SATELLITE AND GROUND BASED MULTISPECTRAL DATA CORRELATIONS WITH AGRONOMIC PARAMETERS FOR FLUE CURED TOBACCO (*Nicotiana tabacum* L).

A THESIS SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF PHILOSOPHY IN CROP PRODUCTION

BY

MUNYARADZI SHAMUDZARIRA

FACULTY OF AGRICULTURE AND NATURAL RESOURCES

AFRICA UNIVERSITY

MUTARE

ZIMBABWE

MAY 2014

ABSTRACT

Tobacco (*Nicotiana tabacum* L.) is an important crop in Zimbabwe. The crop contributes an average of US$ 690 million in sales annually and is a source of livelihood for an estimated 700 000 Zimbabweans involved in the tobacco value chain from production, marketing and distribution. Poor crop monitoring tools are a major hindrance to tobacco crop production in Zimbabwe. Studies were conducted in 2012 and 2013 during rainy seasons to investigate the potential of remote sensing data obtained from ground and satellite based instruments in monitoring in- season agronomic variables of flue cured tobacco at the Tobacco Research Board's, Kutsaga Research Station, in Harare. An experiment to compare Normalized Difference Vegetation Index (NDVI) data from a Multispectral Radiometer (MSR 5) ground based instrument to biophysical variables (plant height, leaf number, leaf length, leaf width and geometric mean leaf area) was conducted at the Kutsaga Research Station. An experiment to compare Satellite derived NDVI to biophysical variables was conducted over 100 Ha at the same research station. The mathematical relationships for the purpose of up-scaling MSR 5 data to satellite resolution were also conducted. From 100 Ha of tobacco crop, sampling sites were randomly selected for reflectance measurements and corresponding leaf length, leaf width, plant height, leaf number counts and above ground biomass. The biophysical variables data was collected for 12 weeks from the age of 1 week after planting in both seasons. The coefficients of determination between MSR 5 NDVI and leaf number (R^2= 0.88), leaf length (R^2 = 0.89), leaf width (R^2 = 0.82), plant height (R^2 = 0.86), Geometric mean length (R^2 = 0.863) and above ground dry mass (R^2 = 0.888) were sufficient enough to allow for accurate assessment of crop health using NDVI. In-field variations in crop variables were also observed in tobacco planted on different dates. Tobacco crop biophysical variables are, hence, positively related to the NDVI, and, suggest that these results can be used to make in-season assessments of tobacco crop health, growth vigor and hence in yield estimation. When Landsat 7 and Moderate-resolution Imaging Spectro-radiometer (MODIS) data correlations with agronomic variables were compared, MODIS data proved more reliable for the monitoring of tobacco crop vigor in-season with coefficient of determination values of above 0.75 for all the biophysical variables measured (leaf length, leaf width, plant height, leaf number and geometric mean leaf area). The research culminated in the development of mathematical estimation models for flue cured agronomic variables based on the established relationships between low spatial resolutions MSR 5 derived NDVI ($NDVI_{MSR}$). From field measured agronomic variables, linear models for estimating biophysical variables (leaf length, Leaf width, plant height, Leaf number and geometric mean leaf area were developed. Using a simple function relating MSR 5 and MODIS derived NDVI and by substitution of $NDVI_{MSR}$ with the $NDVI_{MOD}$, the estimation models for the tobacco biophysical plant variables were also derived. The method is recommended for validation for operational use.

DECLARATION

I………………………………………………………………………………. DECLARE THAT THIS WORK IS ORIGINAL AND HAS NOT BEEN SUBMITTED TO ANY UNIVERSITY FOR THE AWARD OF ANY DEGREE

..……………………………………………………………

STUDENT SIGNATRE

..……………………………………………………………

DATE

APPROVED FOR SUBMISSION

..……………………………………………………………

NAME OF SUPERVISOR

..……………………………………………………………

SIGNATURE OF SUPERVISOR

..……………………………………………………………

DATE

COPYRIGHT

© Correct Citation: Shamudzarira, M.C. (2014). Satellite and Ground Based Multispectral Data Correlations with Agronomic Parameters for Flue Cured Tobacco (*Nicotiana tabacum* L). Master of Philosophy Thesis. Faculty of Agriculture and Natural Resources. Africa University.

ACKNOWLEDGEMENTS

I thank the Lord, my heavenly father for his faithfulness and unfailing grace in taking me this far. I am indebted to Mr. E. Svotwa for the patience and willingness to guide, inspire and motivate me along my academic path. I am eternally grateful to Dr. W. Manyangarirwa for picking up the torch and supervising this research work despite an enormous workload. Thanks are also to the Tobacco Research Board, in particular Dr. D. Garwe and Dr. S. Dimbi for facilitating this research scholarship as well as their unwavering support in establishing the vital links between TRB and Africa University that made this research a success. Lastly, I thank my parents and siblings for the morale encouragement that saw me through the difficult times. God bless you all.

DEDICATION

To my father, a testament to all your wise words and belief in what your son can achieve.

Table of Contents

LIST OF TABLES

LIST OF FIGURES

LIST OF PLATES

LIST OF APPENDICIES

CHAPTER ONE

INTRODUCTION

Tobacco (*Nicotiana tabacum* L.) is an important cash crop in Zimbabwe. The crop is cultivated by an estimated 91 000 farmers in Zimbabwe (T.I.M.B, 2013) with at least 80% of these being small scale farmers who grow the crop on between 1 and 2 ha (Tobacco facts, 2009). The crop is cultivated on an estimated 88 627 ha with about 166 million kg being sold at contract and auction floors in the 2013 selling season (T.I.M.B, 2013). The crop is a major contributor to the GDP of Zimbabwe, with a contribution of $612 million dollars as of 2013 (T.I.M.B, 2013) showing a marked increase of 16.2% from the previous season. A major challenge to the industry is achieving a good quality crop so as to maintain competitiveness in regional and international markets (T.I.M.B, 2013). Assuring good quality tobacco requires close attention to the growing environment during critical periods such as fertilization, topping and sucker removal (TRB, 2013).

Early crop monitoring is an essential tool for determining crop health and physiological status of agricultural crops (Bronson *et al*, 2003) including flue cured tobacco. Several crop indicators such as total leaf number, leaf length, leaf diameter and stem height (Baez Gonzalez *et al*, 2005) provide useful means of assessing the physiological condition of crops. However, these variables are often difficult to monitor in-season for large scale operations due to resource limitations and limited time. In tobacco, technical assessments can be done using these references for monitoring the growth and development of tobacco varieties (Nyoka, 2000). It is necessary to develop techniques to assess tobacco leaf condition at any stage, particularly during the early growth stages and anticipate the crops final physiological condition, quality and ultimately yield (Svotwa *et al*, 2013).

When under environmental or management stress conditions, most commercial crops develop pale leaves with reduced biomass accumulation (Bronson *et al*, 2003). In tobacco, leaf yield and quality can be severely compromised when nitrogen uptake is limiting (TRB, 2013). Tobacco varieties differ in their nitrogen use efficiency and require careful nitrogen management for optimal yields to be realized (Nyoka, 2000). Numerous trials have been conducted on how agronomic management and environmental factors affect the crop canopy of maize (Baez-Gonzalez *et al*, 2005), wheat (Verhulst and Govaerts, 2010) and tobacco (Svotwa *et al*, 2013). There has been little research in Zimbabwe on early and in-season stress identification for commercial tobacco. As a result, there is little information available on how mid-season crop stress and yield limiting environments can be identified and corrected effectively. The major limitation to such tools has mainly been a lack of fundamental research methodologies for monitoring tobacco crop development remotely and in real time.

Currently, tobacco breeders and researchers in Zimbabwe rely heavily on visual assessment techniques to assess the condition of tobacco (Svotwa *et al*, 2013). This 'eyeballing' technique presents several challenges. The major challenge being that the technique requires vast experience on the part of the assessor to accurately identify the cause of the crop stress (Araus *et al*, 2001). Information gathered by this visual analysis technique also introduces considerable bias during interpretation due to the challenges of distinguishing between the sources of stress that affect major crops (Sellers, 1985). In many instances, water stress and nitrogen stress in tobacco present a similar physiological appearance of pale yellow leaves and stunted growth that can be inseparable to an inexperienced eye (T.R.B, 2013).

Another major limitation to visual assessment in determining the health and vigor of commercial crops, especially at large scales, is that the operation is tedious, expensive and time consuming (Manatsa *et al*, 2011). When visual assessment is used for national crop assessment, trained individuals are required to physically visit numerous farms and compile detailed reports on the condition of crops. The final findings are seldom available during the critical periods when the information is most helpful to the farmers (Shoko *et al*, 2009).

Research carried out at the Tobacco Research Board using the Cropscan ground based multispectral radiometer (MSR5) showed that remote sensing can successfully be used to separate varietal and nitrogen differences of flue cured tobacco as well as distinguish the effects of different planting dates on the optical canopy properties of flue cured tobacco varieties (Svotwa *et al*, 2013). The results demonstrated that the Cropscan Radiometer was more accurate and reliable in crop physiological condition assessments than the traditional visual assessment. However, the Cropscan Radiometer must be carried to each individual field for measurements to be conducted. Because of this, large scale simultaneous crop evaluations cannot be done timely and cost effectively enough. The research recommended that this challenge be solved by relating the information obtained from the radiometer to that obtained from space borne satellite remote sensing instruments. The satellite instruments have the distinct advantage of large scale simultaneous land observations thus, real time, fast and accurate data can be potentially obtained.

Remotely sensed satellite data provides a powerful means of monitoring changes in the crop canopy during a growing season and provides crop developmental information in real time which is critical for site-specific crop management (Thomason *et al*, 2007). Plant biochemical compositions such as chlorophyll concentration, water content and starch concentration can be estimated from spectral reflectance characteristics of plants (Hatfield *et al*, 2008) and are directly linked to the vigor and health of crops. Selective absorption and reflection of electromagnetic energy influenced by the presence of chlorophyll, plant pigments and water is detected by sensors in specific regions of the electromagnetic spectrum (Wang *et al*, 2010). Remote sensing has been used widely in wheat assessment to study biomass accumulation and vegetative responses at different spectral and spatial resolutions (Bao, 2009), to characterize properties of vegetation, to estimate yield, to estimate total biomass, and to monitor plant health and plant stress (Jackson *et al*, 1983). Remote sensing data that is obtained from agricultural fields can be used in identification and mapping of crops as well as monitoring crop vigour, nutrient and environmental stress conditions (Broge and Leblanc, 2001).

Ground based and Satellite Bourne Remote sensing instruments differ notably in the effect that the prevailing atmospheric conditions have on reflected and absorbed electromagnetic energy (Jayroe *et al*, 2005). Notable differences have been identified from data collected from the ground based and satellite based sensors (Verhulst and Govaerts, 2010) over the same vegetative surface. Because of these differences, it is necessary to establish up-scaling techniques specific for commercial tobacco, to relate satellite based data to ground based data. Such up-scaling techniques should provide a means of improving the accuracy of information obtained from satellite data in assessing the health and vigor of tobacco.

In order to address the challenges summarized above, a project was carried out at the Tobacco Research Board during the 2012-2013 and 2013-2014 seasons. The Tobacco Research Board is a Zimbabwe Government body formed by an act of parliament [Tobacco Research Act, Chap.18:21] with the mandate of carrying out any research and investigation work of any kind in connection with tobacco.

1.1 The need for Satellite remote sensing methods

In Zimbabwe, tobacco crop growth and physiological condition estimates are based on field reports compiled after visual scouting of the crop by tobacco growers (T.I.M.B, 2005). These reports are often expensive to compile, prone to large errors, and cannot provide real-time, spatially explicit estimates or forecasting of tobacco crop condition. Work has been conducted using ground based remote sensing instruments to monitor the physiological response of tobacco varieties under different planting dates and fertilizer regimes at the Tobacco Research Board (T.R.B, 2013). The study showed that planting dates, variety and fertilizer levels could be identified by their spectral response which posed the possibility of this technology being applied at regional and national level with satellite remote sensing instruments. This is a preliminary study in the framework of research work that aims at developing site specific monitoring method to monitor tobacco development that is more accurate, cost effective and timely than the scouting or 'eyeballing' method.

1.2 Current challenges in Remote sensing tobacco in Zimbabwe

Although different satellite platforms provide regular coverage of the earth's surface with remotely sensed data, research on the potential use of the data to monitor tobacco growth patterns in tobacco growing regions of Zimbabwe is scarce. Its adoption as a site specific monitoring tool at farm, regional and national level. This may be due to inadequate funding for experimentation and inaccessibility of remotely sensed data and a high data acquisition cost (Marumbwa *et al*, 2006). With the introduction of more satellites such as MODIS and Landsat for earth observation missions, remotely sensed data has become more accessible and relatively more affordable (Wu *et al*, 2007). For satellite remote sensing data to be effective in tobacco crop condition monitoring and subsequently yield estimation, the spectral, spatial and temporal resolving abilities need to be optimized and compared to ground based remotely sensed data and where necessary, an appropriate scaling factor be formulated (Hatfield *et al*, 2008). Despite the advancements in remote sensing instruments and their capabilities, little experimentation has been conducted on its application in commercial flue cured tobacco estimation or yield assessment.

A major setback in the use of satellite instruments in agronomic remote sensing is the high cost of data acquisition, especially for high resolution satellites (Wu *et al*, 2007). It has been suggested that functional correlations between high resolution imaging platforms to medium or low resolution platforms may provide a means of mitigating the cost of crop status evaluation (Huete *et al*, 2002). However, certain satellite platforms, despite being cheaper to acquire data from, have resolution characteristics that cannot be useful for agronomic modeling (Pettorelli *et al*, 2005).

According to statistics by the Tobacco Industry and Marketing Board, the majority of small scale tobacco farmers contributing the significant bulk of the national tobacco output in Zimbabwe are growing the crop on an average land size of 1 hectare. This has largely as a result of the land reform program. These small scale farmers are also spread over a large area in the tobacco growing districts (T.I.M.B, 2005). The rule of thumb in remote sensing imagery is that the intended target area must cover an area equal to or larger than the spectral resolution of the satellite instrument in use (Vina *et al*, 2004). It is still to be determined by experimentation, which platforms can accurately map and produce satellite imagery applicable to Zimbabwe tobacco farming and land use dynamics. It is reasonable to assume that once a platform is identified, it becomes feasible to develop a comprehensive tobacco database backed by remote sensing and geographical information systems (G.I.S) data that can readily address the challenges of tobacco production in Zimbabwe.

In light of these challenges, a series of experiments were conducted to determine the appropriate satellite platforms suitable for monitoring in-season tobacco health status that will eventually be used in the development of a yield estimation model for the national tobacco crop. The study objectives and hypothesis tested are outlined below.

1.3 Study Objective

The main objective of this research was to determine the potential use of satellite multispectral images for estimating growth vigor in flue cured tobacco, their correlation with ground based Multispectral radiometer optical properties and the suitability of different satellite platforms in assessing agronomic properties and crop conditions so as to achieve successful crop assessment and yield estimation.

1.4 Specific objectives

1. To establish a correlation between ground based (MSR 5) sensor derived NDVI with agronomic variables (stem height, leaf diameter, total leaf number and geometric mean) of flue cured tobacco.
2. To establish a correlation between Satellite derived NDVI and agronomic variables (stem height, leaf diameter, total leaf number and geometric mean) of flue cured tobacco.
3. To determine the up scaling ratios for ground based sensors to satellite sensors for estimating agronomic variables of Flue Cured tobacco.

1.5 Hypotheses

The hypotheses that guided this study are as follows:

1. There is a correlation between Ground based sensor derived V.I and agronomic variables of tobacco
    - Ground V.I = $\boldsymbol{f}$ (Agronomic variables)

2. There is a positive relationship between Satellite V.I and crop variables (leaf number, leaf diameter and stem length)
    - Sat. V.I = $\boldsymbol{f}$ (Agronomic variables)

3. Ground based Vegetative indices are linearly related to satellite vegetation indices
    - Ground V.I = K (Satellite V.I)

CHAPTER TWO

LITERATURE REVIEW

2.1 Optical properties of vegetation

Vegetation has distinct optical properties compared to other surfaces and matter. The spectral response of vegetation is uniquely influenced by the structure and leaf chemical composition of the vegetation canopy. When electromagnetic energy interacts with vegetative surfaces, absorption, transmission and or reflection occurs within different regions of the electromagnetic spectrum in a manner that is specific to vegetative matter (Hatfield *et al*, 2008). The principle component determining the quantities of reflection, absorption and transmission are dependent on the leaf chemical composition, leaf structure and leaf density. In the 0.4-0.7 um region, light is mainly absorbed due to chlorophyll influence while reflection increases in the 0.7-2.5 um region due to scattering and starch compounds (Blackburn, 2002). Variations in the unique absorption and reflection of light in these regions can be used to distinguish vegetation types and identify factors that affect the crop's health such as nutrition, water stress or disease. Figure 2.1 below shows the general electromagnetic energy interactions in a vegetative surface.

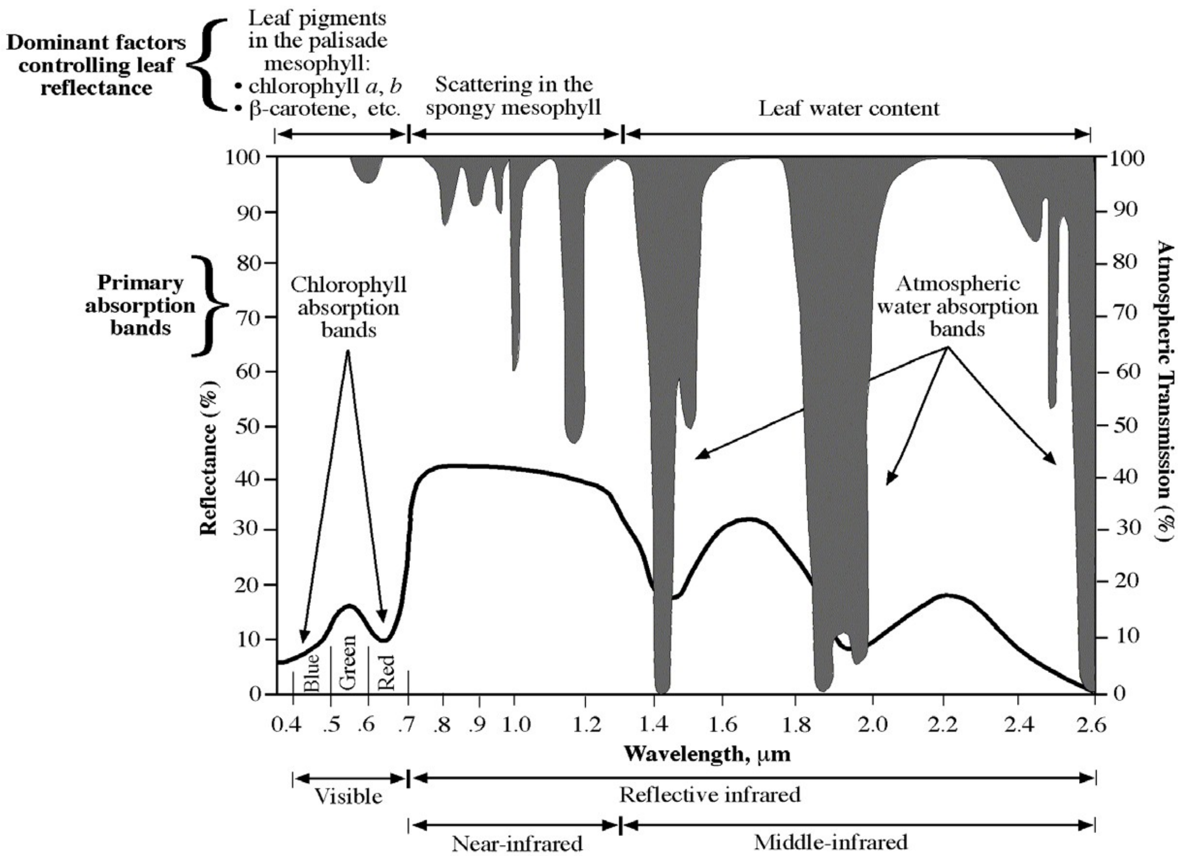

Figure 2.1 Typical optical responses of vegetative surfaces (Hatfield *et al*, 2008)

2.2 Factors Affecting Canopy Reflectance

Environmental stress, management induced stress as well as pest and disease incidence are known to affect the absorptive, reflective and transmission properties of leaves. These effects in turn, cause the overall crop canopy optical properties to differ from that of a normal crop (Curran *et al*, 2001). The crop canopy optical properties offer a more comprehensive assessment tool than individual leaves and thus, must be considered in remote sensing of commercial crops under field management conditions (Daughtry *et al*, 2000: Hatfield *et al*, 2008). Evidence to this has been found in different light absorption properties from upper leaf layers in a canopy to the lower leaf layers, where soil reflection is known to contribute to the optical reflection observed (Gausman, and Escobar, 1973: Curran *et al*, 2001).

In visible wavelengths, the first leaf layer of a canopy, if healthy and perpendicular to the incident light, absorbs approximately 90% of the incident light (Blackburn, 2002). In Near Infra Red (NIR) wavelengths, the first leaf layer absorbs about 10% of the incident light, the rest being about equally divided between transmission and reflection (Blackburn, 2002). Ferri *et al* (2004) reported that NIR radiation transmitted by upper leaf layers is scattered by lower leaves in the canopy until the incident light is attenuated by a Leaf Area Index of soya bean canopies. Visible reflectance from a canopy may only represent the uppermost leaf layers due to the intense absorption by chlorophyll, while NIR reflectance (low absorbance) may represent multiple leaf layers in the canopy (Heute *et al*, 2002). The crop canopy components that dominantly affect reflectance are closely related to planting time differences and fertilizer management. These are Leaf Area Index (LAI), Variety, Soil reflectance, Ambient light and Crop nutrition.

2.3 Vegetation Indices

Vegetative indices (VI) are mathematical ratios of selected reflectance measurements in specific regions of the electromagnetic spectrum that are developed to quantify vegetative density (Hatfield *et al*, 2008). They provide a means of estimating vegetative changes over a period of time (Huete *et al*, 2002). Commonly used vegetation indices are the Normalized Difference Vegetation Index (NDVI), Ratio Vegetation Index (RVI) and the Soil Adjusted Vegetation Index

(SAVI). Normalized Difference Vegetation Index is the most abundantly used vegetation index in experimentation because of its ability to eliminate soil background interference.

2.3.1 Normalized Difference Vegetation Index

The Normalized Difference Vegetation Index (NDVI) is a numerical indicator of the vegetative density of a crop and is widely used to determine the health and vigor of a crop (Huete *et al*, 2002). Normalized Difference Vegetation Index was improved from the Ratio Vegetation Index and is calculated by dividing the difference of NIR and Red energy by the sum of the two.

$$NDVI = (NIR - ¿) \div (NIR + ¿)$$

Where:

N.I.R = reflectance in the near-infrared band

Red = reflectance in the red portion of the visible band

The normalized difference vegetation index (NDVI) has been successfully used to quantify vegetative changes in several studies over the last decade. Research on the NDVI has shown it to be the vegetation index that best predicted percentage cover of vegetation in an assessment of spectral vegetation indices for riparian vegetation in the Colorado River delta (r^2=0·837) (Nagler *et al*, 2001). Experimental work conducted on maize (*Zea mays* L) also showed that it was possible to detect changes in biomass accumulation as well as the onset of senescence and phenological changes that are related to physiological development of maize using NDVI as the primary indicator of vegetation density (Vina *et al*, 2004). Remote sensing instruments have also been successfully used to estimate the nitrogen content in wheat through the NDVI and showed a positive correlation (r^2= 0.52-0.80) between NDVI and nitrogen content (Wright *et al*, 2004).

Further studies in grapes showed that when the NDVI obtained from remote sensing instruments was related to pruning weight, phenol, anthocyanin, and sugar content of grapes measured in 25 to 32 sampling positions within vineyards over two growing seasons, sensor canopy reflectance predicted the spatial variation of biomass production in the two vineyards with varying degrees of precision (Stamatiadis *et al*, 2009).

Although the NDVI has proven to be an extremely useful indicator for vegetation monitoring, its accuracy can be limited by the effects of soil humidity and surface anisotropy (Short, 2008). Surface anisotropy refers to the property of a surface to not reflect electromagnetic radiation at the same angle as its incident angle. It is directly linked to the roughness of a surface and tends to increase with roughness of the surface (Araus *et al*, 2001). As a result, NDVI values may vary due to soil humidity, the particular anisotropy of the target, as well as on the angular geometry of illumination and observation at the time of the measurements (Araus *et al*, 2001).

Limitations of satellite derived NDVI arise from spatial and temporal resolution differences of different satellite sensors as well as atmospheric environmental factors (Short, 2008). Common sources of error in satellite derived NDVI are mixed pixels, and these are pixels that contain reflective data of two or more heterogeneous surfaces that have not been delineated by the sensor (Huete *et al*, 2002). This is normally as a result of low resolution of the sensors and the relative size of the objects under observation. The mixed pixels may exhibit uncharacteristic low or high NDVI which can be misleading (Hansen, 2006).

2.3.1 Justification of NDVI in tobacco related experiments

Among the many vegetation indices that have been described through experimentation (Gausman an Escobar, 1973), the NDVI still remains arguably the most applicable index for monitoring tobacco phenology (Svotwa *et al*, 2012). The NDVI regressions with total leaf nitrogen, plant density and seedling quality have shown that it can be used to accurately assess tobacco crop health at seedling level better than other indices (Svotwa *et al*, 2012). In a review of remote sensing in Zimbabwe, it has been recommended that a similar approach be used for quantifying tobacco plant variables using field tobacco so that up-scaling ratios can be adopted for large scale crop assessments (Svotwa *et al*, 2013). Furthermore, the NDVI is the most readily available index that can be obtained from the majority of satellite remote sensing instruments (USGS, 2013).

2.3.2 Soil-Adjusted Vegetation Indices (SAVI)

The NDVI is known to be affected by high soil reflection which may affect accuracy of observations (Hatfield *et al*, 2008). One approach for dealing with the soil background is to try to eliminate it using indices that correct for the soil reflection. The soil-adjusted vegetation index (SAVI) simplifies the soil relationship to canopy reflectance by adding a simple brightness factor (L), which is typically set to 0.5, but can range from 0 to 1 (Chen and Elvidge, 1993: Huete *et al*, 2002). This provides a more efficient method of estimating ground cover. Although the SAVI possesses some distinct advantages over the NDVI, its use is usually limited by the sensitivity in instruments used in crop assessments. MSR 5 radiometer models are not capable of detecting specific limited electromagnetic energy interactions without introducing bias, therefore, limiting their use for crop assessments.

2.4 Satellite sensors used in crop health assessments and yield estimation

Zimbabwe relies on visual assessment methods for in-season crop health assessments. Agronomists, contracting company representatives and extension agents from the Department of Agricultural Technical and Extension Services (AGRITEX) patrol the tobacco growing districts during the production season, compile district and provincial data and present their findings to the relevant stakeholders (T.I.M.B, 2005). Data compilation, validation and presentation are very slow and tedious. Results are rarely available during the production period itself and thus do not serve the purpose it is expected to serve. As is the case with most visual assessment techniques, crop physiological stress interpretation varies from viewer to viewer, with each individual assessor requiring vast experience and technical qualifications to be able to delineate stress factors in the tobacco crop. With the rapid expansion of farmers venturing into tobacco each year, this problem will likely persist and so will the challenge of correctly identifying yield loss factors.

In order to develop functional methodologies for tobacco crop assessment and yield estimation using satellite instruments, an understanding of satellite sensors is necessary. This involve in depth studies of the remote sensing capabilities of each satellite, as well as the types of tools that can be developed to make tobacco crop monitoring and yield estimation possible using the satellite information. The most commonly referred to in Zimbabwe are Landsat 7, MODIS, MERIS and occasionally Quickbird (Murwira and Skidmore, 2010).

2.4.1 LANDSAT Satellite series

The Landsat satellite series consist of a several moderate resolution land instruments ideal for vegetative assessments and land use change. The most commonly and recently used, the Landsat 7 Enhanced Thematic Mapper has been in use since 1999 and has provided free satellite imagery through the USGS server. The main features of the L 7+ETM are a panchromatic band with 15 m spatial resolution (band 8), Visible (reflected light) bands in the spectrum of blue, green, red, near-infrared (NIR), and mid-infrared (MIR) with 30 m spatial resolution (bands 1-5, 7), a thermal infrared channel with 60 m spatial resolution (band 6) and full aperture, 5% absolute radiometric calibration. The Landsat 7 suffered a permanent mechanical fault with its scan line corrector in 2003 that resulted in substantial data losses in the satellite imagery, however its use continued and meaningful data is still accessible through the platform (USGS, 2013). In 2013, the Landsat 8 was launched to replace the Landsat 7 and its potential use in Agriculture and in particular, Tobacco Production in Zimbabwe is yet to be explored.

Landsat images were used successfully to monitor the Gross Primary Productivity (GPP) of maize (Huete *et al*, 2002) and the results showed that this satellite system was particularly appropriate for detecting not only between- but also within-field GPP variability during the growing season suggesting that it was an applicable means of assessing maize phenology. However, in a separate study in the evaluation of Landsat applicability in wheat monitoring in

Australia, various problems were discussed which included loss of data because of cloud cover, registration accuracy, training techniques, best combinations of bands and dates for classification, confusion classes, computation of very large volumes of data and classification accuracy assessments (USGS, 2013).

2.4.2 Moderate-resolution Imaging Spectro-radiometer (MODIS)

MODIS Terra was launched into Earth orbit by NASA in 1999 on board the Terra (EOS AM) Satellite. The instruments capture data in 36 spectral bands ranging in wavelength from 0.4 µm to 14.4 µm and at varying spatial resolutions (2 bands at 250 m, 5 bands at 500 m and 29 bands at 1 km). Together the instruments image the entire Earth every 1 to 2 days. They are designed to provide measurements in large-scale global dynamics including changes in Earth's cloud cover, radiation budget and processes occurring in the oceans, on land, and in the lower atmosphere. MODIS Terra has a spectral resolution of 250m and is generally regarded as low by the scientific community. It does however, has a relatively high temporal resolution that makes it a potential candidate for large scale operations (USGS, 2013)

Crop yield estimation was studied on maize *Zea mays* in the United States corn growing regions using the Terra MODIS satellite data. Results confirmed that yields of maize could be successfully estimated using MODIS data products such as NDVI and LAI at regional scale (Fang *et al*, 2010). The work also highlighted the need for the development of other remotely sensed products such as crop percentage to aid the existing data and make yield assessments more accurate (Fang *et al*, 2010).

2.4.3 Medium Resolution Imaging Spectrometer (MERIS)

MERIS is a wide field-of-view pushbroom imaging spectrometer with a swath width of 1150km (field-of-view (FOV) = 68.5°) measuring the solar radiation reflected by the Earth in 15 spectral bands from about 412.5nm to 900nm (ESA, 1996). MERIS offers sufficiently high spectral resolution that can be used to determine the chlorophyll content and nitrogen status of commercial crops as well as spectral separation of crop species.

Studies conducted on yield estimation of cereal crops showed that there were sufficiently strong correlations between vegetative indices derived from MERIS spectral bands and yield obtained from cereal crops and the data could be used for national crop area estimation and yield estimation (Chen and Elvridge, 1993).

2.4.4 Cropscan Multispectral Radiometer (MSR)

The Cropscan MSR radiometer is a hand-held field level remote sensing radiometer with spectral bands similar to the first 5 bands of the Landsat Thematic Mapper. The Cropscan MSR obtains passive reflective electromagnetic energy emitted from vegetative surfaces and expresses it as a proportion of the amount of electromagnetic energy that interacts with the vegetative surface, thereby allowing it to characterise unique features of the vegetation with reasonable accuracy (Cropscan, 2013). It has been used successfully to estimate the yield of soyabeans (Cropscan, 2013) as well as to evaluate disease incidence and yield loss caused by *Sclerotinia* Stem Rot of Soybeans (Cropscan, 2013). Recently it was used to estimate tobacco leaf nitrogen content and biomass of flue cured tobacco varieties (Svotwa *et al*, 2012). Despite its success, the Cropscan MSR does have the limitation of very low spatial resolution. It therefore is very difficult to employ it singularly as a yield estimation tool for national yield estimation exercises. It is therefore limited mainly to ground truthing exercises (Svotwa *et al*, 2012).

In Zimbabwe, tobacco cultivation periods are guided by law, beginning on the 1st of September, when first official transplanting begins, to the 15th of May when all tobacco stalks are destroyed. Any platform suitability will, to a certain inevitable extent, be influenced by the rain-season that characteristically extends between mid October and early March (Svotwa *et al*, 2012). With the onset of the rain-season, it is inevitable that cloud cover will influence the quality of data that can be extracted from satellite imagery, particularly the frequency to which cloud free images of an area that can be repeatedly observed is affected (Yang, 2010). Such influences can affect data collection during important vegetative temporal windows and render some satellite platforms with low repeat cycles such as Landsat ETM unfit for tobacco assessment when compared to high temporal repeat cycles of MODIS.

The majority of tobacco cultivated in Zimbabwe originates from the small holder farmers. These farmers usually grow their crop on land sizes of 1 hectare or less and of irregular shape (T.I.M.B, 2005). Satellite platforms of low spatial resolution such as MODIS, with 250m resolution (USGS, 2013) may have challenges in delineating these small cropped lands from natural vegetation as compared to medium resolution platforms such as Landsat TM with 30m resolution (Svotwa *et al*, 2013). This can have a pronounced effect on the suitability of a platform to accurately estimate crop health at national level.

2.5 Data formats, transformations, data indices and interpretation

The most commonly used satellite data formats are Hierarchical Data Format (HDF) and Geographic Tagged Image File Format (GeoTIFF). These formats have been widely used to universally transfer remotely sensed satellite data and will be pivotal in developing Zimbabwean methodologies in tobacco applications (Mutanga, 2004). The NDVI is the most commonly used vegetation index in use to characterize vegetative traits in agronomic trials (Mutanga, 2004). Other indices such as Ratio Vegetation Index (RVI) have several merits that could also be applied (Broge and Leblanc, 2001). A foreseeable challenge is that of spectral confusion of tobacco crop and other crops such as maize and wheat, therefore, during interpretation, it is vital that robust methods of temporal separation are employed (Svotwa *et al*, 2012).

2.6 Recent work in Zimbabwe

The application of remote sensing data in the form of satellite rainfall estimates to forecast yield of maize in Zimbabwe was applied using the Water Requirement Satisfaction Index (WRSI) (Marumbwa *et al*, 2006). Although positive coefficients of variance were obtained in their trials, the authors argued that such an approach was susceptible to bias due to the changes in land use dynamics attributed to the land reform policy of 1999.

Research carried out on irrigation water use in the Mazowe catchment area in Zimbabwe using Landsat TM remote sensing satellite instrument showed that irrigated and dryland wheat production systems could be distinguished using Landsat TM derived moisture indices

(Marumbwa *et al*, 2006). This clearly demonstrated the capability of retrieving soil moisture data from satellite imagery, hence remote sensing and GIS have vast potential for monitoring in-season crop health more efficiently and less costly (Marumbwa *et al*, 2006).

Satellite remote sensing provides the most feasible approach to addressing the highlighted problems in the Zimbabwean tobacco industry. Satellite remote sensing derives its definition from the collection of information from an object or phenomenon without coming into physical contact with it (Hatfield *et al*, 2008). Remote sensing provides a fast, reliable and accurate alternative to the current challenges of visual assessment of agronomic crops. Specifically, satellite remote sensing utilizes space borne sensors to observe the electromagnetic energy interactions on the earth's surface providing an interesting means of assessing spatially absolute areas simultaneously such that national crop assessments become a feasible task (Nowatzki *et al*, 2004). The characteristic property of vegetation to absorb, reflect and transmit electromagnetic energy uniquely in specific regions of the energy spectrum provides the basis for such research. Furthermore, with adequate sensor characteristics, vegetation of similar species but under different environmental conditions or crop management practices is separable through careful study of the absorptive and reflective properties of the crop canopies (Gausman and Escobar, 1973).

2.7 Agronomic variables of Flue cured tobacco

The major variables used to assess the physiological condition of tobacco by growers are leaf number, leaf width, leaf length, plant height and to a lesser extent, Leaf Area Index (Garvin, 1986). The economically important organs of tobacco are the leaves. The size and weight of the leaf is directly related to yield attainable by a tobacco crop (T.R.B, 2013). Any factor that limits the development of an adequate number or size of the leaf reduces the yield potential of the crop significantly and as a result, such factors require constant monitoring during the various stages of crop growth.

The length and width of tobacco leaves is directly related to the nutrient supplying capacity of the soil environment around the crop. The management and environmental interaction both determine the extent to which leaf expansion in tobacco occurs (T.R.B, 2013). A well managed crop tends to develop full bodied leaves with broad leaves (Shoko *et al*, 2009). Disease, nutrient deficiency, especially potassium, and adverse environmental conditions reduce leaf expansion considerably. This in turn affects the optical properties of the canopy (Svotwa *et al*, 2012 and 2013). Since leaf expansion directly influences the surface area available for electromagnetic interaction, the extent to which the leaf lengthens and expands should significantly affect NDVI (Short, 2008). The geometric leaf area mean (Geometric Mean), which is the square root of the product of the leaf length and width, can provide a combined effect of leaf length and leaf width that should correspond well to NDVI (Svotwa *et al*, 2012).

NDVI has been correlated positively to biomass in tobacco (Svotwa, *et al*, 2012), maize (Manatsa *et al*, 2011), sugarcane (Shoko *et al*, 2009), wheat and soybeans (Araus *et al*, 2001) suggesting that NDVI does sufficiently enable estimation of biomass within a crop stand. In tobacco seedlings, a positive correlation was obtained between dried tobacco seedlings and the NDVI obtained from their seedbeds (Svotwa *et al*, 2012).

CHAPTER THREE

THE RELATIONSHIP BETWEEN GROUND BASED MULTI-SPECTRAL RADIOMETER SENSOR DERIVED NDVI AND AGRONOMIC VARIABLES OF FLUE CURED TOBACCO FOR IN-SEASON CROP MONITORING.

INTRODUCTION

In-season tobacco crop status monitoring is an important management tool required to evaluate the physiological crop status of tobacco during a growing season (Garvin, 1986). It is used to evaluate the management and environmental interactions that ultimately determine the yield of flue cured tobacco (Garvin, 1986). An effective in-season crop monitoring tool should be able to delineate a healthy crop from a stressed crop relatively fast and accurately such that any management decisions required can be made timely to ensure that maximum yields and crop performance is achieved (Gausman and Escobar, 1973).

The NDVI obtained from similar hand held instruments such as the Cropscan Multispectral Radiometer (MSR 5) has been correlated to crop nutrient deficiencies and physiological development (Osborne *et al*, 2002), the NDVI has also been related to the final yield in maize (Manatsa *et al*, 2011), wheat and sorghum as well as nutritional deficiencies such as nitrogen (Blackmer *et al*, 1996: Toulios *et al*, 1998) and water stress (Shoko *et al*, 2009). However, NDVI does not exclusively reflect the effect of one parameter (Hatfield *et al*, 2008). NDVI has to be considered as a measurement of the consolidated plant growth that combines various plant growth factors (Verhulst and Govaerts, 2010) rather than a universal descriptor of plant growth (Hatfield *et al*, 2008). The physical characteristics detected by the index are related to some measure of canopy density, measured as leaf number and geometric mean or total biomass (Araus *et al*, 2001) and will likely differ with plant species (Curran *et al*, 2001: Carlson and Ripley, 1997)

The underlying factor for variability in a typical vegetation index cannot be blindly linked to a management input without some knowledge of the primary factor that limits growth (Verhulst and Govaerts, 2010). For example, in a field where nitrogen is the limiting factor to growth, the NDVI may show a strong correlation with the N availability in the soil. However, in another field, where water is the limiting factor, the NDVI may be just as strongly correlated with plant-available soil moisture (Araus *et al*, 2001). Based on this, there is need for careful interpretation of remotely sensed data such that an observed characteristic is correctly attributed to a known and quantifiable agronomic factor. This can be achieved partly by assessing several NDVI-Crop responses and identifying common traits. Such responses include the response leaf number, leaf length, leaf width, plant height, dry mass and geometric mean leaf area in flue cured tobacco to observed NDVI.

The total number of leaves permitted on a tobacco crop is dependent on a combination of crop management by the farmer and the varietal characteristics of the tobacco under cultivation (T.R.B, 2013). In Zimbabwe, the general topping height recommendation is between 18 to 20 leaves so as to maximize translocation of nutrients within the leaves for maximum weight attainment (T.R.B, 2013). Exceeding 20 leaves usually results in thin underweight leaves while topping with fewer than 18 leaves appears to have no significant leaf weight advantage (T.R.B, 2013). A crop under severe nutrient or environmental stress, however, tends to have stunted or retarded growth such that it does not attain the required number of leaves (Svotwa *et al*, 2012, TRB, 2013). The number of leaves on a plant directly affects the absorption and reflection of electromagnetic energy and should directly affect NDVI (Gausman and Escobar, 1973). The topping of the apical region greatly influences the maximum achievable height that a tobacco crop can achieve (T.R.B, 2013). Since leaf body may continue to increase under conditions with adequate nutrient supply, the effect of topping a healthy crop could potentially be different from that of a stressed crop.

The Cropscan MSR radiometer is a handheld field level remote sensing radiometer with spectral bands similar to the first 5 bands of the Landsat Thematic Mapper. The CropscanTM MSR obtains passive reflective electromagnetic energy emitted from vegetative surfaces and expresses it as a proportion of the amount of electromagnetic energy that interacts with the vegetative surface, thereby allowing it to characterize unique features of the vegetation with reasonable accuracy (Ma and Dwyer, 2001). The instrument has been used successfully to estimate the yield of soya beans (Short, 2008) as well as to evaluate disease incidence and yield loss caused by Sclerotinia Stem Rot of Soybeans (Daughtry *et al*, 2000). Recently it was used to estimate tobacco leaf nitrogen content and biomass of flue cured tobacco varieties (Svotwa *et al*, 2012). Despite its success, the CropscanTM MSR does have the limitation of very low spatial resolution: it therefore is very difficult to employ it singularly as a yield estimation tool for national yield estimation exercises. It is therefore limited mainly to ground truthing exercises (Svotwa *et al*, 2012).

The objective of this research was to establish a correlation between ground based (MSR 5) sensor derived NDVI with agronomic variables (stem height, leaf diameter, total leaf number and geometric mean) of flue cured tobacco.

3.1 Materials and Method

The study was carried out at the Tobacco Research Board's Kutsaga Research Station during the 2012/13 season. Kutsaga lies in Natural Region II at an altitude of 1 479 meters above sea level. The station is located on latitude 17`55``S, longitude 31`08``E and receives a mean annual rainfall of 800-1000 mm. Rainfall is normally received during the period November to March. Average temperature is 18^0C in winter and 32^0C in summer. The area has light, well drained, sandy soils of granite origin and are Kaolinitic belonging to group 6 which comprises Paraferrallitic soil with a coarse-grained sand fraction derived from granite (T.R.B, 2013). The soils are position two on the soil catena. These are typically moderately deep to deep well drained soils. The soils are very low in clay content and have low water holding capacity. They are slightly acidic (pH 5.2). The experiment was carried out on lands that are rotated with a Katambora Rhodes grass after every 3 years of tobacco cultivation.

3.2 Cultural practices and treatment application

The land was early ploughed (January to end of March) using a tractor- drawn plough to a depth of 38 cm. Ridging and Nematicide Ethylene Di Bromide (EDB) 98% application at a rate of 125 ml/100 m were done prior to planting. The Nematicide was applied 38 cm below the ridge by an injector gun in the planting station. The ridges were spaced at 120 cm and a plant spacing on the ridge was 56 cm. Compound C (N6: $P_2O_5$18: K_2O17) fertilizer was applied at a standard rate of 750 kg/ha as recommended by the soil fertility analysis laboratory.

3.3 Measurements

A total land area of 100 Ha of tobacco crop was planted in three main blocks, with 33 Ha in September, 25 Ha in October and 33 Ha in November for each block. For each block, three dimensional positions latitude, longitude and altitude for the whole experimental area and for each treatment plot were be taken using a Garmin Personal Navigator (GPS V) to enable repeated sampling at the same location. 10 sub blocks were selected with an area of 5 Ha each within each main block. Ten points were selected randomly from each sub block in order to create variable growth conditions that are necessary to establish the relationship between spectral data, biophysical variables and above ground biomass. In each sub block measuring 5 Ha, stratified GPS assisted random sampling was done to select 10 plants for weekly sampling for leaf variables and NDVI measurements. The measurement taken from 10 samples were averaged to a single unit and, corresponding leaf length, leaf width, plant height, leaf number counts and above ground biomass sampling were also collected at the same time from the 10 plants selected randomly within the 5 Ha blocks and were averaged. This was repeated at weekly intervals up to 12 weeks after planting when reaping intensified. The data analysis and graph plotting was done using Microsoft Excel 2007 package.

CropscanTM Multispectral Radiometer 5 (MSR5) was used to obtain canopy reflectance values in the wavelength ranges of 450–1750 nm using the Crop Canopy Reflectance Procedure. The measurements were taken around solar noon to minimize the effect of diurnal changes in the solar zenith angle in the 10 selected plants at weekly intervals. The NDVI was computed from the reflectance values obtained in the Channel 3 and 4 of the MSR 5 which correspond to the Visible (RED) and Near Infra Red (NIR) respectively using the following formula:

$$NDVI = \frac{nir - red}{nir + red}$$

3.4 Results

3.4.1 Leaf number

The relationship between leaf number and NDVI of flue cured tobacco is summarized by the diagram below.

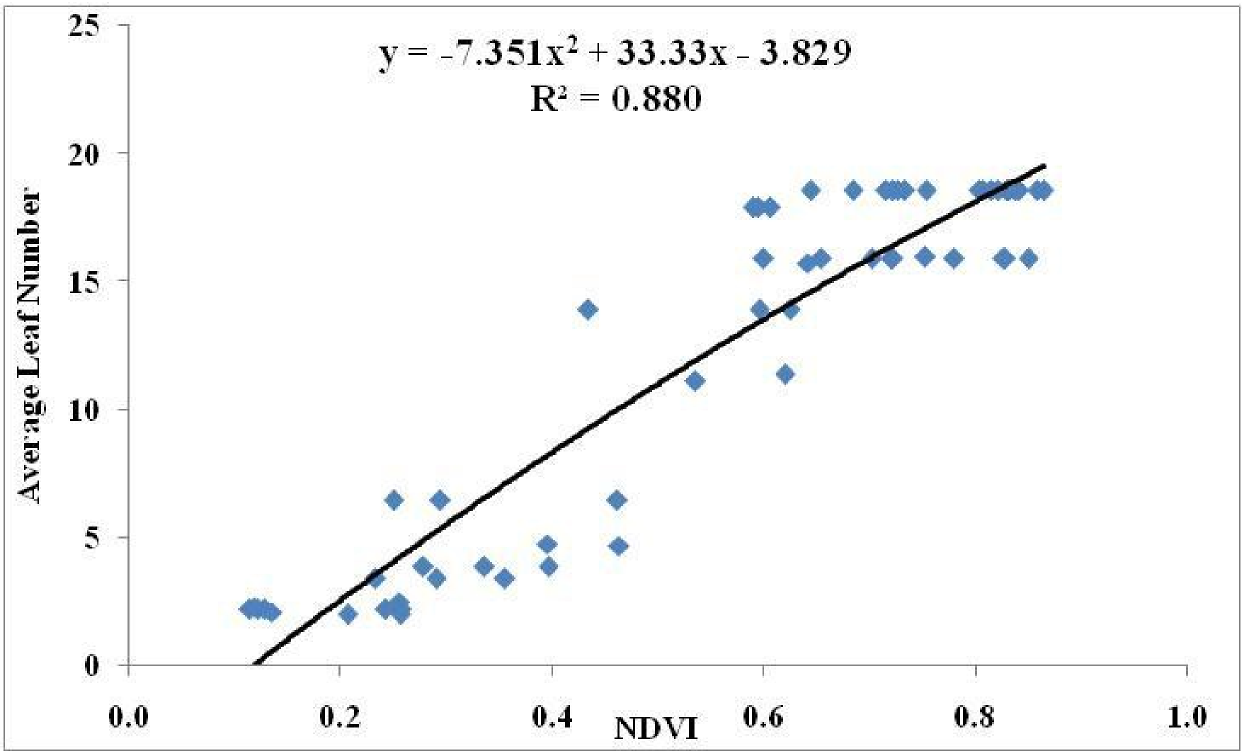

Figure 3.1: The relationship between Leaf Number and CropscanTM derived NDVI

A positive polynomial relationship was observed between NDVI and leaf number per plant with a correlation co-efficient of $R^2 = 0.88$ ($P<0.001$) (Figure 3.1). NDVI continued to increase until a maximum level of 0.86 despite the leaf number becoming constant at 18 leaves (Appendix 2).

3.4.2 Leaf length

The relationship between NDVI and the leaf length of flue cured tobacco is illustrated in figure 3.2 below.

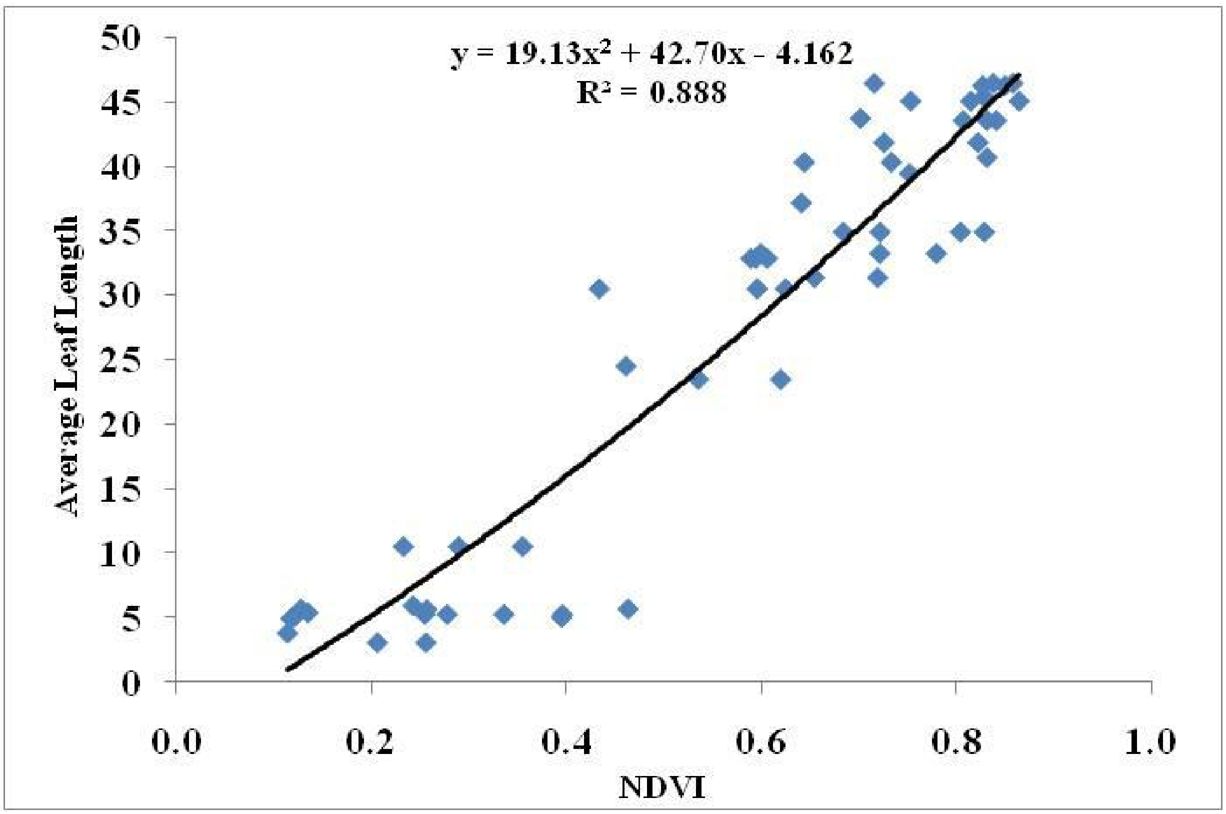

Figure 3.2: The relationship between Leaf Length and CropscanTM derived NDVI

NDVI increased as the average leaf length of tobacco leaves increased (Figure3.2). A coefficient of determination of $R^2 = 0.888$ ($P<0.001$) between average leaf length and crop scan derived NDVI was observed.

3.4.3 Leaf width

The response of NDVI to the changes in flue cured tobacco leaf width is shown in figure 3.3 below.

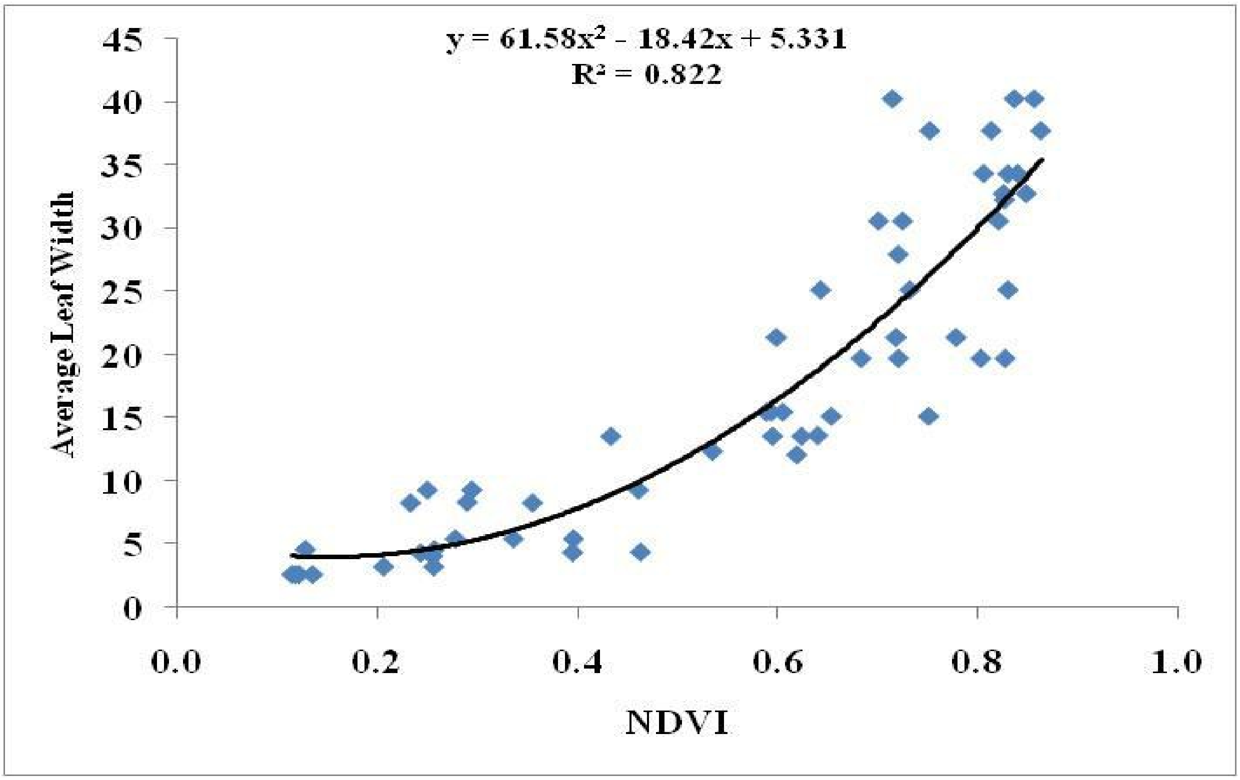

Figure 3.3: The relationship between Leaf Width and CropscanTM derived NDVI

The leaf width NDVI relationship showed a positive relationship ($P<0.001$) ($R^2=0.822$). The correlation coefficient was notably lower than that of leaf length to NDVI

3.4.4 Plant height

The response of flue cured tobacco plant height in relation to NDVI is shown in figure 3.4 below.

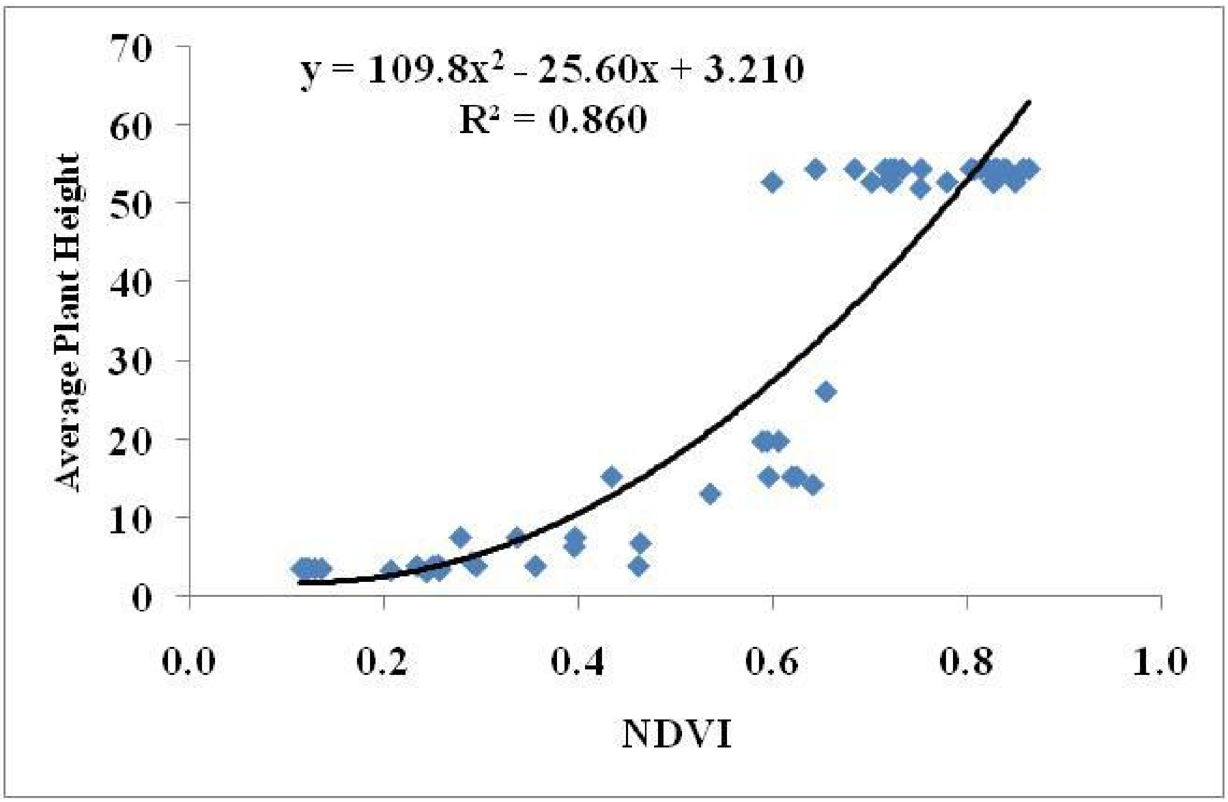

Figure 3.4: The relationship between Plant Height and CropscanTM derived NDVI

A positive relationship was observed between plant height and NDVI with a coefficient of determination of $R^2 = 0.86$ ($P<0.001$) (Figure 3.4). An important observation was that there was considerable variation in NDVI beyond 0.6 despite the plant height being constant.

3.4.5 Geometric mean leaf area

The geometric mean leaf area relationship to NDVI is illustrated in figure 3.5 below.

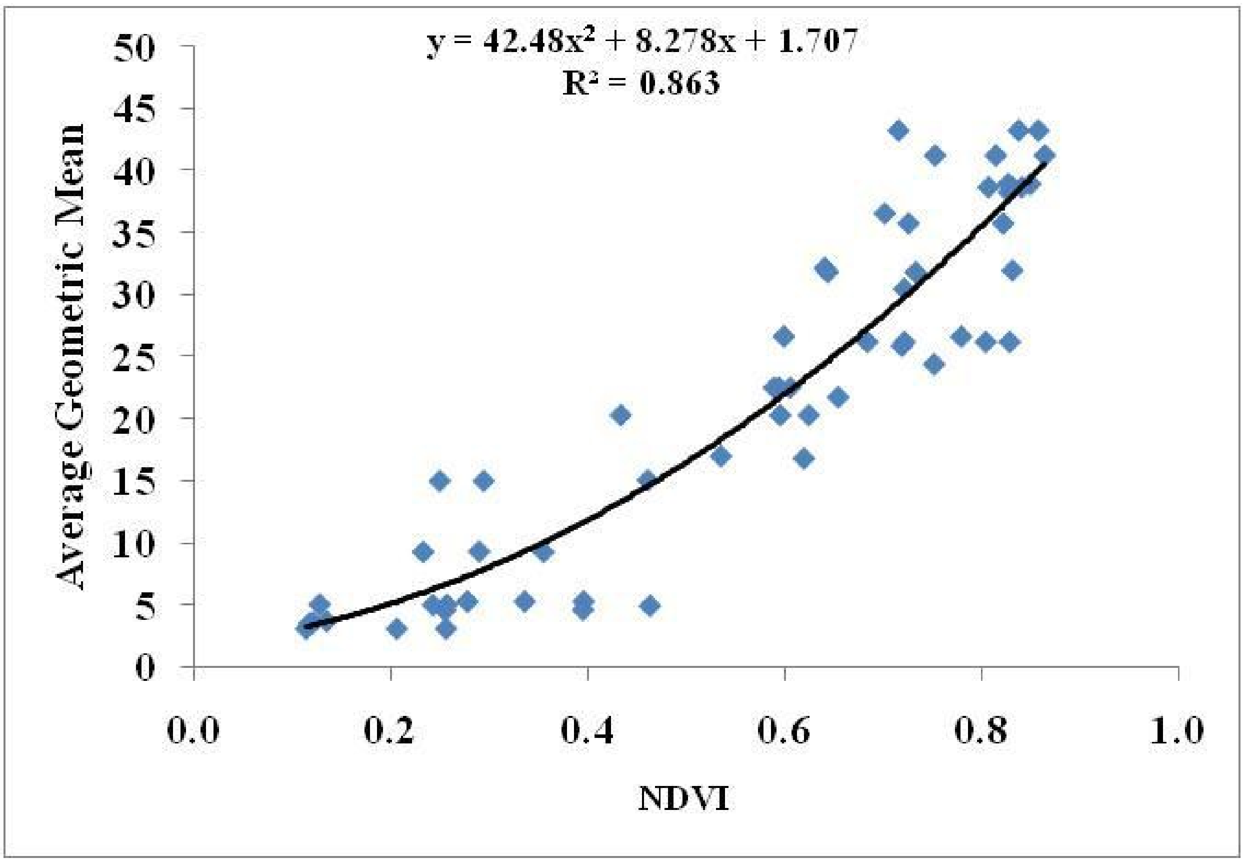

Figure 3.5: The relationship between Geometric Mean and CropscanTM derived NDVI

The relationship between NDVI and Geometric Mean also showed a positive relationship with a coefficient of determination of 0.863 ($P<0.001$) (Figure 3.5). Highest Geometric mean achieved was 43.18 cm that corresponded with the highest NDVI observed of 0.86.

3.4.6 Dry mass

The response of total dry mass of tobacco to the measured NDVI is demonstrated in figure 3.6 below.

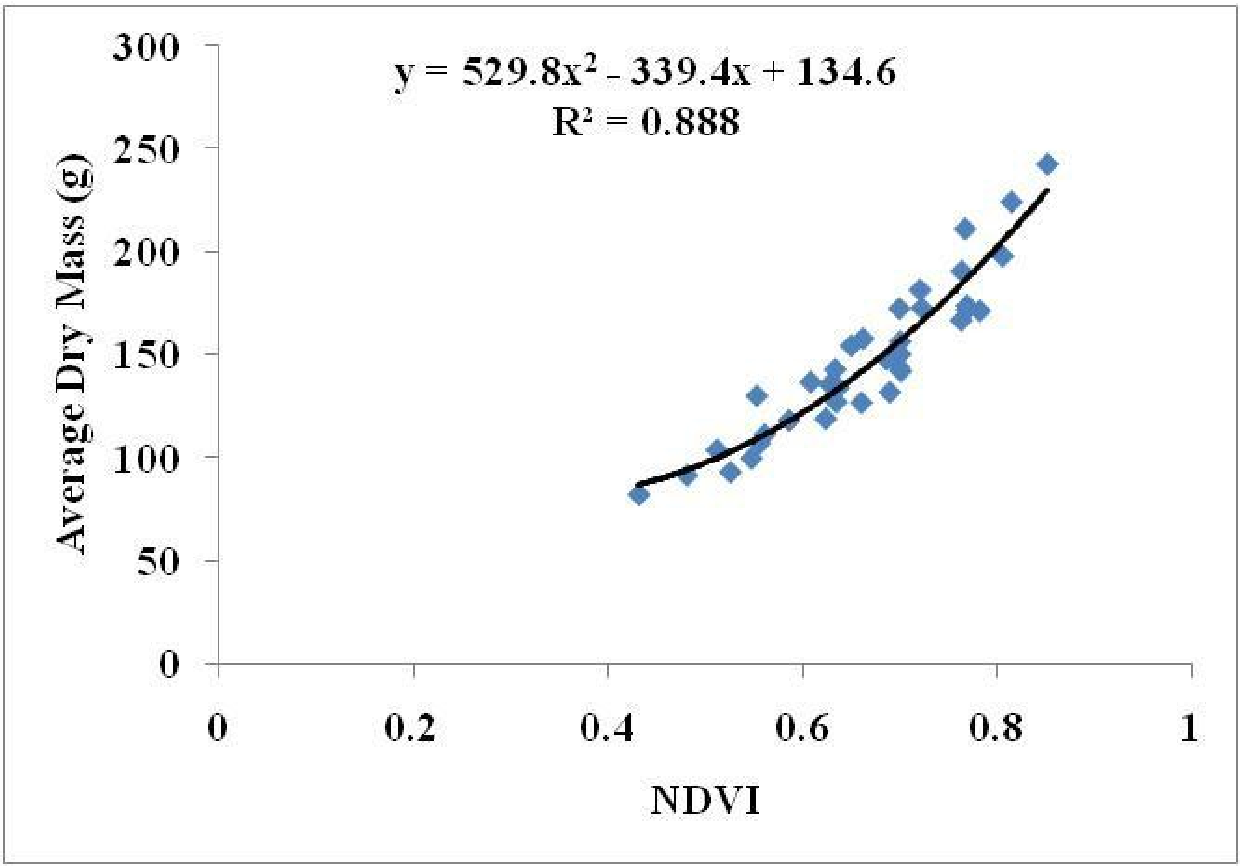

Figure 3.6: The relationship between above ground dry mass and CropscanTM derived NDVI

NDVI was positively correlated to above ground sampled dry mass of tobacco (R^2 =0.89) ($P<0.001$) (Figure 3.6). Maximum NDVI attained during the season was 0.85 which corresponded with the highest dry mass attained of 242.6 g

3.4 Discussion

The strength of the relationship between leaf number and NDVI compares well with the findings in grain yields studying the LAI-NDVI relationship (Osborne *et al*, 2002). Similar coefficients of determination of 0.8 (Sims and Gamon, 2002) were also established in several crop species. The leaf is the photosynthetic machinery in plants and leaf area and is directly related to yield (Curran *et al*, 2001). The leaf number determines Leaf area index (*LAI*), the total one-sided area of leaf tissue per unit ground surface area (Ritchie and Bednarz, 2005). LAI is a key parameter in eco-physiology, especially for scaling up the gas exchange from leaf to canopy level. It characterizes the canopy– atmosphere interface, where most of the energy fluxes exchange (Ritchie and Bednarz, 2005). The linearity of the leaf number and NDVI would allow for the use of crop scan derived NDVI to be used in the estimation of crop yield. However, the two levels of constant leaf number suggest that the approach should target crop species of similar planting times. At growth stages later than 10 weeks after planting, however, leaf number remained constant due to topping, as NDVI continued to increase, probably due to leaf expansion and resultant increase in canopy density as hypothesized by Hatfield *et al* (2008).

The relationship between leaf length and NDVI was also positive, showing an increase in light use efficiency as the crop leaf developed (Yin *et al*, 2011). Leaf expansion directly influences the surface area available for electromagnetic interactions and as a result, contributes sufficiently to the overall NDVI measured by a sensor (Campbell, 2002: Myeni *et al*, 1995). Gross leaf length is measured from the leaf butt, the point where lamina starts to the leaf tip. Leaf length development is used in the assessment of crop development (Yin *et al*, 2011).

The role of the leaf width biophysical factor is equally related to leaf length and it influences NDVI in a similar manner. Leaf width changes indicate canopy development and influence NDVI (Ritchie and Bednarz, 2005: Yin *et al*, 2011: Sellers 1985). At Kutsaga Research station, leaf length and leaf width are used to compute an index for estimating leaf area called Geometric Mean length (cm), which allows for the comparison of varieties with varying length-width ratios (T.R.B, 2013).

Although there was sufficient strength in the coefficient of determination for plant height and NDVI, it may not be an accurate assessment tool for in-season tobacco crop health assessments due to the observed variation in NDVI after crop height becomes constant because of topping. The limitation of NDVI as a universal plant indicator is supported by Hatfield *et al*, (2008) who argued against the use of NDVI alone as a predictor of agronomic variables in crop management. Similar findings were also observed in corn (Xinhua *et al*, 2010). The variation could be as a result of in-field variations of soil fertility and moisture such that biomass accumulation was not homogenous in the fields resulting in it being independent of the height at which the tobacco was topped, as evidenced by similar conclusions in research work on N use efficiency in corn (Tolulios *et al*, 1998).

Another argument could be made as to why NDVI varies after plant height was arrested by topping could be because of the effect of planting date as discussed by Svotwa *et al* (2012). September planted tobacco generally yield better cured leaf mass than subsequent plantings in

October and November (T.R.B, 2013). Therefore, the height at which the tobacco is topped will influence the biomass attenuation of the crop and ultimately, the NDVI response observed.

The positive relationship between NDVI, leaf number, leaf dimensions and plant height is an indication of NDVI being an indicator of productivity and hence final biomass and yield. This makes the NDVI appropriate in in-season crop assessment as well as in identifying in field nutrient and environmental heterogeneity.

3.5 Conclusions

Leaf length, width, and plant height and above ground biomass can be estimated accurately with NDVI derived from CropscanTM Multispectral Radiometer 5. There is merit in attempting to delineate stressed and healthy tobacco crops stands by observing and comparing their NDVI values to those obtained in this study. Corrective management measures that are employed once crop limitation is detected can also be feasibly measured by observing the NDVI changes that might occur due to the crops response to and managerial and environmental changes introduced to the crop stand. Also, field to field variation, in-field variations and environmentally introduced heterogeneity that potentially cause low productivity in tobacco farms can be investigated using the Cropscan sensor.

There is potential for the application of crop scan derived NDVI in the in-season monitoring of biophysical crop variables which are related to yield. The usefulness of the Multispectral radiometer however is limited to monitoring one field at a time. From past research, the MRS was found very compatible with Satellite platforms like MODIS and Landsat. The CropscanTM is still limited in spatial coverage and other means such as Satellite platforms are required to meet national crop status evaluations simultaneously. However, although adequate for localized tobacco fields, this method is impractical for large scale tobacco crop status evaluation such as national tobacco evaluations.

CHAPTER FOUR

COMPARISON OF LANDSAT ETM AND MODIS SATELLITE IMAGERY FOR FLUE CURED TOBACCO CROP STATUS ASSESSMENTS

INTRODUCTION

In-season crop assessments provide valuable insight to the physiology of a tobacco crop within its growing stages such that essential agronomic decisions can be implemented to maximize yield (Svotwa *et al*, 2013). In-season crop assessments provide important feedback information that aids in identifying mid season problems such as drought, fertilizer inadequacies, pest and disease damage as well as climate induced crop responses. Once these physiological anomalies are identified, corrective measures can be easily employed and maximum yields can be attained. Traditional crop assessments involve individual farm visits and visually interpreting crop physiological conditions observed from the crops. Until recently, Remote sensing applications in tobacco crop assessment were conducted using hand held ground based sensors as demonstrated by Svotwa *et al* (2012). The remotely sensed data proved feasible and more accurate than the visual crop assessment methods: however, the research concluded that in order for national crop assessment to be done objectively, there was need for a more robust data collection tool such as satellite remote sensing.

Zimbabwe currently lacks a reliable, fast and accurate means of ascertaining the national tobacco crop status simultaneously during a growing season. As a result, crop husbandry challenges faced by farmers are rarely identified correctly and within acceptable time frames. The evidence of this lies in the low average national tobacco yield recorded in the country annually at the tobacco auction floors approximated at 1000 -1500 kg/ ha (T.I.M.B, 2005). This is in direct contrast to the varietal yield performance data expected from these varieties. Varieties such as K RK 26 and 28 are proven to yield over 3000 kg/ha (Nyoka, 2000) while newer varieties such as T 72 and T 71 are reported to achieve yields in excess of 4000 kg/ha under correct management practices (T.R.B, 2013). A major cause of yield loss potential in tobacco varieties is the time of planting. It is widely accepted that early planted varieties yield significantly higher than later planted varieties (Svotwa *et al*, 2012). When the time of planting has been considered, the next major yield limiting factor is the crop management which varies greatly from field to field (Nyoka, 2000).

A foreseeable challenge to the application of satellite instruments for large data sets such as that of national tobacco assessment is that of the cost of satellite image acquisition. This challenge can be overcome by the adoption of freely available satellite platforms such as the Landsat 7 ETM and MODIS platforms. Satellites sensors with the highest resolutions such as QuickBird and IKONOS are still considerably expensive and may not be feasible for the purposes of national crop assessment where large data sets are involved. Of the freely available platforms, there is need to determine which platform most appropriately monitors tobacco crop phenology during a growing season (Murwira and Skidmore, 2010).

Doraiswamy *et al*, (2004), argued that despite a low spatial resolution of 250 m, MODIS products were suitable for crop assessments of corn and soybeans due to the high frequency of data collection offered by the high temporal resolution of MODIS. However, the trial also suggested that Landsat TM was more applicable as the land sizes became smaller although the low temporal frequency and influence of cloud cover could negatively affect its suitability (Doraiswamy *et al*, 2004). An important conclusion from the work was the need for research work to account for variations that occur due to changes in leaf properties and canopy architecture, this study, in part addresses this challenge.

Other research work has suggested that Landsat TM is not suitable for crop classification at national scales due to the need for lengthy acquisition and processing that is associated with it (Svotwa *et al*, 2013). Also, the data sizes are considerably large and are complicated by relative unavailability of good cloud free quality images during the appropriate temporal windows. This is a foreseeable challenge to tobacco assessment with Landsat TM in Zimbabwe.

4.1 Study objectives

The aim of this study was to compare the ability of Landsat 7ETM and MODIS satellite platforms in monitoring in-season tobacco agronomic variables.

4.2 Specific Objectives

1. To determine the relationships between agronomic variables of tobacco to Landsat 7 ETM derived NDVI
2. To determine the relationships between agronomic variables of tobacco to MODIS derived NDVI

4.3 Method

The experiment was carried out at the Tobacco Research Board’s Kutsaga Research Station, near Harare, Zimbabwe between September 2012 and June 2013 and repeated between September 2013 and February 2014. Tobacco was grown on 5 blocks of land with a total area of 94 Ha at the locations specified in the table below.

Table 4.1: Kutsaga Research station experimental lands

Land Name	**Area (Ha)**	**Latitude**	**Longitude**
A	10	17^{o}54’23.88 S	31^{o}08’28.04 E
B	16	17^{o}55’53.54 S	31^{o}06’57.59 E
C	16	17^{o}54’42.79 S	31^{o}07’26.46 E
D	29	17^{o}54’11.07 S	31^{o}06’56.73 E
E	23	17^{o}54’02.99 S	31^{o}07’09.15 E

The tobacco variety K RK 66 was used and standard fertilizer, topping and weed management practices were used as guided by the Flue Cured Recommendations (TRB, 2013). The variety was chosen because of its popularity among growers. It is now grown by over 80% of the farmers (TRB, 2013).

4.4 Data Collection

Satellite images were freely downloaded from the USGS Glovis website: www.earthexplorer.usgs.gov between the 2012-2013 and 2013-2014 tobacco seasons. MODIS 16 day NDVI data products were selected because of their high data return rates. Landsat 7 ETM images were obtained in GeoTif format.

Weekly plant height, leaf number, leaf diameter and leaf length measurements were collected in all the tobacco lands using the survey design outlined in Chapter 3. Weekly plant variable measurements were taken to correspond with image sampling dates on the 5 lands outlined in table 4.1 above. The scenes selected from the imaging software covered the land area under tobacco cultivation as shown in table 4.1. A personal Global Positioning Satellite Receiver (Garmin GPS V) was used to mark the centre of each field so as to allow repeatability and accurate land identification. Ground truthing was done using the Cropscan Multi-spectral Radiometer (MSR 5) radiometer.

4.5 Data Processing

Agronomic parameter data was processed using Microsoft Excel 2007. MODIS data was provided preprocessed and only required NDVI extraction through ENVI version 4.3 software was done. Landsat Level 1 data products required extraction of Digital Numbers (DN) first using ENVI 4.3 and post processing to obtain Radiance and further processing to obtain Reflectance values that were eventually used to calculate NDVI.

4.6 Digital Numbers to Radiance processing

Pixels within the identified tobacco lands were randomly selected and their DN values noted. Care was taken to avoid boundary pixels that may be influenced by non tobacco reflectance. The Spectral Radiance Scaling Method was used to obtain radiance using the following formula:

$$L_\lambda = ((LMAX_\lambda - LMIN_\lambda)/(QCALMAX - QCALMIN)) * (QCAL - QCALMIN) + LMIN_\lambda$$

Where: $L\lambda$ is the cell value as radiance

QCAL = digital number

$LMIN\lambda$ = spectral radiance scales to QCALMIN

$LMAX\lambda$ = spectral radiance scales to QCALMAX

QCALMIN = the minimum quantized calibrated pixel value (typically = 1)

QCALMAX = the maximum quantized calibrated pixel value (typically = 255)

4.7 Radiance to Reflectance

The radiance values obtained from the above method were further processed into reflectance using the following formula:

$$\rho_\lambda = \pi * L_\lambda * d^2 / ESUN_\lambda * \cos\theta_s$$

Where: $\rho\lambda$ = Unitless plantary reflectance

$L\lambda$= spectral radiance (from earlier step)

d = Earth-Sun distance in astronomical units

$ESUN\lambda$ = mean solar exoatmospheric irradiances

θs = solar zenith angle

4.8 Results

4.8.1 Leaf number

The relationships between NDVI of MODIS and Landsat 7 obtained satellite NDVI to the leaf number of flue cured tobacco are shown in Figure 4.1

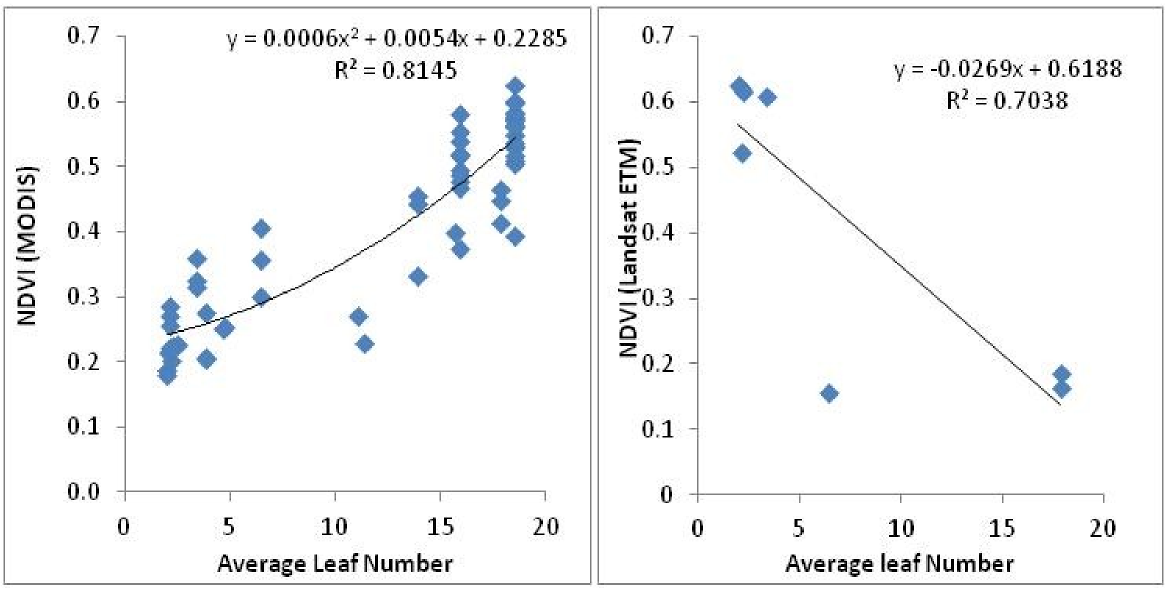

Figure 4.1: The relationship between: A MODIS, B Landsat NDVI and leaf number

A positive polynomial relationship (r^2 = 0.81) was observed between $MODIS_{NDVI}$ and leaf number while the relationship between $Landsat_{NDVI}$ with leaf number was inversely correlated (R^2 = 0.71). The $Landsat_{NDVI}$-leaf number relationship showed poor data distribution.

4.8.2 Leaf length

The relationships between leaf length of flue cured tobacco and NDVI obtained from MODIS and Landsat 7 are shown in figure 4.2.

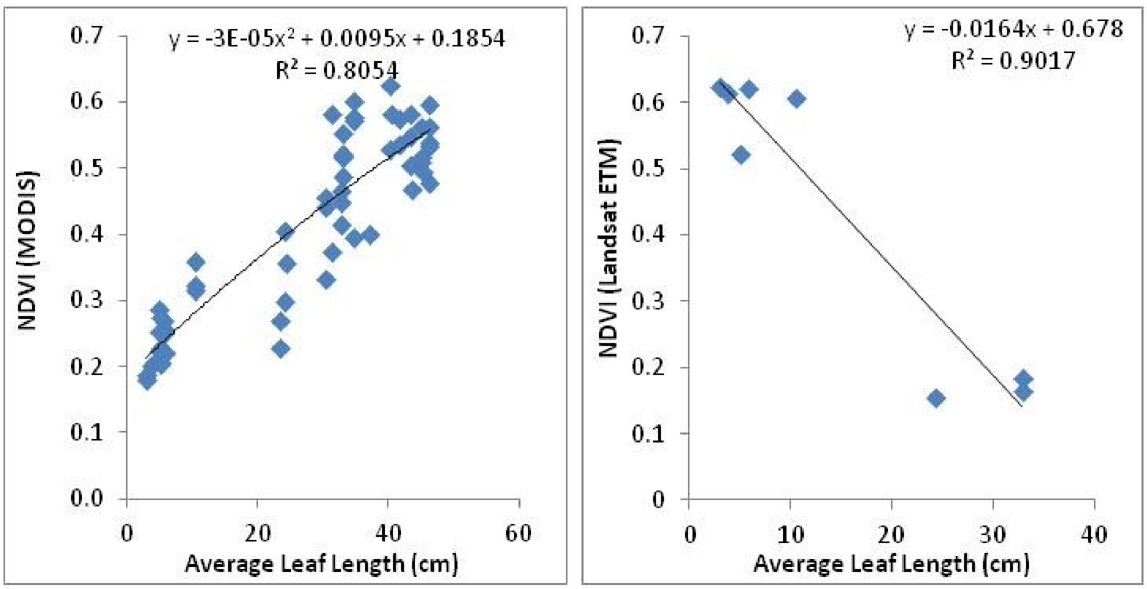

Figure 4.2: The relationship between: A MODIS, B Landsat NDVI and leaf length

As leaf length increased, $MODIS_{NDVI}$ increased correspondingly, a regression coefficient of 0.764 was noted. However, the relationship was reversed with $Landsat_{NDVI}$ that showed a strong inverse relationship with leaf length (Figure 4.2).

4.8.3 Leaf width

The response of MODIS and Landsat 7 NDVI to leaf width changes in flue cured tobacco is given in figure 4.3

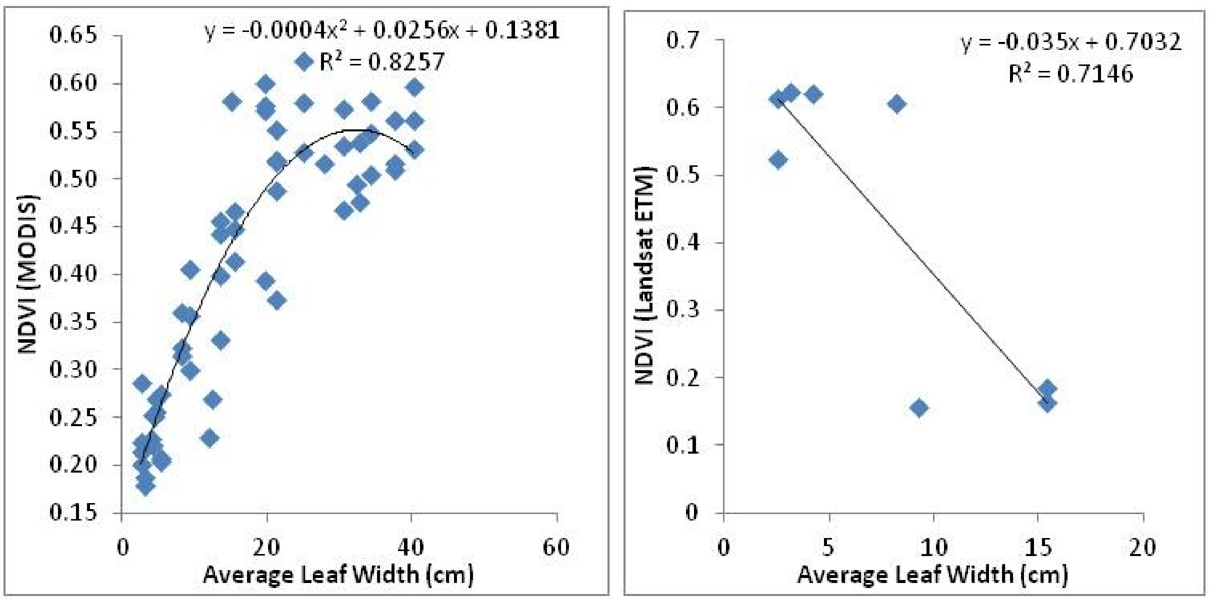

Figure 4.3: The relationship between: A MODIS, B Landsat NDVI and leaf width

Leaf width corresponded positively with $MODIS_{NDVI}$ with a coefficient of regression of 0.707. $Landsat_{NDVI}$ showed an inverse relationship with leaf width similar to that observed with leaf length (Figure 4.3).

4.8.4 Plant height

The response of MODIS and Landsat 7 derived NDVI to the increase in height of flue cured tobacco from transplanting to onset of reaping showing the effect of topping on biomass accumulation (Figure 4.4).

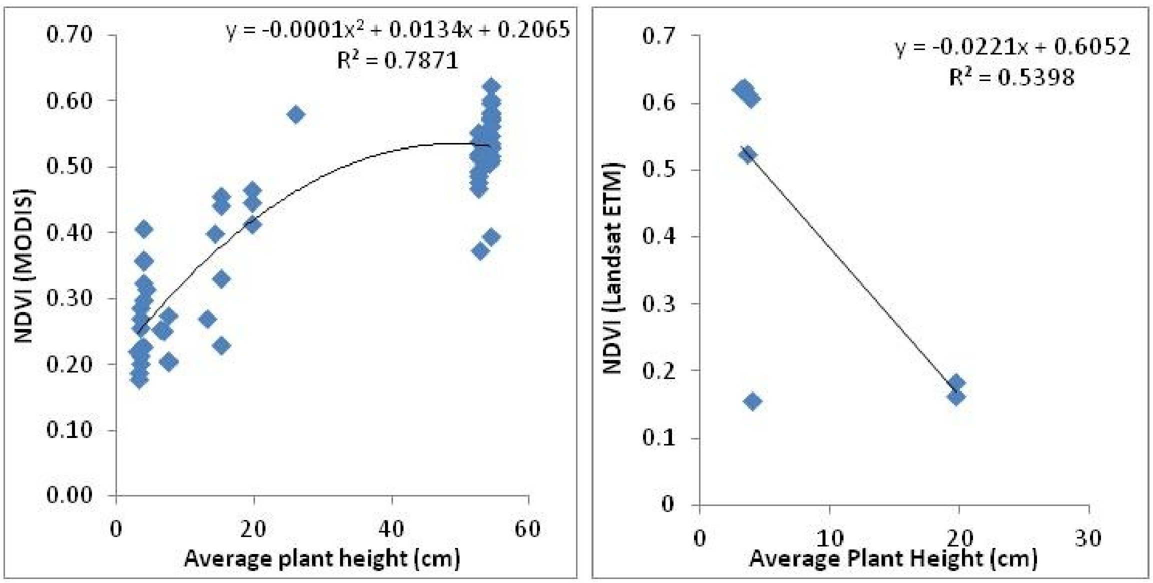

Figure 4.4: The relationship between: A MODIS, B Landsat NDVI and plant height

$MODIS_{NDVI}$ correlated positively with plant height of tobacco with a coefficient of determination of 0.694. There was notable variation in $MODIS_{NDVI}$ between 0.4 and 0.65 despite plant height having reached a constant. This is not noted in the inverse relationship between $Landsat_{NDVI}$ and plant height Figure 4.4.

4.8.5 Geometric mean leaf area

The cumulative effect of leaf expansion is shown through the response of MODIS and Landsat 7 derived NDVI to geometric mean leaf area index of flue cured tobacco given in figure 4.5.

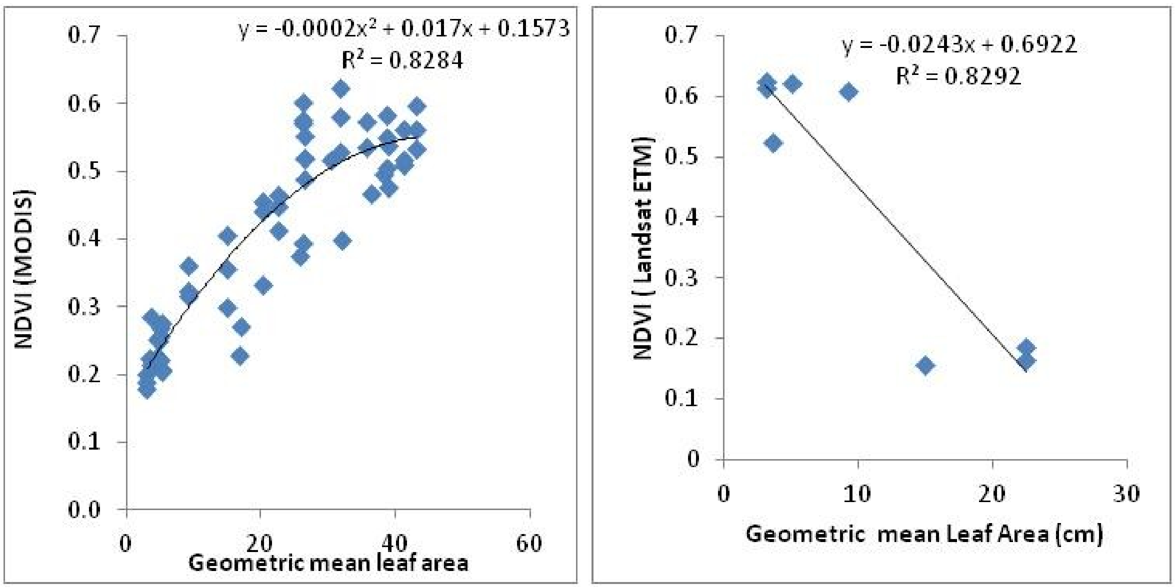

Figure 4.5: The relationship between: A MODIS, B Landsat NDVI and Geometric mean leaf area

The Geometric mean leaf area index correlated positively with $MODIS_{NDVI}$ (r^2=0.82) with lower variation than was observed in leaf length and leaf width independently. $Landsat_{NDVI.}$ showed a characteristic inverse relationship as observed in the earlier discussed agronomic variables. The highest Geometric mean average also corresponded with the highest attained $MODIS_{NDVI}$ (Figure 4.5).

Table 4.2: Effect of cloud contamination and usable data on Landsat 7 and MODIS platforms

Platform	Total Images Available	Cloud free images	Usable data
MODIS	**15**	**15**	**100%**
LANDSAT 7 ETM	**9**	**3**	**33.3%**

Most of Landsat 7 ETM images had significant cloud cover that inhibited the acquisition of usable data for analysis and comparison (Table 4.3). The most affected data sets were during November, December and January as illustrated in plate 1and 2.

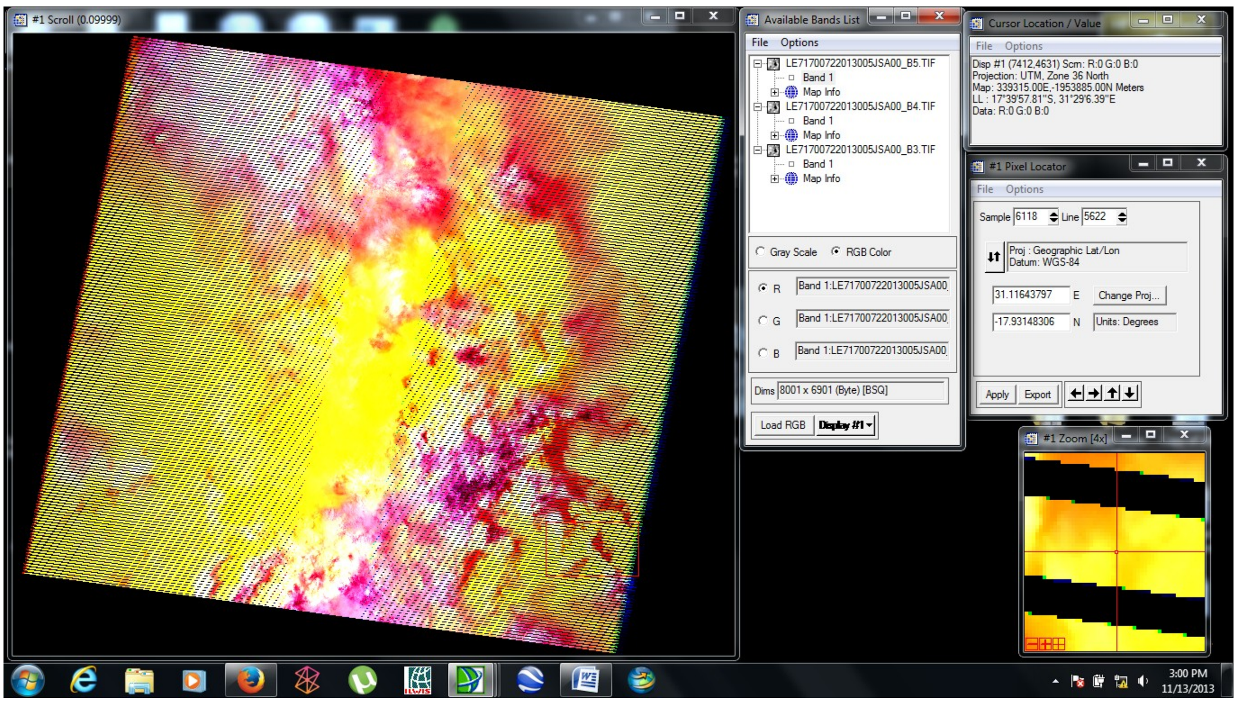

Plate 1: Full scene cloud contamination Landsat scenes

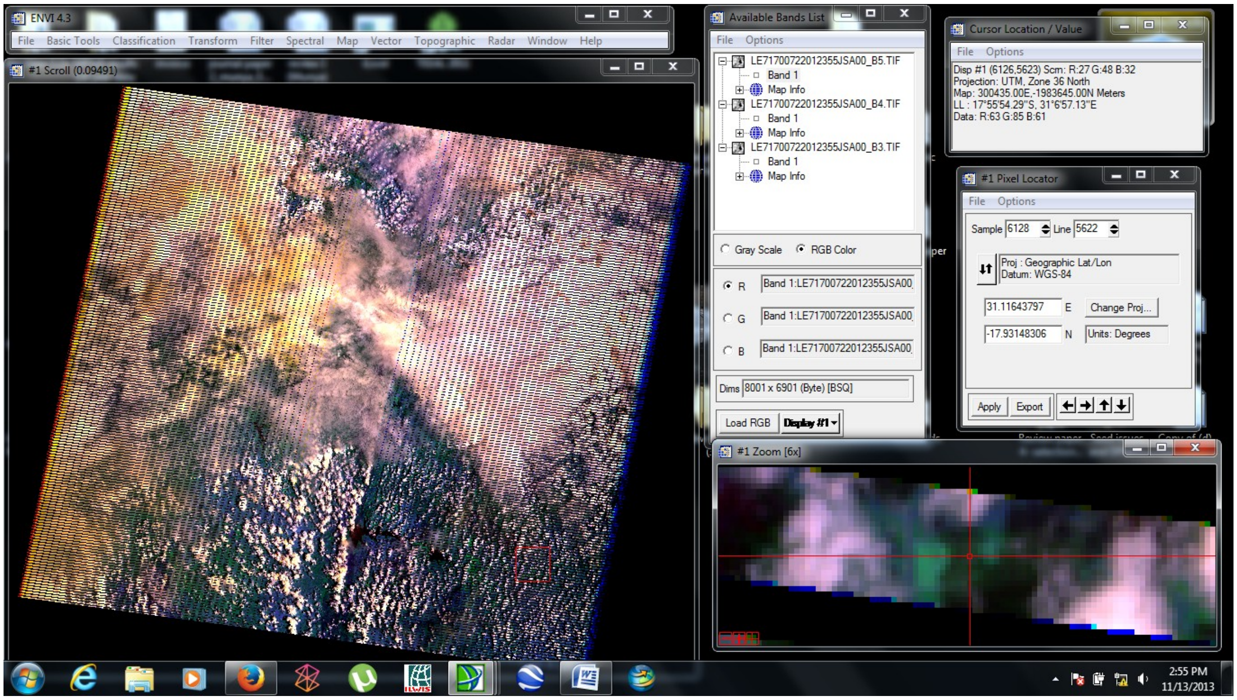

Plate 2: Partial cloud contaminations on Landsat scenes

Partial cloud cover was observed in some Landsat ETM images. The calculated NDVI from such images was higher compared to cloud clear images (Plate 2).

There were positive correlations between NDVI obtained from MODIS satellite platforms to tobacco leaf number, leaf length, leaf width, plant height and geometric mean leaf area in both the 2012-13 and 2013-14 tobacco seasons showing a corresponding increase in measured NDVI to increase in crop growth. An inverse relationship between NDVI calculated from Landsat 7 imagery to leaf length, width, leaf number and geometric mean leaf area was observed. No data was observed from the MERIS platform in the 2012-13 seasons due to server accessibility problems experienced with the MERIS platform. In the 2013-14 season, MERIS data was not obtained due to an unexpected price charge for imagery downloading from the primary data supplier of MERIS imagery in Zimbabwe, the University of Zimbabwe's GIS and Remote Sensing laboratory.

4.9 Discussion

MODIS derived NDVI ($NDVI_{MOD}$) correlated positively with leaf number, leaf length, leaf width, plant height and geometric mean leaf area with a coefficient of determination of 0.81, .080, 0.82, 0.78 and 0.82 respectively. These findings are consistent with the positive relationships observed in other agronomic crops in separate trials (Ritchie and Bednarz, 2005: Sims and Gamon, 2002: Curran *et al*, 2001 and Osborne *et al*, 2002) and demonstrate the suitability of MODIS derived data products in assessing in-season flue cured tobacco. The high temporal resolution characteristics of MODIS satellite platforms allow for more repeated data collection offering more accurate assessments of the phenological changes that occur under field conditions. The correlations of MODIS derived NDVI are in most cases positively and related to the agronomic factor under investigation (USGS, 2013).

In the above discussed data, there is no observed saturation of NDVI at late crop development stages associated with high Leaf Area Index as has been reported by other authors (Hatfield *et al*, 2008). A likely explanation is the comparably lower spectral resolution capabilities of MODIS such that its sensitivity to high LAI of tobacco is reduced. The average yields obtained in the fields under study ranged between 3.6 to 3.9 tonnes/Ha for the two years under which this experiment was conducted. It is possible that tobacco cultivated under exceptionally favorable conditions, particularly climate, may show saturation of NDVI in the late vegetative stages of crop development.

LANDSAT derived NDVI ($LANDSAT_{NDVI}$) showed poor data distribution that was uncharacteristic of a tobacco crop stand. The coefficients of determinations of 0.70, 0.90, 0.70, 0.53 and 0.82 for leaf number, leaf length, leaf width, plant height and geometric mean leaf area respectively in inversely correlated relationship but did not adequately characterize tobacco crop phenology. Other studies have shown similar findings (Mohd *et al*, 1994 and Rajapakse *et al*, 2000), and concluded that limited and contaminated images caused the findings. The results from this study cannot be directly linked to the agronomic conditions observed in the field as there was not enough consistent data collected due to persistent cloud conditions. This was further exacerbated by the low temporal resolution of the Landsat satellite, thereby limiting the number of images that could be used effectively for crop assessment. The vast majority of the data collected in this study suffered from severe cloud contamination and in some instances, the images themselves were not available for downloading for the study site. As demonstrated in Plate 1, when cloud cover severely compromised the image, no NDVI could be extracted and therefore not enough data was available for comparison. In other instances such as Plate 2, partial cloud cover was observed to provide inconsistently high reflectance values in the visible and Near Infra-red regions of the electromagnetic spectrum and as such, the calculated NDVI was not characteristic of a developing tobacco crop canopy profile.

4.10 Conclusion

Although LANDSAT 7 offers higher resolution than MODIS, it may not be suitable for use in tobacco in-season assessments in Zimbabwe as such assessments are conducted during the rainy season when the crop is actively growing. The low temporal resolution of the LANDSAT satellite appears to be the major factor limiting availability of cloud free images and as a result, the platform is not suitable for tobacco crop assessments.

MODIS platform provided the most reliable crop assessment tool for tobacco during the growing seasons, therefore, it was concluded that the MODIS platform is more suitable for tobacco crop variable monitoring over Landsat 7 ETM. Merit lies in the application of LANDSAT for site specific ground verification exercises where there may be need to further investigate with increased accuracy the causes of poor crop performance that may have been identified using the MODIS satellite platform due to the high resolution of LANDSAT scenes. It is possible to further intergrate the two platforms for a more improved data collection and analysis methodology where primary data collection is obtained from MODIS and verified more accurately by LANDSAT.

CHAPTER FIVE

DEVELOPMENT OF MATHEMATICAL MODELS FOR ESTIMATING TOBACCO CROP BIOPHYSICAL VARIABLES USING MULTISPECTRAL RADIOMETER AND UPSCALED MODIS DERIVED NDVI

INTRODUCTION

The Normalized Difference Vegetation Index (NDVI) is an important crop index for the assessment of the health and vigor of agronomic crops (Huete *et al*, 2002). Traditionally, NDVI has been collected from ground based sensors such as the Cropscan Multispectral Radiometer (Bao, 2009) and has been used to describe on field crop response to fertilizer and agronomic management practices (Svotwa *et al* 2012). NDVI has been obtained from space borne satellite platforms such as MODIS (Williams *et al*, 2008), Landsat ETM (Rajapakse *et al*, 2000) and QuikBird (Wu *et al*, 2007). Most research methods have focused on the use of either ground sensor derived NDVI (Svotwa *et al*, 2012: Bao, 2009) or satellite derived NDVI (Rajapakse *et al*, 2000) independently to estimate yields of various crops with little emphasis on the in-season biophysical crop responses of the crop (Svotwa *et al*, 2013).

When remote sensing data is collected from ground based sensors, the sensitivity of the instruments to agronomic variations is higher than that observed from satellite borne platforms due to reduced atmospheric interaction influencing ground based sensors (Ma and Dwyer, 2001).

As a result, low spatial resolutions from ground sensors require an up-scaling exercise to a higher spatial resolution of satellite platforms that can enable large scale observations to be conducted simultaneously and in real time (Williams *et al*, 2008). Up-scaling techniques allow for more accurate comparisons of crop responses observed from two different platforms to be compared and consistent conclusions be derived (Wang *et al*, 2010).

Tobacco in-season crop assessment at national scale is essential in the development of Remote sensing based yield estimation and crop vigor models (Svotwa *et al*, 2013). The leaf number, leaf length, leaf width and stem length of flue cured tobacco are closely related to the attainable yield of the crop (Garvin, 1986). Satellite sensors differ considerably in acquisition cost (Svotwa *et al*, 2013) and resolution capabilities (Short, 2008). Usually, high resolution platforms such as QuickBird, IKONOS and WorldView would be most applicable for crop assessment. However, they have considerably high image acquisition costs (Murwira and Skidmore, 2010). The lower resolution satellites that are freely available tend to have either course resolution or low temporal resolution (Jayroe *et al*, 2005). As a result, vegetation indices obtained from ground based and satellite based sensors may differ considerably when observing a specific phenomenon (Wang *et al*, 2010). In such cases, there is need for special calibration of estimation models to ensure consistent interpretation using up-scaling techniques.

Up-scaling has been defined as a technique of extrapolating information from a low spatial resolution site-specific scale at which direct field observations have been made to a smaller scale resolved previously (Williams *et al*, 2008). Tobacco crop fields are characterized by spatial heterogeneity as soil types, climatic conditions and agronomic management practices differ from one field to the next and non-linear crop responses are common when agronomic variables are observed, it is therefore important to determine whether any relationships that are determined at ground level scales in field research are applicable directly at coarser satellite platform scales (Williams *et al*, 2008). Without sufficient scaling procedures, direct field measurements and experimental models can introduce a considerable amount of error during operational estimation or forecasting activities (Svotwa *et al*, 2013). In the case of flue cured tobacco, heterogeneity is commonly brought about by different crop husbandry techniques of topping, fertilizer rates, weed and pest control, soil type influence and to a limited extend by the variety (Svotwa *et al* 2012).

Previous studies have attempted to correlate ground measurements of Leaf Area Index against satellite derived NDVI (Turner *et al*, 1999) in non commercial cropping systems with higher degrees of heterogeneity. According to Williams *et al* (2008), these studies did not adequately account for the differences in scales between satellite pixels and ground data collections, nor did they assess the relationship between the NDVI and field measured agronomic variables directly at field level for direct comparison to satellite data. This study sought to compare the responses of flue cured tobacco through different satellite and ground based platforms so as to derive a single means of interpreting data observed in future by any one of the selected instruments. In this study, a direct relationship between ground based instruments is assumed to be higher than the relationship observed on the same fields using satellite instruments.

Research conducted on flue cured tobacco optical responses has shown a relationship between NDVI derived from tobacco varieties to above ground dry mass using the Cropscan radiometer

(Svotwa *et al*, 2012). The research however was limited by the low spatial resolution of the ground based instrument such that it was impractical to conduct large scale crop monitoring exercises. MODIS satellite platforms provide adequate spatial resolution for large scale crop assessments. Because of the coarse MODIS resolution its and susceptibility to atmospheric interference (Svotwa *et al*, 2013), there is need to upscale the MODIS NDVI data to Cropscan NDVI scale as it best estimated tobacco phenology in the earlier chapters. The objective of this experiment was therefore to develop models to upscale low spatial resolution Cropscan data to a higher spatial resolution MODIS scale.

5.1 Specific objectives

1. To establish a relationship between biophysical variables (Leaf length, Leaf width, Plant height, Leaf number and geometric mean leaf area) and Cropscan derived NDVI
2. To establish an up-scaling relationship between Cropscan Derived NDVI and MODIS derived NDVI
3. To establish MODIS NDVI based estimation models for biophysical variables of flue cured tobacco

5.2 Hypothesis

1. There is a linear relationship between tobacco variables (leaf length, width, plant height, leaf number and geometric mean leaf area) and MSR 5 derived NDVI
2. There is a mathematical up-scaling equation for MODIS NDVI to MSR 5 NDVI

5.3 Data processing and model development

1. The experiment sought to develop estimation models for flue cured agronomic variables (Leaf length, leaf width, plant height, leaf number and geometric mean leaf area) based on established relationships between low spatial resolution Cropscan derived NDVI ($NDVI_{MSR}$) and field measured agronomic variables. The expected basic linear functions expected are:

    Equation 1: $L_L = K_2 NDVI_{MSR} + b$

    Equation 2: $L_W = K_3 NDVI_{MSR} + c$

    Equation 3: $L_N = K_4 NDVI_{MSR} + d$

    Equation 4: $P_H = K_5 NDVI_{MSR} + e$

    Equation 5: $G_M = K_6 NDVI_{MSR} + f$

Where: K_2, K_3, K_4, K_5, b, c, d, e and f are constants for the models representing the linear intercepts determining the extent to which the dependant variable (leaf length, width, number, plant height and geometric mean) changes.

$NDVI_{MSR}$ is Cropscan derived NDVI and L_L, L_W, L_N, P_H and G_M are Leaf Length, Leaf Width, Leaf Number, Plant Height and Geometric mean Leaf Area respectively

2. The following stage sought to establish the up-scaling factor in the relationship between Cropscan derived NDVI ($NDVI_{MSR}$) and MODIS derived NDVI ($NDVI_{MOD}$) with the expected linear function of: $NDVI_{MSR} = KNDVI_{MOD} + a$.

Up-scaling factor: $\mathbf{NDVI_{MOD} = KNDVI_{MSR} + a}$

Where: $NDVI_{MOD}$ is up-scaled $NDVI_{MSR}$

$NDVI_{MSR}$ is Cropscan derived NDVI

K and **a** are constants showing the extent to which $NDVI_{MOD}$ changes with $NDVI_{MSR}$

3. By substitution of $NDVI_{MSR}$ with the $NDVI_{MOD}$, the estimation models for the tobacco biophysical plant variables were expected to be as follows:

$$\mathbf{L_L = K_2\,(KNDVI_{MOD} + a) + b}$$

$$\mathbf{L_w = K_3\,(KNDVI_{MOD} + a) + c}$$

$$\mathbf{L_N = K_4\,(KNDVI_{MOD} + a) + d}$$

$$\mathbf{P_h = K_5\,(KNDVI_{MOD} + a) + e}$$

$$\mathbf{G_M = K_6\,(KNDVI_{MOD} + a) + f}$$

5.4 Data collection

Multispectral radiometer (MSR) reflectance readings were collected from 6 tobacco fields weekly from one week after transplanting to 12 weeks when reaping was initiated. Each week, the MSR was calibrated for height adjustment using the manufacturer assumption of the sensor height position being twice the radius of the field of view (spatial coverage) so as to eliminate any errors associated with the vertical growth and canopy expansion of the tobacco. Weekly plant height, leaf number, leaf diameter and leaf length measurements were collected in all the tobacco lands using the survey design outlined in Chapter 3. Weekly plant variable measurements were taken to correspond with image sampling dates on the 5 lands outlined in table 4.1. The scenes selected from the imaging software covered the land area under tobacco cultivation as shown in table 4.1

Satellite data was ordered from the USGS Glovis Website using the Earth Explorer interface to identify the experimental fields. The data obtained from the Bulk Download Application program was geo-referenced and preprocessed with the NDVI data calculated.

Weekly plant height, Leaf length, leaf width and leaf number measurements were collected simultaneously with MSR reflectance readings to increase data accuracy. The plant position for agronomic measurements was marked using a GARMIN Global Positioning Satellite Receiver to ensure repeated sampling positions. Regression analysis and goodness of fit tests were calculated using Microsoft excel 2007 package.

5.5 Results

5.5.1 The relationship between $NDVI_{MSR}$ and L_L

The effect of increasing leaf length of flue cured tobacco on the NDVI obtained from the MSR 5 radiometer is given in figure 5.1.

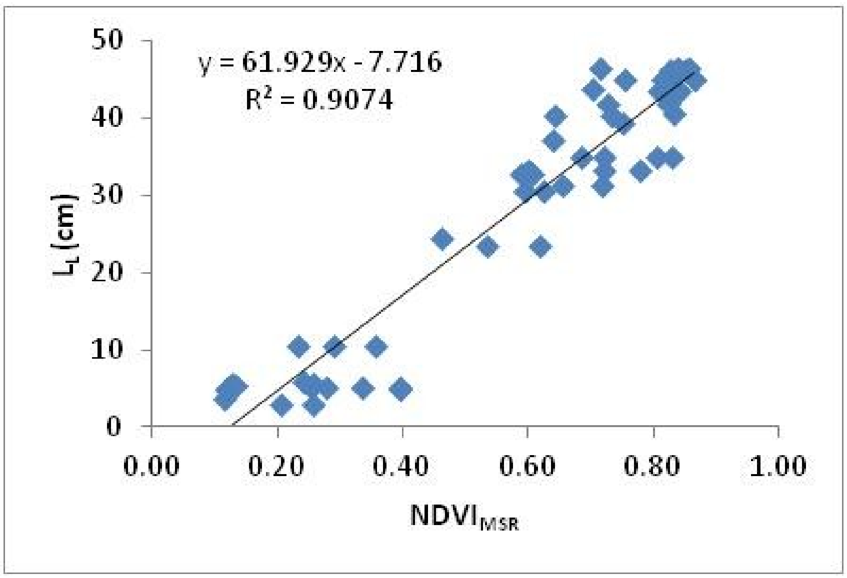

Figure 5.1: The relationship between $NDVI_{MSR}$ and L_L

$NDVI_{MSR}$ showed a corresponding increase as leaf length increased with a linear relationship:

$$L_L = 61.929*(NDVI_{MSR}) - 7.716$$

Where:

L_L= leaf length and $NDVI_{MSR}$ are as earlier defined

5.5.2 The relationship between NDVIMSR and NDVIMOD

The linear relationship between NDVI obtained from MODIS and MSR 5 showing an up-scaling factor for differences in resolution is given in figure 5.2.

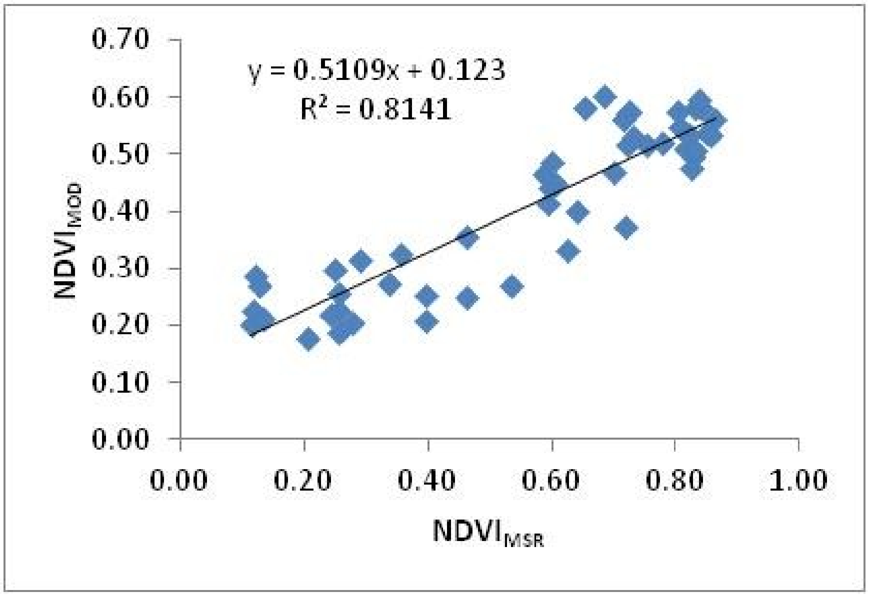

Figure 5.2: The relationship between $NDVI_{MSR}$ and $NDVI_{MOD}$

A positive relationship is observed between $NDVI_{MSR}$ and $NDVI_{MOD}$ with strength of determination of 0.81. Therefore, the up-scaling function for $NDVI_{MSR}$ to $NDVI_{MOD}$ scale as obtained in Fig 5.2 above is:

$$\mathbf{NDVI_{MOD} = 1.5935*(NDVI_{MSR}) - 0.0919}$$

Where $NDVI_{MOD}$ and $NDVI_{MSR}$ are as defined earlier.

The following stages demonstrate the stages involved to develop an estimation model for flue cured tobacco.

Stage 1:

An estimation model for tobacco leaf length based on the relationship between $NDVI_{MSR}$ and measured leaf length obtained in Fig 5.1 is as follows:

$$\mathbf{L_L = 61.929*(NDVI_{MSR}) - 7.71}$$

Stage 2:

By substitution of $NDVI_{MSR}$ with the up-scaling factor obtained in Fig 5.2 earlier:

$$\mathbf{L_L = 61.929*(1.5935*NDVI_{MOD} - 0.0919) - 7.716}$$

The leaf length estimation model can be simplified to:

Equation 1: $\mathbf{L_L = 98.68*(NDVI_{MOD}) - 13.41}$

Where: $NDVI_{MSR}$, $NDVI_{MOD}$ and L_L are as defined earlier

5.5.3 The relationship between LW and NDVIMSR

The response of MSR 5 NDVI to increasing leaf width in flue cured tobacco is shown in figure 5.3 below

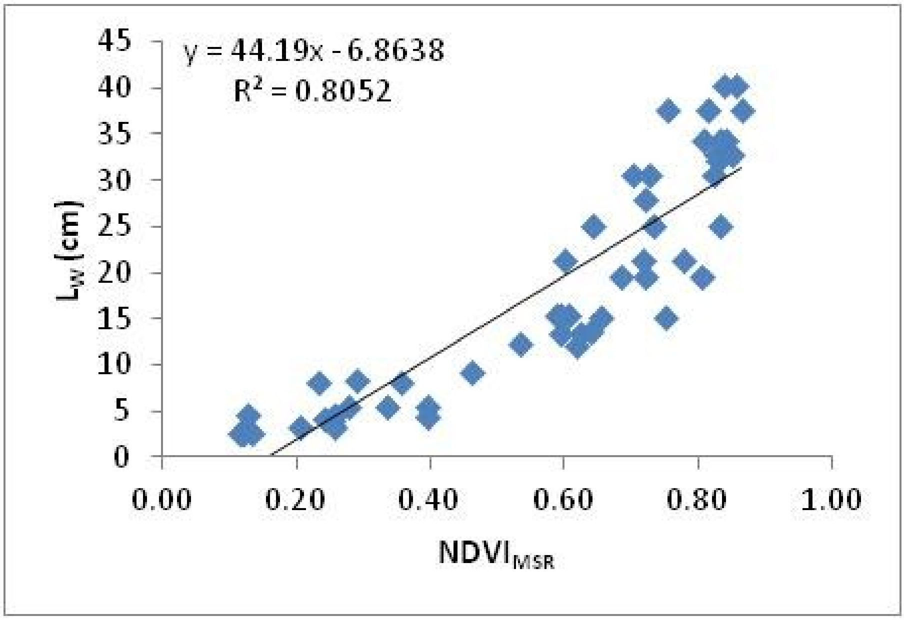

Figure 5.3: The relationship between L_W and $NDVI_{MSR}$

As leaf width expanded, $NDVI_{MSR}$ responded positively with 81% of the variation being accounted for (r^2=0.81). The following relationship was observed:

$$L_W = 44.19*(NDVI_{MSR}) - 6.86$$

By substitution of $NDVI_{MSR}$ by $NDVI_{MOD}$ as in stage 2 earlier, the estimation model for Leaf width can be simplified as equation 2 below:

Equation 2: $$L_W = 70.42*(NDVI_{MOD}) – 10.92$$

Where: L_W, $NDVI_{MSR}$ and $NDVI_{MOD}$ are as defined earlier

5.5.4 The relationship between NDVIMSR and LN

The linear relationship showing the response of MSR 5 derived NDVI to increase in leaf number of flue cured tobacco is given in figure 5.4.

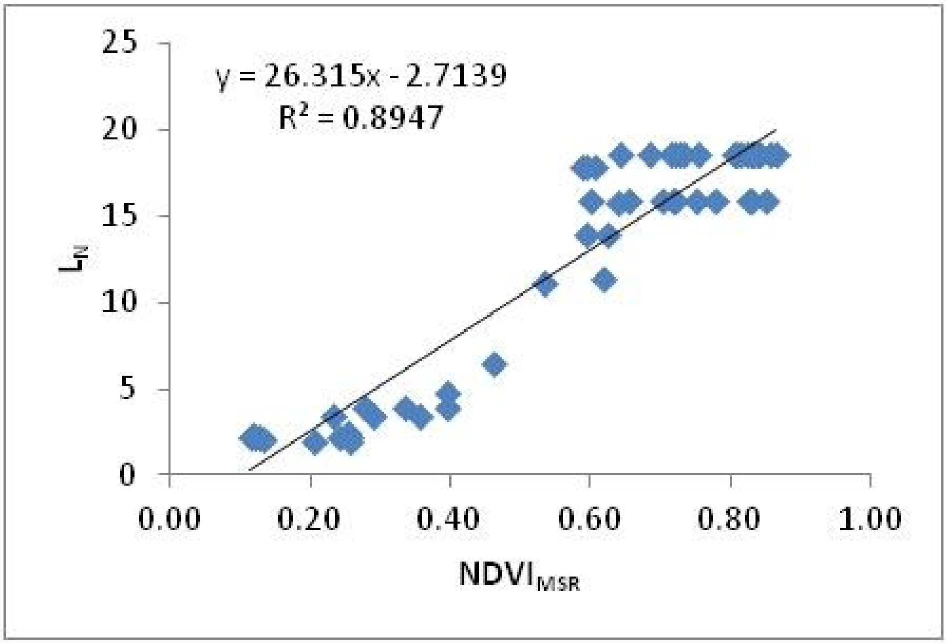

Figure 5.4: The relationship between $NDVI_{MSR}$ and L_N

As leaf number increased, $NDVI_{MSR}$ also increased following a linear relationship with a coefficient of determination of r^2 = 0.89. The $NDVI_{MSR}$ estimation function for leaf width is summarized as:

$$\mathbf{L_N = 26.32*(NDVI_{MSR}) - 2.71}$$

By repeating the substitution of $NDVI_{MSR}$ as demonstrated in stage 2 earlier, a model for estimating leaf number can be simplified as equation 3 below:

Equation 3: $L_N = 41.61*(NDVI_{MOD}) - 5.02$

Where L_N and $NDVI_{MOD}$ are as defined earlier

5.5.5 The relationship between $NDVI_{MSR}$ and P_H

The polynomial response of NDVI to increase in plant height of flue cured tobacco varieties showing the effect of topping is shown in figure 5.5 below.

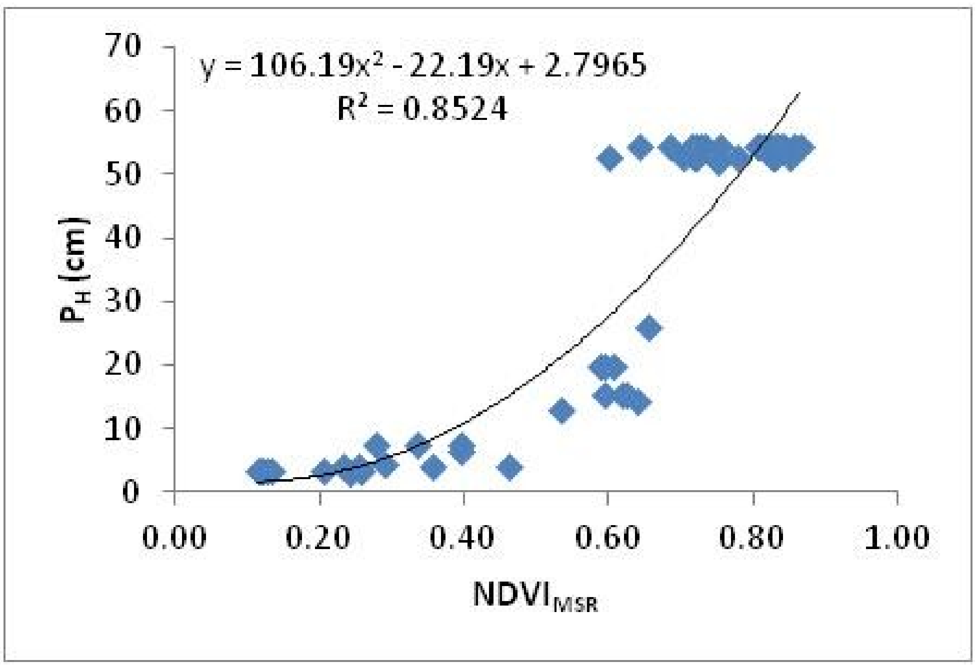

Figure 5.5: The relationship between $NDVI_{MSR}$ and P_H

The variation between plant height and $NDVI_{MSR}$ is best explained by a quadratic relationship. There is no observed change in plant height beyond 62 cm despite an increase in $NDVI_{MSR.}$ The estimation function for plant height is as follows:

$$P_H = 106.19*(NDVI_{MSR})^2 - 22.19*(NDVI_{MSR}) + 2.8$$

By repeating stage 2 and simplifying, the estimation model for plant height is shown as equation 4 below:

Equation 4: $$P_H = 269.64*(NDVI_{MOD})^2 - 66.46*(NDVI_{MOD}) + 5.74$$

Where PH and $NDVI_{MOD}$ are as earlier defined

5.5.6 The relationship between $NDVI_{MSR}$ and G_M

The effect of geometric mean leaf area of flue cured tobacco on MSR 5 derived NDVI is given in figure 5.6.

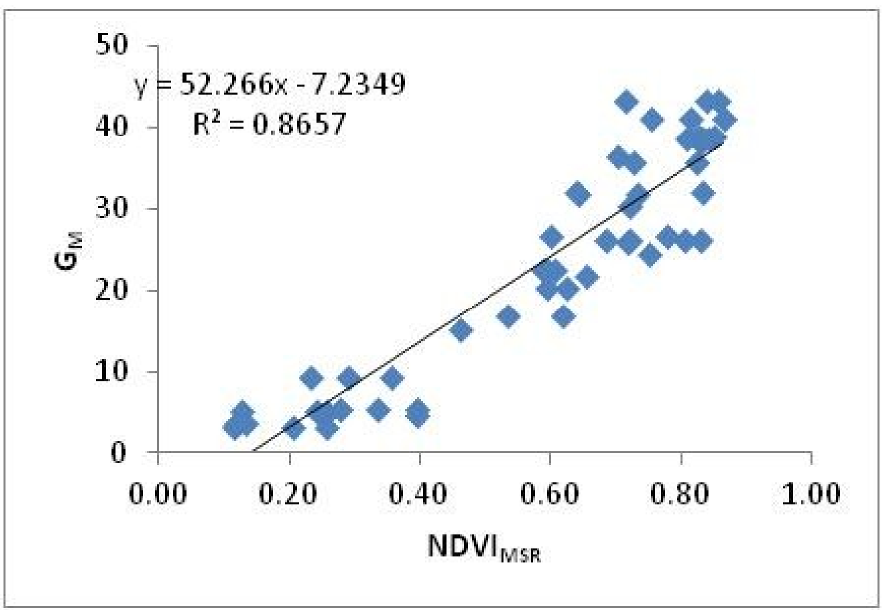

Figure 5.6: The relationship between $NDVI_{MSR}$ and G_M

The geometric mean leaf area (Geo Mean) of flue cured tobacco correlated positively with NDVI with an r^2 of 0.87. Based on the above relationship, a linear function for estimating geometric leaf mean area is:

$$\mathbf{G_M = 52.27*(NDVI_{MSR}) - 7.23}$$

By substitution of $NDVI_{MSR}$ with $NDVI_{MOD}$ obtained from Fig 2 as in stage 2 previously, an estimation model for G_M is summarized as equation 5 below:

Equation 5: $\mathbf{G_M = 83.29*(NDVI_{MOD}) - 12.04}$

5.6 Discussion

The crop variable estimation equations show accurate crop assessment techniques for flue cured tobacco. The linear relationships show the response of NDVI to the overall growth and development of the crop. The positive relationships observed between NDVI and biophysical variables are consistent with findings form researches conducted on corn (Yin *et al*, 2011) as well as in Wheat (Araus *et al*, 2001). The linearity of the relationship between $NDVI_{MSR}$ and canopy biophysical variables is also consistent with results from biomass accumulation monitoring studies done using NDVI in maize varieties Verhuslt and Govaerts (2010). More recently, biomass assessment of flue cured tobacco for yield prediction purposes was attempted on flue cured tobacco (Svotwa *et al*, 2012). Other studies have developed less direct methods of crop biophysical estimation with NDVI through use of indices that are closely linked to biophysical variables such as Leaf Area Index has been successfully attempted in tea (Rajapakse *et al*, 2000) and Soyabean (Haboudane *et al*, 2004).

The continued increase in $NDVI_{MSR}$ despite plant height remaining constant can be attributed to the effect of topping. Topping is done after the crop has achieved between 18 and 22 leaves (T.R.B, 2013) so as to arrest any further apical growth of the crop. This practice promotes carbohydrate storage in the remaining leaves to enhance the quality and biomass (T.R.B, 2013).

The further increase in NDVI can be attributed to carbohydrate and nicotine accumulation along with other leaf chemicals that may occur despite no increase in the physical dimensions of the leaf body. Similar conclusions were drawn by Macnack *et al* (2012) in maize crop that showed an increase in NDVI despite stem thickness showing no changes. The leaf number to $NDVI_{MSR}$ relationship shows a similar response to that of plant height with a similar explanation of artificially arresting further leaf formation of the crop due to the effect of topping as explained earlier.

The relationship between Leaf length and $NDVI_{MSR}$ was comparably stronger than that of Geometric mean leaf area and $NDVI_{MSR}$. Despite this, the Geometric mean leaf area biophysical parameter is sufficient in explaining changes in tobacco crop canopy. Wu *et al* (2007) argued that indices that summarize crop canopy dynamics based on the photosynthetic area available such as LAI tend to become less predictive as canopies become denser. Should Geometric mean leaf area be considered as a means for estimating tobacco crop vigor, it should be done mainly as an attempt to reduce any noise that may be brought about by the effects of varietal differences that exhibit different leaf expansion rates and overall leaf shape differences.

$NDVI_{MSR}$ was comparably higher than $NDVI_{MOD}$ for simultaneous crop measurements during the entire growing period of tobacco. The relationship between $NDVI_{MSR}$ and $NDVI_{MOD}$ was linear in nature and the coefficient of determination was sufficiently strong for an up-scaling model to be developed. Williams *et al* (2008) showed similar findings when NDVI from different scales are regressed. Svotwa *et al* (2013) argued that atmospheric interference would be a likely factor when NDVI from space borne sensors is used for agronomic crops such as tobacco.

5.7 Conclusion

The research carried out led to the development of an up-scaling factor for MODIS derived products using ground based Multispectral Radiometer to improve the accuracy of crop vigor assessment at large scale as well as the following crop biophysical estimation models for flue cured tobacco.

Equation 1: $L_L = 98.68 * (NDVI_{MOD}) - 13.41$

Equation 2: $L_W = 70.42 * (NDVI_{MOD}) – 10.92$

Equation 3: $L_N = 41.61 * (NDVI_{MOD}) - 5.02$

Equation 4: $P_H = 269.64 * (NDVI_{MOD})^2 – 66.46 * (NDVI_{MOD}) + 5.74$

Equation 5: $G_M = 83.29 * (NDVI_{MOD}) – 12.04$

Up-scaling factor: $NDVI_{MOD} = 1.5935 * (NDVI_{MSR}) - 0.0919$

Where: L_L, L_W, L_N, P_H and G_M and $NDVI_{MOD}$ are as defined earlier

5.8 Recommendation

It is recommended that validation exercises be conducted on the above models across different growing conditions and farmer cultural practices to improve the accuracy of estimation of the models. It is also recommended that other vegetation indices be considered and evaluated against the NDVI for efficiency in crop vigor assessment. Lastly, it is recommended that the approach be adopted for other high resolution satellite platforms for more accurate crop assessment methods.

CHAPTER SIX

GENERAL CONCLUSIONS AND RECOMMENDATIONS

6.1 General conclusions

The studies have shown that ground based radiometers such as Cropscan MSR 5 can be used to estimate plant variables such as plant height, leaf length, leaf width, leaf number and geometric mean with remarkable accuracy thereby answering the first objective outlined. The relationships observed suggest that the dry mass accumulation of tobacco varieties as well as organ development, particularly the leaf, can be obtained quickly and accurately during the growing season and used to estimate the health and vigor of the crop. The results in this study provide a basis for comparison of the effects of different management factors that may potentially improve the vigor of tobacco. They also provide a sound means of determining the effect of poor management on the vigor of tobacco.

The second objective was answered by the relationships obtained between MODIS NDVI and crop variables of tobacco. Crop vigor determination using electromagnetic interactions was extended to satellite platforms as demonstrated in this study an in-season crop assessment become holistically possible for large area operations. It is worth noting however, that the temporal resolution of satellite platforms becomes a major consideration factor. The studies conclude that for tobacco monitoring, the period of satellite image acquisition coincides with rainy season that starts in September and persists till late February, as a result, low temporal resolution satellite sensors seldom have adequate cloud free usable images for meaningful use. In such cases, MODIS satellite sensor, due to its higher turnaround time, offers the best approach to acquiring usable images.

In the final objective, the estimation models developed in this study suggest that it is possible to mathematically model and estimate plant variables of tobacco. Under different varieties, similar linear responses can be expected although possibly with varying gradients when the lines of best fit are considered due to differences in vigor and growth rate. However until data verification over several seasons has been collected and validated, researchers can use MODIS data products to compare vegetative vigor of different tobacco fields coupled with the Garvin Method of yield estimation.

6.2 Recommendations

i. There is need for further research to be carried out using newer and more accurate satellite platforms such as IKONOS and LANDSAT 8
ii. Future research is needed to determine in-field crop vigor differences that may be induced by different soil types within a field.
iii. The methodology outlined in this study can be adopted and modified for other crops for the same objectives of crop vigor assessments.

iv. Research work should aim at the adoption of airborne craft mounted sensors with active sensor systems that are not affected by the prevailing weather conditions so as to increase data frequency.

APPENDICES

Appendix 1: Characteristics of the Cropscan Multispectral radiometer

- Size of housing - 80 X 80 X 100 mm.
- Made of brushed, anodized aluminum.
- Sensor bands similar to Landsat Thematic Mapper:
  - 450-520 nm
  - 520-600 nm
  - 630-690 nm
  - 760-900 nm
  - 1550-1750 nm
- Flashed opal glass cosine diffuser covers incident irradiance measuring sensors.
- 28 degree field of view for reflected irradiation sensors.

Appendix 2: Field data on agronomic variables

NDVI(Cropscan)	Leaf Number	Leaf Length	Leaf Diameter	Plant Height	Geometric Mean
0.11	2.20	3.72	2.56	3.56	3.085968
0.26	2.48	5.18	4.02	4.02	4.563288
0.40	3.86	5.18	5.38	7.54	5.279053
0.46	4.67	5.60	4.33	6.80	4.926121
0.62	11.36	23.42	12.03	15.26	16.78499
0.75	15.94	39.39	15.08	51.89	24.3718
0.72	15.90	31.30	21.32	52.82	25.83246
0.72	15.90	33.18	27.89	52.68	30.41962
0.70	15.90	43.66	30.52	52.68	36.50347
0.83	15.90	45.34	32.2	52.68	38.20927
0.83	15.90	46.20	32.7	52.68	38.86824
0.85	15.9	46.2	32.7	52.68	38.86824
0.12	2.16	5.02	2.56	3.56	3.58
0.13	2.16	5.58	4.54	3.56	5.03
0.23	3.38	10.44	8.22	3.92	9.26
0.29	6.42	24.29	9.24	3.92	14.98
0.43	13.88	30.44	13.50	15.26	20.27
0.61	17.88	32.80	15.42	19.74	22.49
0.72	18.52	34.84	19.66	54.34	26.17
0.64	18.56	40.26	25.08	54.34	31.78
0.73	18.56	41.78	30.52	54.34	35.71
0.81	18.55	43.49	34.29	54.27	38.61
0.86	18.56	45.00	37.68	54.34	41.18
0.86	18.56	46.38	40.20	54.34	43.18
0.117748677	2.280	4.860	2.560	3.560	3.527
0.257002245	2.160	5.560	4.540	3.560	5.024
0.355188027	3.380	10.440	8.220	3.920	9.264
0.461003418	6.420	24.440	9.240	3.920	15.027
0.595330544	13.880	30.440	13.500	15.260	20.272
0.588942363	17.880	32.800	15.420	19.740	22.489
0.803800862	18.520	34.840	19.660	54.340	26.172
0.828064341	18.520	34.840	19.660	54.340	26.172
0.830903328	18.560	40.620	25.080	54.340	31.918
0.840460345	18.551	43.490	34.286	54.265	38.614
0.814242723	18.560	45.000	37.680	54.340	41.178
0.837318997	18.560	46.380	40.200	54.340	43.180

0.14	2.08	5.30	2.56	3.56	3.683477
0.24	2.16	5.86	4.26	3.16	4.996359
0.29	3.38	10.44	8.28	4.36	9.297484
0.25	6.42	24.28	9.24	3.94	14.97822
0.62	13.88	30.44	13.50	15.26	20.27166
0.59	17.88	32.80	15.42	19.74	22.48946
0.68	18.52	34.84	19.66	54.34	26.17163
0.73	18.56	40.26	25.08	54.34	31.7761
0.82	18.56	41.78	30.52	54.34	35.7089
0.83	18.54	43.50	34.26	54.26	38.60453
0.75	18.56	45.00	37.68	54.34	41.17766
0.72	18.56	46.38	40.20	54.34	43.17958
0.26	2.00	2.98	3.18	3.34	3.078376
0.21	2.00	2.98	3.18	3.34	3.078376
0.28	3.86	5.18	5.38	7.54	5.279053
0.34	3.86	5.18	5.38	7.54	5.279053
0.40	4.74	4.94	4.3	6.38	4.608904
0.54	11.10	23.42	12.30	13.08	16.96997
0.64	15.72	37.10	13.56	14.23	32.11511
0.65	15.90	31.30	15.08	26.06	21.72565
0.78	15.90	33.18	21.32	52.68	26.59695
0.60	15.90	33.18	21.32	52.68	26.59695
0.32	15.90	33.18	21.32	52.68	26.59695
0.36	15.90	33.18	21.32	52.68	26.59695

7 References

1. Araus, J.L, Casadesus, J. and Bort, J. 2001. Recent tools for the screening of physiological traits determining yield. Application of physiology in wheat breeding. Global Maize Program, International Maize and Wheat Improvement Center (CIMMYT)
2. Baez-Gonzalez A. D., J. R. Kiniry, S. J. Maas. 2005. Large-area maize yield forecasting using leaf area index based yieldmodel. *Agronomy Journal*, **97**(2): 418–425.
3. Bao, Y. 2009. An operational remote sensing algorithm of land surface evapotranspiration based on NOAA PAL dataset. National Center for Biotechnology Information,
4. Blackburn, G.A. 2002. Remote sensing of forest pigments using airborne imaging spectrometer and LIDAR imagery. *Remote Sensing of Environment,* **82:** 311–321
5. Blackmer, T. M, Schepers, J. S, Varvel, G. E, Walter-Shea, E. A. 1996. Nitrogen deficiency detection using reflected shortwave radiation from irrigated corn canopies. *Agronomy Journal,* **88**: 1-5.
6. Broge N.H., E. Leblanc. 2001. Comparing prediction power and stability of broadband and hyperspectral vegetation indices for estimation of green leaf area index and canopy chlorophyll density. *Remote Sensing of Environment*, **76**: 156-172
7. Bronson K. F., T. T. Chua, J. D. Booker, J. W. Keeling and R. J. Lascano. 2003. .In-Season Nitrogen Status Sensing in Irrigated Cotton. *Soil Science Society of America Journal*, **67:** 1439-1448.

8. Campbell J.B. 2002. Introduction to Remote Sensing. (3rd ed.). The Guilford Press. ISBN 1-57230-640-8
9. Carlson T. N. and D. A. Ripley. 1997. On the relation between NDVI, fractional vegetation cover, and leaf area index. *Remote Sensing of Environment*, **62**(3): 241–252.
10. Chen, Z. and C.D Elvidge. 1993. Description of demonstrated high spectral resolution (AVRIS) Green Vegetaion Index. Proceedings of the SPIE: *Imaging Spectroscopy of the Terrestial Environment*. **1937**, 43-54
11. Cropscan Multispectral Radiometer systems. 2013. http://www.cropscan.com/
12. Curran P.J, J.L, Dungan, D.L. Peterson. 2001. Estimating the foliar biochemical concentration of leaves with reflectance spectrometry. *Remote Sensing of Environment*, **76:** 349–359
13. Daughtry, C.S.T., C.L Walthall, M.S Kim, E. Brown de Colstoun, J.E. McMurtrey. 2000. Estimating corn leaf chlorophyll concentration from leaf and canopy reflectance. *Remote Sensing of Environment,* **74:** 229–239
14. Doraiswamy, P. C. T. R. Sinclair, S. Hollinger, B. Akhmedov, A. Stern, and J. Prueger. 2005. Application of MODIS derived variables for regional yield assessment. *Remote Sensing of Environment*. **97**(2), 192-202.
15. ESA. 1996. http://envisat.esa.int/instruments/meris
16. Fang, S., Y. Zhou, Dao-Ji Li, W. Zhu and M. Salama, 2010. MERIS estimation of chlorophyll-a concentration in the turbid sediment-laden waters of the Changjiang (Yangtze) Estuary. *International Journal of Remote Sensing*. **31 (17)**: 4635–4650.

17. Ferri CP, A.R Formaggio, M.A Schiavinato. 2004. Narrow band spectral indexes for chlorophyll determination in soybean canopies [*Glycine max* (L.) Merril]. *Brazilian Journal of Plant Physiology,* **16:** 131–136.

18. Garvin, R. T. 1986. Yield Estimation- A tool for Reducing Losses. *Zimbabwe Tobacco Today*, **9** (12): 32-35.

19. Gausman, H. W, Escobar, D. E. 1973. Discrimination among plant nutrient deficiencies with reflectance measurements. *Annual review of Crop physiology*, **244**: 325

20. Goward. S. 2003. Empirical comparison of Landsat 7 and IKONOS multispectral measurements for selected Earth Observation System (EOS) validation sites. *Remote Sensing of Environment*, **88 (**2): 80-99

21. Haboudane D., J. R. Miller, E. Pattey, P. J. Zarco-Tejada, and I. B Strachan. 2004. Hyperspectral vegetation indices and novel algorithms for predicting green LAI of crop canopies: modeling and validation in the context of precision agriculture. *Remote Sensing of Environment*, **90**: 337–352.

22. Hansen. D. 2006. Techniques for discrimination between agriculture and similar land cover types with fuzzy logic and spectral polygon characteristics. ASPRS 2006 Annual conference.

23. Hatfield, J., A. A. Gitelson, J. S. Schepers, and C. L. Walthall 2008. Application of Spectral Remote Sensing for Agronomic Decisions *Agronomy Journal*, **100** (3): S112-S131

24. Huete A., K. Didan, T. Miura, E. P. Rodriguez, X. Gao, and L. G. Ferreira. 2002. Overview of the radiometric and biophysical performance of the MODIS Vegetation indices. *Remote Sensing of Environment,* **83**: 195–213.

25. Jackson, R. D. P. N Slater, and P. J Pinter. 1983. Discrimination of growth and water stress in wheat by various vegetation indices through clear and turbid atmospheres. *Remote Sensing of the Environment*, **15**:187 – 208.

26. Jayroe C. W., W. H. Baker, and A. B. Greenwalt. 2005. Using multispectral aerial imagery to evaluate crop productivity. *Online Crop Management*. oi: 10.1094/CM-2005-0205-01-RS.

27. Ma, B.L and Dwyer, L. M. 2001. Early prediction of soybean yield from canopy reflectance measurements. *Agronomy Journal,* **93** (6): 1227-1234.

28. Macnack, N, J. Kelly, J. Mullock and W. Raun. 2012. By-Plant Prediction of Maize (Zea Mays L.) Yield Using Stalk Diameter and Plant Height. *Plant and Soil Science*.

29. Manatsa, D, Nyakudya, I. W., Mukwadab, G. and Matsikwa, H. 2011. Maize yield forecasting for Zimbabwe farming sectors using satellite rainfall estimates. Springer Science+Business Media B.V.

30. Marumbwa F. M., A. Murwira, E. K. Madamombe, S. Kusangaya, F. Tererai, 2006. Remotely sensing of irrigation water use in Mazowe Catchment. University of Zimbabwe.

31. Mohd, I. S. M., S. Ahmad and A. Abdullah, 1994. Agriculture Applications Of Remote Sensing: Paddy Yield Estiamtion from Landsta-5 Thematic Mapper Data. http://www.gisdevelopment.net/magazine/gisdev/index.htm.

32. Murwira, A. and Skidmore, A.K. 2010. Comparing direct image and wavelet transform - based approaches to analysing remote sensing imagery for predicting wildlife distribution. *International journal of remote sensing,* **31** (24): 6425-6440

33. Mutanga, O. 2004. Hyperspectral Remote Sensing of Tropical Grass Quality and Quantity PhD Thesis,. *Wageningen University. ITC Dissertation Number 111.*

34. Myneni, R. B, Hall, F. G, Sellers, P.J. and Marshak, A.L. 1995. The interpretation of spectral vegetation indexes. *IEEE Transactions on Geoscience and Remote Sensing*, **33**: 481-486.

35. Nagler, P., E. P. Glenn and A. R. Huete. 2001. Assessment of spectral vegetation indices for riparian vegetation in the Colorado River delta, *Mexico Journal of Arid Environments* **41**: 91-110

36. Nowatzki, J., R. Andres and K. Kyllo, 2004. Agricultural Remote Sensing Basics. North Dakota State University Agriculture and University Extension. http://www.ag.ndsu.edu

37. Nyoka, A. 2000. Advances in flue cured tobacco breeding. Tobacco Research Board,

38. Osborne, S. L, Schepers, J. S, Francis, D. D. and Schlemmer, M.R. 2002. Use of spectral radiance to estimate in-season biomass and grain yield in nitrogen- and water-stressed corn. *Crop Science,* **42**: 65-171.

39. Pettorelli. N, J. O. Vik, A. Mysterud, J. Gaillard, C. J. Tucker and Nils Chr. Stenseth. 2005. Using the satellite-derived NDVI to assess ecological responses to environmental change. *Trends in Ecology & Evolution,* **20** (9): 503-510

40. Rajapakse R. M. S. S, K. N. Tripathi, and K. Honda. 2008. Modelling Tea (*Camellia* (L) O. *Kuntze*) yield using satellite derived LAI, landuse and meteorological Data. GISdevelopment.net. http://www.gisdevelopment.net/aarc/2000/index.htm. Downloaded on 13 may 2012.

41. Ritchie G. L. and Bednarz, C.W. 2005. Estimating defoliation of two distinct cotton types using reflectance data. *Journal of cotton Sciences* **9**: 182-188.

42. Sellers, P. J. 1985. Canopy reflectance, photosynthesis, and transpiration. *International Journal of Remote Sensin*g, **6**: 1335-1372.

43. Shoko, M. D, Tagwira, F, Zhou, M. and Pieterese , P.J. 2009. Biophysical Measurements as Basis for Exploring Yields of an Irrigated Plant Crop of Sugarcane Variety N14 in Semi-Arid Zimbabwe. *World Journal of Agricultural Sciences*, **5** (1): 83-89.

44. Short, N. M., 2008. Vegetation Applications: Agriculture, Forestry, and Ecology. Remote Sensing Tutorial. http://www.rst.gsfc.nasa.gove/htm

45. Sims D.A. and Gamon. J. A. 2002. Relationships between leaf pigment content and spectral reflectance across a wide range of species, leaf structures and developmental stages. *Remote Sensing of Environment,* **81**: 337–354.

46. Stamatiadis. S, Christos. T and Schepers. J. 2009. Ground-based canopy sensing for detecting effects of water stress in cotton. *Plant and Soil journal*. **331**: 277-287

47. Svotwa E., A. J. Masuka, B. Maasdorp, A. Murwira, and M. Shamudzarira. 2013. Remote Sensing Applications in Tobacco Yield Estimation and the Recommended Research in Zimbabwe. *Hindawi Publishing Corporation ISRN Agronomy*. **2013:** Article ID 941873

48. Svotwa E., B. Maasdorp, A. Murwira, and A. Masuka. 2012. Selection of Optimum Vegetative Indices for the Assessment of Tobacco Float Seedlings Response to Fertilizer Management. *ISRN Agronomy*. **2012**: Article ID 450473

49. Thomason, W.E., S.B. Phillips, and F.D. Raymond. 2007. Defining useful limits for spectral reflectance measures in corn. *Journal of Plant Nutrition*. **30**:1263-1277.

50. Tobacco Facts. 2009. Zimbabwe Tobacco industry http://www.tobacco-facts.net/tobacco-industry/zimbabwe-tobacco-industry.

51. Tobacco Industries Marketing Board (T.I.M.B). 2005. Annual report and Accounts for the Year Ended 30 June, 2004.

52. Tobacco Industries Marketing Board (T.I.M.B). 2013. Annual report and Accounts for the Year Ended 30 June, 2013.

53. Tobacco Research Board. 1986. Tobacco Production Guide. Tobacco Research Board. Harare. 1st Edition

54. Tobacco Research Board. 2013. Annual reports. June, 2013.

55. Toulios, L, Pateras, D, Zerva, G, Gemtos, T.A .and Markinos. T. H. 1998. Combining satellite images and cotton yield maps to evaluate field variability in precision farming. In: Proceedings of the World Cotton Research Conference.

56. Turner, D.P, Fassnecht, K.S., Briggs, J.M. 1999. Relationships between Leaf Area Index and Landsat 7 spectral vegetation Indices across three temperate zone sites. *Remote sensing of the Environment.* **70**: 52-65

57. USGS. 2013. Glovis website: www.earthexplorer.usgs.gov

58. Verhulst N., and B. Govaerts. 2010. The normalized difference vegetation index (NDVI) GreenSeeker™ handheld sensor: Toward the integrated evaluation of crop management Part A: Concepts and case studies. Mexico. International Maize and Wheat Improvement Center (CIMMYT.).

59. Vina, A., A.A. Gitelson, D.C. Rundquist, G. Keydan, B. Leavitt, J. Schepers. 2004. Monitoring maize (*Zea mays* L.) phenology with remote sensing. *Agronomy Journal*, **96** (4), 1139-1147

60. Wang T. W., V. P. Sammis, M. Gutschick, S. Gebremichael, O. Dennis and R. E. Harrison. 2010. Review of Satellite Remote Sensing Use in Forest Health Studies. *The Open Geography Journal*, **3**: 28-42.

61. Williams M., R. Bell, L. Spadavecchia, L. E. Street, and M. K. Wijk. 2008. Upscaling leaf area index in an Artctic landscape using multi-scale reflectance observations. *Global Change Biology*, **38:** 1

62. Wright, L., V. P. Rasmussen, R. D. Ramsey, and D. J. Baker. 2004. Canopy Reflectance Estimation of Wheat Nitrogen Content for Grain Protein Management. *GIScience and Remote Sensing*, **41**(4): 287-300

63. Wu J., D. Wang and M. E. Bauer. 2007. Assessing broadband vegetation indices and Quickbird data in estimating leaf area index of corn and potato canopies. *Field Crops Research* **102** 33–42.

64. Xinhua, A, McClure, Y, and Tyler, D. 2010. Relationships of plant height and canopy NDVI with nitrogen nutrition and yields of corn. Proceedings from the 2010 Annuak Science Review Conference, Shanghai Research Academy.

65. Yang Z. 2010. A study on hyperspectral estimating models of tobacco leaf area index Agronomy College of Henan Agriculture University, **39** (3): 321-325

66. Yin X., M. A. McClure, J. Ngowari, D. D. Tyler, and M. Robert. Hayes. 2011. In-Season Prediction of Corn Yield Using Plant Height under Major Production Systems. *Agronomy Journal*. **103**:923-929.