences in amplitudes for the five areas were at maximum during this third period. The differences in maximum NDVI values were as high as 0.275. Otjikovares was the area where the highest NDVI value was reached (0.36). Thereafter followed Omurumba, Hobatere, Khowarib and Sesfontein in decreasing order of maximum NDVI.

No actual growing season was observed in Sesfontein. For this reason the 8 plots located in the Sesfontein area were all excluded from the correlation to the grass vegetation and the maximum NDVI concerning the woody vegetation. Therefore only 22 plots were used in these cases. The correlation between woody parameters and background NDVI on the other hand, all the plots could be used, since this NDVI parameter was formed during the period before the growing season.

The appearance of the NDVI curves after the last dekad of May was obviously not clear. Even though the NDVI was increasing for the Khowarib and Sesfontein area it was assumed that there would be a continuous decrease in NDVI after the last dekad of May until the beginning of the next growing season.

5.3 Calculations from field measurements

The results from the comparisons of the woody dry weight calculated using Dep of Forestry’s and K Olsson’s equations are described below as well as the woody and grass parameters calculated for each plot.

5.3.1 Woody dry weight calculations using K Olssons and Dep of Forestrys methods

Totally 114 trees or shrubs were measured within this study. 60 of these had stem diameters less than 5 cm and could not be calculated using the Dep of Forestry’s equations. Therefore only 53 trees were used for the comparisons. Out of the 53 trees examined, 25 trees belonged to group 2, 4 and 6 and were calculated using Dep of Forestry's equation number 1. 28 trees belonged to group number 5 and were calculated using equation number 2. No group 1 and 3 trees were found in the five areas. Appendix 3 shows the calculated dry weight for the 53 trees compared within this study.

In figure 9 the dry weight calculated using Dep. of Forestry's equation are plotted against the dry weight calculated using Olsson's equation.

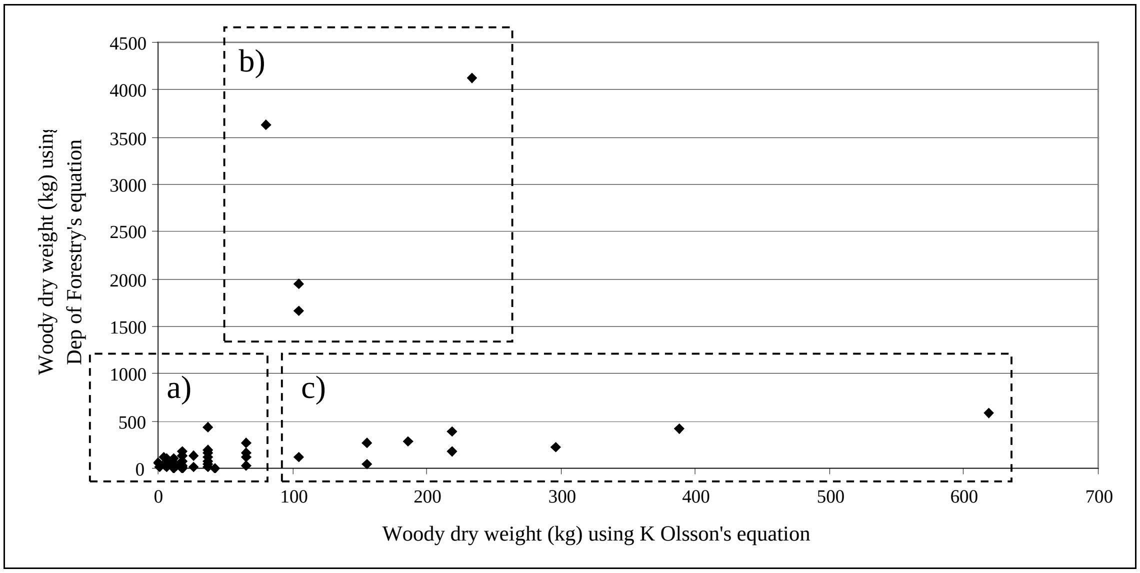


Figure 9. Woody dry weight calculated using Dep. of Forestry's equation plotted against woody dry weigth calculated with Olsson's equation. The trees in the square a) are also shown in figure 10.

The four trees inside square b) are all group 6 species (*Colosphermum mopane*) and the 7 trees inside square c) are all group 5 species (*Accacia Tortillis*, *Salvadore Persika* and *Faidherba Albida*).

Trees with low dry weight were not satisfactory displayed in figure 9. Figure 10 displays only the trees inside square a). The clustering of data in a vertical direction is due to the fact that the canopy measurements were only measured with a half-meter accuracy.

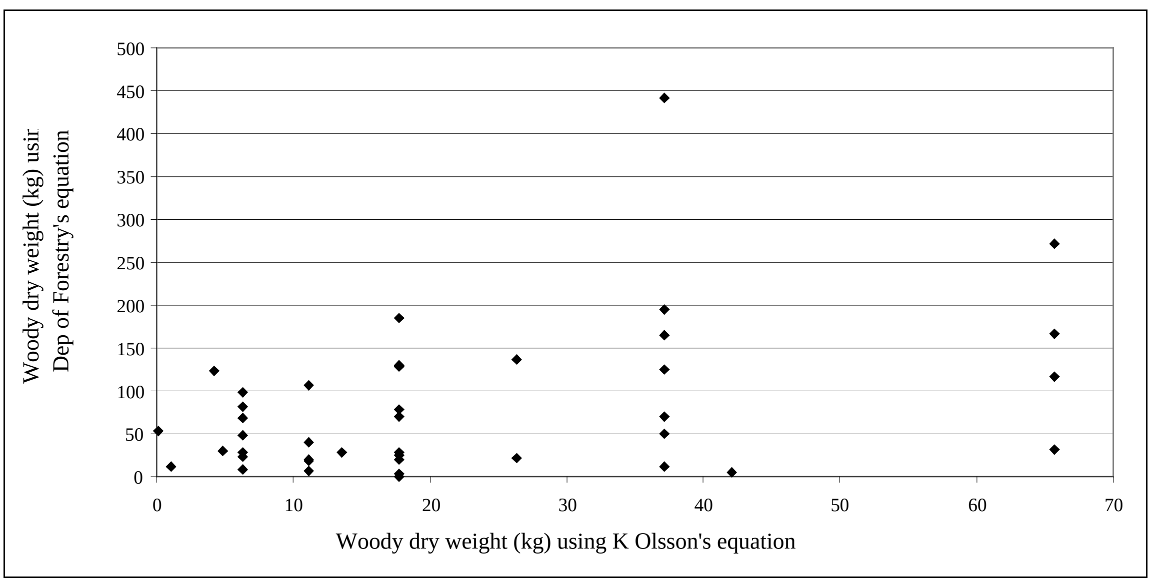


Figure 10. Trees inside square a) in figure 9.

To find how well the dry weight calculated using K Olsson's equation corresponds to the Dep. of Forestry's dry weight, the correlation between the two results was examined. The correlation between Olsson and Dep of Forestry dry weights was 0.29 and is just above 0.266, which is the table value for a two-tailed significance at a 0.05 level.

To find which trees that were responsible for the relatively low correlation value, the ratio of the dry weight calculated using Dep of Forestry's and Olsson's equations was calculated (from now on called F/O ratio) for each tree (appendix 3). Form this ratio it was found that over 80% of the trees resulted in a higher dry weight using Dep. of Forestry's equation. The *Combretum imberbe* for example, in plot number 2, had a dry weight calculated using Dep. of Forestry's equation that was more than 500 times larger than the dry weight calculated with Olsson's equation.

To investigate if Dep of Forestry’s equation 8 or 9 generally resulted in higher or lower dry weight compared to Olsson’s, it was noticed that trees that over 90% of the trees that were calculated with equation 9 mainly resulted in F/O ratios above 1. Using equation 8 resulted in approximately 50% of the trees with F/O ratios above 1.

To see if the answer to the relatively low correlation value could be found in the differences in growth form, the ratio the crown and stem diameter was calculated. The result showed that the crown diameter was between 2 and 30 times greater than the stem diameter (appendix 3) for all the 53 trees.

It was also found that over 60% of the trees measured in this project had more than 1 stem in breast height and over 30% had more than 4 stems, which also has been taken into consideration when studying the growth form.

5.3.2 Total woody dry weight

The total woody dry weight in the 30 plots calculated using Dep of Forestry’s (with the additional calculations from Erkillä and Siiskonen) and K Olsson’s equations are shown in figure 11. Several plots, for example 13 and 14, showed great differences between the dry weights calculated using K Olsson and the Dep of Forestrys equations. The woody vegetation in these plots consisted of trees with very large stem diameters. Additionally, the woody dry weight varies considerably between two plots, even for adjacent plots in the same area. No trees were found in plot number 19 and the dry weight of the trees found in plot number 17 is to small (8 kg/ha using K Olsson’s equation and 48 kg/ha using Dep of Forestry’s) to be displayed in figure 11.

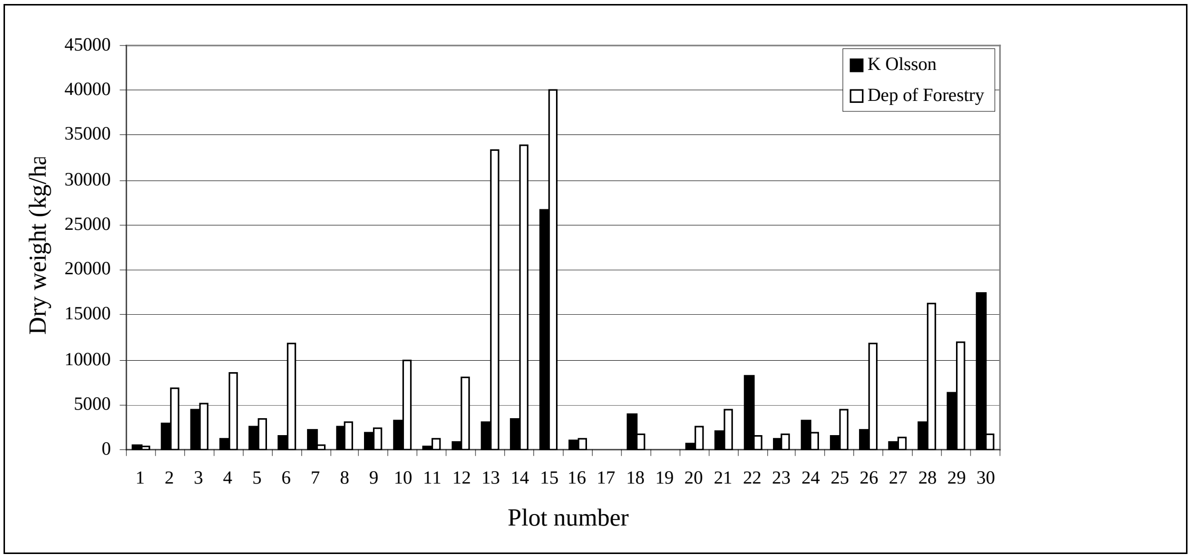


Figure 11. The woody dry weight (kg/ha) for each plot calculated with Olssons and Dep of Forestrys equations (plot number 1-2 and 5-8 are located in the Kowarib area, 3-4 and 9-14 in Sesfontein, 15-20 in Omuramba, 21-24 in Otjikowares and 25-30 in the Hobatere area).

The average dry weights for all plots were 3600 kg/ha using K Olsson's equation and 7600 kg/ha using Dep of Forestry's equation.

5.3.3 Canopy cover

The canopy cover in each plot is shown in figure 12. The canopy cover in plot number 17 was too small (0.1%) to be displayed. As for the woody dry weight the cover varied a lot between different plots even for plots located in the same area.

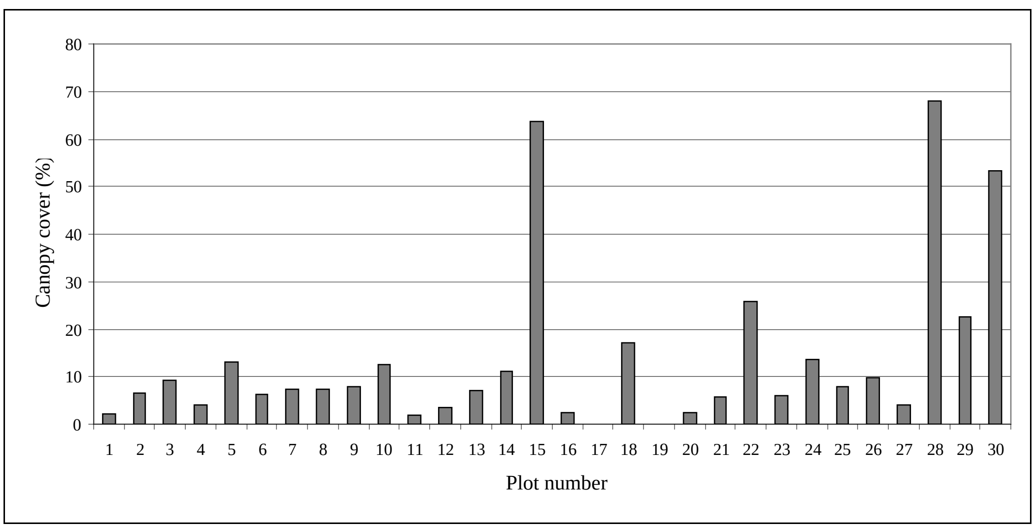


Figure 12. The canopy cover (%) in each plot (plot number 1-2 and 5-8 are located in the Kowarib area, 3-4 and 9-14 in Sesfontein, 15-20 in Omuramba, 21-24 in Otjikowares and 25-30 in the Hobatere area).

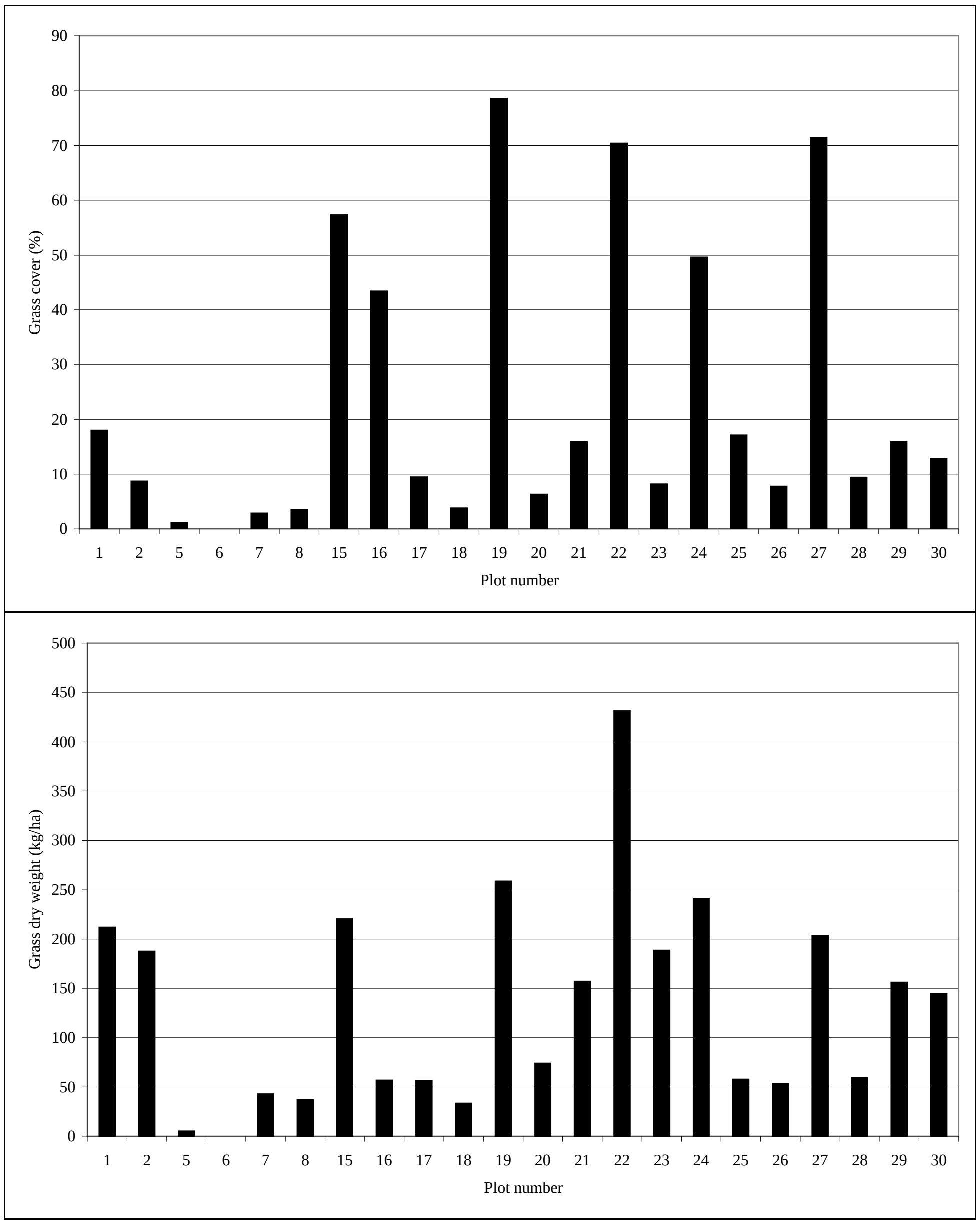
The canopy cover in most plots did not exceed 10% even though the cover in three plots was over 50%.

5.3.4 Grass parameters

As for the woody parameters a great variance existed within and between each of the five areas for the grass weight, cover and volume (figure 13 a, b and c). This was also the case for nearby situated plots. As a result of this, it was difficult to depict any trends in the data set, but to get an idea some results are listed below.

The grass cover in the Khowarib area never exceeded 20% for any plot. For all the other areas the maximum varied between 70% and 80%, even if some of the plots in the areas experienced values as low as in Khowarib.

The cover and the logarithm of the volume showed evidently similar trends. The highest cover was recorded in plot number 19 with 78%, whereas plot number 15 recorded the highest volume of 600 m^3/ha.



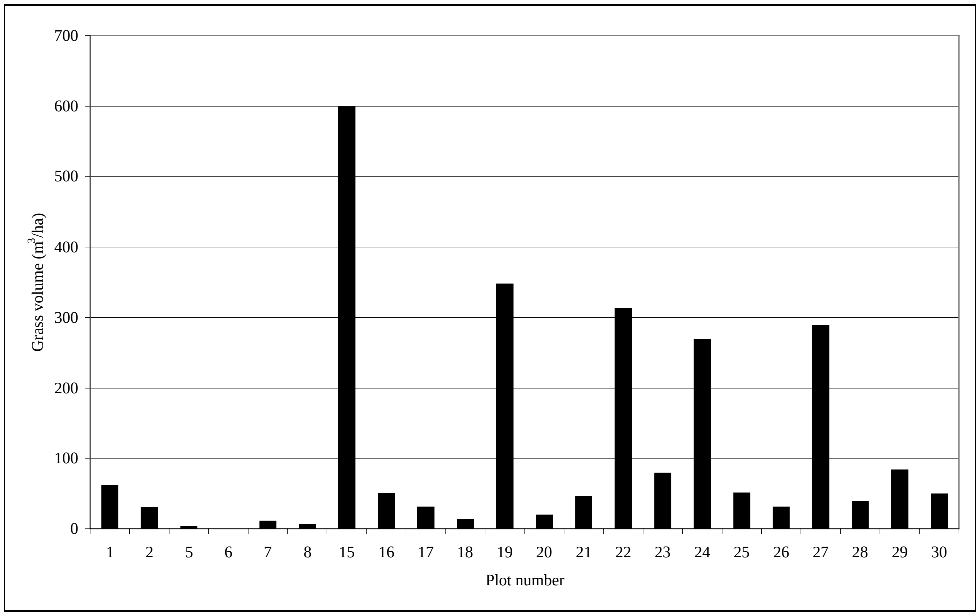


Figure 13. Presentation of grass cover (%), grass weight (kg/ha) and grass volume (m^3/ha). (plot number 1-2 and 5-8 are located in the Kowarib area, 15-20 in Omuramba, 21-24 in Otjikowares and 25-30 in the Hobatere area. The Sesfontein area was not included in the results, since the growing season had not yet started.

5.4 Comparing field measurements with NDVI

The relationship between the different NDVI and the woody and grass parameters calculated from field measurements are presented below. The relationship was studied for all plots (30 plots for woody parameters with background NDVI and 22 for woody and grass parameters with the other NDVI parameters). As mentioned before when investigating if the correlation values differed with a decreasing trend in data, the 16 plots in Otjikovares, Omuramba and Hobatere were studied separately. The correlations were studied with the field measurements as the independent variable and the NDVI as the dependent.

As a result of the small number of plots special attention should be given to the visual interpretation of the scatter plots, which are present in the case of significant correlations (appendix 4).

5.4.1 Woody parameters with NDVI

As mentioned before the background and max NDVI were correlated to the woody dry weight and canopy cover. Figure 14 shows the correlation for the all 30 plots between background NDVI and the woody dry weight and canopy cover. The horizontal line represents the table value for a one tailed test and a significance value of 0,05. Even though canopy cover showed the best correlation to background NDVI all correlations were well below the significance level. The correlation to the dry weight calculated with the Dep of Forestry's equation showed a negative correlation.

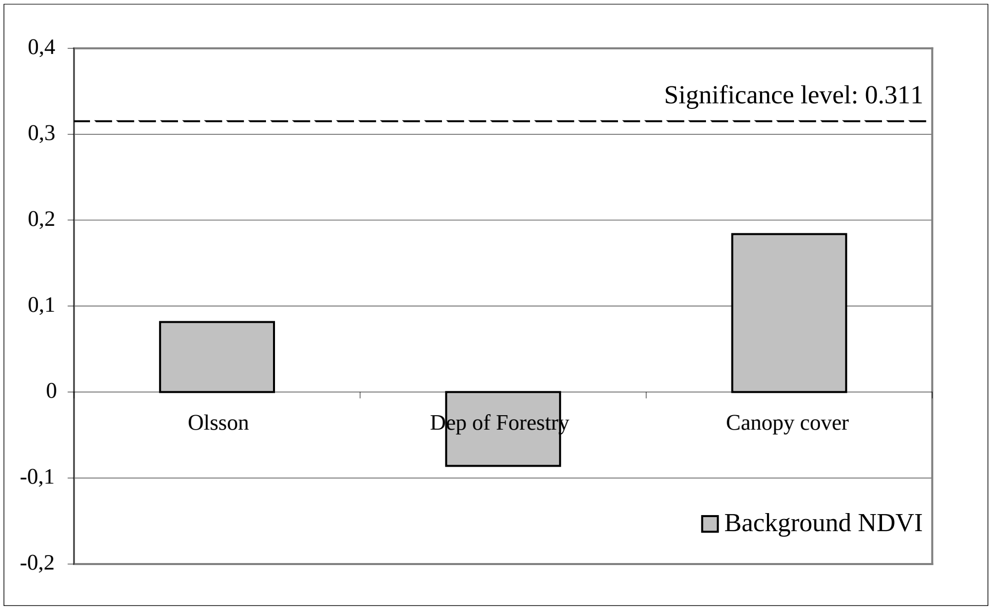


Figure 14. Correlations between the woody dry weight and canopy cover with background NDVI for 30 plots. The dotted line shows the table value for a one tailed test at a significance value of 0.05.

Figure 15 shows the correlation with maximum NDVI, instead of background NDVI. The number of plots was reduced to 22 since the plots in Sesfontein were excluded from the correlations during the growing season. The best relationship was found for woody dry weight using K Olsson's equation but none of the correlations were significant. The woody dry weight using Dep of Forestry's equations showed a negative correlation value.

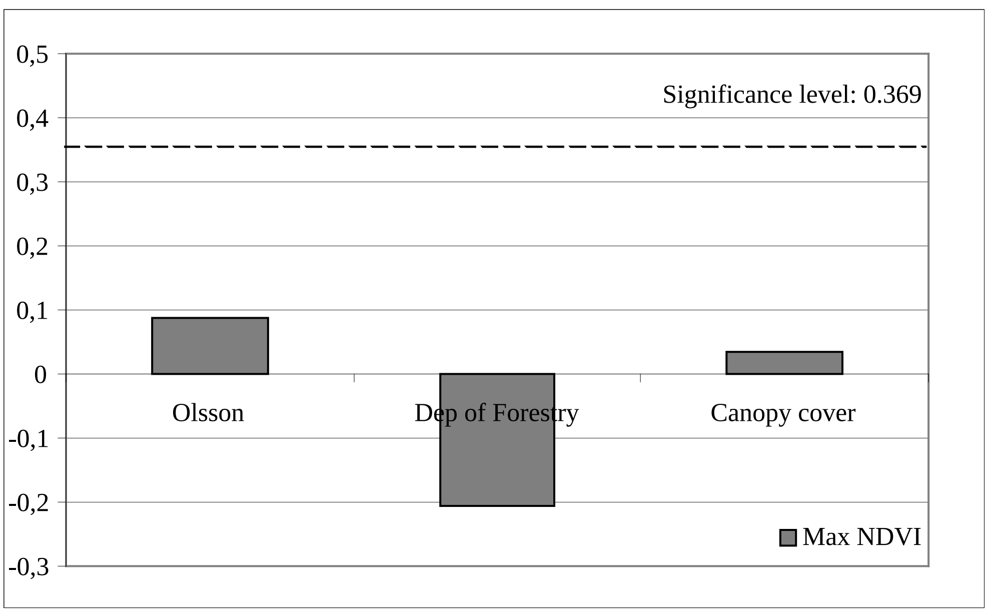


Figure 15. Correlations between the woody dry weight, canopy cover and maximum NDVI for 22 plots. The dotted line represents the table value for a one-tailed test at a significance value of 0.05.

To investigate if the correlation values differed with a lower trend in the data set, the correlation between the woody parameters and NDVI were studied for the 16 plots in Otjikovares, Omuramba and Hobatere (figure 16). No improvement of correlation values was found when investigating only 16 plots. The woody dry weight calculated using Dep of Forestry's equations was even more negative with 16 plots. The significance level of correlation was never reached.

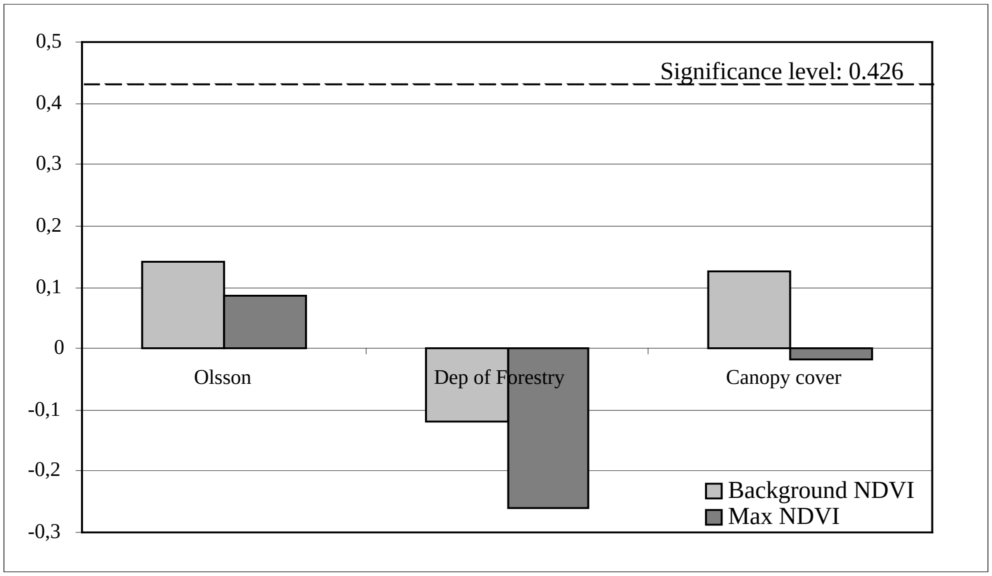


Figure 16. Correlations between the woody dry weight, canopy cover and background and maximum NDVI for 16 plots. The dotted line represents the table value for a one-tailed test at a significance value of 0.05.

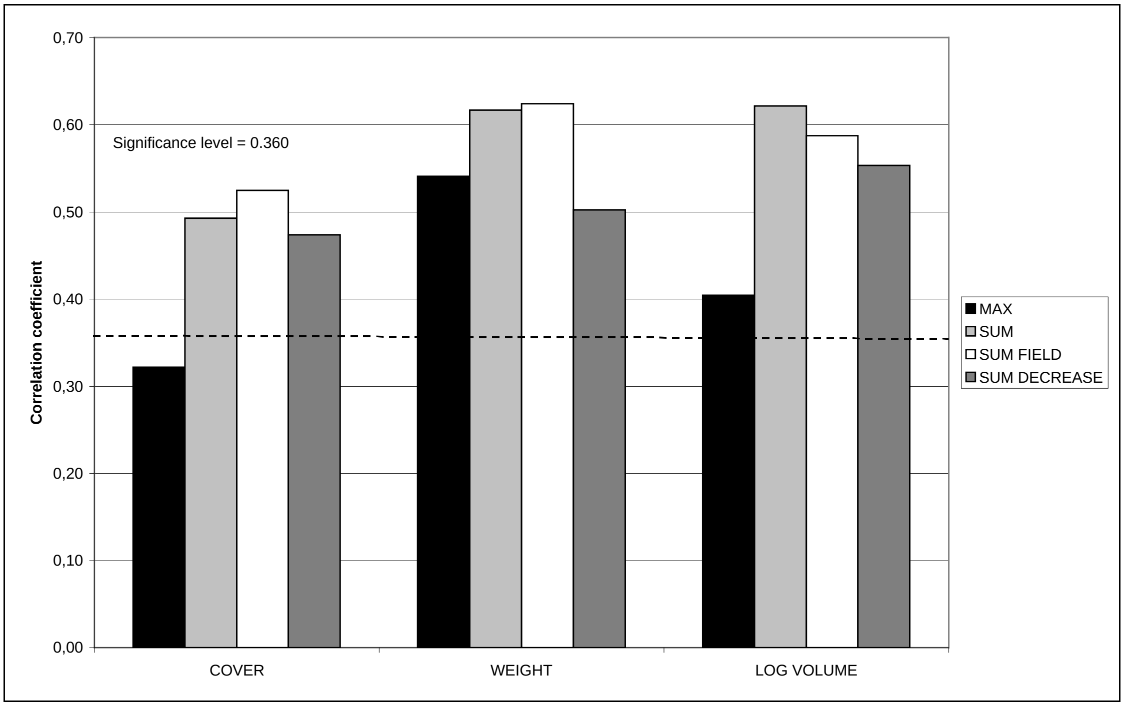
5.4.2 Grass parameters with NDVI

As mentioned before the NDVI parameters correlated to the grass measurements were max, sum field, sum decrease and sum (see Method and Material, *NDVI Parameters* for description of parameters). The grass parameters were the cover, the weight and the logarithm of the volume. For both the 16 and 22 plots, the sum field, sum, max and sum decrease correlated to the grass parameters in decreasing order of magnitude (figure 17 and 18).

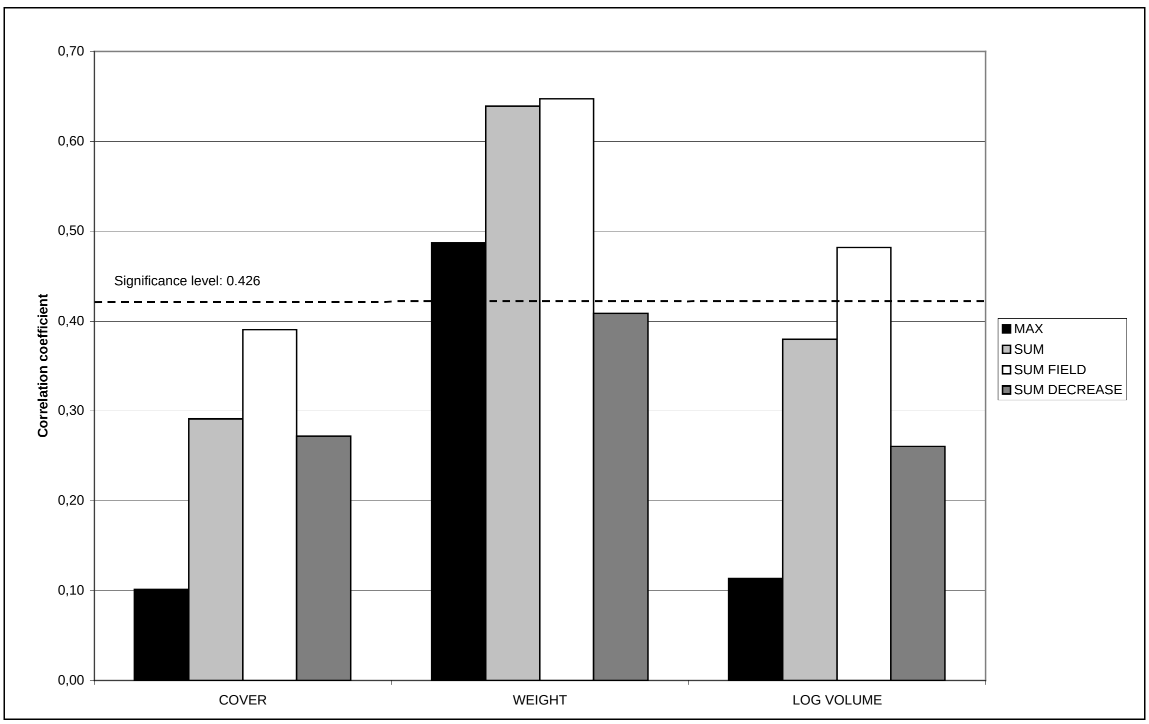
The correlation values for the 22 plots were generally more significant than the 16 plots. This was visualized in figure 17 and 18 by the horizontal line representing the table value for a one-tailed test at a significance value of 0.05. For the 22 plots the values ranged from 0.32 to 0.62 (table value of 0.360) and 11 of the 12 correlation values were found significant. For the 16 plots the values ranged from 0.10 to 0.65 (table value of 0.426) and 4 of the 12 correlation values were found significant.

For both the 22 and the 16 plots the sum field generally correlated best to the grass measurements, even though the values in most cases were almost as high for the sum (excluding correlation values that were not significant). The relatively highest correlation of all was 0.62 and was returned for the 22 plots between the sum field and the weight as well as between the sum and the logarithm of the volume.

The sum decrease and the max returned the lowest correlation values of the four.



Figur 17. The correlation values for all four NDVI parameters to the grass parameters for the 22 plots. The total of 22 plots corresponds to a table value of 0.360 at a significance level of 0.05, which is represented by a horizontal line in the figure.



Figur 18. The correlation values for all four NDVI parameters to the grass parameters for the 16 plots. The total of 16 plots corresponds to a table value of 0.426 at a significance level of 0.05, which is represented by a horizontal line in the figure.

It is not only interesting to study how the different NDVI parameters correlated to the measurements of the grass, but also how the three different grass measurements influenced the correlation. When correlating with the logarithm of the volume the values were almost as high as for the weight for the 22 plots, whereas the correlation values with the cover were the lowest for both the 22 and the 16 plots.

The relationships between the NDVI and grass parameters found significant were visualized in scatter plots (appendix 4).

5.5 Sensitivity test of the ε, a and b parameters in the Monteith equation

Table 9 shows the average, minimum, maximum and standard deviation values from 100 NPP calculations in plot number 22 for the three options listed below:

1. ε, a and b varied
2. Only e varied and a and b was held constant
3. a and b varied and e was held constant

Table 9. The resulting NPP (kg/ha) of the Monte-Carlo simulation for plot number 22.

Opt.	ε	a	b	Average NPP (kg/ha)	Std	Max NPP	Min NPP
1	0.07-3.9	1.21-1.67	-0.19-0.4	2676	1709	6483	148
2	0.07-3.9	1.44	0.105	2591	1555	5276	135
3	1.98	1.21-1.67	-0.19-0.4	3400	426	4315	2547

Table 9 shows that varying all parameters (option 1) gave the highest standard deviation and the largest range between the resulting minimum and maximum NPP. The first option resulted in an average NPP of 2676 kg/ha and a standard deviation of just above 1700 kg/ha. The NPP varied from just below 150 kg/ha to just above 6480 kg/ha.

The second option gave a slightly lower average NPP and standard deviation. The maximum NPP were lower than for option 1 but the minimum value was just as low.

The result from option 3 showed that NPP calculations were quite insensitive to variations in a and b parameters. The average NPP was 3400 kg/ha and the standard deviation was only 426 kg/ha.

6 Discussion

This chapter includes a discussion whether non-destructive measurements of woody dry weights are possible or not using the two methods described in this study or not. The result of the comparisons between vegetation parameters measured in field and different NDVI parameters are also discussed.

6.1 Comparing the woody dry weight using Dep of Forestry's method with K Olsson's

To investigate the utility of the non-destructive measurements of woody dry weight the calculated dry weight using Dep of Forestry's was compared to the dry weight using K Olsson's. The correlation value between the two calculations of dry weight was just above the significant level. This indicates that using existing equations for calculating dry weight from non-destructive measurements might be a possible alternative to the time consuming and harmful destructive measurements. It can be concluded though that there must be some important differences between the two methods that can explain the considerable differences in dry weight for some trees that has to be taken into consideration. Therefore the discussion is focused on the differences and the advantage and disadvantage with the two methods.

6.1.1 Differences between the two methods

One of the reasons for the differences in dry weight could be that two different equations and six different constants were used when calculating dry weight using Dep of Forestry's method while only one equation was applied to all species using K Olsson's method. This means that if the variances in for example tree density and water content were large between the species in the area, these differences would not be reflected as well using K Olsson's equation.

Another explanation to the differences in dry weight could be that stem diameter was raised by the power of 4 in Dep of Forestry's equation 9. This indicates that small errors in when measuring stem circumference in field would result in increased errors in dry weight.

Further, K Olsson's equation suggested that there was a constant relationship between crown diameter and the woody dry weight of the tree. In areas with a large number of different species, growing conditions and grazing pressure, the relationship between crown and stem diameter might vary a lot. This was shown when examining the crown to stem ratio for the trees measured in the Hoanib catchment. The ratio varied from 2 to just over 30. The *Combretum imberbe* that differed in dry weight over 500 times between Dep of Forestry's and K Olsson's calculations had a crown to stem ratio of 3. The *Combretum imberbe* is of great importance to people, livestock and game in Namibia. Apart from being browsed by animals it is an outstanding fuel-wood and its leaves and roots are used medicinally (Van Wyk, 1998). Because of its utility the crown of these trees is often very narrow and the dry weight calculated with K Olssons equation will therefore be under estimated.

Another important difference was probably the fact that the Dep of Forestrys equations were based on the measurements of single-stemmed trees since most trees measured in Bushmanland or Caprivi only had one stem in breast height whereas many multi stemmed trees occurred in the Hoanib catchment. When calculating the woody dry weight of multi-stemmed trees using Dep of Forestry’s equations, the dry weight for the average stem was initially calculated. This was then multiplied with the number of stems to get the total woody dry weight of the tree. The accuracy of this procedure is dependent on the characteristics of the branching since the branching of a multi-stemmed tree can either start at ground level, just below breast height or anywhere in between. The measured dry weight of two trees with the same stem diameter and number of stems in breast height will be different if the branching start at ground level for one tree or just below breast height for the other. The calculated dry weight, on the other hand, will be the same independent of the level of branching. This in combination with the sensitivity to stem diameter in equation 9 can probably to some extent explain the differences in dry weight with the two methods.

Even though crown diameter was used as the non-destructive parameter in K Olsson’s equation the number of stems will probably influence the result. The reason is that the crown of each stem in a multi-stemmed tree will compete for space with its neighbors. A multi-stemmed tree is therefore more likely to have a smaller crown diameter than a tree with only one stem. This will result in an under estimated dry weight with Olssons equation for multi stemmed trees.

From the discussion above it was clear that the dry weight equations were dependent on the species and growth form that they were established for. It is difficult to evaluate the calculated dry weight to the true dry weight since no destructive measurements of woody vegetation was carried out within this project. When using existing equations from destructive measurements in the future it is therefore important carefully study the species composition and the growth form of the species used to establish the equation. It is also important to let the advantage and disadvantage with the methods decide which one to choose.

6.1.2 Advantages and disadvantages

The advantage with K Olsson's method is that there is a direct relationship between crown diameter measured in field and NDVI values from NOAA images. Stem diameter can only be related to NDVI in an indirect way.

Measuring crown diameter is also a quick and easy way of estimating dry weight since the species composition is irrelevant and crown diameter is an easy parameter to measure. For individuals that branch below breast height it is more convenient and probably more accurate to measure crown diameter even though the competition for space is a limiting factor. Applying one equation to all species includes many generalizations though.

The advantage of the Dep of Forestrys method is that two equations and several constants will probably result in a more accurate dry weight. The accuracy of the dry weight calculations is not validated within this project though. The disadvantage is that the species composition has to be known which is time consuming. The equations are also based on the fact that trees branch above breast height, which is not always the case in semi arid areas.

Before deciding which one of the two methods to use one has to validate the accuracy of the two different methods.

6.2 Comparing woody parameters with NDVI

Before the correlations between the woody dry weight and NDVI were examined it was important to know if the calculated dry weights were reasonable. Therefore the calculated woody dry weight was compared with results from other studies. It has to be kept in mind that since these studies have not been performed in identical regions to the Hoanib catchment, they can only be seen as rough estimates. Table 10 shows the average woody dry weight per hectare calculated within this study and the results from a four other studies. It can be concluded that the woody dry weight calculated in this study were in the same magnitude as the result from the other studies.

Table 10. Estimates of above ground woody dry weight from the literature (Franklin & Hiernaux,1991)

Author	Dry weight (kg/ha)	Precipitation (mm)	Study area	Type of vegetation
Elmqvist & Lundström (2000)	K Olsson: 3600 Dep of Forestry: 7600	100-300 100-300	Namibia	Mopane savannah
Kelly & Walker (1976)	21400	500	Zimbabwe	Mopane woodlands
Olsson (1985)	4700-15000	150-450	Sudan	Woodland
UNESCO (1979)	3500	250	Senegal	Mixed woodland
Nichol (1989)	3000-10500 30800	600	Nigeria	Shrubland Forest reserve

Since the correlation between the woody parameters and NDVI were not significant when studying the plots in Otjikowares, Omuramba and Hobatere it is not further discussed within this section. See grass correlation with NDVI for discussion in detail.

6.2.1 Woody parameters with background NDVI

Other studies have found significant correlations between canopy cover and background NDVI. K Olsson (1985) measured canopy cover in field and in aerial photos in an area in Sudan and established significant correlations to NDVI from Landsat MSS images during dry season. This was explained by the differences in the amount of shadows for areas with different canopy covers. Another reason was the fact that the disturbing reflectance from grass vegetation was absent during the dry season. Therefore, significant correlations between background NDVI and canopy cover was expected in this study too. Background NDVI was also expected to correlate fairly well to the woody dry weight because of the fact that most areas with a dense canopy cover also has a large dry weight. Neither canopy cover nor woody dry weight calculated in this study showed significant correlations to background NDVI though. This can have several explanations.

The tree cover in most plots does not exceed 10 %. Areas with a low tree cover had a large percentage bare soil. The reflectance from the soil varies with for example soil type, water content, degree of trampling from cattle and the amount of litter on the ground. The lower the tree cover the greater is the NDVI values a result of differences in background properties. The differences in shadows between areas were probably to small to be detected in the NDVI values. The correlations can be improved by taking differences in soil type into account. Rasmussen (1996) tried to add a soil factor and found that soil information improved the explanation of dry weight variations for millet in Senegal.

The difficulty in choosing representative sampling plots can also contribute to the low correlations. The location of the 30 plots was chosen randomly but before sampling the surrounding areas was visually investigated. If the species composition and vegetation cover in the plot were no good representative of the vegetation in the surrounding 1 times 1 km, another plot area was chosen. Even though effort was made in choosing plots, the difficulties in deciding representative plots had to be considered as a source of error. If the plot was located for example close to an ephermal river the measured dry weight and canopy cover in the plot would be much higher than the surrounding area. The correlations to canopy cover could have been improved if the canopy cover was measured in aerial photos since the cover in the entire pixel could be measured instead of only 50 times 50 meter. This would reduce the error caused by letting the cover in only one plot represent an area with a possibly different cover.

6.2.2 Woody parameters with max NDVI

None of the correlations between woody parameters and max NDVI were found significant. This can probably also be explained the low tree cover in the region. The reflectance from the growing grass vegetation might influences the NDVI values more than the reflectance from the trees. In areas where grasslands are mixed with trees such as the Hoanib catchment the NDVI values represent the overall production of grass vegetation and leaves in the area. A classification of the area into different vegetation types could improve the result. Rasmussen (1996) tried to apply a vegetation parameter to the NPP equation and found that this improved the result.

Apart from the influence of the herbaceous vegetation the increased amount of shadows during growing season also lowers the NDVI in areas with a dense tree cover. This will affect the correlations considerably since the reflectance from the trees in areas with a dense cover, that otherwise should have high NDVI values, will be much lower due to shadows.

6.3 Comparing grass parameters with NDVI

The relative order of correlation values for 22 and 16 plots was the similar for each grass measurement; therefore the discussion is the same for the two cases. As mentioned the 22 plots included all the plots except the ones around Sesfontein, where the growing season was not yet detected by the NDVI values. The 16 plots on the other hand included only the eastern plots (Omuramba, Otjikovares and Hobatere).

The data was analyzed with 22 and 16 plots respectively to draw attention to the fact that a trend in the data set might increase the correlation values. This was shown by the fact that the 22 plots returned more significant values than the 16 plots. To avoid the trend in the data caused by the east-westerly precipitation gradient, measurements could instead be carried out along a south-northerly axis in the catchment where the vegetation types would be more similar. There would still exist differences caused by for example different soil types and erratic precipitation, but the trend due to the annual precipitation gradient of the data would probably decrease.

In common for both the 22 and the 16 plots was that the sum field showed the strongest relationship to the grass measurements in most cases. It had to be noted though that the increase in NDVI in Kowarib did not occur until after the field measurements were carried out, which affected the correlation values (se appendix 4). The growing season in the other areas had started when the field measurements were carried out and was also registered by the NDVI, even though it was only noted in 1 to 3 dekads (figure 8). However, the correlation values with the sum field were in most cases found significant, which was also found by other studies (Wylie *et al*, 1991 and Prince, 1991).

Interesting to note is that the relationships with the sum did not differ considerably from those of the sum field. This is noticeable since the sum is made up by NDVI values registered after the period of field measurements. It was evidently a source of error to compare field measurements from one date with NDVI values from later dekads, as the field measurements were carried out too early. It also has to be kept in mind that the earlier the grass starts to grow; the longer time is available for the grass to accumulate dry weight. This might be the reason why the sum and the sum field showed similar results. Ideally the field measurements should be carried out when the vegetation is just at or close to its maximum. In other words the sum field should correspond to the same period of time as the sum decrease or the sum. It is often hard to match the period in the field with the phenology of the vegetation though, as the precipitation is so unpredictable. The similarities in correlation values might suggest that these kinds of studies are not that dependent on when the field measurements are carried out after all.

Sum decrease should return a higher correlation than the sum according to Wylie *et al* (1992). They found that the correlation increased if the time period when the reflectance from the standing dead vegetation obscuring the NDVI signal was not considered. Similar results were found by Todd *et al* (1998) when studying grazed and ungrazed grasslands. The grazed grasslands returned higher correlation values than the ungrazed, because not much litter influenced the signal in the case of the grazed grasslands. The same relations between the sum and the sum decrease were not true for this study; maybe because the litter did not obscure the signal as animals and humans in the region more or less directly consume it.

Also max have been shown to give higher correlation values than the sum (Fuller, 1998 & Tucker *et al*, 1985), but it was not the case in this study.

Another interesting fact was the good correlation values with the logarithm of the volume. This signifies that this non-destructive method (measuring the coverage and the height) might be an alternative to the destructive method of the weight (cutting, drying and weighing the grass).

It is also evident that even if the grass was not very high it is important to consider the height parameter, which was concluded from the fact that the correlation values were higher for the logarithm of the volume than for the cover.

Additionally, it has to be noted that all the grass comparisons were influenced by the tree cover; their greenness as well as shadows from the trees. This draws attention to the problem of separating grass and woody biomass with NDVI. As mentioned for the woody vegetation, a possible vegetation classification of the region could be done. Other sources of errors were as for the woody dry weight the small plot size and the influence of the ground, because of the low vegetation cover.

6.4 Sensitivity test of the ε, a and b parameters in the Monteith equation

The result of the Monte-Carlo simulation showed that the calculated net primary production, NPP, were quite insensitive to variations in a and b parameters but very sensitive to variations in ε.

It is found that the ability to convert light into organic matter, ε, is species dependent, which necessitates variation in ε over large heterogeneous areas to get correct calculations of NPP. Variations in the physical environment such as temperature, soils, water and nutrition are also found to affect the ε value (Prince, 1991). Other factors found to influence ε are the atmospheric conditions, such as clouds. ε is increased under cloudy conditions since the radiation is distributed more uniformly over all leaves in the canopy rather than saturating some leaves that are sunlit and leave others in dark shade (Gower *et al*, 1999 after Norman and Arkebauer, 1991).

The variation in ε is not only spatial but also temporal. In semi arid regions the ε value will vary over the growing season in accordance to periods of rainfall and the intermittent periods of drought (Prince, 1991).

Several studies have found that even though (Prince 1991, after Gosse *et al*, 1986, Kniry *et al* 1989 and Russel *et al* 1989) the spatial variations in vegetation type and physical environment influence the ε values, the variations only occupy a quite narrow range. They therefore suggested that ε could be regarded as constant throughout the entire growing season. The result of this study indicates that using a constant ε will cause errors in the calculated NPP, even if the variations in ε are small.

This means that the choice of ε value is of great importance and that the use of a constant ε in large areas is probably a source of error when calculating NPP. The advantage with using NDVI from NOAA images is that the net primary production over the entire growing season can be calculated for large areas. Since the sensitivity of the model limits the use of a constant ε, the advantage with NDVI from NOAA decreases when calculating NPP. To solve this problem the variations in vegetation and physical environment has to be included in the ε value. Different approaches are:

- Include the variations of vegetation in ε by classifying the area into vegetation classes and to determine a specific ε value for each class.
- Use thermal-infrared measurements to estimate the variations in surface temperature and soil moisture.
- Estimate the cloud cover from thermal-infrared wavelength bands and adjust the ε values from these estimations.

Finally it would have been interesting to compare the calculations of NPP with dry weight calculated from the field measurements. This could have been done with the grass weight calculated in this study. It has not been done though, since estimations of foliage would probably be needed to receive acceptable results. Foliage estimations were not possible within this study.

Some other sources of errors that might have influenced the measurements were positioning errors in the GPS, difficulties of choosing an average tree and the rough estimate in the calculations of PAR.

7 Conclusion

When studying the relationships between NDVI and the field measurements of the woody vegetation, no significant correlation values were found. This was believed to be a result of for example the low tree cover, the influence of grass vegetation and possible errors when calculating woody dry weight. The correlation values for the grass on the other hand were found significant. The NDVI integrated during the growing season until the dekad corresponding to the field measurements returned the highest correlation values of the parameters investigated. For all the correlation values attention has to be paid to the small number of plots.

Comparing the two non-destructive methods to calculate woody dry weight showed that the correlation value was just above the level of significance. This indicates that using existing equations for non-destructive measurements of woody dry weight might be a possible alternative to the time consuming and harmful destructive measurements. Comparing the calculated dry weight for individual trees revealed large differences in dry weight for some trees though. Some of the trees were species that were not used to establish the equations. Others were trees with growth form that differed to a great extent from the trees that were used to establish the equations. This indicates that a lot of effort has to be done when choosing equation so that species composition and growth form in the two study areas are in agreement.

For the grass measurements it is suggested that non-destructive measurements might be as useful as destructive ones, since the logarithmized volume of the grass returned almost as significant values as the dry weight.

This study also draws attention to the fact that a trend in the data set increased the correlation values in the case of the grass. One should therefore try to avoid the annual precipitation gradient when choosing sampling areas, if the precipitation is the controlling factor for the vegetation.

The NPP calculations from the Monteith equation showed to be very sensitive to variations in ε but less sensitive to variations in a and b parameters. This indicates the importance to vary ε over time and space instead of using a constant value since ε is dependent on species, physical environment and atmospheric conditions. When calculating NPP using Monteith equation in the future, a stratification of the area into different ε classes might increase the accuracy of the results.

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Appendix 1. PAR Calculations

The following PAR calculations (Oke, 1987) are applicable at the 16^{th} of February for the study area with the approximate latitude and longitude:
Latitude = - 19.00.00
Longitude = 13.00.00

The photosynthetic active radiation (PAR) is approximated to 50 % of the incoming radiation at the top of the atmosphere (SI) according to the following equation.

PAR = 50 % * SI

S1 in turn can be calculated with:

S1 = I cos z

z = zenith angle
I = solar constant = 1367 W/m^2

The zenit angle is the angle between the sun's rays and the zenith direction and it can be calculated with:

$\cos z = \sin \phi * \sin \delta + \cos \phi * \cos \delta * \cos h$

ϕ = latitude ≈ -19
δ = the solar declination
h = the hour angle

The solar declination is the angle between the sun's rays and the equatorial plane. The hour angle is the angle through which the Earth must turn to bring the meridian of the site X directly under the sun. t is a function of the day. Solar declination, δ, for the 16^{th} of February and the hour angle, h is calculated with:

$\delta = -23{,}4 \cos (360 (tj + 10) / 365)$
$\delta = -13$ for tj = 47 (Julian day number for the16th of February)

h = 15 (12 –t)

t is the local apparent solar time and is calculated by adding 4 minutes to the local standard time for each degree of longitude the point is east of the standard meridian. This gives the local mean solar time, t_{local}. If the meridian of the study area is 13.00.00

$t_{local} = 13 * 4 = 52$ min.

To receive t the t_{local} has to be added with the equation time of correction.
If 1 Feb = -13,6 and 1 mars = -12,6 the 16 Feb = -13,1.
This gives t = 52 – 13,1 = 38,9 min = 0,648 h

h can now be calculated 15 (– 0,648)
h = -9,725

When δ and h is known z can be calculated:

cos z = sin (-19) * sin (-13) + cos (-19) * cos (–13) * cos –9,725
cos z = (0,073) + (0,908) = 0,981
z = 11,2 °

It is now possible to calculate SI and finally PAR:

SI = 1367 * 0,981 = 1341 W/m^2

PAR = 0,5 * 1341 = 670,5 W/m^2

Appendix 2. Image processing

Dekads being altered because of believed atmospheric effects are listed below as well as entirely missing dekads.

Dekad	Plot number
3 October	1-30
1 November	1-30
2 February	15, 16, 20
3 February	16, 19, 20, 28
1 March	2, 19, 22, 23, 24, 26, 29
2 March	2, 15, 17, 19, 28, 30
3 March	15, 17, 18, 19
1 April	1, 21, 24, 25, 27
2 April	6, 15, 16, 20
3 April	17, 18, 19, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30
1 May	25
2 May	1-30

Appendix 3. Woody dry weight

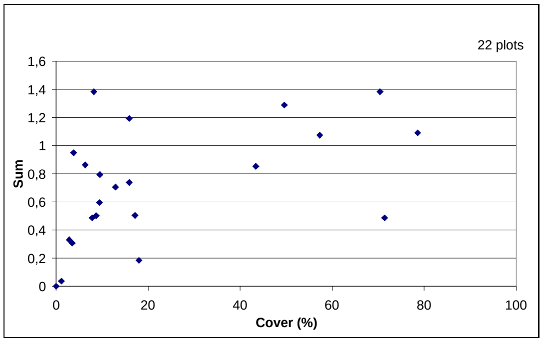
Calculations of woody dry weight using K Olsson's and Dep of Forestry's method.

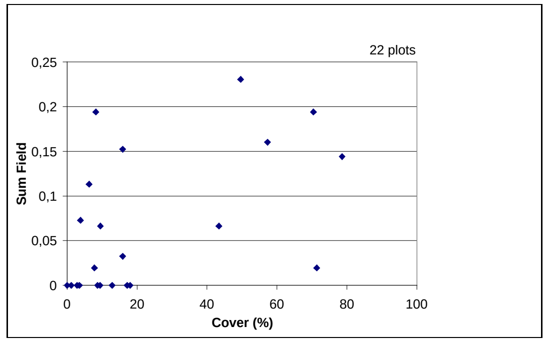
Group no	Species	Crown diam (m)	Stem diam (m)	K Olsson dry weight (kg)	Dep of Forestry dry weight (kg)	F/O	Crown/ Stem
5	Accacia tortillis	4,2	0,43	42,07	5,51	0,131	9,70
5	Terminalia prunoides	3	0,41	17,78	3,50	0,197	7,36
5	Salvadore persika	7	1,37	155,57	38,35	0,247	5,13
5	Salvadore persika	4	1,10	37,13	11,60	0,312	3,63
5	Terminalia prunoides	5	0,26	65,74	31,56	0,480	19,21
5	Boscia foetida	2,5	0,27	11,15	6,93	0,622	9,35
5	Faidherba albida	9	0,37	296,03	231,05	0,780	24,59
5	Accacia tortillis	8	0,26	218,97	176,12	0,804	30,65
6	Colospherum mopane	3,5	0,12	26,38	21,80	0,826	28,19
5	Accacia tortillis	12	0,80	618,27	591,92	0,957	15,08
5	Accacia tortillis	10	0,63	387,68	423,52	1,092	15,95
5	Accacia tortillis	6	0,75	104,84	118,84	1,134	7,99
4	Maerua schinzii	3	0,09	17,78	20,29	1,141	32,50
4	Maerua schinzii	2	0,20	6,30	7,88	1,251	10,13
6	Colospherum mopane	4	0,55	37,13	50,17	1,351	7,28
4	Ziziphus mucronata	3	0,19	17,78	24,35	1,370	16,11
5	Accacia tortillis	7,5	0,50	185,62	277,92	1,497	14,96
5	Boscia foetida	3	0,56	17,78	28,60	1,609	5,35
5	Commiphora multiljuga	2,5	0,57	11,15	18,38	1,648	4,36
5	Accacia tortillis	7	0,37	155,57	271,10	1,743	19,12
5	Accacia tortillis	8	0,54	218,97	383,46	1,751	14,78
6	Colospherum mopane	5	0,52	65,74	117,03	1,780	9,55
4	Maerua schinzii	2,5	0,09	11,15	20,29	1,820	27,08
4	Maerua schinzii	4	0,16	37,13	70,24	1,892	25,65
5	Boscia foetida	2,7	0,32	13,58	28,01	2,063	8,48
5	Salvadore persika	5	0,25	65,74	166,35	2,530	19,88
5	Accacia tortillis	4	0,83	37,13	124,41	3,350	4,81
6	Colospherum mopane	2,5	0,27	11,15	39,93	3,582	9,24
4	Maerua schinzii	2	0,15	6,30	23,70	3,763	13,66
5	Euclea pseudobenus	3	0,32	17,78	69,41	3,904	9,52
5	Accacia tortillis	5	0,37	65,74	271,10	4,124	13,66
6	Colospherum mopane	3	0,65	17,78	78,24	4,401	4,64
6	Colospherum mopane	4	0,50	37,13	165,36	4,453	7,98
5	Accacia tortillis	2	0,11	6,30	28,64	4,549	17,95
5	Accacia tortillis	3,5	0,22	26,38	136,11	5,160	15,71
5	Terminalia prunoides	4	0,28	37,13	195,13	5,255	14,28
6	Colospherum mopane	1,8	0,10	4,81	29,50	6,135	18,85
4	Boscia albitrunca	3	0,19	17,78	127,53	7,173	15,71
6	Colospherum mopane	3	0,18	17,78	129,77	7,299	16,83
5	Boscia foetida	2	0,21	6,30	48,93	7,771	9,38
6	Colospherum mopane	2,5	0,25	11,15	106,23	9,529	10,20
4	Boscia albitrunca	1	0,05	1,07	10,99	10,296	18,48
6	Colospherum mopane	3	0,39	17,78	185,01	10,406	7,66

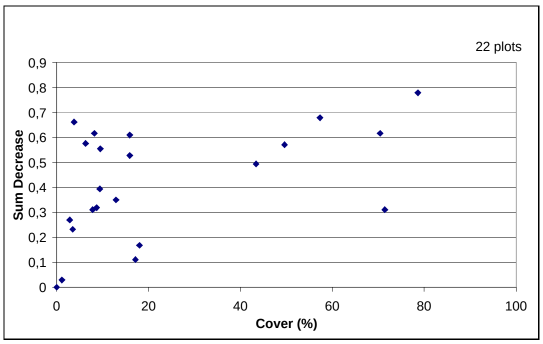
6	Colospherum mopane	2	0,14	6,30	69,07	10,970	14,61
5	Boscia foetida	4	1,09	37,13	441,20	11,882	3,65
4	Boscia albitrunca	2	0,30	6,30	82,47	13,097	6,68
4	Maerua schinzii	2	0,34	6,30	97,92	15,552	5,90
6	Colospherum mopane	6	1,05	104,84	1666,37	15,894	5,71
6	Colospherum mopane	8,2	3,24	233,26	4118,96	17,658	2,53
6	Colospherum mopane	6	0,75	104,84	1952,21	18,620	8,02
4	Boscia albitrunca	1,7	0,32	4,15	122,76	29,554	5,31
6	Colospherum mopane	5,4	1,34	80,06	3624,16	45,270	4,04
2	Combretum imberbe	0,4	0,13	0,10	52,80	516,292	3,06

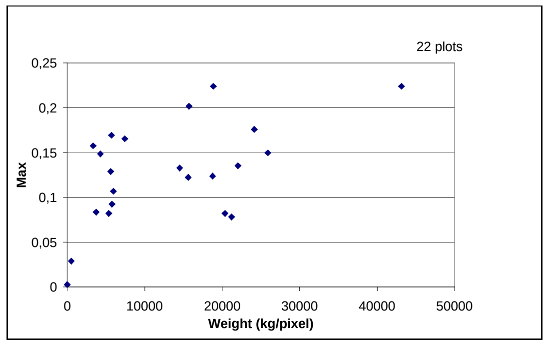
Appendix 4. Grass parameters vs NDVI

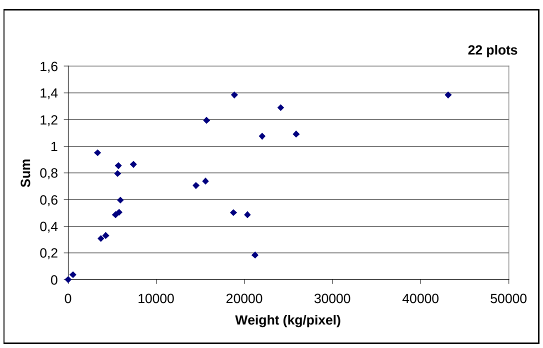
Scatter plots visualizing all the significant correlations between any grass and NDVI parameter (22 and 16 plots).

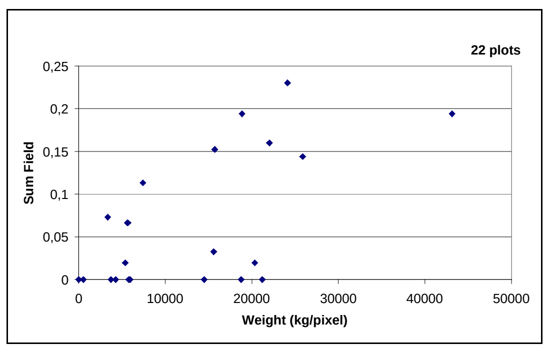


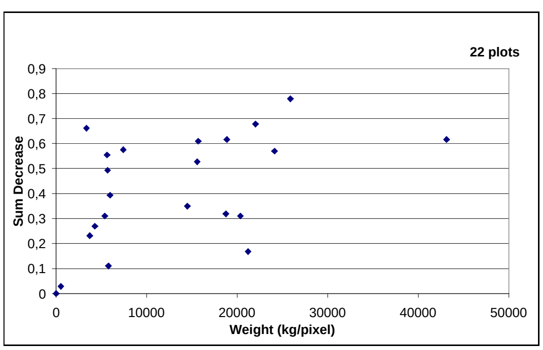


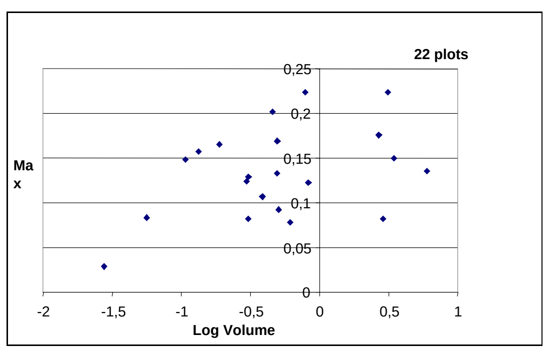


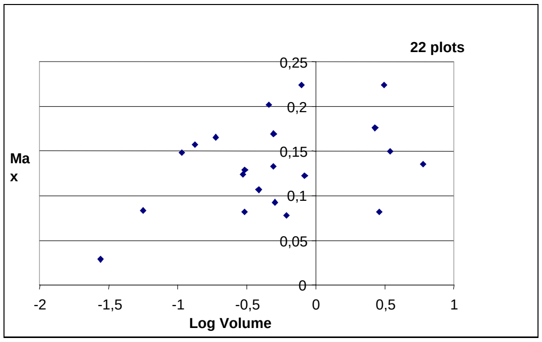


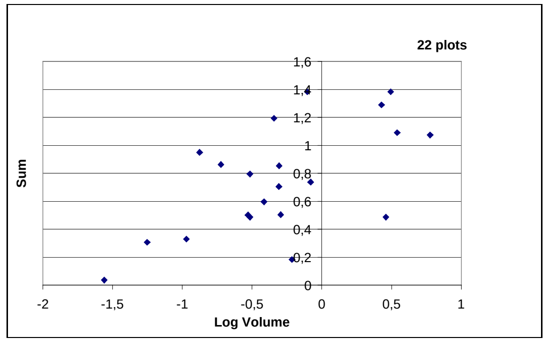


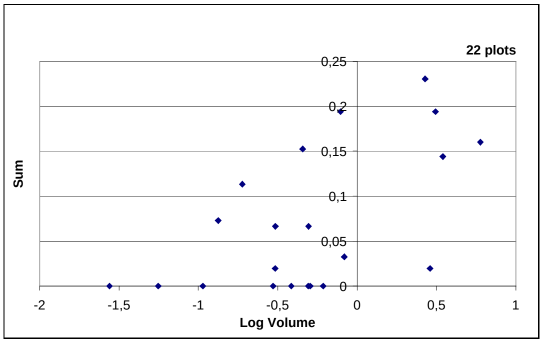


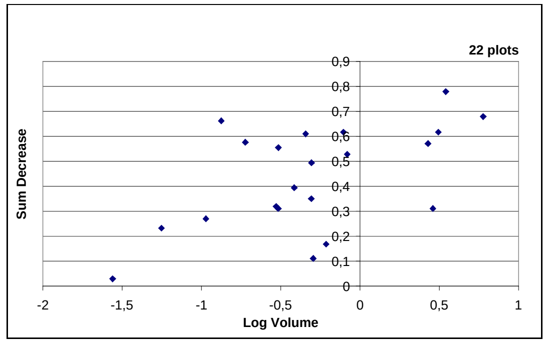


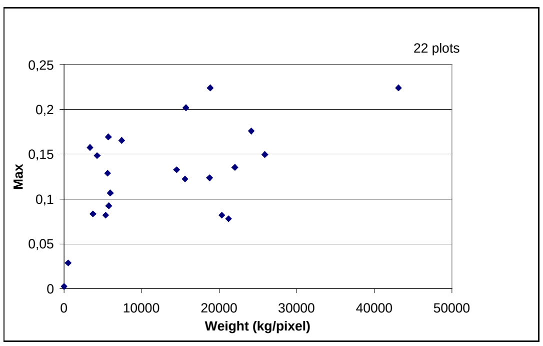


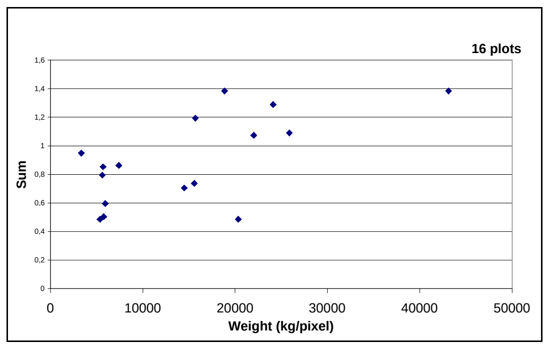

22 plots
Ma
x
Log Volume

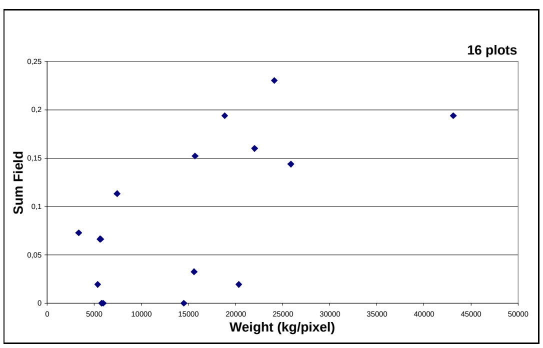

22 plots
Sum
Log Volume


22 plots
Sum
Log Volume


22 plots
Sum Decrease
Log Volume


22 plots
Max
Weight (kg/pixel)


16 plots
Sum
Weight (kg/pixel)


16 plots
Sum Field
Weight (kg/pixel)

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