SPECTRAL DIFFERENTIATION OF *CANNABIS SATIVA* L FROM MAIZE USING HYPERSPECTRAL INDICES

BY

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Declaration

The work described in this thesis was carried out at the Agricultural Research Council Institute for Soil, Climate and Water (ARC-ISCW) in collaboration with the University of KwaZulu-Natal, Pietermaritzburg under the supervision of Professor Onisimo Mutanga from January 2007 to December 2009.

I **Phila Sibandze** hereby declare that this thesis is my original work and that all work taken from other sources has been accurately reported and acknowledged. This thesis has not been in its entirely or in part been submitted at any academic institute for the purpose of acquiring a qualification.

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Phila Sibandze Date

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Prof. Onisimo Mutanga Date

List of Abbreviations:

ARC-ISCW	: Agricultural Research Council-Institute for Soil Climate and Water
ASD	: Analytical Spectral Device
ASTER	: Advanced Spaceborne Thermal Emission and Reflection Radiometer
CAN	: Cannabis
CASI	: Compact Airborne Spectrographic Imager
CRI	: Carotenoid Reflective Index
EMS	: Electromagnetic Spectrum
EOS	: Earth Observation System
FAO	: Food and Agriculture Organization
GPS	: Global Positioning System
INT-CAN	: Intercropped Cannabis
INT-MAZ	: Intercropped Maize
LAI	: Leaf Area Index
LANDSAT	: Land Satellite
NDVI	: Normalized Difference Vegetation Index
NIR	: Near Infra Red
NOAA	: National Oceanic and Atmospheric Administration
ONOC	: Office of Narcotics, Organized Crime
PRI	: Photochemical Reflective Index
REP	: Red Edge Position
RS	: Remote Sensing
SAM	: Spectral Angle Mapper
SAPS	: South African Police Service
SID	: Spectral Information Divergence
SPOT	: Satellite Pour l'Observation de la Terre
THC	: Tetrahydrocannabinol
TSAVI	: Transformed Soil Adjusted Vegetation Index
TUT	: Tshwane University of Technology
UNODC	: United Nations Office on Drugs and Crime
USA	: United States of America

Abstract

Cannabis sativa L. is a drug producing crop that is illegally cultivated in South Africa. The South African Police Service (SAPS) use aerial spotters on low flying fixed wing aircrafts to identify cannabis from other land cover. Cannabis is usually intercropped with maize to conceal it from law enforcement officers. Therefore the use of remote sensing in identifying and monitoring cannabis when intercropped with maize and other crops is imperative.

This study aimed to investigate the potential of hyperspectral indices to discriminate cannabis from maize under different cropping methods, namely, monocropped and intercropped. Cannabis and maize were grown in a greenhouse. The spectral signatures were measured in a dark room environment. Green pigments (chlorophyll and carotenoid) from the treatments were also measured. These pigments were then compared with their respective indices. Photosynthetic reflective index (PRI) and Carotenoid Reflective Index (CRI) were two of the indices used to discriminate cannabis from maize using carotenoid content while the Red Edge Position (REP) and the narrow band Normalized Difference Vegetation Index (NDVI) used chlorophyll content and morphological differences respectively to discriminate the two plant species.

CRI and NDVI proved to be capable of identifying cannabis under the two cropping conditions. NDVI showed a 25% spectral overlap for the monocropped treatments and 60% overlap for the intercropped treatments. CRI displayed 18% and 58% overlap for the monocropped and intercropped treatments, respectively. As a result CRI emerged as the most suitable index for discriminating cannabis from maize. With proper calibration of airborne or space borne imagery, the study offers potential to detect cannabis using remote sensing technology.

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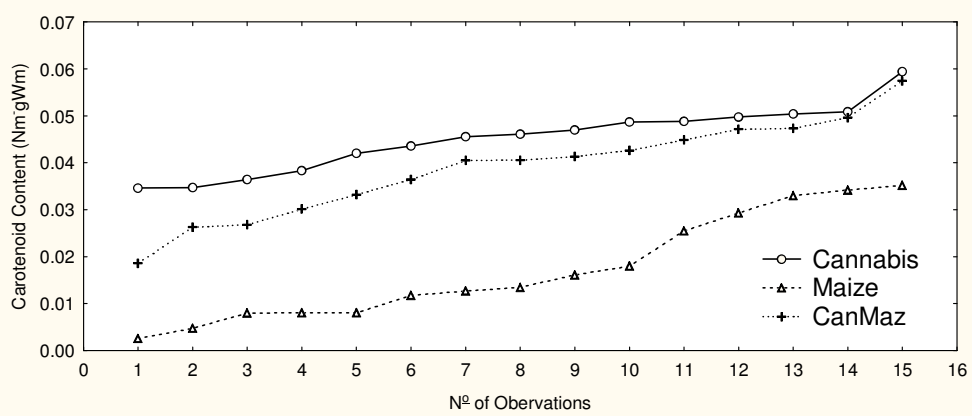

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Chapter 1

1 Introduction

Remote sensing (RS) has become a technology of choice in applications where study sites are not easily accessible and are expensive to monitor by ground-based methods. According to Lillesand *et al*. (2004), it is relatively efficient and accurate in detecting objects, areas and phenomena on the ground. This ability can help in identifying cannabis as illegal cannabis growers tend to grow the plant in remote and inaccessible areas. The potential to identify cannabis cultivated fields using RS does however have limitations as successful detection of features depends on factors such as the sensor used for capturing data, spectral properties of the features being mapped, experience in mapping features using spectroscopy and also the availability of ground-truthing data (Jensen, 2005; Lillesand *et al*., 2004)

These limitations were the subject of the Vienna Conference (October 1989) during which a group of remote sensing scientists discussed the potential use of RS techniques in identifying fields cropped with drug-producing plants (FAO, 1997). One of the resolutions emerging from deliberations of this meeting was that RS could be used to detect and monitor the cultivation of illicit crops. Since then there has been an increased use of RS to identify illegal cultivation of coca crop in Colombia and cannabis fields in the Unites States of America (USA), Afghanistan, Peru, Bolivia, Laos and Morocco. Results from different studies indicate a high success rate in the ability of RS to detect concealed drug-producing crops especially when good ground reference information is used to support image interpretation (Thiessen, 2007; UNODC, 2005; UNODC, 2006a).

Of all the illicit drugs available on the streets, cannabis is one of the least difficult to obtain (UNODC, 2006b). According to Marijuana and Youth (2002), cannabis has negative effects on human health and social well being of excessive users. Research has shown that cannabis has as much negative effects to the brain, lungs and heart as do other illicit drugs (Marijuana & Youth, 2002).

Apart from health related problems, cannabis does influence one's social behavior (Marijuana & Youth, 2002) Research undertaken to investigate the social behavior of juveniles between the ages of 12 and 17 years who smoked cannabis every week showed that they were four times more likely to engage in violent acts than non-cannabis smokers. In addition, these smokers were also less likely to obtain high levels of education because of increased absenteeism and anti-social behavior (Marijuana & Youth, 2002).

In South Africa, cannabis is known by many street names based on its place of origin, such as "Durban poison" from Durban, "Swazi gold skunk" from Swaziland and "Transkei white" from the Eastern Cape. Internationally it is also known by different names: marijuana or crack in the USA (Infofacts, 2004) and Ma in China (Hong & Clarke, 1996). Its botanical name is Cannabis *sativa L. subsp. sativa* (Small & Cronquist, 1976). Cannabis is normally found in different colors; the most common is green and brown. When mature, cannabis can reach a height of 4 to 5 meters (Latta & Eaton, 1975; Wilmot-Dear, 1999). *Cannabis sativa* L has two chemotypes: the fiber type and the drug type (Teramura & Lydon, 1987).

The fiber chemotype (known as hemp) is usually used for making textile, ropes and other products. The seeds produced by this type are crushed to extract oil used for both medicinal and

domestic purposes (Bocsa *et al.*, 1997). The chemotype variety has an organic compound called delta-9-tetrahydrocannabinol (∆-9-THC) (Clarke & Pate, 1994; Fetterman, 1971; Latta & Eaton, 1975, Seamon *et al.*, 2007). This is the psychoactive compound that causes hallucination when cannabis is smoked or used in other forms (Mel, 1997).

Cannabis has been cultivated for centuries (Coyle *et al.*, 2003). Studies have been conducted on cannabis to determine its chemical composition for medical purposes (Porcella *et al.*, 2001; Russo *et al.*, 2002). In China, studies on this phenomenon date back to the early 1950s (Hong & Clarke, 1996).

In South Africa, it is illegal to cultivate and to be in possession of cannabis. The United Nations Office of Drug and Crime (UNODC) reported that the cannabis industry in South Africa is estimated to be worth R24-billion (Eliseev & Maughan, 2006). South Africa is seen as the gateway for exporting cannabis to European countries due to the large international harbors and airports in the country. Eliseev and Maughan (2006) stated that South African customs officials inspect only 16% of incoming and outgoing cargo. This means that substantial amounts of illegal substances, including cannabis, pass undetected through the customs officials to overseas shores. Most of the cannabis exported to European countries is locally grown and a small portion is brought into the country from neighboring countries especially Lesotho, Malawi and Swaziland (Strydom, 2000).

Though RS is capable of aiding the detection of illegal drug-producing crops, effective identification of cannabis has tended to be constrained by inadequate understanding of its spectral characteristics (Walthall, 1998). This knowledge gap necessitates the need for scientific investigation of this crop's spectral properties in order to enhance our potential to fully exploit the

detection capabilities offered by RS. This requires research to thoroughly explore the potential use of RS techniques in differentiating cannabis from other vegetation species under different environmental conditions. To achieve improved detection, there is a need to device methods that increase classification accuracy. One way of doing this is to compile ground-truth using spectral devises that accurately measure reflected radiation at targets of investigation similarly located by using dependable Global Positioning Systems (GPSs).

The South African Police Service-Office of Narcotics, Organized Crime (SAPS-ONOC) unit regularly conducts drug eradication operations throughout the country, where cannabis-cultivated fields are identified using fixed-wing low-level flying planes and helicopters. Even though the SAPS-ONOC unit is still using the traditional method of spotting cannabis using the traditional method of visual identification from planes and helicopters they are doing their level best to identify unknown cannabis fields.

During the operation, experienced spotters are tasked with identifying cannabis from other types of vegetation. At times the growers conceal the cannabis by intercropping it with other crops especially maize. This is a challenge to inexperienced spotters as it becomes difficult for them to discriminate cannabis from other crops. According to Walthall *et al*. (2003) the traditional method of spotting is of limited success because accurate detection depends on the training and experience of individual spotters. The identification process is tiring, especially when it is conducted over large areas. This limitation can be overcome by using RS.

Usually, most cannabis fields in South Africa are in mountainous, inaccessible and remote areas and range in size from small patches to football-sized fields. RS-based image spectroscopy

can be used in identifying unknown sites and to monitor traditionally known fields. The discrimination of cannabis from other plants can be enhanced by using spectral information gathered from the ground and selected image classification methods (Thiessen, 2007).

One of the disadvantages of the traditional identification methods is that it is time consuming. To increase detection accuracy, the aircraft must fly at low altitude which implies reduced spatial coverage at any given time. On the other hand, depending on the sensor's spatial and temporal resolutions, remotely sensed data have a greater spatial coverage and data could be available on a regular basis making it possible to identify pattern changes on the known fields. As a result the information extracted from the RS data can assist law enforcement agencies to make informed decisions on when and where to conduct cannabis eradicating operations.

Records from the SAPS–ONOC showed that in South Africa, the Eastern Cape and KwaZulu-Natal provinces are the areas where cannabis is cultivated in large areas and also with the greatest number of dry bag seizers (Rehder, 2002). The SAPS-ONOC has been destroying illegal cannabis fields from these provinces for the past 15 years and beyond and as a result these areas are known as traditional growing areas (Rehder, 2002). According to Superintendent Jan Rehder of the SAPS–ONOC (personal communication, 9 July 2006), it is difficult to make arrests, as cannabis is grown on communal land where no one claims ownership. As a result arrests are hardly made since there is no one to reprimand. By destroying cannabis fields the SAPS-ONOC hopes to discourage the growers from continuing with the illegal cultivation of cannabis. To bring sustainability to the eradication program, there is a need to identify interventions that will maximize the success of cannabis identification. The use of

remote sensing can facilitate the extraction of information and improve intelligence in ensuring that the challenges encountered during cannabis identification are minimized by using imaging spectroscopy as a method for discriminating cannabis from neighboring vegetation

1.1 Statement of the problem

The main problem is that in South Africa, there is lack of a dependable methodology for rapid detection of cannabis intercropped with like-colored plants. The cannabis growers illegally cultivate cannabis in remote and inaccessible areas. The SAPS-ONOC has noticed that there are two cropping methods that are used by the illegal growers. The first method is when cannabis is grown independently as a crop (monocropping) and the other method is when it is intercropped with other green types of vegetation. According to Superintendent J. Rehder and Captain Malangeni from the SAPS-ONOC, a number of crops have been found to have been intercropped with cannabis including tomatoes but the most dominant crop is maize. Though aerial spotters reported that cannabis can be clearly distinguished from other green types of vegetation because of differences in biological, spectral and physical characteristics such as canopy structure (Rehder, personal communication, 9 July 2006), it is still difficult to distinguish cannabis from a wide range of other crops.

Cannabis which has planophile architecture, as compared to the erectophile leaf structure of maize, contributes to the physical differences observed between these two species. Furthermore, the color difference between these two species could be the result of the chlorophyll content within them. Nonetheless, it is difficult to visually identify cannabis when intercropped with maize and this is one of the challenges that the aerial spotters have highlighted. Therefore this research investigates the spectral and physical properties of cannabis grown in South

Africa. The information gathered will aid in spectrally discriminating cannabis from maize using earth observation systems. This study therefore sets itself to the following objectives:

1.2 Objectives

- To use remote sensing to discriminate cannabis from maize by:
    a) Conducting green house investigations to quantify differences in their spectral reflectance characteristics.
    b) Using measured differences in these spectral reflectance characteristics to enhance confidence in the discrimination of these crops.
- To investigate the influence of chlorophyll and carotenoid contents on spectral signatures and assess their potential to discriminate cannabis from maize.
- To spectrally differentiate cannabis from maize when grown under different cropping methods.

1.3 Hypotheses

- There are quantifiable differences in the spectral reflectance characteristics of cannabis and maize.
- Differences in the spectral reflectance characteristics of cannabis and maize can be used to enhance the discrimination of these crops through the interpretation of remotely sensed data.
- Chlorophyll and carotenoid absorption can be used to discriminate cannabis from maize.
- Spectral regions that respond to physical properties can discriminate cannabis from maize.

1.4 Research question

Can cannabis be spectrally identified when intercropped with maize and to what extent can the concentrations of chlorophyll and carotenoids assist in the discrimination process?

Chapter 2

2 Literature Review

2.1 History of Cannabis

Cannabis is an indigenous plant of central Asia cultivated around the world for both therapeutic and recreational purposes (Coyle *et al*., 2003; Mahlberg & Hillig, 2004; Watts, 2006). It is an annual crop that grows up to 4-5m tall with 5-11 leaves protruding outwards from the stem base (Latta & Eaton, 1975; Wilmot-Dear, 1999). The biophysical appearance differs between male and female plants. Male plants grow taller and are thinner than their female counterparts. Female plants have broader leaves than male plants and survive for months after flowering, whereas male plants die just after flowering (Pate, 1994). Cannabis, scientifically known as *Cannabis sativa L* or *Cannabis Indica Lam*, has a blue-green (emerald) color which results from light reflected from the unique surface and interior of the leaves (Walthall *et al*., 1999).

The scientific classification of cannabis dates back to the second half of the 18th century. The first variety; *Cannabis sativa Linnaeus* was named so by Carolus Linnaeus in 1753. The second variety (*Cannabis indica Lam*) was discovered to be different from *Cannabis sativa. L.* by the French biologist Jean-Baptiste Lamarck in 1758. The differences noticed by Jean-Baptiste were in the stem, leaves, bark, and flowers and the second variety is named after him in honor of his discovery (Watts, 2006).

During the 19th century, different cannabis samples were brought forward to be classified as new species. However, none of those plants had distinct differences to qualify them as new cannabis

species. In 1924, Janichevsky, a Russian botanist, succeeded in defending his proposal to name cannabis plants found in central Russia as a new species. This species was named *C. sativa L. var. ruderalis Janisch.* Despite these classifications there are still questions about the actual number of cannabis species available. A number of scientists still argue whether C*. indica* and *C. ruderalis* are different species (Clarke & Pate, 1994).

2.2 2.2 Species discrimination using remote sensing

Remote sensing (RS) has been used in various studies where a number of techniques have been investigated in discriminating different vegetation species. Some of these methods investigated are sensitive to biochemical and biophysical properties of the species being investigated. Depending on the nature of the study, multispectral or hyperspectral techniques are used. Multispectral RS involves the acquisition of images using broad bands of the electromagnetic spectrum (EMS) whereas hyperspectral RS is when the image is captured in continuous narrow bands of EMS (Carter, 1994; Lillesand *et al*., 2004).

Multispectral sensors were used by early earth observation systems (EOS) to investigate the phenology of different vegetation types. Some of the sensors used include LandSat, NOAA and SPOT. Different vegetation indices were developed for multispectral RS applications that include measurement of vegetation quality and vegetation biomass for example. Some of the indices include the widely used Normalized Difference Vegetation Index (NDVI), Leaf Area Index (LAI) and the Transformed Soil Adjusted index (TSAVI) (Tucker *et al*., 1985). Though these indices have proved to be useful in areas with different and open vegetation cover, they have not been very

successful in discriminating different vegetation species (Nagendra, 2001; Tucker, 1979).

To address the spectral limitations of multispectral sensors, hyperspectral sensors have been developed and have proved to be useful in investigating the physiological and biochemical properties of different vegetation species. Most of the indices developed were relative to vegetation and were sensitive to subtle variations within bands of close proximity. Some of the biophysical attributes detected by hyperspectral indices include chlorophyll and carotenoid (Carter, 1994; Stylinski *et al*., 2002).

Hyperspectral techniques used in discriminating different vegetation species are well documented in the literature. Sobhan (2007) used both ground and airborne hyperspectral data in discriminating various vegetation species and noted that many studies failed to recommend band combinations that can be applied across diverse landscapes because of overlaps in closely related spectral bands. Sobhan (2007) attempted to address this constraint by using different methods such as the Mann Whitney U test, Principal Component Analysis, Stepwise Discriminant Analysis and the Genetic Neural Network-based feature selection approach. These techniques were able to identify critical spectral regions that could discriminate the 26 tree species investigated.

Although these methods were able to differentiate the 26 species, there were nonetheless species that could not be differentiated due to similarities in spectral properties. Therefore, Sobhan, (2007) further investigated other techniques which could discriminate species with closely related spectral properties. He considered four extensions of his pioneer technique that involved use of: a) the spectral correlation measure (SCM), b) the spectral angle mapper (SAM), c) the spectral information divergence (SID), and d) a combination of SAM and SID. These techniques

improved the ability of hyperspectral data to discriminate a broader range of different vegetation species with closely related spectral properties with the SAM–SID combination yielding the most satisfactory results.

2.3 Discriminating vegetation species using hyperspectral indices

2.3.1 Photochemical reflective index

Photochemical reflectance index (PRI) previously known as "physiological reflectance index" (Gamon *et al.*, 1995) is one of the hyperspectral indices applied by scientists in the past to identify vegetation species based on carotenoid concentration. This index is a reflective measure sensitive to changes in carotenoid concentration (Cho *et al.*, 2008; Gamon *et al.*, 1992; Gitelson *et al.*, 2001). PRI uses two spectral bands (531nm & 570nm) which are differently affected by constituents of carotenoid (xanthophylls). According to Guo and Trotter, (2004), 531nm is sensitive to xanthophyll activity while 570nm is not affected by xanthophyll activities. Therefore such a response resulted in a normalized differential index which is a ratio of these bands now known as the photochemical reflectance index as evident in equation 1 below.

Photochemical Reflectance Index

$$PRI = \left(\frac{X_{531} - X_{570}}{X_{531} + X_{570}} \right) \quad (1)$$

Where X represents the spectral band.

PRI has been used as a measure of photosynthetic activity at leaf and canopy level because carotenoids indicate photosynthetic light efficiency in plants (Gamon *et al.*, 1992; Wikipedia, 2008). Cho *et al.* (2008) conducted a study where PRI was used to

differentiate 15 pairs of species at leaf and canopy levels. Their study concluded that PRI was able to differentiate all 15 species as compared to the five species which were differentiated at leaf level. These results were consistent with the statement made by Gamon *et al*. (1995: 2) that "PRI is strongly influenced by canopy structure and phenology at landscape scale".

2.3.2 Carotenoid reflectance index

Carotenoid reflectance index (CRI) is also one of the hyperspectral indices which have been formulated in the past to calculate carotenoid content in green vegetation. Carotenoid is one of the main pigments in green leaves which are strongly absorbed in the blue region of the spectrum (Gitelson *et al*., 2002). Several attempts have been made in previous studies to identify spectral bands which are solely sensitive to carotenoid. Chapelle *et al*. (1992) conducted a study where they investigated spectral bands sensitive to pigment content. In their study they noted a peak at 500nm and attributed it to carotenoid concentration. As a result they formulated a ratio between the reflectance region of 760nm and 500nm as a quantitative measure of carotenoid concentration. In contrast, Blackburn (1998) argued that the most favorable wavelength for carotenoid content was at 470nm and as such he devised a pigment specific normalized difference index for carotenoid content using the wavelengths 800nm and 470nm $(R_{800}-R_{470})/(R_{800}+R_{470})$.

In another independent study, Gitelson *et al*. (1996) identified an interesting peak in the range 500nm and 520nm where they concluded that it was due to carotenoid content. However, Zur *et al*. (2000) noted that within the 470nm and 500nm range chlorophyll affects reflectance. Therefore there was a challenge to develop a method that could nondestructively estimate carotenoid content. Gitelson *et al*. (2002) formulated an index that could eliminate the interference of chlorophyll. This index

was called the carotenoid reflectance index (CRI) and it was solely sensitive to carotenoid concentration. For Gitelson *et al*. (2002) to successfully remove the chlorophyll effect at 510nm, they used a reciprocal reflectance at either 550nm or 700nm. As a result they suggested three spectral bands to be used in the CRI as shown in equation 2 below.

$$CRI = R_{800}\left(\frac{1}{R_{500}} - \frac{1}{R_{550}}\right) \quad (2)$$

2.3.3 Red edge position

The red edge position (REP) is a point of maximum slope in vegetation spectra between far red and near infrared (640-740) (Curran *et al*., 1990; Dawson & Curran, 1998). The sudden change in vegetation reflectance at the red edge is due to chlorophyll absorption in the red region and a strong reflectance in the infrared region. Studies have shown that there is a relationship between REP and chlorophyll concentration. As a result an increase in chlorophyll content shifts the REP towards the longer wavelengths and vice-versa (Cho & Skidmore, 2006; Horler *et al*.,1983; Shafri *et al*., 2006). Curran *et al*. (1990) attributed this phenomenon to the law of gas and spectroscopy which states that “the bandwidth of an increased absorption is related to the concentration of the feature being mapped”. Therefore over the years scientists have determined the REP as a measure of chlorophyll concentration between vegetation species.

Different methods have been developed to calculate the REP; such techniques include the linear interpolation method (Guyot & Baret, 1988) which determines the REP by calculating a mid-point from a straight line assumed to be between the reflectance curve of the far red and NIR. This method involves two steps: the reflection has to first be calculated where the line intersects the reflection curve (equation 3 below) and the second step is the

calculation of the REP where the reflectance is an input parameter in (equation 4 below).

(i) Calculation of reflectance between the straight line and the spectral curve.

$$R_{re} = (R_{670} + R_{780})/2 \quad (3)$$

Where R is the reflectance.

(ii) Calculation of the REP.

$$REP = 700 + 40\ (R_{re} - R_{700} / R_{740} - R_{700}) \quad (4)$$

The second method is the maximum first derivative spectrum which determines the REP based on the wavelength of the first derivative calculated within the red edge (Dawson & Curran, 1998). Its calculation is based on the following formula (5):

$$D_\lambda(i) = (R_\lambda(j+1) - R_\lambda(j))/\Delta_\lambda \quad (5)$$

Where:

D_λ = is the first derivative transformation at wavelength.

i = mid-point between wavebands j and $j+1$.

$R_\lambda(j)$ = is the reflectance at the j waveband.

$R_\lambda(j+1)$ is the reflectance at the $j+1$ waveband.

Δ_λ is the difference in wavelengths between j and $j+1$.

The third method is the Gaussian technique (Bonham-Carter, 1988) which uses a model that estimates the REP to be the mid-point of a line within the spectral reflectance between 660-780nm defined by (6).

$$R(\lambda) = R_s - (R_s - R_0)\exp\left(-\frac{(\lambda_0 - \lambda)2}{2\sigma 2}\right) \quad (6)$$

Where:

R_s = is the maximum spectral band.

R_0 and λ_0 = is the minimum spectral band and corresponding wavelength.

σ = The Gaussian function variance. The REP is then defined as:

$$\text{REP}= R = \lambda_o + \sigma \quad (7)$$

Finally there is the linear extrapolation technique (Cho & Skidmore, 2006) which was developed by calculating the intersection of two lines that emanate from the edges of two peaks at the far red (680 – 700nm) (8) and on the NIR (725 – 760) (9) resulting in the final REP (10).

Far red line: $$R = m_1\lambda + c_1 \quad (8)$$

NIR: $$NIR = m_2\lambda + c_2 \quad (9)$$

Where m and c represent the slope and intersect of the straight lines respectively.

$$REP = \frac{-(c_1 - c_2)}{(m_1 - m_2)} \quad (10)$$

This method requires four spectral bands which are the slope and intersects for each of the two lines which are 680nm and 700nm for the far red line and 725nm and 760nm for the NIR line (Cho & Skidmore, 2006). In the study that Cho and Skidmore (2006) conducted, they compared the above mentioned techniques against the method they developed (linear extrapolation method) based on four factors which were: a) complexity, b) type of spectra required, c) suitability to coarse spectra, and d) its relationship with nitrogen. The linear extrapolation method proved to be the best amongst the other three methods to determine the

REP. Most importantly it performed well in maize which is one of the variables under investigation in this study. In this study the REP of the cannabis and maize was determined using two of the closely related methods which are the linear extrapolation method by Guyot and Baret, (1988) and the linear extrapolation method by Cho and Skidmore, (2006).

2.3.4 Normalized Difference Vegetation Index

Normalized Difference Vegetation Index (NDVI) is one of the widely used vegetation index in remote sensing. It has been used to study different vegetation phenomena such as plant productivity and fractional vegetation cover (Myneni *et al.*, 1995; Seller, 1985). However, the standard NDVI calculated from multispectral data has shown that in high density canopies, this vegetation index gets saturated at about 0.3gcm^{-1} (Mutanga & Skidmore, 2004). To overcome this problem, Mutanga and Skidmore (2004) demonstrated that narrow band NDVI solves the saturation problem when they estimated grass biomass at high canopy cover. The narrow band index used the following spectral band: 740nm in the red and 755nm in the near infrared (see equation 11). The narrow band NDVI has prevailed over the challenges encountered with the standard NDVI by being receptive to subtle changes in canopy greenness, leaf area and canopy architecture and other biochemical and physiological properties of canopies (Asner *et al.*, 2006; Seller, 1985).

Narrow band NDVI

$$NDVI = \left(\frac{R_{833} - R_{680}}{R_{833} + R_{680}} \right) \tag{11}$$

2.4 Remote sensing of cannabis

Remote sensing (RS) has emerged as a cost-effective yet productive alternative in identifying, mapping and monitoring features of interest on a wider geographic landscape (Lillesand *et al.*,2004). To successfully discriminate cannabis from other landcover types using RS cannabis must have unique spectral features at certain wavelengths that can be used to isolate it from other vegetation species (Walthall *et al.*, 2003).

In the early stages of using earth observation systems (EOS) to identify illegal cultivation of drug producing crops, LandSat, SPOT and ASTER were the widely used multispectral sensors. The information extracted from these sensors was not satisfactory as there was a misclassification of features due to the sensors' limited spatial and spectral resolution (Thiessen, 2007; UNODC, 2005; UNODC, 2006a).

In the United States of America and Canada, cannabis fields are relatively small in size and the growers go to great lengths in concealing their plants from law enforcements (Bronskill, 2003; Walthall *et al.*, 2003). In some cases cannabis plants are intercropped with other green type of vegetation as a way of masking them from possible intruders. Due to the limited spatial and spectral information obtained from multispectral sensors, it is difficult to spectrally identify cannabis from confined areas encircled by other green vegetation species.

However, in South Africa, the growing pattern is different from the American and European style of cultivation. The field sizes range from small patches to football-pitch sized fields, where little or nothing is done to conceal the plants from intruders. In some known areas where some of the largest cannabis fields are found cannabis is at times intercropped with maize (see Figure 1).

Figure 1: Cannabis intercropped with maize on a mountain slope. (Picture taken in the Eastern Cape during field visit with SAPS-ONOC, 30 January 2009.)

To investigate the extent of the challenges encountered with multispectral sensors, researchers compared the outcomes of multispectral and hyperspectral data in discriminating cannabis from other vegetation species. Thiessen, (2007) from the Canadian Police Research Centre conducted a study on outdoor detection of cannabis using both multispectral and hyperspectral data; the efficiency of multispectral and hyperspectral detection were compared. The multispectral images used were from SPOT, IKONOS and Quickbird and hyperspectral imagery used were from CASI. Spectral signatures of cannabis were compared with those of other land cover such as grass, low-lying vegetation and soil. Using hyperspectral data, they were able to spectrally differentiate cannabis from the other landcover. They identified the regions of 450-500nm and 630-690nm as the bands that can be used to discriminate cannabis from other green type of vegetation.

Interestingly, Daughtry and Walthall (1998) conducted a similar study where the use of RS techniques in identifying cannabis was investigated. This study identified the wavelength regions of 550nm, 680nm, 720nm and 800nm being the spectral bands at

which cannabis shows major differences from other herbaceous green vegetation. Although the spectral bands recommended by Daughtry and Walthall (1998) were different from the spectral bands recommended by Thiessen (2007) these bands were not significantly different from one another. In addition, Daughtry and Walthall (1998) stated that cannabis can be visually differentiated from other green type of vegetation due to its blue-green (emerald) color which was different from other green vegetation and they attributed such distinct color to the unique interior and surface structure of the cannabis leaf architecture. The SAPS Aerial spotters confirmed Daughtry and Walthall's findings by stating that cannabis does have a unique color thus making it easier to distinguish from other vegetation. Nonetheless, they do encounter difficulties in identifying it when intercropped with other plant species, especially maize.

2.5 The basis of discriminating cannabis from maize using spectroscopy.

The two plant species, maize and cannabis, have different morphologies which can aid in differentiating one from the other. When the structural profile of their leaves is compared, cannabis has palmately compound leaves which emanate from a stem attached to the main stem of the plant while maize leaves are needle shaped protruding from the main erect stem (Armstrong, 2001; Wikipedia, 2009). Furthermore, maize leaves have smoothed edges (ciliate) while cannabis leaves have rugged edges (double serrate) (Raven *et al*., 2005; Wikipedia, 2009). Due to these differences, cannabis has a planophile structure while maize has an erectophile structure. As such when viewed at nadir, cannabis has a circular like shape and maize has a rectangular like shape (see Figure 2).

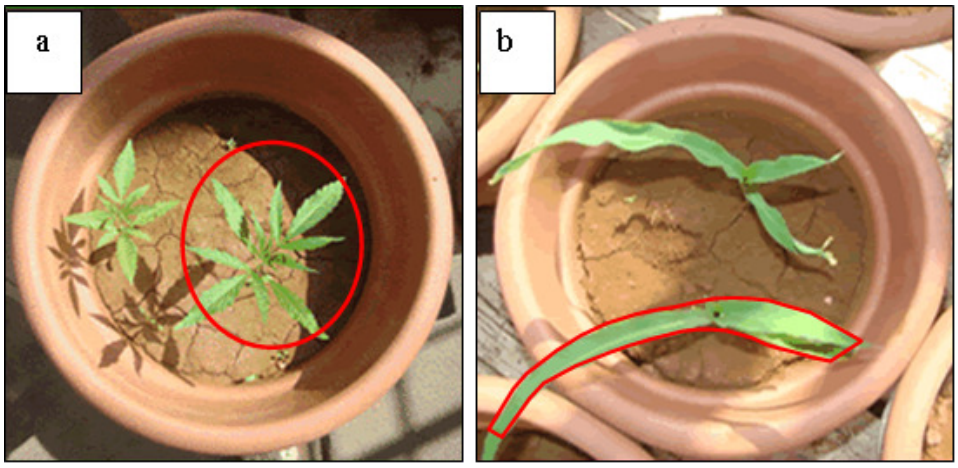

Figure 2: Picture a shows planophile structure of cannabis shown in red circle and picture b shows the erectophile structure of maize shown in a red parabolic shape.

There are hyperspectral techniques which are sensitive to the structural differences observed between these two species. The widely used NDVI is one of those indices used to differentiate diverse canopy material (Stylinski *et al*. 2002).This study uses the narrow band NDVI to investigate whether the morphological differences between these two species can be used as a measure of discrimination. Finally the other indices which are REP, PRI and CRI can also be employed to distinguish these two species using their chlorophyll and carotenoid content as they influence reflectance at the red and NIR regions.

2.6 Lessons learnt from the literature review

The studies reviewed for this research highlight important points especially from a scientific perspective, the possibility to discriminate cannabis from other crops using RS. Data sets from both multispectral and hyperspectral sensors were investigated, compared and contrasted for identification. Challenges were encountered with multispectral data. The review has shown that due to the multispectral RS's limited spectral resolution, identification options were limited to visual interpretation.

Nevertheless, the advent of using hyperspectral RS has proven the possibility of mapping cannabis due to its detailed information. In addition, hyperspectral RS broadens the classification criteria by providing numerous classification techniques. Some of the methods available can differentiate vegetation based on biochemical features, such as chlorophyll and carotenoid contents. This proves to be an ideal advantage of using hyperspectral RS as some vegetation species have similar morphology.

In spite of the methods discussed above, there were gaps identified which are specific to the South African cannabis situation. It was mentioned earlier that the growing pattern in South Africa ranges from small patches to large fields where the growers intercrop cannabis with maize. None of the methods discussed above investigated the possibility of identifying cannabis when intercropped with other species especially maize. Therefore this study investigates whether cannabis can be spectrally differentiated from maize when grown under different cropping methods and if the influence of chlorophyll and carotenoid contents on reflectance in the red and NIR can be used as measures to discriminate the two species.

Chapter 3

3 Materials and methods

3.1 Treatments and experimental design

The experimental design of the research was a randomized design. The factors tested were monocropped cannabis, monocropped maize, and intercropped maize and cannabis (see Figure 3).

Figure 3: Research treatments: monocropped cannabis (A), monocropped maize (B) and intercropped cannabis and maize (C).

3.2 Planting

The seeds used in this study originated from the Eastern Cape Province of South Africa and were supplied by the SAPS-ONOC. As the quality and background of the seeds were not known, a germination trial was done to establish whether the seeds would grow and how long it would take them to grow. Although the seeds supplied were from the same genus they varied in color ranging from green, grey and black. In view of this the researcher sorted them into two groups, namely black and green to grey seeds (see Figure 4). For the trial study, twenty seeds were sown in a germination tray comprising ten seeds from each group.

Figure 4: Cannabis seeds sorted into two groups: black (A) and green to grey seeds (B).

The seeds started to germinate five days after planting but 90% of the black seeds germinated whereas only 10% of the green seeds germinated. According to Clarke (1993), cannabis seeds mature 14-35 days after the plant has shed pollen hence the differences observed between the grouped seeds could have been as a result of premature shedding of the seeds from their kernel. The color of the seeds ranged from green to black according to maturity. Conclusively the green and grey seeds were immature thus the black seeds were subsequently selected for the study,

The black seeds were sown in 90 pots where each pot was 10-liters with a diameter and height of 30cm and 28cm respectively. Four seeds were sown in each pot of the monocropped treatments. For the intercropping treatment comprising four seeds two were maize seeds and the other two were cannabis. Seven days after planting the seeds 90% of the seeds had germinated from all the treatments. In the second week all the seeds sown had germinated and at that stage the researcher thinned the plants to two seedlings per pot. The thinning was done to provide enough space for the remaining plants in the pots so as to improve their growth rate and to minimize competition for water and nutrients (Norberg, 1988). In the intercropped treatment the two remaining plants were cannabis and maize.

3.3 Soil preparation

The soil used in the research was taken from the Agricultural Research Council's research fields in Rooderplat. The soil was obtained at a depth of 50cm using the simple random method (Roberts, 1998). Thorough precautions were taken to prevent the soil from being contaminated; clean spades and large polythene bags were used (Fisher *et al.*, 1987). The soil was then transported to the greenhouse where it was sieved to homogenous particle size through a 2 mm aperture (Carter, 1993). The soil was then air-dried at room temperature for 7 days and a spade was used to regularly mix the soil.

Samples were subsequently taken from the air-dried soil and sent to the laboratory and tested for water holding capacity, pH value and nutrient composition. Table 1 depicts the results of the tested macronutrients in the soil which are nitrogen phosphorus and potassium. The results showed that the soil's average pH value was 6.4 which was acceptable for the study as it was within the required pH range for both species. According to Stekar *et al.* (1991) the pH value for maize must be between 5 and 7. Linger *et al.* (2005) recommend a pH range of 5.5 and 6.5 for soil used for cultivating cannabis.

TABLE 1: SOIL NUTRIENT RESULTS.

Sample	Nitrogen cmol(c)/kg	Potassium cmol(c)/kg	Phosphorus cmol(c)/kg	pH
A a	0.260	1.207	5.636	6.28
A b	0.274	1.181	6.525	6.30
B1 a	0.382	0.599	5.790	6.41
B1 b	0.361	0.517	5.552	6.37
B2 a	0.330	0.265	5.029	6.56
B2 b	0.335	0.273	5.250	6.57
Average	**0.32**	**0.67**	**5.63**	**6.42**

3.4 Watering

The plants were watered once a day to field capacity of 16g of water per 100g of soil, therefore 1.6 liters of water was added to each 10kg pot. Before watering the plants, each pot was weighed to determine the amount of water to be added so as to maintain the water present in the pot to field capacity. As the plants gained biomass through growth, their water intake also increased (Hirata *et al*., 2007). As a result the water added had to be proportional to the weight of the plants to maintain the soils field capacity to hold water.

Another test was done where samples of water from a tap and from a distiller were sent to the laboratory to determine the concentration of dissolved minerals and metals in the distilled water and the tap water which fed the distiller. Table 2 shows the laboratory results of both samples. The results revealed that there were significantly lower dissolved solids in the distilled water than in the tap water. Furthermore, the pH value of the tap water had significantly dropped from pH 7.25 to pH 5.6 after being purified (distilled) (see Table 2). As a result distilled water was used for watering.

TABLE 2: DISSOLVED ANIONS AND CATIONS FROM DISTILLED WATER AND TAP WATER.

Anions	Tap water		Distilled water	
	mg/l	mmol(c)/l	mg/l	mmol(c)/l
Flouride (1.5)	0.18	0.01	0.00	0.00
Nitrite(4.0)	0.00	0.00	0.00	0.01
Nitrate (44.0)	8.33	0.03	0.64	0.01
Chloride (250)	20.37	0.57	0.42	0.01
Sulphate(500)	20.53	0.43	0.21	0.00
Phosphate	0.00	0.00	0.83	0.02
Carbonate (20.0)	0.00	0.00	0.00	0.00
Bicarbonate	140.91	2.31	4.27	o.07
Subtotal	190.32	3.36	6.37	0.11
Cations				
Sodium (400)	12.77	0.56	1.04	0.05
Potassium (400)	2.63	0.07	0.63	0.02
Calcium (200)	34.11	1.71	0.83	0.04
Magnesium (100)	17.51	1.44	0.22	0.02
Boron (1.5)	0.03	0.01	0.02	0.01
Sodium Carbonates	0.00	0.00	0.00	0.00
Sodium Bicarbonates	0.00	0.00	0.41	0.00
Alkalinity	115.50	2.31	3.50	0.07
Temp. Hardness	115.50	2.31	3.26	0.07
Perm. Hardness	42.19	0.84	0.00	0.00
pH	**7.25**		**5.60**	
Total dissolved solids	**186.55**		**6.87**	

3.5 Experimental setup

3.5.1 Greenhouse

The greenhouse pot experiment was a 3 x 3 factorial design. Factor A (cropping methods) consisted of 3 levels: monocropped cannabis, monocropped maize, and intercropped cannabis and maize (Figure 5). Factor B (sampling time) consisted of 3 levels: week 4, 5, and 6.

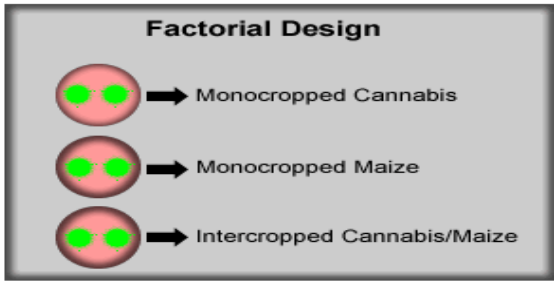

Figure 5: 3 X 3 factorial design of the pot trials.

The experiment was of a completely random design where statistical analysis was done to test for differences in pigment quantity and spectral differences between the treatments (Cho *et al.*, 2008b; Hendry & Grime, 1993 and Carter & Knapp, 2001). The data were acceptably normal with homogeneous treatment variance. Treatment means were separated using Fishers' protected t-test least significant difference (LSD) at the 5% level of significance (Snedecor & Cochran, 1980).

3.5.2 Darkroom

Spectral measurements were taken in a darkroom to obtain noise free spectra of the treatments. The experimental set-up in the darkroom and method used to measure the spectral signatures were based on those of Mutanga *et al.*, (2003). The canopy spectral measurements taken were from ten randomly selected pots from each treatment. Each pot was placed directly under the sensor and light. The sensor and an ASD-supplied quartz-tungsten halogen lamp used to illuminate the samples were mounted on a tripod at nadir position 2m above the ground (see Figure 6).However, maize was always taller than cannabis and this was consistent throughout the sampling period of the study.

Figure 6: Experiment set-up in the dark room.

3.6 Spectral measurements

An analytical spectral device (ASD) spectrometer widely used in collecting field and laboratory spectral readings was used to measure spectral reflectance of the treatments between the wavelength range of 350-2500nm. The spectrometer had a sampling interval of 1.4nm between the regions of 350-1000nm and 2nm between the regions of 1000-2500nm. It had a spectral resolution of 3nm and 10nm between the regions of 350-1000nm and 1000-2500nm respectively. This instrument uses an optical sensor that has a 25º full conical angle field of view (ASD, 2006).

The plant that was being measured was rotated 45º after every 5th reading to minimize the effects of bi-directional reflectance function (BDRF) (Knobelspiesse *et al.*, 2008; Mutanga 2005; Xiaowen & Strahler, 1986). To minimize the background effect from the soil, the spectral measurements were taken from the fourth week after germination when the plants had sufficient canopy to cover the soil. The spectral measurements were

subsequently taken from the three treatments (a) monocropped cannabis, (b) monocropped maize and (c) intercropped cannabis and maize. The spectrum from the intercropped treatment was a mixed spectrum of the cannabis and maize as both species were intercropped when taking the measurements.

3.7 Extraction of chlorophyll and carotenoid

3.7.1 Harvesting leaf samples

Leaves were harvested from plants in each treatment to test for chlorophyll and carotenoid content. A pruning shear was used to cut the leaves after which the samples were wrapped in metal foil to prevent them from being exposed to direct sunlight as this might have altered the green pigment content in the leaves. Ziploc bags were used to keep the samples fresh. The zip-locked samples were then stored in a refrigerator at 5ºC for 24hours and the green pigments were extracted in a laboratory at Tshwane University of Technology (TUT).

3.7.2 Extracting chlorophyll a, chlorophyll b and carotenoid

There were three green pigments extracted from the leaves: chlorophyll a, chlorophyll b, and carotenoid. The method used to extract these pigments were based on those of Hendry & Grime (1993) and Carter & Knapp (2001). The samples were weighed to equal masses per plant species (cannabis and maize) and grinded in 10ml of cold absolute ethanol on a cold mortar. This process was done in a black plastic bag to prevent light from reacting with the extracted pigments. From then on the mixture was transferred to test tubes and kept on ice in the dark after which a spectrophotometer was used to take absorbance readings at crucial wavelengths of 450nm, 645nm and 663nm as required in equations 12, 13 and 14. After each measurement ethanol was used to recalibrate the spectrophotometer to zero.

Chlorophyll a concentration in $Nm^{-}gWM = 12.7 \times A_{663} - 2.69 \times A_{645}$ (12)

Chlorophyll b concentration in $Nm^{-}gWM = 22.9 \times A_{645} - 4.68 \times A_{663}$ (13)

Carotenoid concentration in $Nm^{-}gWM = (A_{480} + (0.114 \times A_{663})-(0.638 \times A_{645})) \div 112.5$ (14)

WHERE

$A_{663,}$ A_{480} AND A_{645} ARE THE VALUES FOR ABSORBANCE AT WAVELENGTHS 663, 480 NM AND 645 NM RESPECTIVELY.

$NM^{-}GWM$ = NANOMETERS PER GRAM OF WET MASS.

Chapter 4

4 Data analysis

First the differences between treatments were assessed using laboratory measured pigment concentrations. Then the relationship between pigment concentrations and spectral indices was assessed. Lastly, the ability of the indices to discriminate between treatments was assessed. The statistical analyses done to assess the differences were the t-test and the linear regression test.

4.1 Spectral analysis

Spectral measurements taken from the treatments were averaged and compared between the sampling periods of week 4, week 5 and week 6 (see Figures 7, 8 and 9). These spectral signatures were analyzed using STATISTICA where the research hypothesis was statistically tested at 95% confidence limit with one-way ANOVA. The means of the spectral signatures were compared to investigate their significance at different spectral bands within the sampling period of the study (Mutanga *et al.*, 2003; Siegal & Castellan, 1998).

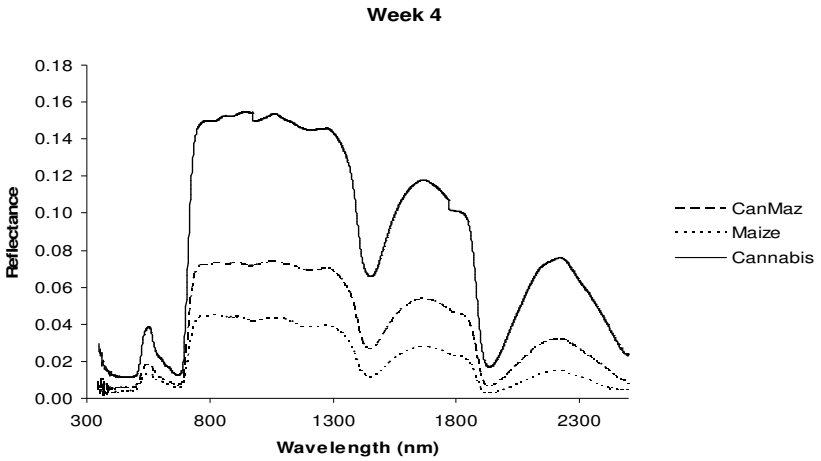

Figure 7: Mean spectral signatures of monocropped cannabis, monocropped maize and intercropped cannabis and maize for week 4 (CanMaz represents a mix spectrum of intercropped cannabis and maize).

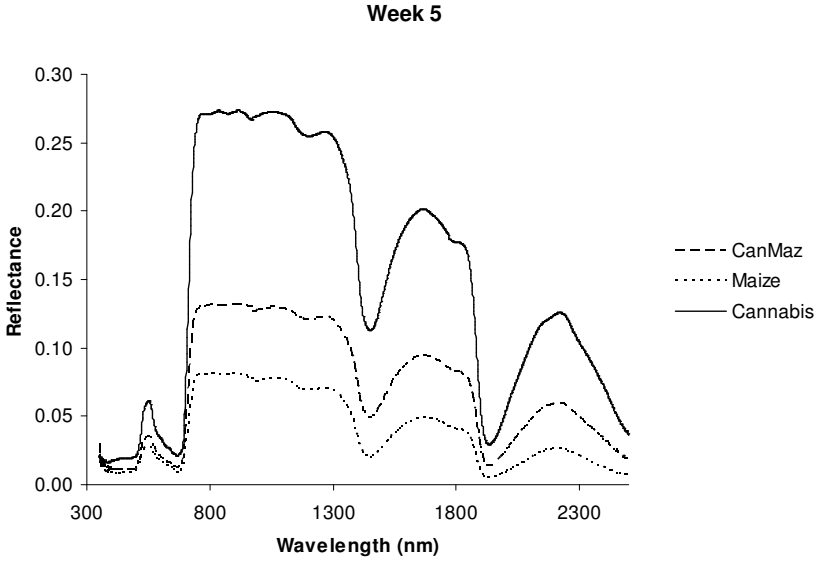

Figure 8: Mean spectral signatures of monocropped cannabis, monocropped maize and intercropped cannabis and maize for week 5 (CanMaz represents a mix spectrum of intercropped cannabis and maize).

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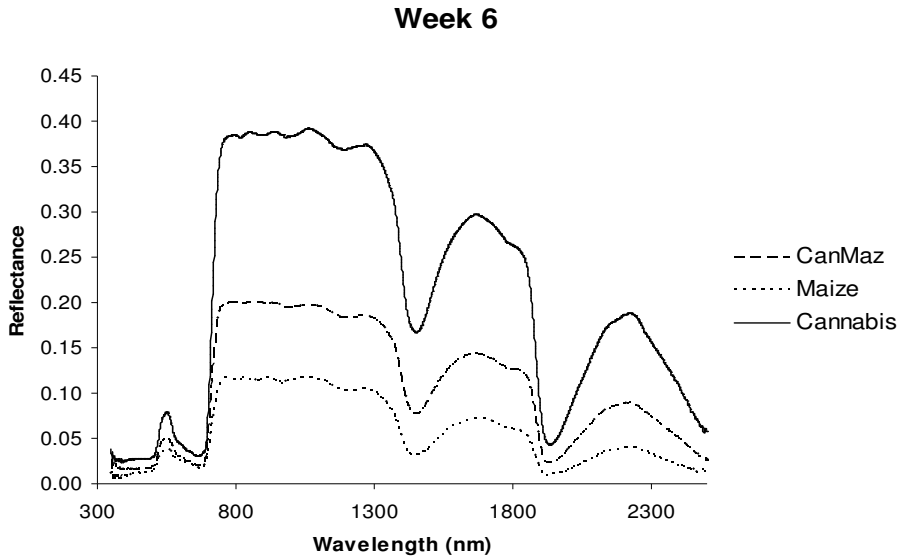


Figure 9: Mean spectral signatures of monocropped cannabis, monocropped maize and intercropped cannabis and maize for week 6 (CanMaz represents a mix spectrum of intercropped cannabis and maize).

4.2 Hyperspectral indices

Hyperspectral indices have been used in the past to detect features affected by vegetation health (Pu *et al.*, 2008), pigment content (Gitelson *et al.*, 2001) and other factors which influence light absorption in the vegetation spectrum. In this study the four indices listed in Table 3 were used to investigate the potential use of these indices in discriminating cannabis from maize.

TABLE 3: LIST OF HYPERSPECTRAL INDICES USED IN THIS STUDY.

Index Name	Application
Photochemical Reflectance Index (PRI)	Measures carotenoid content
Carotenoid Reflectance Index (CRI)	
Red Edge Position (REP)	Measures chlorophyll content
Normalized Difference Vegetation Index (NDVI)	Shows vegetation cover (plant morphology)

4.2.1 Photochemical Reflectance Index

Photochemical reflectance index (PRI) is one of the commonly used indices sensitive to changes in carotenoid pigments (Gamon *et al.*, 1992; Gamon *et al.*, 1997, Sobhan, 2007). It is normally used to study seasonal variations in carotenoid content and photosynthetic activity (Stylinski *et al.*, 2002). In this research PRI values were calculated to investigate temporal variations in carotenoid content between the treatments at canopy level. A study conducted by Cho *et al.*, (2008b) proved that PRI can better discriminate vegetation species at canopy scale than at leaf level. Therefore the researcher calculated the PRI using canopy reflectance at 531nm and 570nm (see equation 1) (Cho *et al.*, 2008b; Gamon *et al.*, 1992; Sobhan, 2007; Stylinski *et al.*, 2002). A statistical t-test method calculated at 95% confidence limit was used to determine how the means of the treatments differ. Furthermore, the t-test was also used to test the hypothesis that carotenoid content differs between the treatment, namely H_o: $\mu_1=\mu_2=\mu_3$ versus the alternate hypothesis, H_1: $\mu_1=\mu_2=\mu_3$ where μ_1, μ_2 and μ_3 are the treatments monocropped cannabis, monocropped maize and intercropped cannabis and maize, respectively.

Photochemical Reflectance Index

$$PRI = \left(\frac{X_{531} - X_{570}}{X_{531} + X_{570}} \right) \quad (1)$$

4.2.2 Carotenoid Reflectance Index

The CRI by Gitelson *et al*. (2002) (see equation 2) was used to calculate the carotenoid content in the treatments. This method was chosen as it does not have the effect of chlorophyll at 510nm, thus making it an ideal technique to measure carotenoid content from green vegetation. The t-test calculated at 95% confidence limit was used to test the hypothesis that carotenoid content differs between the treatment H_o: $\mu_1=\mu_2=\mu_3$ versus the alternate hypothesis, H_1: $\mu_1=\mu_2=\mu_3$ where u_1, u_2 and u_3 are the treatments monocropped cannabis, monocropped maize and intercropped cannabis and maize, respectively.

Carotenoid Reflectance Index

$$CRI = R_{800}\left(\frac{1}{R_{500}} - \frac{1}{R_{550}} \right) \quad (2)$$

4.2.3 Red Edge Position

The REP is the point which occurs between 680nm and 750nm due to chlorophyll absorption in red and leaf internal scattering in near infrared (Cho and Skidmore, 2006; Curran *et al*., 1995; Fillella and Penuelas, 1994; Mutanga and Skidmore, 2004; Pu *et al*., 2003). As a result REP was used as a measure of chlorophyll content in the treatment. An increase in chlorophyll concentration shifts the REP towards the longer wavelengths and a decrease in chlorophyll content shifts the REP towards the shorter wavelengths (Cho and Skidmore, 2006; Cho and Skidmore, 2008a; Horler *et al*., 1983). Consequently the t-test was done on

the REP results from the treatments to test the hypothesis that the chlorophyll concentration was different between the treatments where H_o: $\mu_1=\mu_2=\mu_3$ versus the alternate hypothesis, H_1: $\mu_1=\mu_2=\mu_3$ where μ_1, μ_2 and μ_3 are the treatments monocropped cannabis, monocropped maize and intercropped cannabis and maize respectively.

Over the years different methods have been developed to calculate the REP. Four of those methods were discussed in Chapter 2. For the purpose of this study two of the four methods were selected: the linear interpolation method by Guyot and Baret (1988) and the linear extrapolation technique by Cho and Skidmore (2006). These two methods were used to calculate the REP of the treatments (see equation 4 and 10) as they proved to be less complex to execute at the same time producing convincingly better results than the other methods.

Linear interpolation method

$$REP = 700 + 40\left(\frac{Rre - R700}{R740 - R700}\right) \tag{4}$$

Where R is the reflectance.

Linear extrapolation method

$$REP = \frac{-(c_1 - c_2)}{(m_1 - m_2)} \tag{10}$$

Where m and c represent the slope and intersect of the straight lines respectively.

4.2.4 Normalized Difference Vegetation Index

As the narrow band NDVI (see equation 11) is sensitive to subtle changes in leaf area and canopy architecture and other biochemical and physiological properties of canopies (Asner *et al.*, 2006; Seller, 1985). In this study it was used to investigate whether it was capable to differentiate cannabis from maize due to the structural differences between the canopies of the treatments. In general cannabis has a different morphology from that of maize as the former consists of a dicotyledonous plant with a planophile structure and the latter is a monocotyledonous plant with an erectophile structure. As a result these two species have different cellular structures (Nelson & Dengler, 1997). These structural differences cause these two species to have different responses to light reflected at both leaf surface and at intercellular level. Therefore to test whether cannabis can be differentiated from maize based on their respective structural differences, narrow band NDVI which has a linear relationship with leaf area index (Fan *et al.*, 2007) was calculated from the treatments. A t-test was calculated to test the hypothesis that differences in spectral characteristics due to different structural phenology between the treatments can be used to discriminate cannabis from maize.

Narrow band NDVI

$$NDVI = \left(\frac{R_{833} - R_{680}}{R_{833} + R_{680}} \right) \tag{11}$$

4.3 Calculating the green pigments.

The green pigments calculated from the treatments were chlorophyll a, chlorophyll b, and carotenoid. The differences

observed between the green pigment concentrations aided in explaining the outcomes of the calculated hyperspectral indices. The concentrations of chlorophyll and carotenoid were compared for t_4, t_5 and t_6 where t represents week 4, week 5 and week 6 respectively. Statistical t-test method was used to test the significance of their concentration at 95% confidence limit and correlation matrices were also done to establish the relationship between the calculated green pigments and the measured pigments from the hyperspectral indices.

Chapter 5

5 Results

This chapter reports on the results of the analysis of the data to test the hypotheses of the research. Hyperspectral indices were calculated from spectral signatures measured from the treatments. The indices calculated were PRI, CRI, REP and the narrow band NDVI. These indices were further correlated with their corresponding calculated green pigments. Measured pigments (carotenoid and chlorophyll)

The pigments were calculated from the treatments using equation 14 (Chapter 3) for carotenoid and equations 12 and 13 (Chapter 3) for chlorophyll a and chlorophyll b respectively. The following graphs (see figure 10 to 14) show the mean variations in concentration between the treatments. Table 4 shows statistical results of the t-test between monocropped cannabis with monocropped maize and the intercropped treatments.

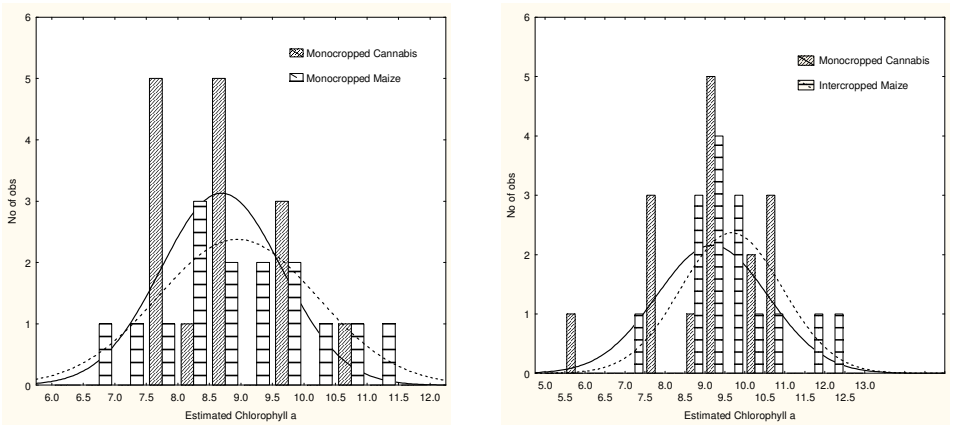
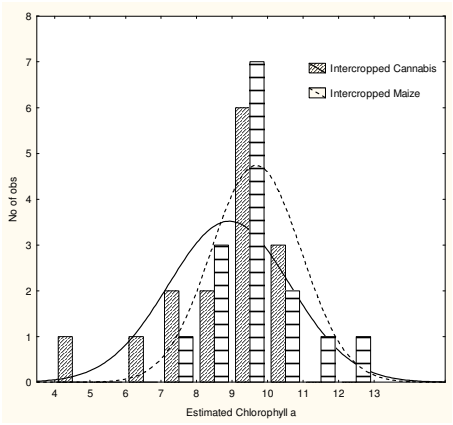


Figure 10: The graph on the left shows estimated mean chlorophyll a concentration from week 4, 5 and 6 between monocropped cannabis and maize and the graph on the right show estimated mean chlorophyll a concentration from week 4, 5 and 6 between monocropped cannabis and intercropped maize.



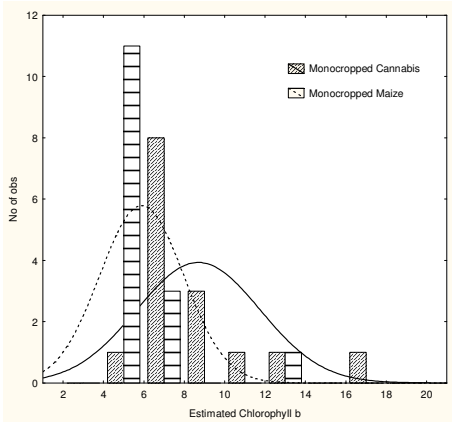
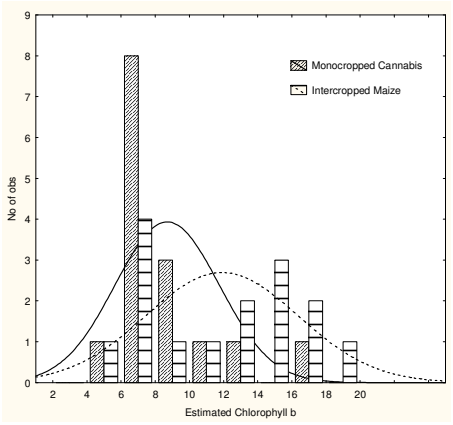


Figure 11: The graph on the left shows estimated mean chlorophyll a concentration from week 4, 5 and 6 between intercropped cannabis and maize and the graph on the right show estimated mean chlorophyll b concentration from week 4, 5 and 6 between monocropped cannabis and monocropped maize.



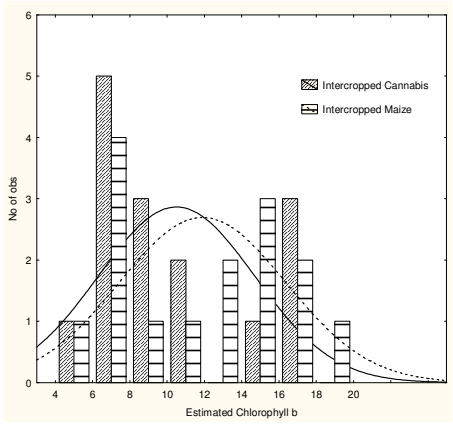
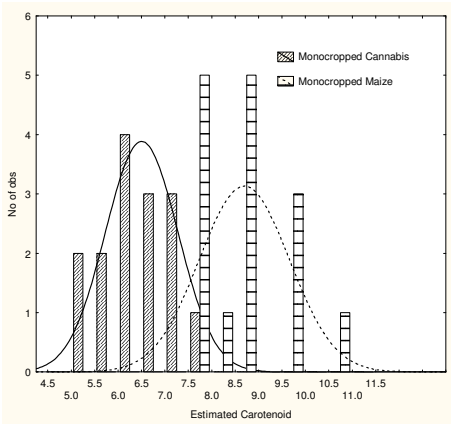


Figure 12: The graph on the left shows estimated mean chlorophyll b concentration from week 4, 5 and 6 between monocropped cannabis and intercropped maize and the graph on the right show estimated mean chlorophyll b concentration from week 4, 5 and 6 between intercropped cannabis and intercropped maize.



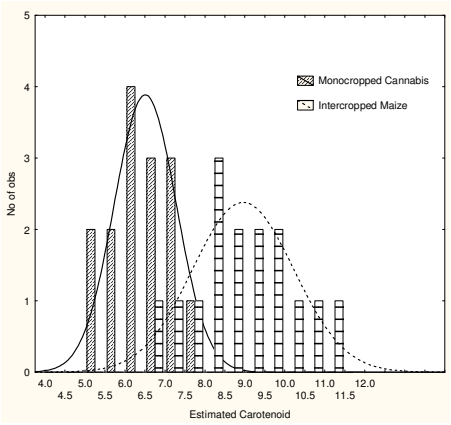


Figure 13: The graph on the left shows estimated mean carotenoid concentration from week 4, 5 and 6 between monocropped cannabis and maize and the graph on the right show estimated mean carotenoid concentration from week 4, 5 and 6 between monocropped cannabis and intercropped maize.

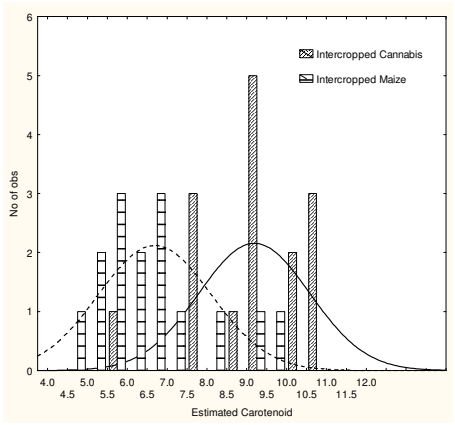


Figure 14: The graph on the shows estimated mean carotenoid concentration from week 4, 5 and 6 between intercropped cannabis and intercropped maize.

TABLE 4: T-TEST RESULTS SHOWING T AND P VALUES OF THE MEASURED PIGMENTS. (* MEANS VALUE IS SIGNIFICANT: CAN = CANNABIS; MAZ = MAIZE; INT = INTERCROPPED).

Treatments	Chlorophyll a		Chlorophyll b		Carotenoid	
	t-value	p-values	t-value	p-values	t-value	p-values
Can vs. Maz	0.754	0.457	0.279	0.783	5.14*	0.000019
Can vs. Int-Can	0.476	0.638	-1.357	0.187	4.08*	0.000338
Can vs. Int-Maz	-0.998	0.326	0.246	0.808	4.54*	0.000096

The results of the calculated pigments as seen in Table 4 show that there were no significant differences between the chlorophyll

concentration of the treatments. However, there were significant differences observed in carotenoid concentration between the treatments. The estimated pigments were therefore correlated with their respective spectral indices to evaluate the accuracy of quantifying these pigments.

5.1 The relationships between spectral indices and measured pigments (chlorophyll and carotenoids)

The measured pigments were correlated with the spectral indices of carotenoid and chlorophyll. The two indices used to extract carotenoid from the spectral signatures of the treatments were PRI and CRI. Figures 15 to 18 show significant correlations between the measured and estimated carotenoid content using the PRI and CRI. The linear regression for monocropped cannabis between CRI and carotenoids is higher (R^2 = 0.963) than for PRI (R^2 = 0.874). The same trend was also witnessed for monocropped maize. Interestingly, the correlation of the intercropped treatments between CRI and PRI was highest for PRI in both species.

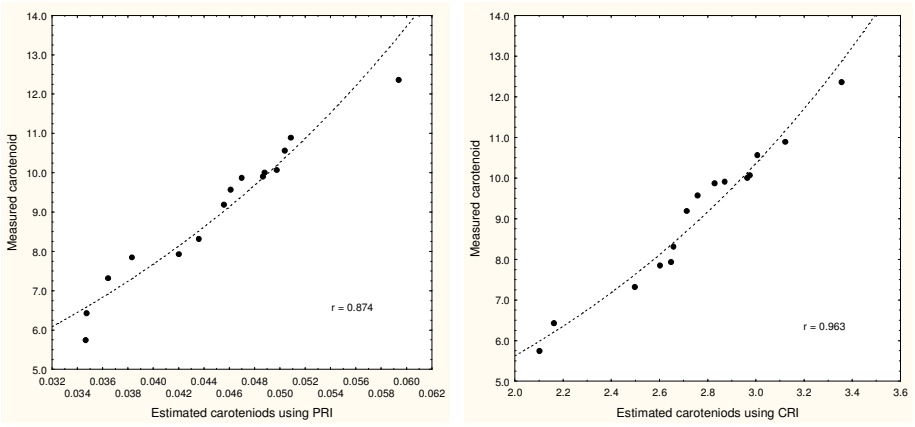


Figure 15: Correlations between measured carotenoid of monocropped cannabis and estimated carotenoids using PRI and CRI.

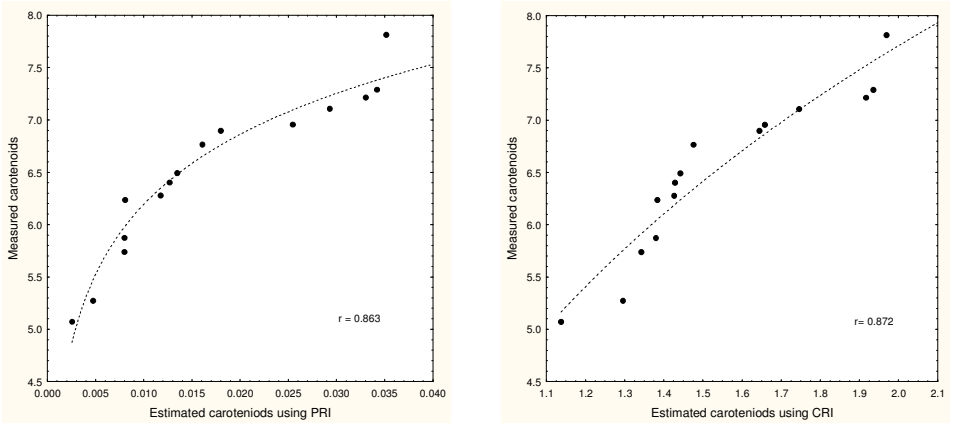


Figure 16: Correlations between measured carotenoids of monocropped maize and estimated carotenoid using PRI, CRI.

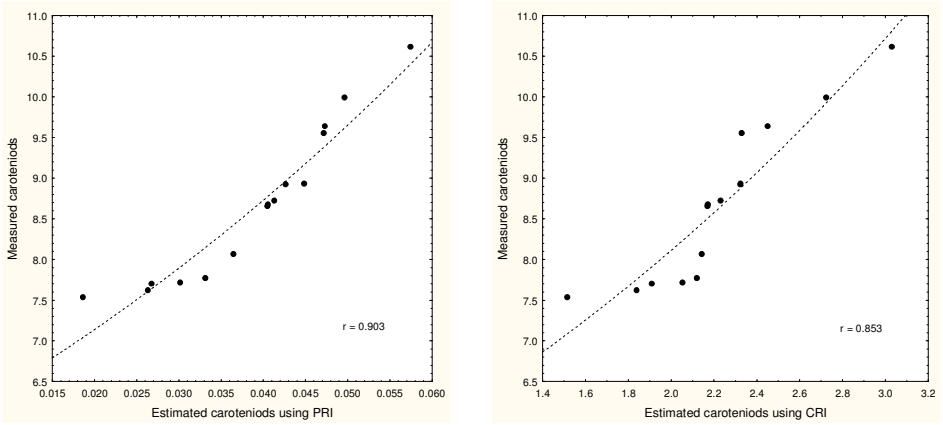


Figure 17: Correlations between measured carotenoids of intercropped cannabis and estimated carotenoids using PRI and CRI.

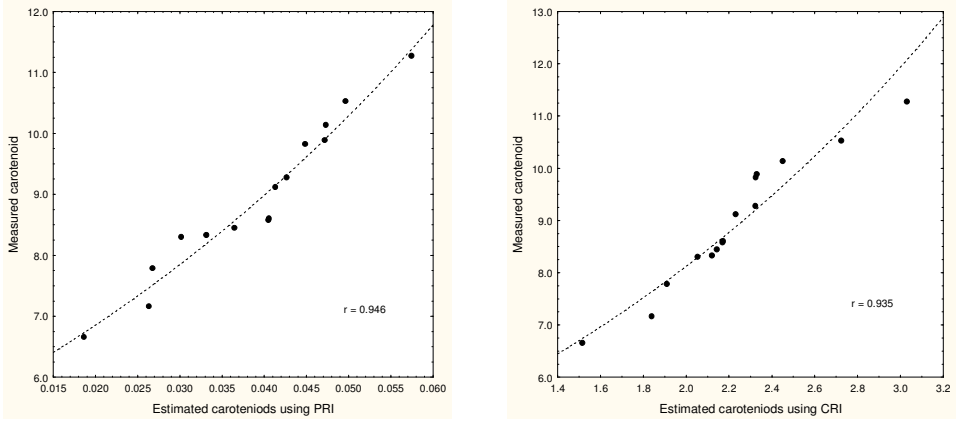


Figure 18: Correlations between measured carotenoids of intercropped maize and estimated carotenoids using PRI and CRI.

Chlorophyll was measured from the spectral signatures of the treatments using two REP methods: one by Guyot and Baret (1988) and the other by Cho and Skidmore (2006). Figures 19 to 22 show the correlations between the measured and estimated chlorophyll pigments.

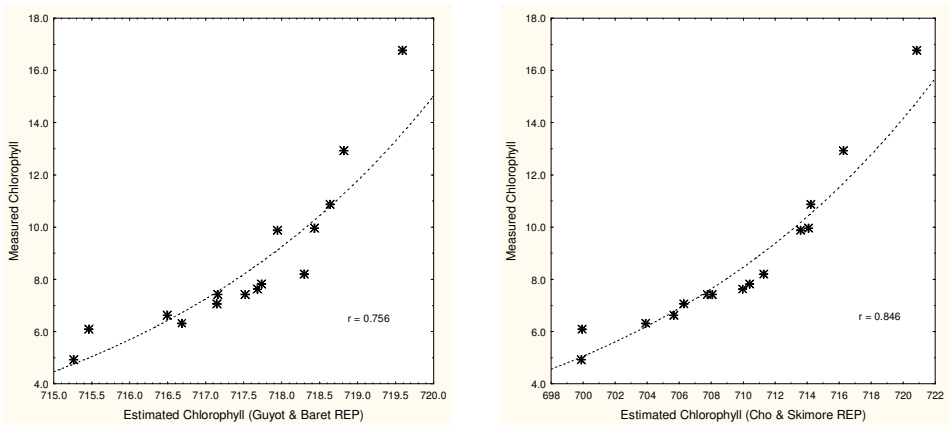


Figure 19: Correlations between measured chlorophyll and calculated chlorophyll of monocropped cannabis by Guyot and Baret (1988) and by Cho and Skidmore (2006).

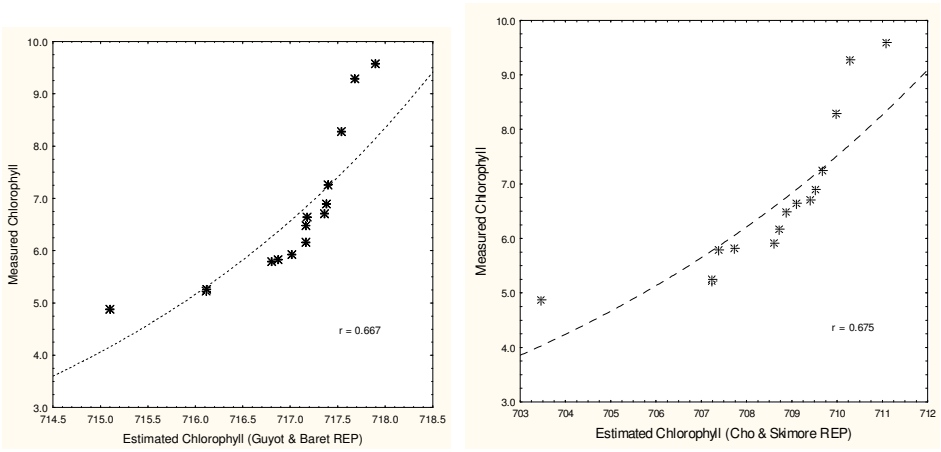


Figure 20: Correlations between measured chlorophyll and calculated chlorophyll of monocropped maize by Guyot and Baret (1988) and by Cho and Skidmore (2006).

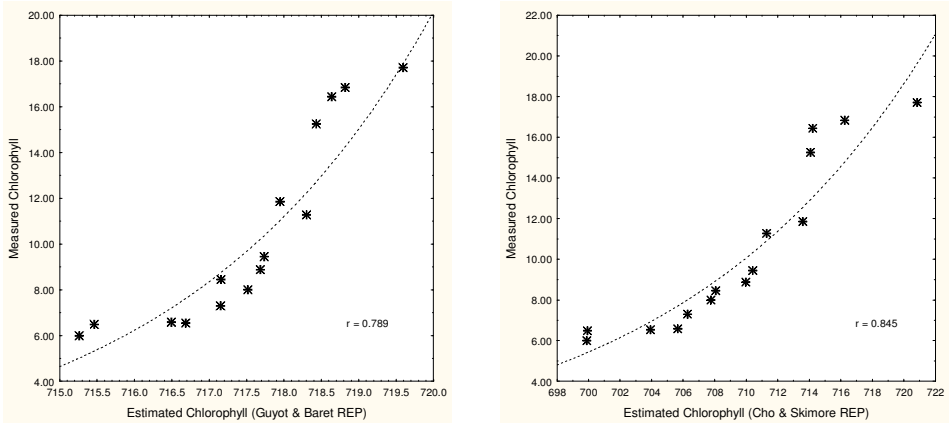


Figure 21: Correlations between measured chlorophyll and calculated chlorophyll of intercropped cannabis by Guyot and Baret (1988) and by Cho and Skidmore (2006).

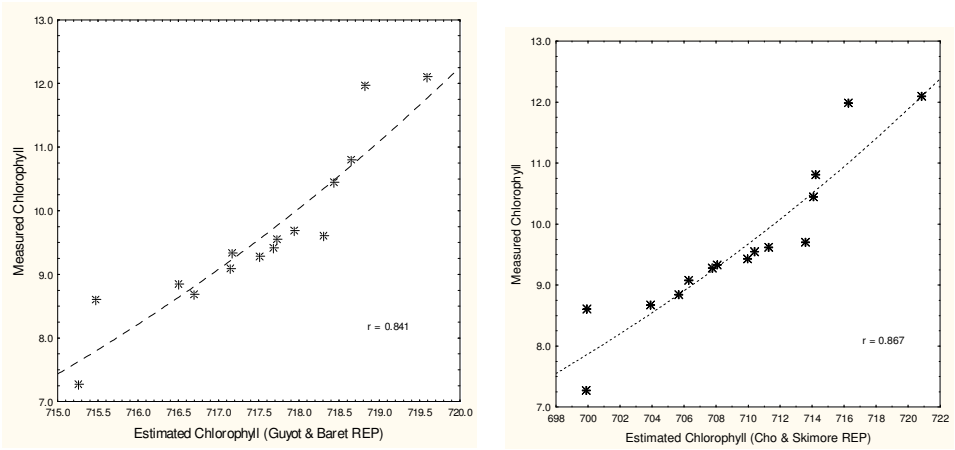


Figure 22: Correlations between measured chlorophyll and calculated chlorophyll of intercropped maize by Guyot and Baret (1988) and by Cho and Skidmore (2006).

The correlation results showed that there was a strong linear relationship between the estimated and the measured carotenoid and chlorophyll pigments. Based on these results the researcher is confident that the carotenoid and chlorophyll analysis done on this study using the hyperspectral indices was a true representation of what could be measured on the ground.

REP was therefore used as a proxy for chlorophyll and, CRI and PRI as proxies for carotenoids to assess whether plant pigments could be used to differentiate between the treatments.

5.2 Hyperspectral indices

Since it had been observed from the correlations that there were strong relationships between the estimated green pigments and the indices, we therefore used hyperspectral indices to assess the differences of the treatments. There were four hyperspectral indices investigated to test the hypotheses of the study. The REP was calculated to investigate the potential use of chlorophyll content to differentiate cannabis from maize while PRI and CRI were calculated to explore the possibilities of discriminating cannabis from maize using carotenoid content. To investigate if the differences in structural morphology between cannabis and maize can be used to distinguish these two species, the narrow band NDVI was used.

5.2.1 Photochemical reflective index

PRI was calculated from the spectral signatures of the treatments using equation (2) in Chapter 2. Figure 23 shows the carotenoid concentration for each treatment. The results showed that there were differences in carotenoid content between the treatments where carotenoid pigment were highest in monocropped cannabis followed by the intercropped treatment of cannabis and maize and the lowest being monocropped maize. To investigate the significance of the differences observed between monocropped cannabis and the other two treatments the t-test at 95% confidence limit was used. The statistical results of the t-test were significantly higher between monocropped cannabis and monocropped maize than in the intercropped treatment (see Table 5). These results were consistent with the results shown in Figure

24 and this means that by using PRI, carotenoid content can be employed to identify cannabis from maize when grown as independent species (monocropped) but cannot be used to discriminate cannabis when intercropped with maize.

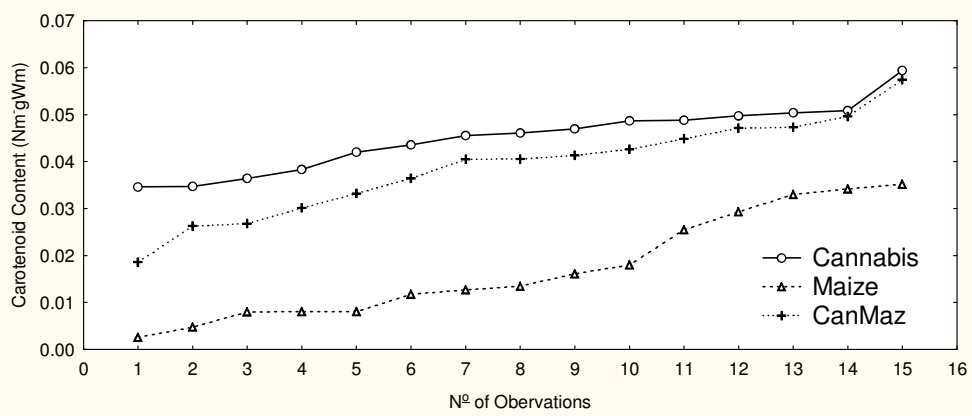


Figure 23: Carotenoid concentration between treatments.

TABLE 5: T-TEST VALUES OF THE PRI BETWEEN THE COMPARED TREATMENTS. (* MEANS P VALUE IS SIGNIFICANT).

Treatments	PRI	p values
Monocropped cannabis vs. monocropped maize	8.14	0.000*
Monocropped cannabis vs. intercropped cannabis & maize	1.94	0.062

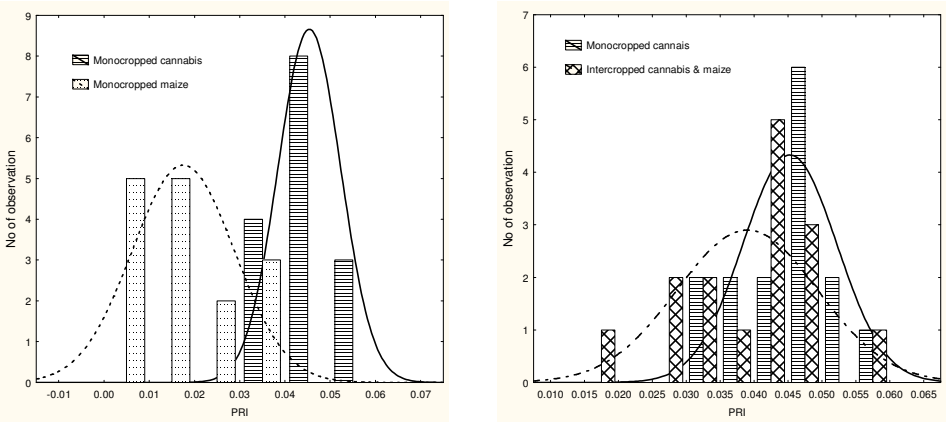


Figure 24: The graph on the left shows PRI separability between monocropped cannabis and monocropped maize and the graph on the right shows CRI separability between monocropped cannabis and the intercrop treatment.

5.2.2 Carotenoid Reflective Index

Figure 25 shows the results of CRI analysis. The results demonstrated that CRI can successfully differentiate between cannabis and maize. The differences in carotenoid content between the treatments were significant enough to discriminate cannabis from maize when grown under different cropping methods. Figure 26 shows a graph of the carotenoid content for each of the treatments. These results were consistent with the findings observed in Figure 25 where monocropped cannabis had the highest carotenoid content followed by the intercropped treatment and lastly the monocropped maize treatment.

In addition, CRI proved to be a better method to measure carotenoid pigments from the treatments as this was observed from the t-test results shown in Table 6. These results revealed that CRI is capable of discriminating cannabis from maize when grown under different cropping methods an important objective which PRI failed to achieve in this study.

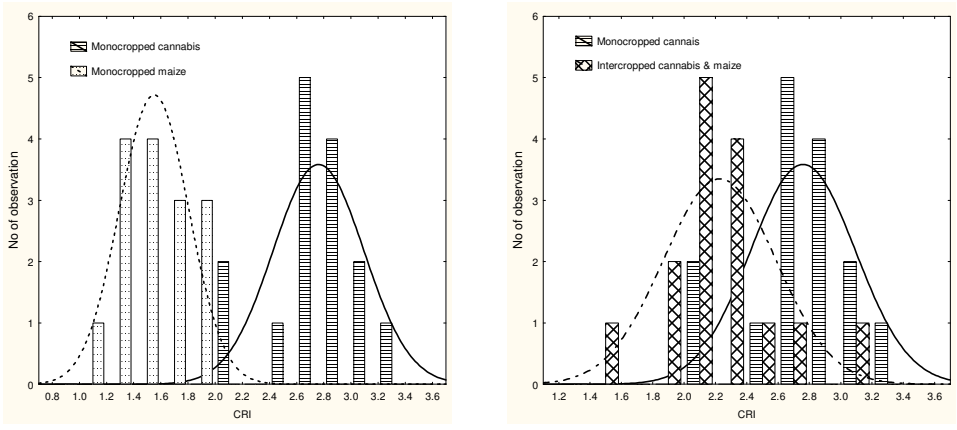


Figure 25: The graph on the left shows CRI separability between monocropped cannabis and monocropped maize and the graph on the right shows CRI separability between monocropped cannabis and the intercrop treatment.

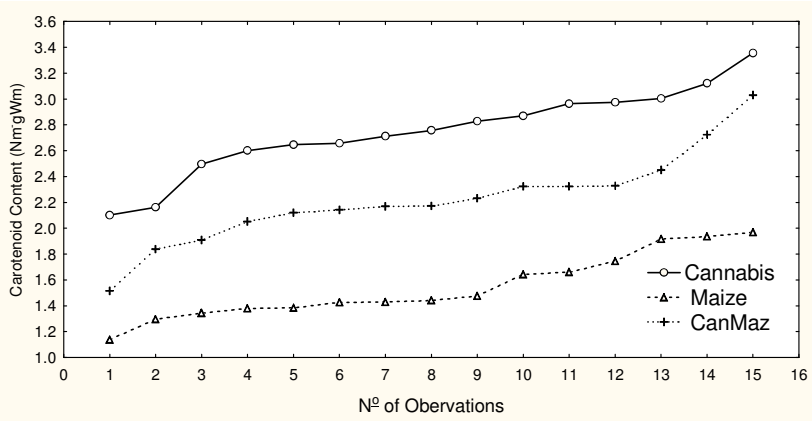


Figure 26: Carotenoid concentration between treatments.

TABLE 6: T-TEST VALUES OF THE CRI BETWEEN THE COMPARED TREATMENTS. (* MEANS P VALUE IS SIGNIFICANT).

Treatments	CRI	p values
Monocropped cannabis vs. monocropped maize	**11.14**	0.000*
Monocropped cannabis vs. intercropped cannabis & maize	**4.19**	0.000*

5.2.3 Normalized Difference Vegetation Index

The NDVI results showed a consistent trend between treatments where the monocropped cannabis had the highest NDVI values than the other two treatments (see Figure 27). These results were consistent with the phenological differences that exist between the canopies of the treatments where the NDVI responded to the spatial distribution of the treatments leaf area and canopy architecture (Asner *et al.*, 2006; Myneni & William, 1994; Seller, 1985).

The variation in the NDVI values can be attributed to the different phenological structure of the cannabis and maize. Myneni and William (1994) stated that planophile plants (cannabis) tend to intercept most of the incident radiation than erectophile plants (maize) resulting to higher and lower NDVI values respectively. They also stated that vegetation with brighter canopy can have

lower NDVI values. Therefore as cannabis has a planophile structure and a darker canopy than maize, it consequently registered higher NDVI values than maize and these results do not contradict the explanation given by Myneni and William (1994).

There was nonetheless a surprising observation where the intercropped treatment had lower NDVI values than the monocropped cannabis. It was expected that the intercropped treatment would have higher NDVI values than the other two treatments due to its closed canopy and there were fewer spaces between the plants allowing more light to be intercepted by the plants' leaves. Even so the results proved that for this research the planophile structure prevailed over the intercropped structure of the planophile and erectophile canopy. The researcher therefore compared the NDVI to investigate the separability of the treatments. The results as shown on the two graphs on Figure 28 indicate that NDVI can be used to distinguish cannabis when grown with maize under different cropping methods. This was possible because the NDVI differences between monocropped cannabis and monocropped maize were greater than that of monocropped cannabis and the intercropped treatments. The latter results imply that it is challenging to differentiate cannabis when intercropped with maize than when differentiating it from monocropped maize.

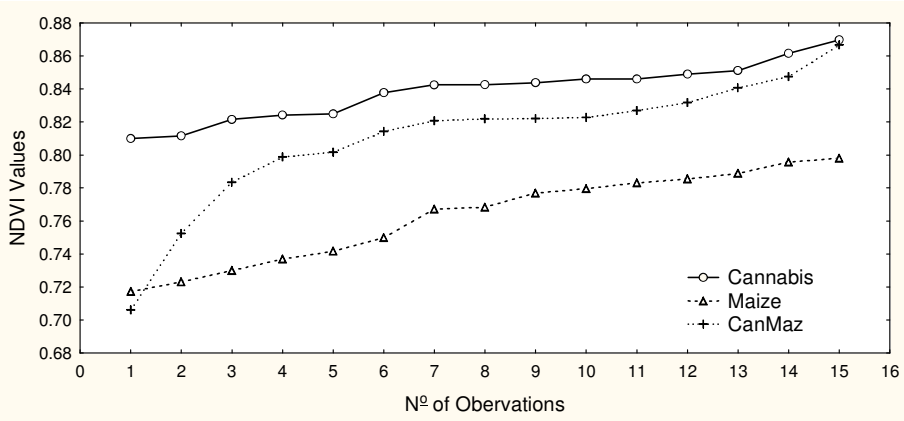


Figure 27: NDVI variation between treatments.

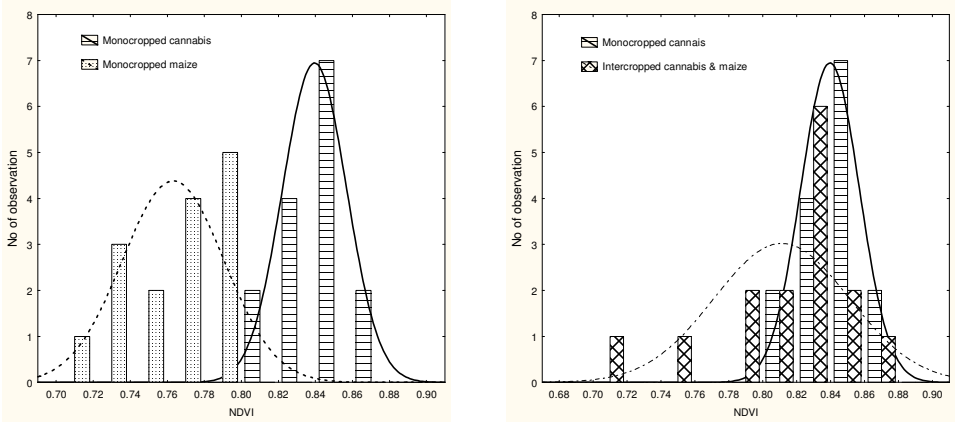


Figure 28: The graph on the left shows NDVI separability between monocropped cannabis and monocropped maize and the graph on the right shows NDVI separability between monocropped cannabis and the intercrop treatment.

As there were variations between NDVI values of the treatments, the researcher investigated how well NDVI can discriminate cannabis from monocropped maize and from the intercropped treatment. A t-test was used to test the significance at 95% confidence limit. The results shown in Table 7 were significant and consistent with the results shown by the graphs in Figure 28. The results revealed that NDVI can be used to differentiate cannabis from monocropped maize and when intercropped with maize. In support of the results shown by the two graphs (Figures

27 and 28) the t-values were lower for NDVI comparison between monocropped cannabis and the intercropped treatment than for monocropped cannabis and monocropped maize. This confirms that it would be a challenge to use NDVI to identify cannabis when intercropped with maize as compared to when used to differentiate it when independently grown along maize.

TABLE 7: T-TEST VALUES OF THE NDVI BETWEEN THE COMPARED TREATMENTS. (* MEANS P VALUE IS SIGNIFICANT).

Treatments	NDVI	p values
Monocropped cannabis vs. monocropped maize	**9.11**	0.000*
Monocropped cannabis vs. intercropped cannabis & maize	**2.54**	0.017*

5.2.4 Red Edge Position

The two methods used to calculate the red edge positions were the linear interpolation method by Guyot and Baret (1988) and the linear extrapolation technique by Cho and Skidmore (2006). The REP calculated for monocropped cannabis was compared with the REP of monocropped maize (Figure 29) and the REP of the intercropped treatment (Figure 30). These graphs show that REP cannot be used to discriminate cannabis from maize as the differences of the REP between the treatments were not significant.

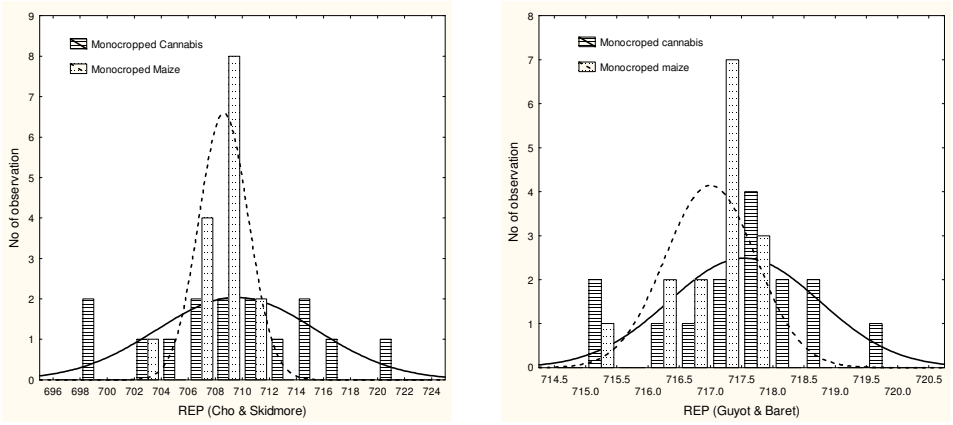


Figure 29: The graph on the left shows Cho and Skidmore (2006) REP separability between monocropped cannabis and monocropped maize. The graph on the right shows Guyot and Baret (1988) REP separability between monocropped cannabis and monocropped maize.

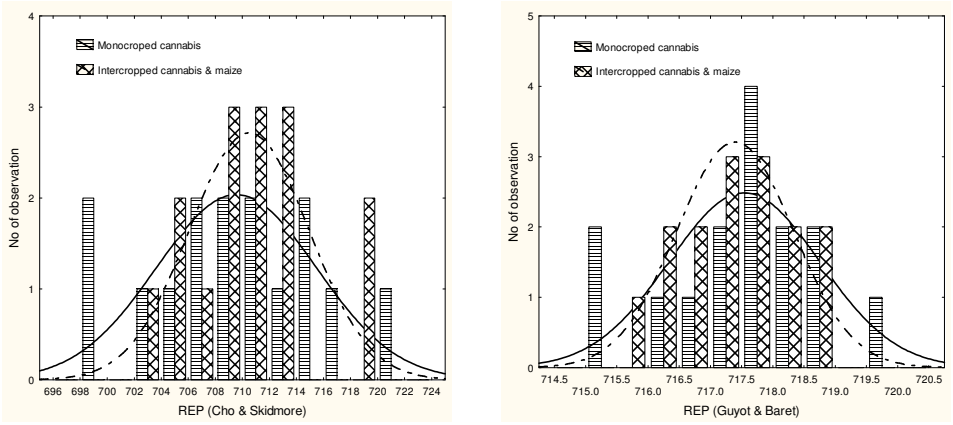


Figure 30: The graph on the left shows Cho and Skidmore (2006) REP separability between monocropped cannabis and the intercrop treatment and the graph on the right shows Guyot and Baret (1988) REP separability between monocropped cannabis and the intercrop treatment.

The REP methods were further compared using the t-test calculated at 95% confidence limit.

TABLE 8: T-TEST VALUES OF THE REP BETWEEN THE COMPARED TREATMENTS

Treatments	Cho & Skidmore		Guyot & Baret	
	REP	p values	REP	p values
Monocropped cannabis vs. monocropped maize	0.59	0.562	1.49	0.148
Monocropped cannabis vs. intercropped cannabis & maize	-0.49	0.625	0.37	0.712

The results in Table 8 were also consistent with those in Figures 29 and 30 as they demonstrated that REP cannot be used as a technique to identify cannabis from maize. Therefore chlorophyll content cannot be used to discriminate cannabis from maize as indicated by the results from both the REP methods. .

Chapter 6

6 Discussions

6.1 Spectral Indices

In this study four hyperspectral indices were used to discriminate cannabis from maize when grown under different cropping methods (monocropped and when intercropped). The indices used to test the hypotheses of the study were PRI, CRI, REP and NDVI. PRI and CRI were used to test the hypothesis that carotenoid content can be used to discriminate cannabis from maize where the null hypothesis was $H_0:\mu_1=\mu_2=\mu_3$ versus the alternate hypothesis $H_1:\mu_1\neq\mu_2\neq\mu_3$. The null hypothesis was rejected as the results of the study showed that carotenoid content can be used to differentiate the three treatments.

The REP was used to investigate if chlorophyll content can differentiate cannabis from maize where the null hypothesis was $H_0:\mu_1=\mu_2=\mu_3$ versus the alternate hypothesis $H_1:\mu_1\neq\mu_2\neq\mu_3$. For this study the null hypothesis was rejected as chlorophyll content proved to be unsuccessful in differentiating cannabis from maize. As a result the alternative hypothesis was adopted. On the other hand, it was also hypothesized that cannabis and maize can be spectrally differentiated due to their differences in structural features; the narrow band NDVI was used to test this hypothesis. The null hypothesis was $H_0:\mu_1=\mu_2=\mu_3$ versus the alternate hypothesis $H_1:\mu_1\neq\mu_2\neq\mu_3$. The null hypothesis was rejected as the narrow band NDVI proved to be successful in differentiating cannabis from maize.

The objectives of the study were about the use of photosynthetic pigments as indicators to separate cannabis from maize.

Therefore the hyperspectral indices were correlated with the measured green pigments to investigate the degree of accuracy within the indices. The correlation results showed that there was a strong relationship between the measured and estimated pigments. This suggests that the pigments estimated by the indices were a true representation of the measured green pigments from the plant leaves. Therefore the results of the analysis done on the indices are confidently accepted.

The results of the analysis done on PRI and CRI proved that carotenoid content can be used to differentiate cannabis from maize. Both indices proved to be capable of discriminating monocropped cannabis from monocropped maize. However, there was an exception where PRI could not distinguish cannabis when intercropped with maize. This was the reason why CRI was proved to be the better carotenoid index. Nonetheless, these two indices were rated in the study. CRI proved to be the best index for differentiating cannabis from maize as it proved to be capable of identifying cannabis when intercropped with maize where in this instance PRI could not succeed.

As it had been seen that the CRI is the better index to differentiate cannabis from maize using carotenoid content, the researcher then focused on the use of chlorophyll content to differentiate these two species. As the REP was sensitive to chlorophyll concentration, it was used to test the hypothesis that chlorophyll concentration can be used to differentiate cannabis from maize. The two REP methods used were by Guyot and Baret (1988) and the other method by Cho and Skidmore (2006) these methods proved that chlorophyll cannot be used to differentiate cannabis from maize. This could be attributed to the differences in chlorophyll content which were not significant enough to spectrally differentiate cannabis from maize (see Table 8).

The last index used was the narrow band NDVI which was calculated from the treatments to investigate whether the differences in structural morphology between cannabis and maize can be used to differentiate these two species. The results of the analysis demonstrated that NDVI can distinguish cannabis from maize when grown under different cropping methods. As much as NDVI can differentiate these two species, it is more challenging for NDVI to identify cannabis when intercropped with maize than to identify it when monocropped alongside maize. This was observed on the t-test results where the t-value of the monocropped treatment (9.11) was higher than the t-value of the intercropped treatment (2.54), NDVI could nonetheless spectrally differentiate these two species as their p values were significant at $p<0.05$ (see Table 7).

6.2 Statistical analysis

Having identified which of the investigated indices can differentiate cannabis from maize, we therefore used the t-test results to rank the indices as shown in Table 9. Table 9 show that CRI was the best index to use as it had the highest significant t-values within the compared treatments. The least index to use was PRI which could only differentiate cannabis when independently cultivated along maize but not when intercropped with it. On the other hand, the REP t-values were low and insignificant for both REP methods used. This means that chlorophyll cannot be used to differentiate cannabis from maize in both cropping methods.

TABLE 9: T-TEST RESULTS OF INDICES FOR THE TREATMENTS COMPARED (CAN = CANNABIS: MAZ = MAIZE: CANMAZ = CANNABIS AND MAIZE: * MEANS INDEX IS SIGNIFICANT).

Treatments	NDVI	PRI	CRI	REP	
				Cho	Guyot
Monocropped Can vs. monocropped Maz	**9.11***	**8.14***	**11.14***	0.59	1.49
Monocropped Can vs. intercropped CanMaz	**2.54***	1.94	**4.19***	-0.49	0.37

The above analysis was consistent with the graphs created to compare the differences of the indices between the treatments. Table 10 below shows an interpretation of the graphs indicated on Chapter 5.

TABLE **10**: INTERPRETATION OF THE DIFFERENCES IN INDICES BETWEEN THE TREATMENTS

Treatments	**Index**	**Spectral Range**		**Spectral Overlap**	**% overlap**
		Cannabis	**Maize**		
Monocropped cannabis vs. monocropped maize	PRI	0.02 - 0.07	0.01 - 0.06	0.03 -0.05	33%
	CRI	1.6 - 3.6	0.8 - 2.4	1.8 - 2.3	18%
	NDVI	0.78 - 0.90	0.7 - 0.86	0.79 - 0.84	25%
	REP (Cho & Skidmore)	696 -724	704 - 714	704 - 714	100%
	REP (Guyot & Baret)	714 - 720	715 - 718	715 - 718	100%
Monocropped cannabis vs. intercropped cannabis & maize	PRI	0.025 - 0.07	0.01 - 0.07	0.025 - 0.065	67%
	CRI	1.8 - 3.6	1.2 – 3.2	1.8 - 3.2	58%
	NDVI	0.78 - 0.9	0.7 - 0.1	0.78 - 0.9	60%
	REP (Cho & Skidmore)	696 - 724	698 - 722	698 - 722	100%
	REP (Guyot & Baret)	714 - 721	715 - 720	715 - 720	100%

Table 10 indicates that there was a low overlap in differences between monocropped cannabis and monocropped maize than the monocropped cannabis and the intercropped treatment. The low overlap between the indices indicates that the remaining spectral range of the indices can be used to differentiate the compared treatments using that index. On the other hand, there was a total overlap of differences between the REPs of the treatments. In conclusion it can be stated that CRI and NDVI can effectively discriminate cannabis from maize when grown under different cropping methods.

Chapter 7

7 Synthesis of the study

7.1 Findings

The results of the study demonstrated that cannabis can be differentiated from maize under different cropping methods using two out of the four methods investigated. Both REP methods investigated demonstrated that the estimated chlorophyll content between cannabis and maize cannot differentiate these two species as their REPs were similar with a 100% overlap (see Table 10). The method tested that did not yield favorable results was the PRI. This index was able to differentiate cannabis from maize where it had a 33% overlap for the monocropped treatments. However, the 67% spectral overlap for the intercropped treatment was not significant enough ($p=0.062$) to discriminate cannabis from maize (see Table 5). Therefore PRI was not accepted as a suitable index to differentiate cannabis from maize using carotenoid. On the other hand, CRI and NDVI proved to be capable of identifying cannabis from maize when grown independently (monocropped) or when intercropped with maize. Therefore carotenoid content and structural differences between the treatments were the ideal criteria for differentiating these two species.

7.2 Recommendations for further research.

As the SAPS aerial spotters use low-level fixed wing aircrafts to identify cannabis, a hyperspectral sensor with a spectral range between 746nm and 800nm can be mounted on the aircraft to map and monitor unknown and known areas respectively. This spectral range is where CRI (500_{nm} and 800_{nm}) and the narrow

band NDVI (746_{nm} and 755_{nm}) spectral bands are. There are hyperspectral airborne sensors with high spatial resolution that can be used for this application and they are shown in Table 11 below. However, the disadvantage of airborne remote sensing is that the data is affected by atmospheric noise. The imagery recorded by space borne and airborne sensors between 400 $_{nm}$ and 2500 $_{nm}$ is affected by atmospheric gases, aerosols and clouds (Zagolski & Gastellu-Etchegorry, 1995). Therefore atmospheric correction of the data is compulsory as the radiance has to be converted to reflectance. Fortunately, studies done over the years have developed models to correct these atmospheric disturbances such as the High Accuracy Atmospheric Correction for Hyperspectral Data (HITACHI) (Goetz, *et al.*, 2002; Pu & Gong, 2004) and the moderate resolution atmospheric Transmittance and radiance code (MODTRAN) (Berk, *et al.*, 1998). In addition, some of the hyperspectral airborne sensors have onboard calibrating capabilities where the imagery is corrected for atmospheric disturbances.

Table 11: Airborne hyperspectral sensors.

Sensor	Wavelength (nm)	Bands	Spatial Resolution
AVIRIS	400 - 2500	224	17 m
Hymap	450 - 2500	128	2 – 10m
Casi 1500	380 - 1050	288	25cm
AISA Dual	400 - 2450	244	2.5 m
Probe	400 - 2450	128	1 – 10m

The SAPS can perform statistical analysis on the information extracted from the hyperspectral imagery to study trends and formulate criteria for identifying other illegally grown areas. Eventually these criteria can be used to develop models that can automate the identification process.

In the absence of suitable and readily available space-borne hyperspectral data, practical applications of this study are currently limited to air-borne exploration. It is envisaged that in future there will be satellite hyperspectral data with sufficient ground resolution that can be used by the law enforcement agencies to apply the results of this study. At the present stage, sensors with relevant spectral bands as required by CRI and NDVI can be mounted on fixed wing aircrafts for discrimination of cannabis from maize. It is therefore recommended that pilot studies using any of the above mentioned sensors (Table 11) are carried out in one of the traditionally known cannabis growing areas in the country to assess on the ground the findings of this study.

At times maize is not the only crop that is used by the illegal growers to conceal cannabis but it emerged as the preferred crop in South Africa to mask cannabis from intruders and law enforcement agencies. For that reason further studies should be done to identify cannabis from other landcover using spectroscopy. This would not only add value to the limited cannabis spectral information available, it would also contribute to the United Nation's global efforts to fight against drug.

Through spectroscopy this study has proven that limited access or lack thereof to hyperspectral space-borne data should not be the reason studies are not conducted in pursuit of answering research questions as the outcomes might change the landscape of RS. By using only spectroscopic data the hypotheses were tested in this study.

In conclusion, it is recommended that the South African law enforcement agencies in the office of drug and organized crime adopt the methods proven in this study to enhance identification of cannabis especially when intercropped with maize.

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