GROUND VEGETATION BIOMASS DETECTION FOR FIRE PREDICTION FROM REMOTE SENSING DATA IN THE LOWVELD REGION

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ABSTRACT

Wildfire prediction and management is an issue of safety and security for many rural communities in South Africa. Wildfire prediction and early warning systems can assist in saving lives, infrastructure and valuable resources in these communities. Timely and accurate data are required for accurate wildfire prediction on both weather conditions and the availability of fuels (vegetation) for wildfires. Wildfires take place in large remote areas in which land use practices and alterations to land cover cannot easily be modelled. Remote sensing offers the opportunity to monitor the extent and changes of land use practices and land cover in these areas.

In order for effective fire prediction and management, data on the quantity and state of fuels is required. Traditional methods for detecting vegetation rely on the chlorophyll content and moisture of vegetation for vegetation mapping techniques. Fuels that burn in wildfires are however predominantly dry, and by implication are low in chlorophyll and moisture contents. As a result, these fuels cannot be detected using traditional indices. Other model based methods for determining above ground vegetation biomass using satellite data have been devised. These however require ancillary data, which are unavailable in many rural areas in South Africa. A method is therefore required for the detection and quantification of dry fuels that pose a fire risk.

ASTER and MAS (MODIS Airborne Simulator) imagery were obtained for a study area within the Lowveld region of the Limpopo Province, South Africa. Two of the ASTER and two of the MAS images were dated towards the end of the dry season (winter) when the quantity of fuel (dry vegetation) is at its highest. The remaining ASTER image was obtained during the middle of the wet season (summer), against which the results could be tested. In situ measurements of above ground biomass were obtained from a large number of collection points within the image footprints.

Normalised Difference Vegetation Index and Transformed Vegetation Index vegetation indices were calculated and tested against the above ground biomass for the dry and wet season images. Spectral response signatures of dry vegetation were evaluated to select wavelengths, which may be effective at detecting dry vegetation as opposed to green vegetation. Ratios were calculated using the respective bandwidths of the ASTER and MAS sensors and tested against above ground biomass to detect dry vegetation.

The findings of this study are that it is not feasible, using ASTER and MAS remote sensing data, to estimate brown and green vegetation biomass for wildfire prediction purposes using the datasets and research methodology applied in this study.

Correlations between traditional vegetation indices and above ground biomass were weak. Visual trends were noted, however no conclusive evidence could be established from this relationship. The dry vegetation ratios indicated a weak correlation between the values. The removal of background noise, in particular soil reflectance, may result in more effective detection of dry vegetation.

Time series analysis of the green vegetation indices might prove a more effective predictor of biomass fuel loads. The issues preventing the frequent and quick transmission of the large data sets required are being solved with the improvements in internet connectivity to many remote areas and will probably be a more viable path to solving this problem in the near future.

DECLARATION

I Anthony Goslar (Student Number 0310612G) am a student registered for
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PREFACE

Wildfire prediction and management is an issue of safety and security for many rural communities in South Africa. Proper early wildfire prediction and warning systems can assist in saving lives, infrastructure and valuable resources in these communities. Timely and accurate data are required for accurate wildfire prediction on both the weather conditions and availability of fuels (vegetation) for wildfires to occur. Remote sensing offers the opportunity for data on the state and quantity of vegetation in the remote and often large expanses of these rural areas to be collected and quantified. This will assist in better wildfire prediction and management services.

Data on fuels must be available before fires occur in such an area. No current well tested techniques are in place for detecting dry vegetation using satellite data. Dry vegetation however poses the greatest wildfire risk in these areas.

The aim of this study is establish if data from the ASTER and MAS remote sensors can be used to determine the dry biomass of fuel over a portion of the Lowveld adjacent to the Kruger National Park. In order to accomplish this, ground vegetation biomass data and spectral response signatures will be utilised. The specific objectives of this research area:

- Establishing if the available ground vegetation biomass data from the Agricultural Research Council is suitable for use with ASTER imagery for ground biomass detection.
- Utilise dry vegetation spectral response signatures in an attempt to detect 'brown' vegetation using the ASTER imagery.

The research report is organised as follows – Chapter 1 introduces the research aims and objectives for the study. It provides a background on wildfires, remote sensing and the utilisation of remote sensing for fuel mapping. Chapter 2 will clarify the type of data utilised as well as the data sources. The methodology for the research undertaken is described. Chapter 3 presents results for the correlation of the calculated values derived from satellite images with the ground data. It presents the results of the detection of dry vegetation and presents recommendations for a future research methodology in response to the findings. Chapter 4 concludes the report.

Prof. Harold Annegarn of the University of Johannesburg (formerly of the University of the Witwatersrand) is thanked for his generous contribution of the remote sensing data, hardware and software utilised in this report. Mrs Melanie Kneen is thanked for her invaluable assistance in the use of the software, satellite data and statistical analysis in this report. Both of these persons have selflessly provided steady direction and support in this research at their own cost.

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Spectral Response signatures were reproduced from the ASTER Spectral Library through the courtesy of the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California.

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AFRI	Aerosol Free Vegetation Index
ANPP	Annual Net Primary Productivity
APAR	Absorbed Photosynthetically Active Radiation
ARC/FRI	Agricultural Research Council / Forest and Rangeland Institute
ASTER	Advanced Spaceborne Thermal Emission and Reflectance Radiometer
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DEAT	Department of Environmental Affairs and Tourism
DFMC	Dead Fuel Moisture Content
FDI	Fire Danger Index
FDRS	Wildfire Danger Rating System
IR	Infra-red
KZNFPA	KwaZulu Natal Wildfire Protection Agency
LFMC	Live Fuel Moisture Content
MAS	MODIS Airborne Simulator
MIR	Mid infra-red
MODIS	Moderate Resolution Imaging Spectro-radiometer
NWS	National Weather Services (United States of America)
NDVI	Normalized Difference Vegetation Index
NFDRS	National Fire Danger Rating System
NOAA AVHRR	National Ocean and Atmospheric Administration Advanced Very High Resolution Radiometer
RS	Remote Sensing
SAFARI 2000	Southern Africa Regional Science Initiative 2000
SAFARI-92	Southern Africa Fire Atmosphere Research Initiative 1992
SAFNet	Southern African Fire Network
SAVI	Soil Adjusted Vegetation Index
SAWS	South African Weather Services
STARE	Southern Tropical Atlantic Regional Experiment
SWIR	Short Wave Infra-Red
TIR	Thermal Infra-Red
TVI	Transformed Vegetation Index
VI	Vegetation Index
VNIR	Visible Near Infra-Red

CHAPTER 1: OVERVIEW

The aim of this research report is presented. The study area is described. The science of wildfires and wildfires within the South African context are discussed. The use of remote sensing in the detection of vegetation is discussed, with a specific focus on its use for wildfire prediction. .

Introduction

Research Aim

The aim of this research is to determine if it is feasible to use ASTER and MAS remote sensing data to estimate brown and green vegetation biomass for wildfire prediction purposes. The aim will be investigated by:

- Assessing and evaluating the ASTER and MAS data against the ground truth data.
- Utilising dry vegetation spectral response signatures to detect ‘brown’ vegetation using ASTER imagery.

The purpose of this research is to provide more precise and accurate data on the quantity and state of available fuels for wildfire. Wildfire prediction and danger rating require regular monitoring for up to date data on the conditions and characteristic of fuels. The conditions and characteristics of fuels vary on spatial and temporal scales. The remote location of fuels and large areas which they cover create challenges in collecting data on these fuels.

Satellite imagery allows for regular monitoring of large remote areas with less labour intensive techniques than conventional field data collection techniques. This monitoring provides potential for more recent data over larger areas on the conditions and characteristics of fuels to be collected. The recent availability of cost effective moderate resolution satellite data, such as ASTER data (15 meter resolution), provides potential for such mapping applications.

The Study Area

The study area is located in the Lowveld region of the province of Mpumalanga, South Africa (Figure 1.1).

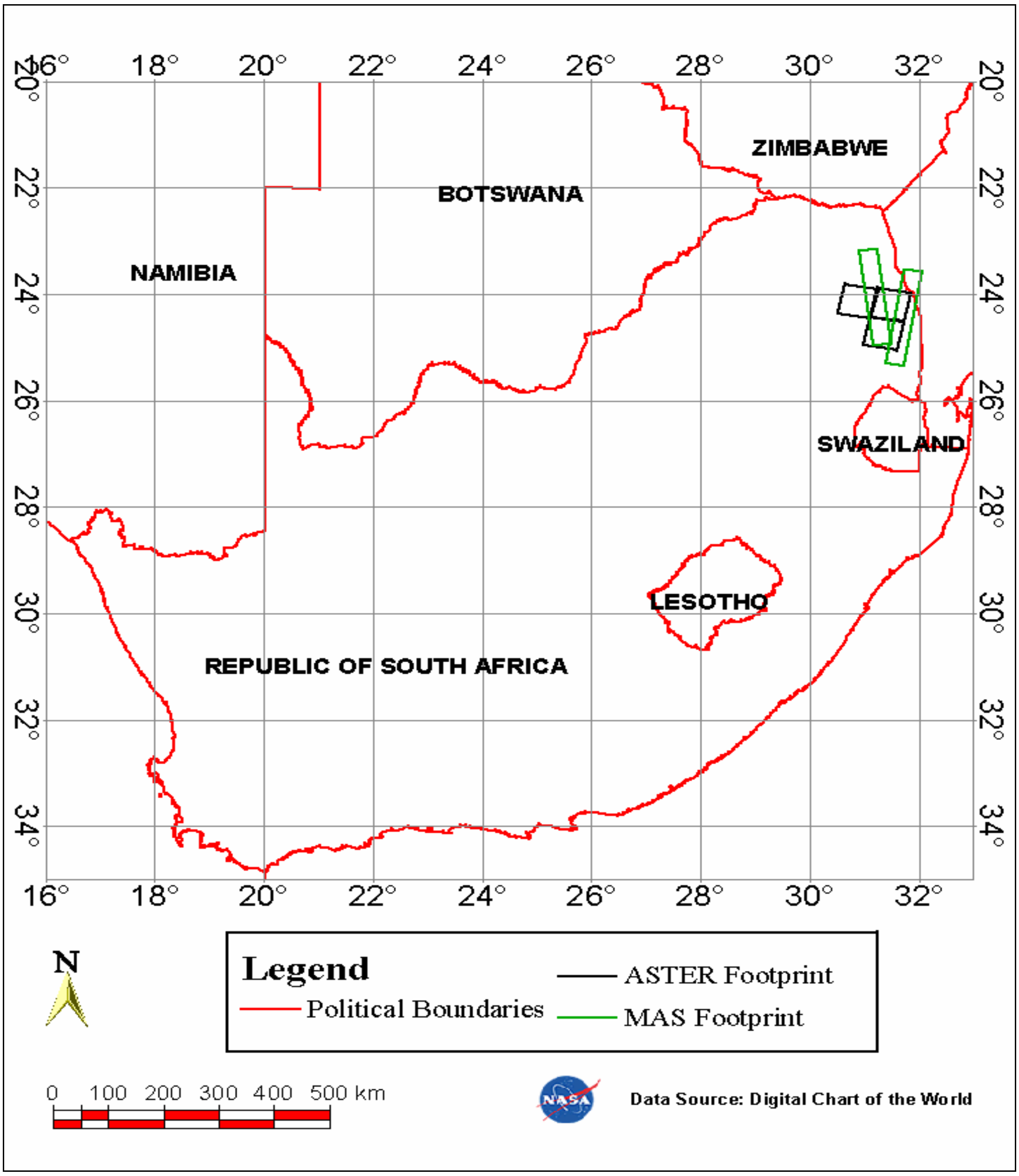

Figure 1.1: Location of the study area in relation to South Africa as illustrated by the footprints of the selected satellite images.

The study area is apart of the Olifants River catchment of the Phalaborwa area. This catchment region drains in an easterly direction into Mozambique and the Indian Ocean. The geology consists of meinhardstrall granite, sand river gneiss, iron, jaspilite, synite, hornblende granite, foskorite, gabbro, potassic granite and diorite (DEAT, 1997). The Drakensberg Mountain range extends to the far western portion of the study area. This mountain range marks the start of the Mpumalanga Lowveld in this area.

The closest available long term climatic data for this area is Skukuza (Table 1.1) (SAWS; 2003). The majority of rainfall takes place in the summer period beginning in November and ending in March. High temperatures are recorded throughout the year with the average daily maximum temperature in the coldest month of winter being 26°C. A greater variation exists between the winter daily high and low temperatures than the summer daily highs and lows. During the dry winter months hot midday temperatures provide favourable weather conditions for wildfires.

Table 1.1: Long term climatic data (1961-1990) for Skukuza. (SAWS, 2003)

Month	**Temperature (° C)**				**Precipitation**		
	Highest Recorded	**Average Daily Maximum**	**Average Daily Minimum**	**Lowest Recorded**	**Average Monthly (mm)**	**Average Number of days with >= 1mm**	**Highest 24-hour Rainfall (mm)**
January	43	33	21	11	94	9	104
February	43	32	20	10	96	9	120
March	42	31	19	8	66	9	82
April	40	29	15	6	38	6	72
May	38	28	10	1	14	3	57
June	35	26	6	-4	11	2	40
July	36	26	6	-4	11	2	75
August	38	27	9	-4	8	2	40
September	42	29	13	1	28	3	86
October	44	30	16	6	40	7	44
November	43	31	18	10	63	10	57
December	42	32	20	10	92	10	98
Year	**44**	**30**	**14**	**-4**	**561**	**71**	**120**

The majority of the land to the north of the 24°S latitudinal line is open expanses of rural land with diverse land use including crop agriculture, subsistence farming, game farming, game reserves, and cattle farming especially close to the rivers (Chief Directorate: Surveys and Land Information, 1996). The majority of settlements are far apart comprising of isolated farmhouses and nucleated settlements. Phalaborwa, the largest urban settlement within the study region, is located close to the 24°S and 31°E lines. The economy of Phalaborwa is dominated by mining for minerals such as copper, phosphate and vermiculite.

The eastern portion of the study area is comprised mostly of game reserves. The largest of these is the Kruger National Park which comprises the majority of the extent of the eastern study area. The boundary of the Kruger National Park varies between 31°20" E and 31°35" E. To the west of the Kruger National Park is a collage of private and state owner game reserves as well as communal lands which comprise the central to central-eastern portion of the study area. The largest of these game reserves are the Timbavati, Manyaleti, Klaserie, Umbabat and Sabi Sands (Chief Directorate, Surveys and Land Information, 1996). The largest of these communal lands are Mhala and Mapulaneng (Chief Directorate, Surveys and Land Information, 1996).

A variety of land uses occur within this area. The general area to the south of 24°S and 31°45" E (Figure 1.2) have mixed land uses and land cover. The farms progressively become smaller whilst the settlements grow larger and closer together towards the south of this area. The general land use in the southern portion of the study area are cultivation and open lands comprising of a mixture of state owned land, commercial cattle farming, subsistence cattle farming and wildlife management (Trollope, 1984b). The subsistence cattle farms are generally characterised by overstocking, overgrazing and fuelwood gathering, which lead to visibly degraded areas easily distinguished on the satellite imagery when compared to the land use maps (Trollope, 1984b). Various small scale mining also takes place in these areas. The bottom western corner of the study area is dominated by forestry plantations.

Wildfires

Wildfire Science

Wildfires occur in rural areas where correct vegetation quantities and characteristics are available as fuels. These fires perform an important function in natural ecosystems (Booysens and Tainton, 1984). They are instrumental in the removal of dead vegetation that hinders growth of new vegetation and in release of nutrients into the soil. Wildfires reduce invader species, encourage the growth of native species and create habitats that attract new wildlife (Higgins *et al.*, 2003). Wildfires are responsible for changes in soil characteristics and plant productivity and quality (Frost and Robertson, 1987). Extensive damage to infrastructure, rural land use such as agriculture and people are however also caused by wildfires. As a result proper preparation and management of wildfires in communal and commercial rural areas are vital.

For adequate prediction and management of wildfires, the physics of fires must be understood. Environmental conditions are important controlling factors of wildfires and have a direct effect on the combustion factors. These conditions are usually referred to as the wildfire environment and consist of three interconnecting components: fuel, weather and topography (Figure 1.3) (Andrews and Williams, 1998). The interaction of these factors, as well as their variation in space and time, define the basic wildfire environment.

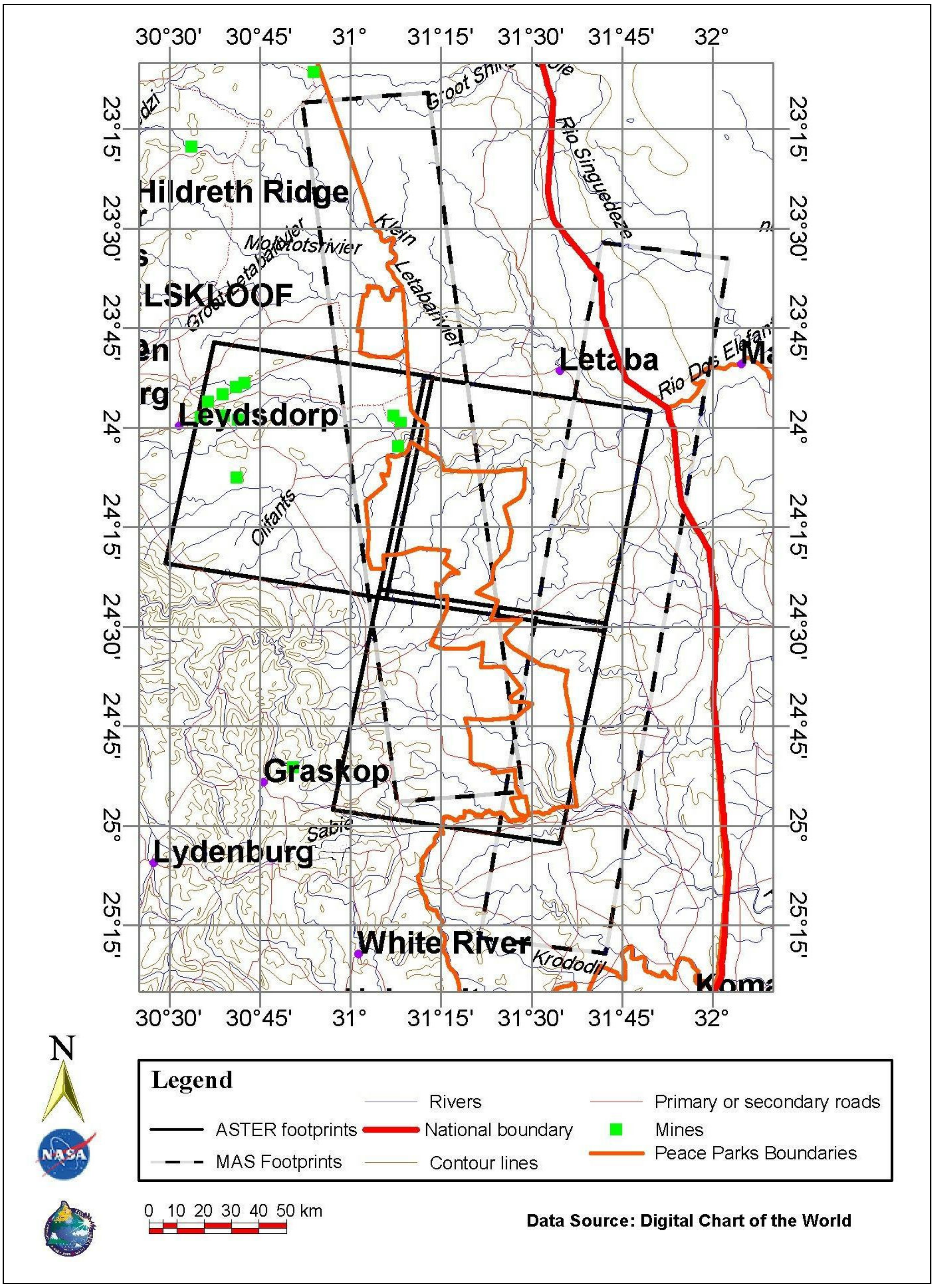

Figure 1.2: Footprint of the ASTER and MAS study areas.

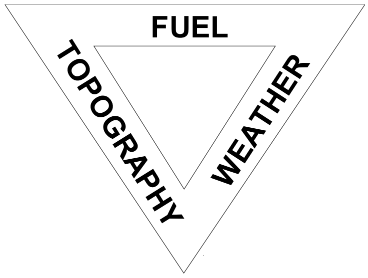

Figure 1.3: The wildfire environment. (Andrews and Williams, 1998)

For combustion to occur three factors are required: oxygen, heat and fuel (Andrews and Williams, 1998; Cheney and Sullivan, 1997). When combustion occurs, both heat and light energy are released (Cheney and Sullivan, 1997). The chemical reactions of combustion are the reverse process to photosynthesis, as illustrated by the reactions (Trollope, 1984a):

Combustion

$(C_6H_{10}O_5)_n + O_2 + \text{ignition temperature} \leftrightarrow CO_2 + H_2O + \text{heat}$ (Equation 1.1)

Photosynthesis

$CO_2 + H_2O + \text{solar energy} \leftrightarrow (C_6H_{10}O_5)_n + O_2$ (Equation 1.2)

For a wildfire to potentially occur, an ignition source and sufficient quantity of fuel in a proper state are required. Availability of these is referred to as the 'ignition potential' (Van Wilgen and Scholes, 1997). Today, wildfires are ignited primarily by two major sources, lightning and humans (Trollope, 1984a). The ease of ignition is determined by the moisture content of the dead fine fuel (Cheney and Sullivan, 1997).

The frequency at which fires occur in a given area is referred to as 'fire frequency'. The fire frequency is determined in part by the rate of accumulation of fuel after a previous wildfire. The rate of accumulation is governed by a variety of factors such as the rate of growth of the vegetation species, weather conditions, soil conditions, herbivory and land use activities (Luke and McArthur, 1978).·

The intensity or heat energy released by a wildfire during combustion is referred to as 'fire intensity' (Trollope, 1984a). Fire intensity is determined by the amount of fuel available for combustion (fuel load) and the weather conditions during the wildfire.

Fires are further characterised by horizontal progression relative to the wind direction, and height of main fire propagated relative to ground surface. Wildfire spread in the horizontal plane, is referred to as heading fires, backing fires or flanking fires (Figure 1.4). These vary in accordance with the orientation of the edge of the wildfire to the wind (Trollope, 1984a; Cheney and Sullivan, 2001):

- *Head fires* are fires where the flame edge burns in the direction of the wind
- *Back fires* are fires where the wildfire edge burns into the wind and
- *Flank fires* are fires that burn parallel to the wind.

Head fires burn more intensely than back fires because the wind supplies the wildfire with more oxygen for combustion and aids in the spreading of heat energy toward fresh fuel (Trollope, 1984a). Back fires burn into the wind and the spread of the wildfire is inhibited as sensible heat of combustion is carried away from the fuel.

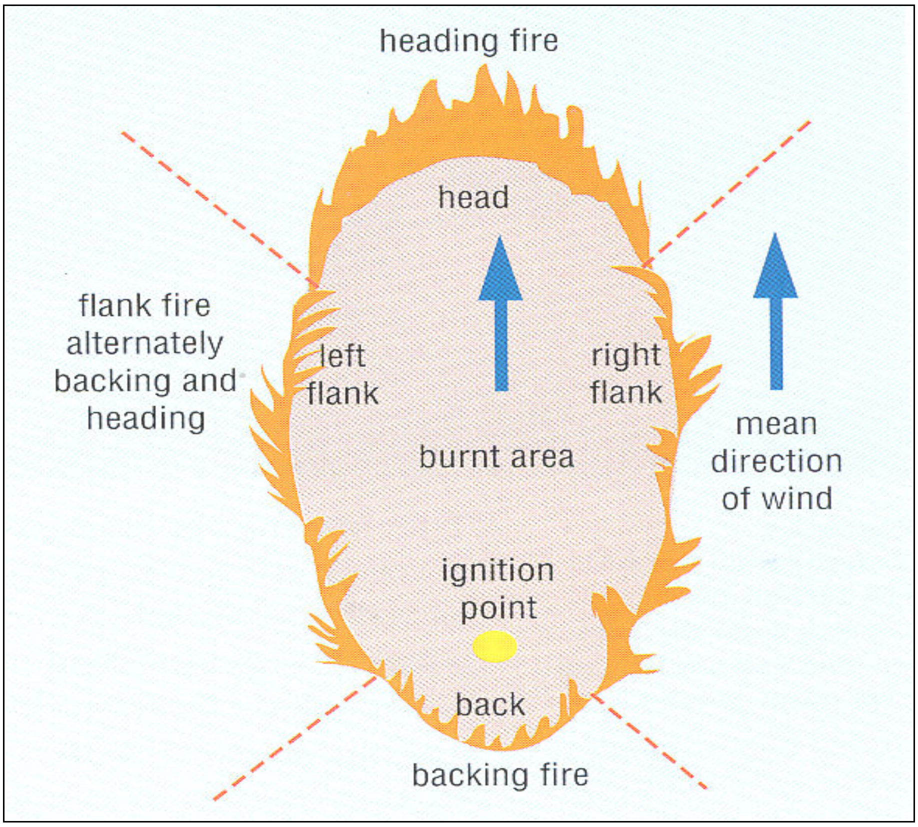

Figure 1.4: Types of fires. (Cheney and Sullivan, 2001)

Four types of fires are defined relative to the vertical plane (Figure 1.5), classified according to the layers of vegetation that are burnt (Luke and McArthur, 1978; Trollope, 1984a; NWS, 2003):

- *Ground fires* in plant debris at the soil surface, and sometimes below the surface in organic rich soils (peat).
- *Surface fires* burn in the surface vegetation such grasslands and shrubs, up to a height of approximately one meter,
- *Crown fires* burn in the canopies of trees.

- *Spotting fires* occur when large embers, falling from trees, or carried by the winds and intercepted by topographical features, cause 'spots' or smaller fires ahead of the flame edge of the main wildfire.

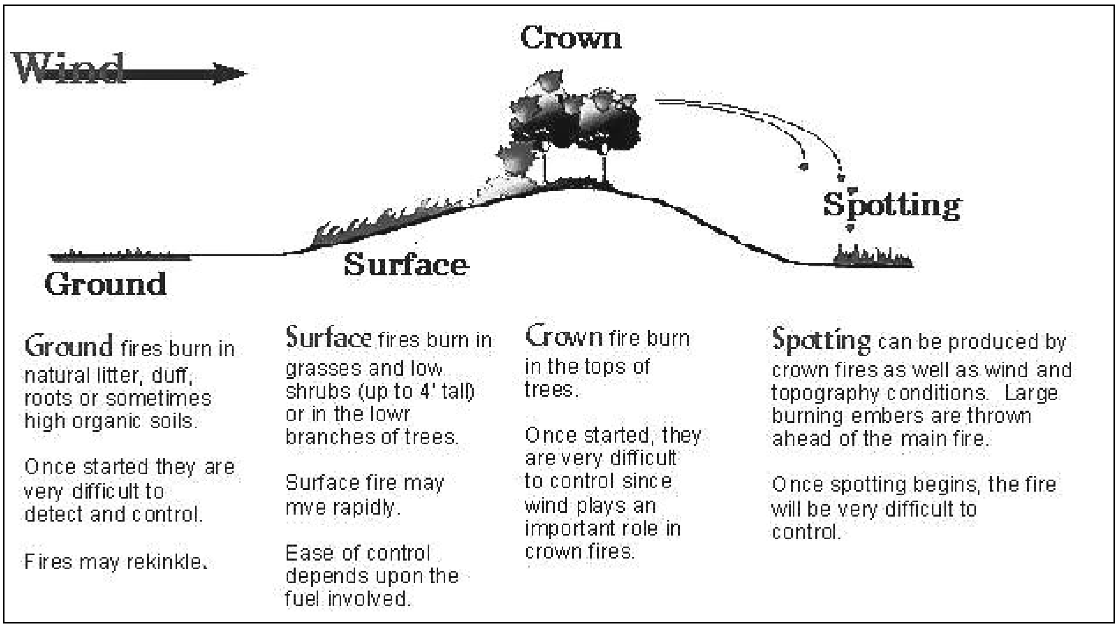

Figure 1.5: Types of fires. (NWS, 2003)

Wildfire Fuels

For a proper understanding of the fuel component of wildfires and its relationship to wildfires, the basic characteristics of the fuels must be considered (Luke and McArthur, 1978; Trollope, 1984a; Cheney and Sullivan, 1997):

Fuel continuity (compaction)

The continuity of fuel refers to the location of fuel elements relative to each other (Luke and McArthur, 1978; Trollope, 1984a; Cheney and Sullivan, 1997). A continuous fuel covers 100% of the ground area, while a discontinuous fuel covers anything less than 100% (Cheney and Sullivan, 1997). Fuel continuity has an effect on the spread of fires. A discontinuous fuel cover can either be caused by the natural distribution of the fuel type according to plant species, grazing practices of animals and/or land use practices in the area (Cheney and Sullivan, 1997).

Fuel size (particle size)

The thickness or diameter of the fuel has an effect on the ease at which the fuel is ignited (Luke and McArthur, 1978). Fuels sizes can be divided into two broad categories: fine and heavy fuels (Luke and McArthur, 1978; Trollope, 1984a). Fine fuels (less than 6 mm in diameter) are substances such as grasses, dead leaves, branches and twigs and usually ignite instantaneously (Luke and McArthur, 1978). Heavy fuels (greater than 6 mm in diameter) will not ignite easily and usually do not completely combust (Luke and McArthur, 1978). A lack of fine fuels within a given area may prevent combustion from taking place (Trollope, 1984a).

Fuel load (quantity)

The load or quantity of fuel can be measured by weight per unit area, typically in tons per ha ($t\ ha^{-1}$). Alternatively it can be measured by the height of the main fuel component (Luke and McArthur, 1978). The fuel load plays an important role in the spreading of the wildfire, and has a direct proportionate relationship to the wildfire intensity (Trollope, 1984a; Cheney and Sullivan, 1997).

The fuel load or quantity of biomass burnt in a region is calculated by (Van Wilgen and Scholes, 1997):

$$Y = abcf \qquad \text{(Equation 1.3)}$$

where Y is amount burnt; a is the area of the region; b is the fraction of region burnt per annum; c is the completeness of the burn (fraction of biomass that is oxidised) and f is total fuel load.

The size of available fuel plays a role in wildfire intensity due to available fuel for combustion. In the case of woody areas with shrubs and tress, the vertical distribution of these fuel types is important because the heat of the wildfire convects upwards (Luke and McArthur, 1978). This is especially the case where fires spread from ground level into the canopy of trees.

Fuel Moisture Content (FMC)

The moisture content of the fuel will initially affect the ignition potential of the fuel. In the case of combustion, it will reduce the quantity of fuel consumed as well as the rate of combustion (Trollope, 1984a). Two general categories of fuel moisture content are considered in wildfires: dead fuel moisture content (DFMC) and the live fuel moisture content (LFMC).

The fuel moisture content may be measured by determining the loss of moisture of a fuel whilst being oven dried, also referred to as oven dry weight (Luke and McArthur, 1978). The moisture content may alternatively be indirectly measured by the use of the relative humidity and air temperatures and a table that lists their relationships with fuel moisture (Luke and McArthur, 1978). Fine dead fuels, like grasses, dry very quickly but coarser dead fuels such as trees take longer (Van Wilgen and Scholes, 1997). The moisture content is dependent on the weather conditions of rainfall, air temperature, humidity and radiation from the sun (Van Wilgen and Scholes, 1997).

The LFMC will vary with the seasonal weather patterns, soil moisture content, aspect and the stages at which the vegetation types are in their respective lifecycles (Luke and McArthur, 1978). Once the plants have died, the rate of curing (drying) varies according to the species, fuel size and climatic conditions (Luke and McArthur, 1978).

Dead fuels absorb moisture as the cell walls of the plant tissues are hygroscopic (Luke and McArthur, 1978). The rate at which fuels will dry by desorption is a function of surrounding air temperature, relative humidity and wind speed (Luke and McArthur, 1978).

The monthly variations of fuels that are almost cured are governed by the monthly absorption and desorption rates (Luke and McArthur, 1978). The daily and hourly variations are controlled by the temperature and relative humidity (Luke and McArthur, 1978). The rate at which dead fuels change their moisture content in accordance with the weather conditions is known as a timelag (NWS, 2003).

Wildfire Climate and Weather

Climate refers to the average weather at a place over a long period and is expressed using statistical analysis such as averages, totals, extremes and frequencies (Luke and McArthur, 1978). Certain climatic conditions will result in a wildfire season known as a wildfire climate. Wildfire climates are meaningful on larger temporal scales as they define the wildfire season and context in which wildfire weather conditions are calculated.

Weather refers to the atmospheric conditions over a short period such as pressure, relative humidity and temperature (Luke and McArthur, 1978). Weather conditions are used on a small temporal scale in order to determine the potential of a wildfire within a certain number of days. The following weather conditions are important in relation to fuels and wildfire:

Wind

The most dynamic weather variable that is involved in wildfires is wind (Cheney and Sullivan, 2001). This is due to fluctuations over short periods as well as over varying distances and at varying heights in the atmosphere (Cheney and Sullivan, 2001). Wind increases oxygen supply to a wildfire at a faster rate. It also spreads the flames onto unburned areas of vegetation affecting the rate of spread of the wildfire, and preheating and drying of fuels (Trollope, 1984a; Brown and Hall, 2000). Wind on a local scale can have a greater effect on wildfire than larger prevailing winds within a region.

Air Temperature

Air temperature affects the temperature of the fuels to be ignited (Trollope, 1984a). The air temperature also exerts an influence upon the relative humidity and the evaporation driven moisture losses of the fuel (Trollope, 1984a; Brown and Hall, 2000). In some cases, air temperature has been found to play a significant role in the intensity of grassland fires (Trollope, 1984a).

Relative Humidity

Relative humidity plays a role in the dryness of the environment and the dead fuel moisture content (Trollope, 1984a; Brown and Hall, 2000; Cheney and Sullivan, 2001). Dead fuels will reach a point of saturation known as the *saturation moisture content* (Cheney and Sullivan, 2001). If the relative humidity of the surrounding air remains constant, the fuel will eventually reach an *equilibrium moisture* content, which equals the relative humidity of the surrounding air (Cheney and Sullivan, 2001). With a relative humidity of 100%, the dead fuel will become saturated.

Rainfall

Rainfall plays a role in the lifecycle of the species of vegetation as well as the fuel moisture content and fuel load (Cheney and Sullivan, 2001). If drought periods are experienced, it may take many years before there is sufficient fuel in that area to sustain another wildfire (Cheney and Sullivan, 2001). Rainfall has a close link to the live fuel moisture content. It therefore plays and an important role in both wildfire potential and wildfire behaviour (Brown and Hall, 2000). Rainfall has an influence on growth and availability of fuels, which in turn influences the wildfire frequency (Van Wilgen and Scholes, 1997).

Slope (Topography)

Slope has an influence on wildfire behaviour. Fires, burning up a slope, spread more quickly to the increased pre-heating of the fresh fuel by the down slope flames (Trollope, 1984a). This is due to the angle of the flames relative to the fuel. Fires burning down a slope have the opposite effect on the wildfire. Slopes can be divided into the categories of moderate slopes (0 - 20º), steep slopes (22 - 35º) and very steep slopes (35 - 45º) (Trollope, 1984a). Whenever a head wildfire burns up a slope, the rate of increase of spread is double relative to the degree of slope it is burning up (Trollope, 1984a). The rate of spread relative to the slope can be calculated by (Trollope, 1984a):

$$R = R_o e^{bx} \qquad \text{(Equation 1.4)}$$

where, R is the rate of spread (m s^{-1}); R_o is the rate of spread on level ground (m s^{-1}); b = 0,0693 and x is the angle of slope (º).

Wildfire in South Africa

Wildfires are frequent events in the South Africa. Of the eight biomes in South Africa, fires occur regularly in the forest, fynbos, savannah, grassland and karoo biomes (Low and Rebelo; 1996). These fires form an important ecological function in these biomes.

The forest biome receives fires least frequently with the evergreen forests combusting every 100 to 300 years in rare extreme weather conditions. The dry/deciduous forests receive fires on a frequency of 20 to 100 years in the dry seasons of June to September (Van Wilgen and Scholes, 1997).

Fires occur in the *fynbos* on a frequency of 4 to 40 years with a mean frequency of 15 years. These wildfires usually occur in the dry summer months can also occur at other periods in extremely dry conditions.

The *moist infertile savannah* wildfires are restricted to the dry winter periods. These fires occur in a frequency of 1 to 6 years with a mean of 3 years. The *arid fertile savannah* wildfires have the same restrictions as the moist fertile savannah, except that fires occur with a frequency of 2 to 11 years, with a mean of 8 years in the Kruger National Park (Van Wilgen and Scholes, 1997).

The infertile, or moist grasslands as described by Van Wilgen and Scholes (1997), have a wildfire frequency of 2 to 4 years however annual wildfires are possible. These wildfires occur on the dry winter months. The fertile, or arid grasslands as described by Van Wilgen and Scholes (1997), have wildfire events every 4 to 10 years also mostly in the dry winter periods (Van Wilgen and Scholes, 1997).

The karoo biome is comprised of succulent arid shrublands. The rainfall is low (50 - 300 mm per year) resulting in a vegetation consisting of succulents, ephemeral forbs and patches of annual grasses. Fires occur on very low frequencies and reach low intensities due to the low percentages of fuel available for burning (Van Wilgen and Scholes, 1997).

Fire frequency in South Africa is influenced by land uses and land management. Many wildfires are ignited by humans and not natural sources which has an influence on the vegetation of these biomes and the frequency at which fires occur.

The components of the wildfire environment form the basis of wildfires in these biomes. South African Weather Services (SAWS) have been mandated with the management of wildfires and wildfire risk in South Africa. In order to address this, legislation such as the National Veld and Forest Fires Act (Republic of South Africa, 1998) has been promulgated. According to Chapter Three of the National Veld and Forest Fires Act (Republic of South Africa, 1998), a fire danger rating system (FDRS) must be provided for South Africa. This is in line with other countries with frequent and large scale wildfire events such as the United States of America, Australia and Canada (Reifsnyder, 1978). According to Chapter three of the National Veld and Fires, the following is required for the FDRS to be initiated:

- Consultation with the South African Weather Services and the various wildfire protection associations
- The division of the country into separate regions that are sufficiently uniform for meaningful danger ratings to be provided for that region
- The FDR for each region must take into account "the topography, vegetation, climatic cycle as well as the typical, recent, current (if possible) and forecasted weather conditions"
- The proper formulae must be utilised in order to rate the wildfire danger, and
- This information must allow for clear wildfire danger to be shown and for that danger to be communicated to the public and necessary bodies.

Such wildfire danger rating systems require data on the key components of the fire environment for these systems (fuel, topography and weather).

A Fire Danger Index (FDI) is available for certain regions of the country, such as KwaZulu-Natal, Mpumalanga and the Western Cape (KZNFPA, 2003). These FDIs are regional and in many cases inaccessible to residents in the rural areas since they do not have access to the data required for the fire danger rating systems. No national based integrated Fire Danger Rating System is in existence in South Africa.

Research has been undertaken to implement FDRS in South Africa. The FDRS derived from the Rothermel Wildfire Model has been tested by Everson *et al.* (1988) in the Drakensberg. This involved the implementation of the Rothermel Wildfire Model (the basis for the United States of America's NFDRS) in these grasslands using a series of hand held calculators with pre-programmed chips for field use of this model. Whilst the study yielded positive results, the hand-held computers are expensive for wide scale use in rural areas and require a comprehensive set of data. The same model and calculators were utilised by Van Wilgen *et al.* (1985) for wildfire prediction in fynbos. The results of the study noted that the predictions of the rate of spread of fire in the fynbos and flame length were good. The authors noted that fire intensity was underestimated in the cases where the biomass measurements and fire hazards were considered to be high. The required input data for the model were live and dead biomass, fuel moisture content and weather conditions. In many cases, such input data are not readily available for large areas of the South Africa in which wildfires take place.

Whilst FDRS relate to data over large areas and numerous biomes, authors have undertaken studies on wildfires without specifically focusing on wildfire prediction and danger rating. This research has resulted in the accumulation of scientific data and building of a fairly strong knowledge base on wildfires in South Africa (Van Wilgen 1984, Van Wilgen *et al.* 1985; Trollope 1984a; Trollope 1984b; Everson *et al.,* 1988; Delmas *et al.,* 1991, Trollope, 1993; Trollope *et al.,* 1996; Stocks *et al.,* 1996, Scholes *et al.*, 1996; Van Wilgen and Scholes, 1997). These studies range over a variety of topics within the field of wildfires. Titshall *et al.* (1999) have researched the effects of wildfire exclusion of soils and herbivory, and Snyman (2002) has researched the short term impacts of wildfire on soil characteristics. Scholes *et al.* (1996) have determined the quantities of biomass burned in Southern Africa utilising remote sensing while Balfour and Howison (2001) have undertaken an analysis of the spatial and temporal variations of wildfire regimes over 41 years in the Hluhluwe-Umfolozi Park in KwaZulu-Natal. Further research is however still required to integrate this knowledge on various spatial and temporal scales for application to better wildfire prediction and danger rating systems.

The KwaZulu Natal Wildfire Protection Agency (KZNFPA) manages wildfire risk and related topics in South Africa. As apart of the required FDI, KZNFPA has an online wildfire danger calculator making use of several weather variables for the calculation: dry bulb temperature; relative humidity; wind speed; number of days since rain; and rainfall. KZNFPA runs a variety of programmes in order to raise awareness and education surrounding wildfires in KwaZulu Natal (KZNFPA, 2003).

As some of the biomes of South Africa extend beyond political borders, so does the effect of wildfires and need prediction and management. SAFNet (Southern African Fire Network) is a regional body created to co-ordinate efforts in wildfire management and monitoring. SAFNet membership comprises: managers from national parks; government forest wildfire sectors; regional Non-Governmental Organizations; Community Based Organizations; independent consultants; and university and research bodies in Southern Africa (Smith, 2005). SAFNet is involved in a host of activities relating to wildfire. These include collection of data for a variety of uses surrounding wildfires, focusing on early detection of fires that could endanger persons, their livelihoods or precious natural resources. SAFNet is involved in the mapping and quantifying of areas affected by fires, which in turn help to inform wildfire management policy. Data are provided for validation of satellite sensors and integrated research on land uses in communities to reduce the negative impacts of fires caused by humans. SAFNet is involved in other activities that encompass wildfire management monitoring, management and policy (Smith, 2005).

The Southern Africa Wildfire Atmospheric Research Initiative in 1992 (SAFARI-92) and The Southern African Regional Science Initiative in 2000 (SAFARI-2000) are research initiatives which have also extended beyond the borders of South Africa (Regional Subsahara Wildland Fire Network, 2005). These international cooperatives formed a part of Southern Tropical Atlantic Regional Experiment (STARE) have provided extensive knowledge on wildfires and their related impacts in Southern Africa (Regional Subsahara Wildland Fire Network, 2005).

SAFARI-92 focused on the emission of trace gas elements from burned soils and the factors which exerted an influence on biomass burning. This involved investigations on the atmospheric chemical and ecological role of wildfire in African savannahs (Goldammer, 1997; Swap *et al.*, 2002; Regional Subsahara Wildland Fire Network, 2005). SAFARI-92 measurements were complemented by regional airborne and ground based studies and involved studies on biomass burning from remote sensing. The major focus of the SAFARI-92 was linked to the atmospheric impacts of wildfire and their connectivity over the Southern African region (Goldammer, 1997).

SAFARI 2000 investigated emissions, transport, transformation and deposition of trace gases and aerosols over Southern Africa (Swap *et al.*, 2002). SAFARI 2000 built upon the legacy of SAFARI-92 by providing additional quantified data, and validated regional emissions from fires and other sources. It furthermore contributed to the understanding of the impacts of these emissions on the bio-geographical system (Swap, 1999). SAFARI 2000 was a large scientific initiative, which contributed to regional knowledge on the atmosphere and wildfire.

Articles from the publications for the SAFARI-92 initiatives have contributed substantially to knowledge on wildfire in southern Africa, and to the study region in particular (Scholes, *et al.*, 1996; Stocks *et al.*, 1996; Trollope *et al.*, 1996; Goldammer, 1997; Kendall *et al.*, 1997; Van Wilgen *et al.*, 1997, Stocks *et al.,* 1997).

Other projects on a regional scale have been undertaken, such as by Shea *et al.* (1993) who undertook to test vegetation physiognomy, available fuel loads, levels of biomass consumed by wildfire, environmental conditions and wildfire behaviour in both the South African and Zambian savannahs. This study has provided more quantitative data and collection techniques on these factors for African savannah fires.

Wildfire bodies such as SAFNet and research initiatives such as SAFARI-92 and SAFARI 2000 are invaluable for regional cooperation on wildfire prediction and management. The Kruger National Park, located within the same biome and to the east of the study area for this research, also formed a part of the data collection area for the SAFARI campaigns. The Kruger National Park forms an important source of wildfire research for the study area.

Research on wildfire in the Kruger National Park has taken place as part of park management in order to assess the impact of burning regimes on the ecosystem. Wildfire behaviour and dynamics within the Kruger National Park have been characterised on a large scale by Stocks *et al.* (1996). Trollope *et al.* (1993) have conducted experimental burns on a smaller scale to characterise biomass and wildfire behaviour in this Park and to determine wildfire regimes in the Park. This research has aided in establishing the characteristics of wildfire within the study area and specifically within the arid fertile savannahs with its particular flora diversity and weather conditions.

The major cause of fires (90%) in the Kruger National Park is due to man-made fires (Trollope, 1993). The majority of these fires are ignited as controlled burns, or by refugees passing through the park.

Wildfire in the Study Area

The study area is located within the mixed Lowveld bushveld of the savannah biome (Low and Rebelo, 1996). In South Africa, the type of savannah is determined by the broad soil fertility and rainfall gradients of the area (Van Wilgen and Scholes, 1997). The majority of the biomass in the savannahs is made up of trees and grasses. The fuel load of grasses in these savannahs varies inversely with the canopy cover of the trees as the shade of the trees inhibits growth of the grass (Van Wilgen and Scholes, 1997). The study area is specifically located within the arid fertile savannah of the Lowveld that occupies approximately 24% of South Africa's land area (Huntley, 1984; Van Wilgen and Scholes, 1997).

This savannah is characterised by base-rich soils in which calcretes are a common feature. The herbaceous grasses are xerophytic tussock grasses that are of low nutritional value. These support a variety of indigenous ungulates at lower densities compared to the commercial farming of wild animals and cattle. The typical biomass productivity of these grasses is 500 – 1,000 kg ha^{-1} yr^{-1}. The woody vegetation in this area consists of short trees as well as scattered shrubs. The general biomass productivity of the woody vegetation is ~20,000 kg ha^{-1} yr^{-1}.

Erect grasses with discontinuous (patchy) distribution support fires in the arid/fertile savannahs (Huntley, 1984; Van Wilgen and Scholes, 1997). The patchy distribution of the grasses contributes to a lower efficiency in total combustion. The trees are less important in the spread of wildfire. However the woody material does undergo smouldering combustion. Dung often also forms a common part of the smouldering fuels. Wildfire frequency of natural fires is once every eight years (Van Wilgen and Scholes, 1997). Approximately 9% of the arid/fertile savannah burns annually (Van Wilgen and Scholes, 1997, p. 44).

This savannah occurs within the summer rainfall region and fires typically take place at the end of the dry season in September to October (Trollope, 1984b). Both crown and surface fires occur in the savannah but surface fires occur more frequently (Trollope, 1984b). Crown fires will only ignite under extreme conditions, as the trees in these areas are generally resistant to wildfire. Savannahs have a broken canopy in most instances where canopy fires, such as those found in forest fires, are not possible.

Land use practices play a large influential role in the wildfire regime in the area. Legislation governing the burning of the savannah exists but in reality, only the commercial cattle farming and wildlife management practitioners adhere to these laws. Commercial cattle and/or game farming burn most areas under their management on two or four year cycles. Subsistence ranches tend to conduct burns throughout the year whenever the vegetation has a sufficient fuel load and is dry enough to burn (Trollope, 1984b).

Remote Sensing

Remote Sensing and Vegetation

Remote sensing has been utilised in a variety of fields with various applications (Lillesand and Keifer, 2000) Vegetation constitutes a large portion of the Earth's surface cover is commonly detected utilising remote sensing. Detection of green vegetation using satellite data has grown to become a common application of remote sensing imagery (Richardson and Wiegand, 1977; Leblon *et al.,* 1991; Pickup *et al.,* 1993; Ray *et al.,* 1994; Avitable *et al.,* 2005). Remote sensing of green vegetation is orientated on the absorption and reflection of different wavelengths of light. The properties of chlorophyll cause a reflection of infra-red and absorption of red light (Tucker, 1979; Ray, 1994). These two electromagnetic wavelengths have been extensively tested and used in various applications forming the basis of most vegetation indices (VI).

Vegetation biomass refers to the weight of all organic matter comprising vegetation within a specified area. Above ground biomass is the weight of all organic matter comprising vegetation above the soil surface within a specified area (Drake *et al.,* 2003). Below ground biomass is the weight of all organic matter comprising vegetation below the soil surface within a specified area. Wet biomass includes moisture in the weight while dry biomass is the weight without moisture (Miller, 2000). Many vegetation indices have been tested and calibrated to accurately reflect the relative green vegetation contributing to the image. Three main approaches have been utilised in estimating ground vegetation biomass (Moreau, *et al.*, 2003): empirical relationships with vegetation indices; Monteith efficiency model; and process based models.

The empirical relationship of vegetation indices makes use of mathematical transformations which assess the different multi-spectral observations and the spectral contribution of vegetation (Elvidge and Chen, 1995). The most used vegetation indices use the near infrared (NIR) (0.7 to 1.3 µm) and red bands (0.6 to 0.7 µm) in the sensors. This is because the NIR bands are highly reflective of plant materials and the red band is efficient at detecting chlorophyll content in plants (Elvidge and Chen, 1995). Three basic types of vegetation indices are used: ratio, orthogonal and hybrid indices (Elvidge and Chen, 1995).

Various researchers have used vegetation indices to detect biomass. Burgan *et al.* (1998) produced initial vegetation maps using a fire danger fuel model map with a 1.1 km resolution on a national level for the USA, using NOAA/AVHRR images. The initial vegetation map was produced by creating eight monthly composites of the Normalised Difference Vegetation Index (NDVI) for the country, which was then applied to a Wildfire Potential Model. The study results showed a strong correlation with the occurrence of fires. A similar methodology was applied to Europe for forest wildfire risk at the pan European scale (Lopez *et al.*, 2002).

Scholes *et al.* (1996) performed an extensive study in southern Africa using NOAA/AVHRR satellite imagery. They calculated the NDVI and combined this with a vegetation classification map for Southern Africa. The biomass, including multi-year accumulation, herbivory and decay of fuel, was calculated using a production model driven by rainfall. The combustion was calculated using the fuel load and type that had been collected from the field. Results were tested against the conventional method of testing biomass burnt (based on classification) and a result lower (90 – 264 Tg dry matter) the conventional method (247 – 2719 Tg dry matter) was obtained.

Some concern has been raised on the use of NDVI for assessing biomass because the relationship between the NDVI and biomass is asymptotic. Data must be accurately calibrated or else the ground data and satellite data will conflict. It has been noted that the sensitivity of vegetation indices to biomass can vary meaning resulting in a certain degree of inconsistency of results utilising the same research method. Further, most vegetation indices do not make use of all the available spectral data making it more difficult to distinguish features utilising spectral signatures (Foody *et al.*, 2001). With the addition of bands covering additional wavelengths, scope is available for the development of new indices and refining of established indices for more accurate results. Even with this additional scope, the NDVI, though a simple and dated VI, is still utilised in land cover and land use change analysis (Kusangaya *et al.*, 2005).

Ishiyama *et al.* (2001), Wylie *et al.* (2002) and Moreau *et al.* (2003) have performed biomass studies using vegetation indices and yielded promising results (Ishiyama *et al.*, 2001; Wylie *et al.*, 2002; Moreau *et al.*, 2003). Ishiyama *et al's.* (2001) study specifically exhibited a strong correlation between vegetation indices and dry vegetation biomass (dried physically) using ASTER imagery (R^2 value of 0.82). The field vegetation was no naturally dried and therefore the strong correlation with the NDVI values is not expected.

Vegetation indices which exclude background noise produce better results in the detection of vegetation. The soil adjusted vegetation index (SAVI), can be used to minimise the background noise effects from soil (Huete, 1988; Rondeaux *et al.*, 1996). The aerosol free vegetation index (AFRI) can be used to minimise atmospheric interferences such as smoke or sulphates (Karnieli *et al.*, 2001). The SAVI requires that a constant be applied to the index to remove the background noise created by the reflectance of the soil. This constant is calculated according to the percentage of ground covered by vegetation. The AFRI index makes use of the Short Wave Infra-Red (SWIR) bands in the same ratio index as used with the NDVI (Karnieli *et al.*, 2001). The short wave infra-red electromagnetic energy has a longer wave length that is able to penetrate aerosols and thus it is possible to "see through" obstructions such as smoke plumes from wildfires.

The Monteith efficiency model was prepared for estimation of the annual net primary productivity (ANPP) of vegetation (Monteith, 1972). This was to be achieved through estimating the ANPP as a product of the absorbed photo-synthetically active radiation (APAR) of the vegetation that the plants transform into dry biomass. Justification for this method is based upon the strong relationship that exists between the fraction of incident photo-synthetically active radiation absorbed by the vegetation (f_{APAR}) and its strong correlation with vegetation indices (Moreau *et al.*, 2003). However, it has been found that the atmospheric effects and soil background may distort this method. There also exists a further lack of knowledge of the conversion efficiency of APAR and its conversion into biomass varies according to plant phenology and botanical composition (Leblon *et al.*, 1991).

Processed based models incorporate satellite data with various ancillary data. Hély *et al.* (2003) assessed the fuel load of the savannah using a net primary production model (process based model) consisting of vegetation, radiation, meteorological and grazing factors with satellite data. Within the Sahelian grasslands grassland biomass and productivity were derived utilising a combined ecosystem process model. This model incorporated the data categories of vegetation species, evaporation, transpiration, photosynthesis, respiration, senescence, litter production and litter composition with satellite data (Lo Seen *et al.*, 1995; Mougin *et al.*, 1995). Delmas *et al.* (1991) describe a method of applying a net primary production model (process based model) to estimate the sub-Saharan savannah biomass for a study on the biomass burned in Africa using NOAA/AVHRR imagery. This study found biomass burning in Africa to have a large influence on the atmospheric chemistry of the global troposphere. Moreau *et al.* (2003) investigated the use of vegetation indices and Monteith efficiency model for determining total humid biomass, total dry biomass and photo-synthetically active material. Whilst Hély *et al.* (2003) and other such models have been considered effective for the spatial and temporal availability of fuels for different regions, vegetation indices will be utilised in this study as the Monteith efficiency model and process based models require ancillary data which was not available for the study. Such data would be difficult to obtain if the methodology of this study were to be applied over a large scale South African context.

Vegetation indices are measures of the relative extent of properties associated with the chlorophyll that are observed in the spectral results of remote sensing data. However, most vegetation associated with wildfires has low chlorophyll concentration as they are dry and dormant (Ray, 1994). This is especially the case in fine fuels (grasses etc) that are primarily involved in the ignition of fires. This leads to a difficulties in applying vegetation indices to the risk of wildfire as the conventional vegetation indices are not sensitive to brown-coloured material. The PD54 Vegetation Index (Pickup *et al.*, 1993) is a vegetation index that has been tested in order to discriminate between dry vegetation, green vegetation and bare soils (Ray, 1994; CSIRO, 2004). The PD54 Index was derived for Landsat imagery and works well in areas where the dominant soil colour is red or red-brown in colour. The Australian Centre for Scientific (CSIRO, 2004) calculated PD54 using MicroBrain software that produces cross plots of the visible green and visible red bands of Landsat MSS data. A soil line is fitted to the cross plot and the vegetation cover is read off this graph. The area over which the PD54 index was utilised is located in desert regions, which forms a contrast to the study area in question. This index was not utilised in this study due to a lack of soil data for the large study area.

Due to the increasing availability of satellite images, vegetation indices, including time series data, are being utilised for the determination of above ground biomass (Avitabile *et al.*, 2005; Kusangaya *et al.*, 2005; Mohamed *et al.*, 2005; Thompson *et al.*, 2005). Difficulties in downloading large data sets and slow postal systems were inhibiting factors for real time analysis of fire risk in South Africa. These problems are disappearing with the spread of internet ISDN and ADSL technology, and the availability of direct download images (for example MODIS), but at the beginning of this project, they were a larger issue.

Fuel Mapping Techniques for Wildfire Prediction

Wildfires often occur over large areas that are relatively inaccessible. This makes comprehensive data collection in these areas difficult. A wildfire season poses a wildfire threat over large areas for many months of the year. It is difficult to collect data using manual field data collection techniques for such large areas over a long period. In order to overcome these data obstacles, models such as fuel models were developed to provide data on fuel types, fuel load and fuel moisture for these systems (Luke and McArthur, 1978; Cheney and Sullivan, 1997; Verbesselt *et al.*, 2002; NWS, 2003; CSIRO, 2001).

These modelling techniques involved initially mapping the vegetation type and subsequently applying a fuel model for each vegetation classification (Keane *et al.*, 2000). Fuel mapping techniques, such as the Australian method as described by Luke and McArthur (1978), have traditionally mapped fuels according to the botanical composition of the vegetation into classes such as ‘grasses’ and ‘forests’ (Luke and McArthur, 1978). These maps have then been prepared through the integration of a map of semi-permanent composition of fuels with the data collected from aerial photographs and field observations (Luke and McArthur, 1978). The United States of America’s technique, as described by NWS (2003) has mapped fuels by dividing them into four broad categories based on botanical composition. These categories have then been further subdivided into 20 sub-categories, which provide greater depth on the fuels (NWS, 2003). These fuel models are mathematical models, which provide quantitative results that are then scaled according to the wildfire risk.

As fuels for wildfires are mapped using non-satellite image applications over larger spatial and temporal areas, so the chance of error and inaccuracies increases. Variables such as land use are difficult to determine over large remote areas over long periods using pre-remote sensing data collection techniques. Remote sensing has been used to provide more comprehensive and up to date data on these areas and allowed for more precise and accurate data collection over such areas (Justice *et al.*, 1993; Anderson *et al.*, 1976; Thompson, 1996). This will assist in more accurate results from models as the input data of the models will be more current and accurate. Satellite sensors have been used for detecting various fuel characteristics such as fuel load, fuel moisture content and fuel size (Chuveico *et al.,* 2000; Chuveico *et al.,* 2003; Moreau *et al.*, 2003).

CHAPTER 2: RESEARCH METHODOLOGY AND DATA

A description is provided of the research methods employed in this study. This includes the preparation and manipulation of the data for analysis. The nature and type of satellite data are described as well as the nature and collection techniques of above ground biomass.

Introduction

The aim of this research is to investigate the feasibility of using ASTER and MAS imagery for green and brown vegetation detection for the purposes of wildfire prediction. In order to investigate this aim both satellite and above ground biomass were acquired. The satellite data required preparation and analysis of images for classification of vegetation. The classified vegetation data required statistical testing against the above ground biomass to establish possible relationships.

For dry vegetation detection, spectral response signatures were used to identify bandwidths in the satellite data that are effective at detecting dry vegetation. The results from the dry vegetation analysis were tested against the above ground biomass from annual surveys of standing biomass at fixed locations within the study area.

Satellite Data

Types of Satellite Data Utilized

Two satellite data sources were utilised. The first set of data utilised were from the Advanced Spaceborne Thermal Emission and Reflectance Radiometer (ASTER) located onboard the TERRA spacecraft (Abrams *et al.*, 2002). The second set of images were from MODIS Airborne Simulator (MAS) carried on-board the ER2 high altitude aircraft (King *et al.*, 1996; King *et al.*, 2003).

The ASTER sensor has 14 bands in which electromagnetic energy is recorded (Table 2.1). The sensor comprises the subsystems in the Visual and Near Infra Red Bands (VNIR), the Short Wave Infra Red Bands (SWIR) and the Thermal Infra Red bands. The VNIR has a spatial resolution of 15 m, SWIR of 30 m and TIR of 90 m.

The TERRA spacecraft (Figure 2.1) flies at an altitude of 705 km in a circular near polar sun-synchronous orbit crossing the equator at about 10:30 am GMT (Abrams *et al.*, 2002).

Table 2.1: Characterisation of the three ASTER sensors. (Abrams *et al.*, 2002: 10)

Subsystem	Band No.	Spectral Range (μm)	Spatial Resolution (m)	Quantization Levels
VNIR	1	0.52 - 0.60	15	8 bits
	2	0.63 - 0.69		
	3N	0.78 - 0.86		
	3B	0.78 - 0.86		
SWIR	4	1.60 - 1.70	30	8 bits
	5	2.145 - 2.185		
	6	2.185 - 2.225		
	7	2.235 - 2.285		
	8	2.295 - 2.365		
	9	2.360 - 2.430		
TIR	10	8.125 - 8.475	90	12 bits
	11	8.475 - 8.825		
	12	8.925 - 9.275		
	13	10.25 - 10.95		
	14	10.95 - 11.65		

Three ASTER images were obtained for the study area. Two images, GB99280 and GB99284, were recorded on the 8th September 2000 at the end of the dry season (Table 2.2). The third image, GB68186, was recorded on the 28th December 2000 during the wet season (Table 2.2).

MODIS is the Moderate Airborne Imaging Spectro-radiometer. It has a ground resolution of between 250 m and 1 km for 36 channels and covers the same range of wavelengths as ASTER. MODIS was not used for this project due to the coarse ground resolution, which is unsuitable for comparison with the ground data. It is however probably the sensor that would be used for national level monitoring of the wildfire risk. “MAS” stands for the MODIS Airborne Simulator and is the aircraft based simulator of the MODIS sensor (Figure 2.2). It is used to refine the MODIS design and calibrate the MODIS satellite based sensor. It has a ground resolution of 50 m when the aircraft is at an altitude of 20 km (King *et al.*, 1996; King *et al*., 2003). These data were acquired to continue the development of an algorithm, if a relationship was established, following from the ASTER work towards a system that could be used with MODIS regional data.

Figure 2.1: The TERRA spacecraft on which the ASTER and MODIS sensors are located. (NASA, 2005)

Figure 2.2: ER2 aircraft on which the MAS sensors are flown. (California Institute of Technology, 2005)

The MAS data over the study area were flown as a part of the SAFARI 2000 campaign. Two flight paths covered the study the area: Flight 158 strip 3 (158_3) and flight 158 strip 11 (158_11). In this report the MAS images are referred to as "MAS 158_3" and "MAS 158_11". The MAS data was collected on the 7th September 2000 (Table 2.2).

Table 2.2: Dates and image identifications of satellite images used for analysis.

Sensor	Image name in this report	Image Number	Date
ASTER	GB68186	GB2003868186	28 December 2000
ASTER	GB99280	GB2003799280	8 September 2001
ASTER	GB99284	GB2003799284	8 September 2001
MAS	MAS 158-3	MAS Flight 158 Strip 3	7 September 2000
MAS	MAS 158-11	MAS Flight 158 Strip 11	7 September 2000

Even though the MAS images were collected at a lower altitude (20 km), the data encounters a similar range of atmospheric transmittance noise as the MODIS and ASTER since the electromagnetic energy passed through approximately 95% of the atmosphere. MAS data has a resolution of 50 m and covers a wider range of bandwidths, including the VNIR, SWIR, mid infra-red (MIR) and TIR bandwidths.

Table 2.3: Spectral and radiometric characteristics of MAS and nearest equivalent MODIS bands. (King *et al.*, 1996)

MAS Band Number	Equivalent MODIS Band*	MAS Central Wavelength (nm)	MAS Band Number	Equivalent MODIS Band*	MAS Central Wavelength (nm)
1	3, 4, 8, 9, 10, 11, 12	0.547	26	-	2.96
2	1, 13	0.657	27	-	3.11
3	14	0.704	28	-	3.28
4	15	0.745	29	-	3.42
5	-	0.786	30	-	3.59
6	16	0.827	31	20	3.74
7	2, 16	0.869	32	21, 22	3.9
8	17	0.909	33	23	4.05
9	5, 18, 19	0.947	34	-	4.21
10	6, 26	1.609	35	24	4.36
11	-	1.663	36	25	4.52
12	-	1.723	37	-	4.67

MAS Band Number	Equivalent MODIS Band*	MAS Central Wavelength (nm)	MAS Band Number	Equivalent MODIS Band*	MAS Central Wavelength (nm)
13	-	1.775	38	-	4.82
14	-	1.825	39	-	4.97
15	-	1.879	40	-	5.12
16	-	1.932	41	27	5.28
17	-	1.979	42	28, 29	8.6
18	-	2.03	43	30	9.79
19	-	2.08	44	-	10.55
20	7	2.129	45	31	11.02
21	-	2.1783	46	32	11.96
22	-	2.227	47	-	12.88
23	-	2.276	48	33	13.23
24	-	2.327	49	34, 35	13.72
25	-	2.375	50	36	14.17

Some of the bands of MAS and MODIS cover different wavelengths. In such cases, the MODIS band number has been placed within the column of the closest MAS wavelength.

Land Use and Land Cover

The false colour composite images of the ASTER data are representative of the land use that takes place within the study area. This is most evident in the display of vegetation cover since the major land use in the area is agriculture. GB99280 presents a good example of this since it has a variety of agricultural practices take place in the study area (Figure 2.3).

The bottom left hand corner of the image has a high vegetation coverage (indicated by the bright red colour) which is an area in which forestry takes place. The areas to the east and northern portion of the figure are covered by private and national game reserves that are managed and show lower, but more prevalent vegetation cover (indicated by the scattered dark to light green). The areas in the central and central western portion are communal lands that are characterized by overgrazing and decline in trees cut down for fire wood. Consequently, these areas indicate low vegetation cover and are dominated by soils (white areas spotted with dull green and grey). Cultivation takes place in the bottom central portion of the image (small red area). The dark green patches located in the central northern portion, central north eastern portions and central south eastern portion of the image are burn scars.

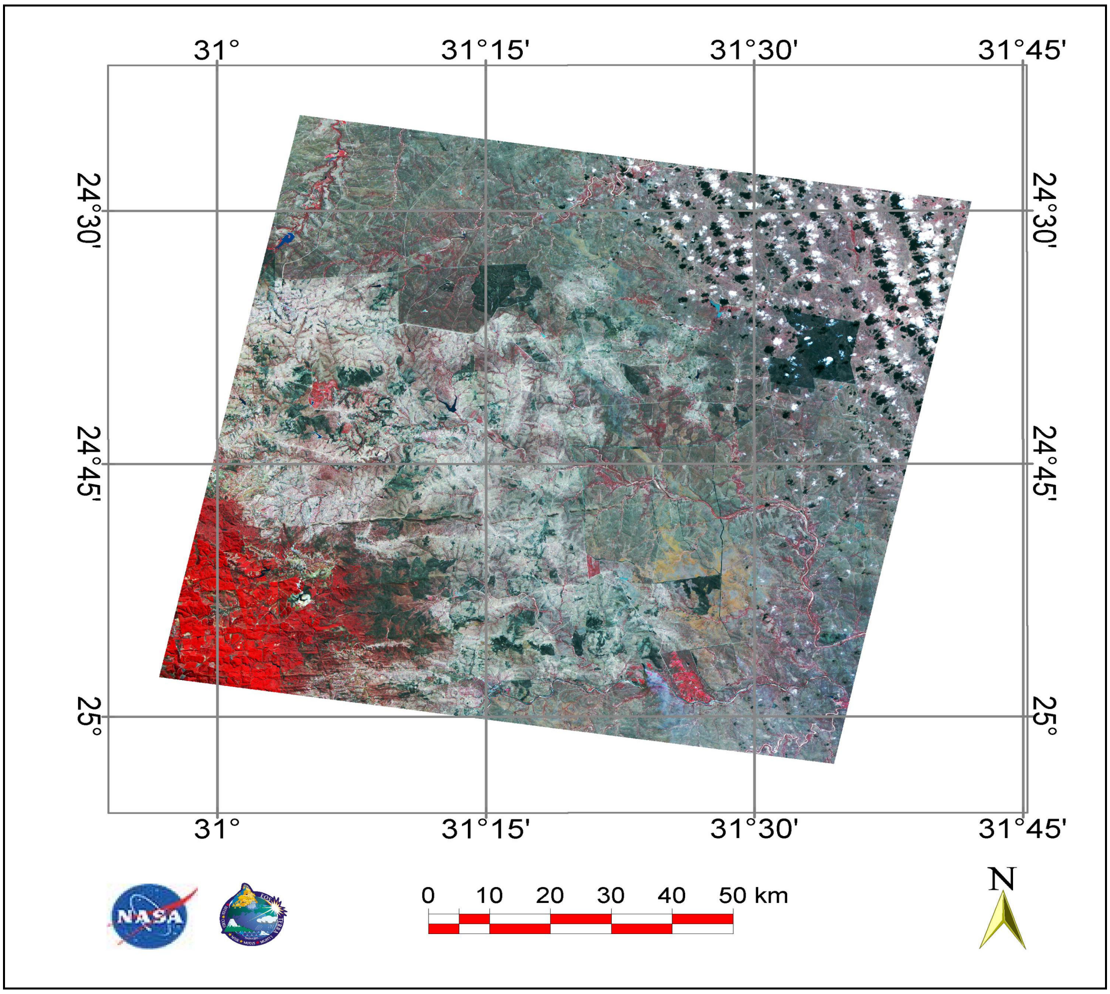

Figure 2.3: False colour composite of the green (Band 1), red (Band 2) and near infra-red bands (Band 3N) of the ASTER image GB99284 collected on 8 September 2001.

Data Limitations

The MAS imagery were collected as a part of a once off campaign. As a result, multiple MAS images over time are not available. The collection of ASTER images does not take place routinely for the same spot, which ruled out the availability of time-series imagery for this study. These limitations meant that time series analysis was not feasible. The images were chosen due to the following reasons:

- The images cover a region for which ground vegetation biomass data are available
- The images are dated at the end of the winter periods where the fuels are at their driest and wildfires are most likely to occur
- The above ground biomass corresponds with this period even though it was collected over a more extensive period.

Measurement of Standing Biomass

The ground truth data comprises above ground grass standing crop biomass expressed as kg ha^{-1}. Data were collected annually during the period mid-March to the end of May. Data collection involved the sampling of 1 x 100 m transect lines using a disk pasture meter (Bransby and Tainton, 1977). The transect lines were logged with GPS coordinates and for more accurate positioning, relocation instructions were recorded such as the beginning of a strip was tied to species 'x', which stands in the shade of species 'y'. Directions were taken as well as annual photographs recorded showing the direction of the transect line. The data were collected annually at the end of the growth season.

The above ground biomass were obtained from Mr. Mike Peel of Agricultural Research Council - Livestock Business Division (Range and Forage). These data were collected as a part of a long-term project that started in 1989. Vegetation ground biomass monitoring started in the period of 1992 to 1993 with an annual frequency of data collected. Data were collected for determining the impact of climate (rainfall in particular) on vegetation in the Lowveld savannahs. Information on herbaceous biomass was collected for decision making relating to grazing (stocking rates) and burning management. Particular focus was placed on small to intermediate sized protected areas in an attempt to improve management. Complementary above ground biomass data were collected in the communal lands by the Agricultural Research Council - Livestock Business Division (Range and Forage) and the Wits Rural Facility for use in monitoring and management of communal lands in this region.

A field trip was undertaken to the Wits Rural Facility in order to observe the data collection points and to establish familiarity with the data collection techniques.

Of the data points provided by ARC, 205 covered the ASTER image footprints and 130 covered the MAS image footprints. Data collection points took place in game reserves and communal lands.

Other data collected during sampling involved the collection of grass composition and cover as well as tree density, structure and canopy. These data were however unavailable for the requested dates. The collection points which fell within the boundary of the study area are represented in Figure 2.4.

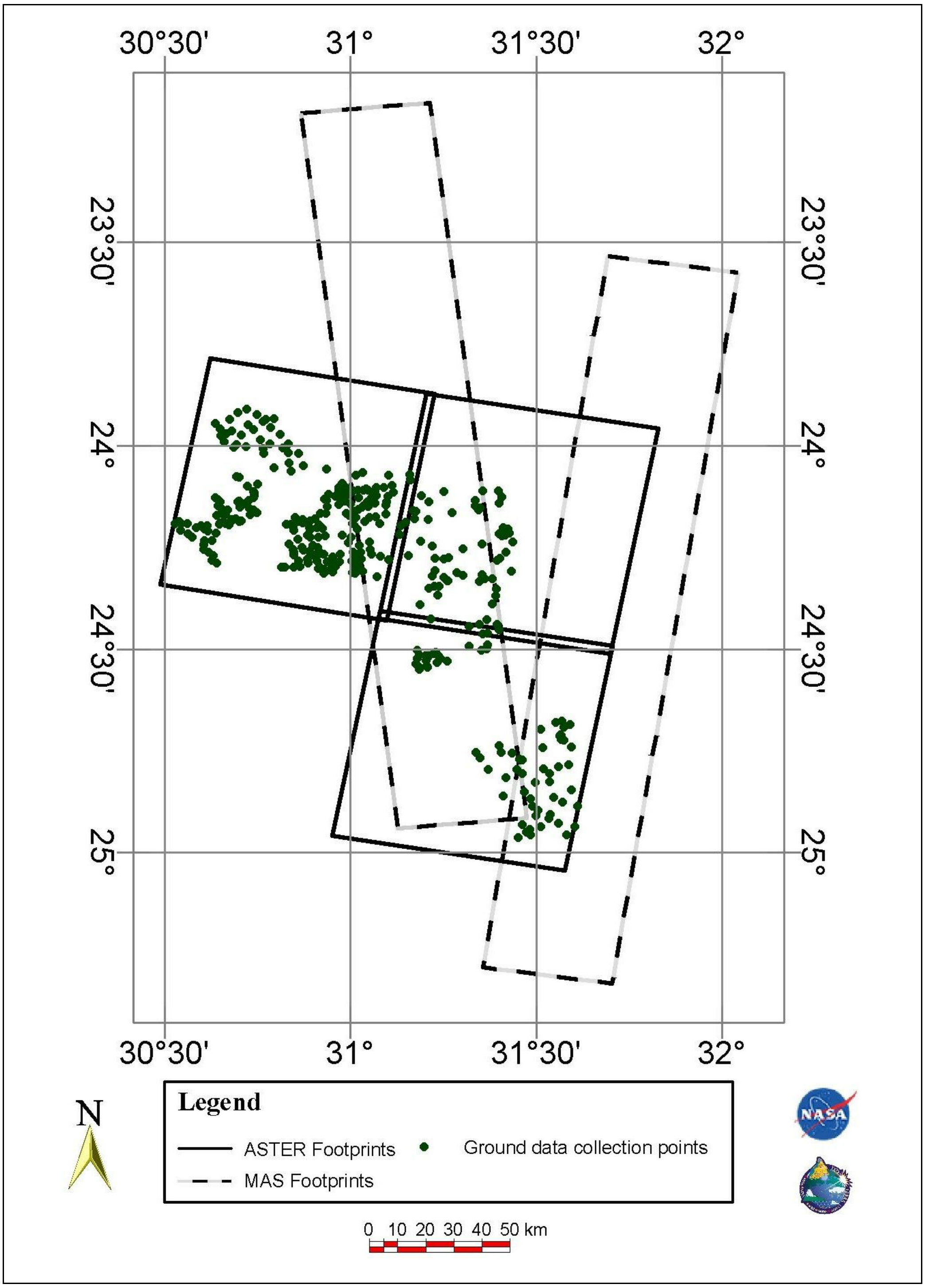

Figure 2.4: Ground vegetation biomass data sampling points for 2000 and 2001 over the ASTER and MAS study areas.

Research Methodology

Geometric and Radiometric Corrections

Before analysis could take place on the satellite data, radiometric and geometric corrections were required. Pre-processing of the ASTER images before this study involved radiometric and geometric corrections performed by Dr. Rob Harris of Geodatec (Pty) Ltd. Once acquired, the ASTER and MAS data were then geo-referenced to 1:50 000 digital topographical maps into the geographical reference system WGS84 in decimal degrees as a part of the study.

Radiometric corrections made include radiometric corrections of effects due to a variety of possible errors or impediments in the data (Lillesand and Keifer, 2000). These include sensor sensitivity caused by the actual calibration errors of the sensors on the satellite. Radiometric corrections due to sun angle and topography correct for impediments such as sun spots and shading due to the sun angle and topography of the landscape. Further corrections required are atmospheric corrections due to impediments such as scattering and absorption of electromagnetic radiation within the atmosphere. Geometric corrections are caused by the attitude, altitude and velocity of the satellite on which the sensors are located (Lillesand and Keifer, 2000).

The test locations for determining standing biomass were recorded using a GPS receiver in same geographical reference system as the satellite data (WGS84). These ground truth points were overlaid onto the satellite images data and all data at those points were extracted to an Earth Resource (ER) Mapper file format. The digital numbers for each band of the satellite data, which corresponded with the above ground biomass data points, were then extracted using Micorimages TNTMips image processing software (Table 2.2). Once extracted, the data were ready for analysis. These points were exported to a text file and were processed using MS Excel.

Vegetation Indices and Biomass Correlation

To classify vegetation within the satellite datasets, the Normalised Differentiated Vegetation Index (NDVI) and Transformed Vegetation Index (TVI) were calculated (Table 2.4) (Lillesand and Keifer, 2000).

Table 2.4: Vegetation Indices utilized.

Acronym	Vegetation Index	Equation	Source
NDVI	Normalized Difference Vegetation Index	$NDVI = \frac{NIR - red}{NIR + red}$	Rouse *et al.*, 1974
TVI	Transformed Vegetation Index	$TVI = \left[\frac{DN(NearIR) - DN(red)}{DN(NearIR) + DN(red)} + 0.5 \right]^{1/2} \times 100$	Deering *et al.*, 1975

* NIR = Near Infra-Red Band. Red = Red band. DN = Digital Number

NDVI is a ratio index that utilises the red band and near infra-red (NIR) band. Band 2 of the ASTER sensor is the red band and Band 3N is the NIR band. Band 6 of the MAS sensor is the red band and Band 4 is the NIR band.

The TVI is also a ratio index and makes use of the red and NIR bands. Band 2 of the ASTER sensor the red band and Band 3N is the NIR band. Bands 3 to 5 of the MAS sensor are the red bands and Band 6 is the NIR band (Table 2.1).

The results of the vegetation indices were then plotted against the above ground vegetation biomass on an x-y scatter plot graph. A linear regression was applied to the data and plotted on the same x-y scatter graph as a trend line with the trend line equation and R^2 value. The results were visually interpreted in order to examine the graphs for any trends in the data.

Dry Vegetation Detection

Spectral data based on the spectral response signatures of dry and green vegetation were used for determining dry vegetation. The spectral response signatures were obtained from a study of South African savannah vegetation by Kneen *et al.* (2004) and data from the ASTER online spectral signature library (California Institute of Technology, 2000). No reference is made as to whether the standard ASTER signatures distinguish between tropical and temperate grasses. The spectral response signature of dry grass differs from that of green grass at different wavelengths (indicated in Figure 2.5 by the red ellipsoids). In addition to these, differences in the thermal infrared bandwidths were noted by Kneen *et al*. (2004).

To discriminate the dry and green vegetation in the satellite data, ratios were plotted between the bands of the applicable MAS and ASTER data. The MAS data allowed for a greater scope of application and testing as the bandwidths extend over a greater proportion of the electromagnetic spectrum. The MAS data utilised data at the wavelengths indicated in ellipsoids 1, 2 and 3 of Figure 2.5, whilst the ASTER imagery could utilise the wavelengths at ellipsoids 1 and 3, as point 2 falls outside of ASTER's bandwidth range.

The ratios were applied using the extracted satellite data and compared with the above ground biomass. An x-y scatter graph was then applied between the ratio values and ground biomass values for each data collection point. A linear regression analysis was applied to the data and plotted on the x-y scatter graph in the form of a trend line with the equation of the trend line and the R^2 value. The results were visually interpreted in order to examine the graphs for any trends in the data.

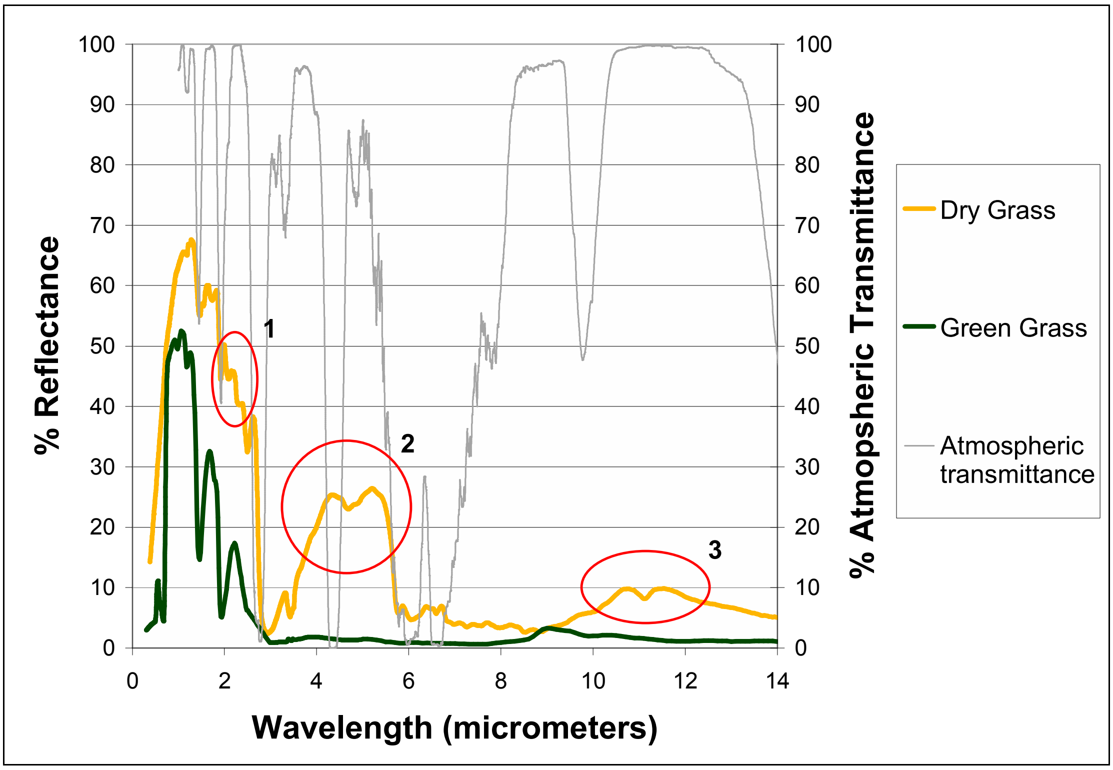

Figure 2.5: Spectral response signatures of dry and green grass. (California Institute of Technology, 2000)

CHAPTER 3: RESULTS AND DISCUSSION

This chapter describes and discusses the results of the statistical analysis of the vegetation indices and above ground biomass. Further discussion is presented on the assumptions and limitations of the study and the possible affect they may exert on the results. Recommendations are made for possible improvements that should be made for possible future studies on this topic.

Introduction

The analysis of data compared the calculated vegetation index values from the ASTER and MAS data with the above ground biomass (kg ha^{-1}). The results of the linear regression of the vegetation indices and ground data are presented followed by the result of the brown vegetation detection. Both the statistical and visual trends for the ASTER and MAS correlations are presented. The results are then followed by discussion on the results in relation to the research aims.

Assumptions and limitations are discussed in light of the results from the applied study as well as possible methods that could be incorporated in improving the research. Conclusions are drawn from the findings in addressing the research aim.

Results of the Calculated Vegetation Indices and Ground Truth Data

ASTER Data

The linear regression between the biomass and NDVI values for the ASTER images GB99280 and GB99284 (both for collected on 8th September 2001 during the dry season) and vegetation standing crop biomass values were very weak returning a R^2 value of 0.024 (Figure 3.1). The linear regression between TVI values for the same images and the vegetation standing crop biomass values for these two images were even weaker with a R^2 value of 0.002 (Figure 3.2).

Visual inspection of the scatter plots and linear regression lines for the analysis of the vegetation indices for the GB99280 and GB99284 images and vegetation standing crop biomass display a visual trend (Figure 3.1 and Figure 3.2).

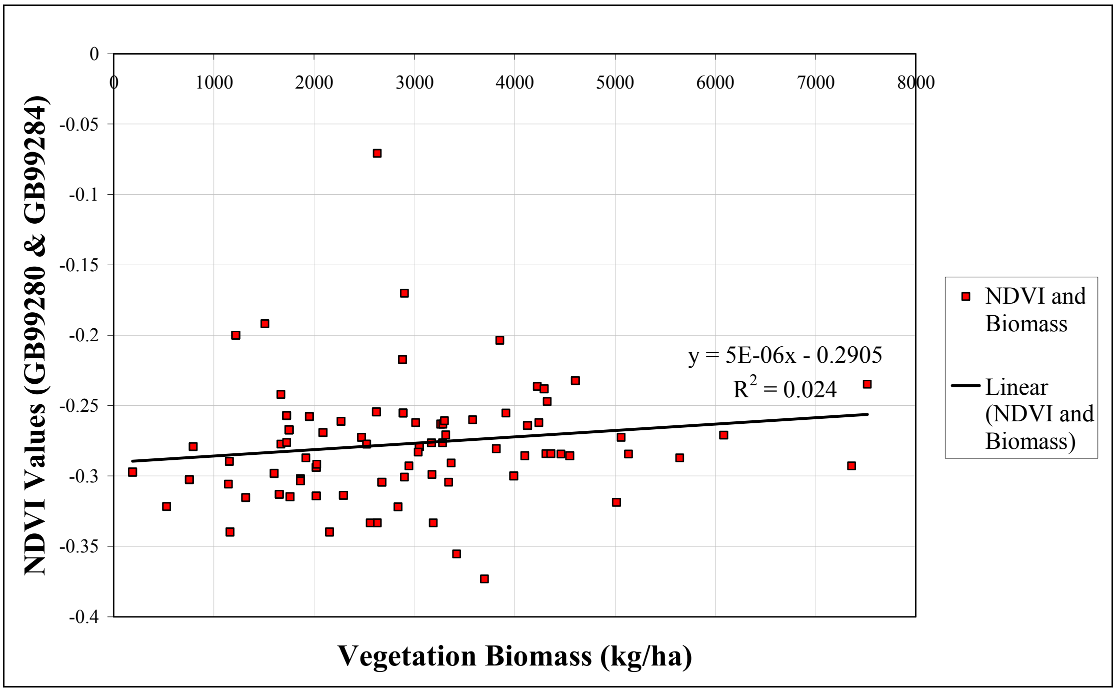

Figure 3.1: X-y scatter plot graph with linear regression line between the NDVI values of GB 99280 and GB99284 and the ground vegetation biomass points.

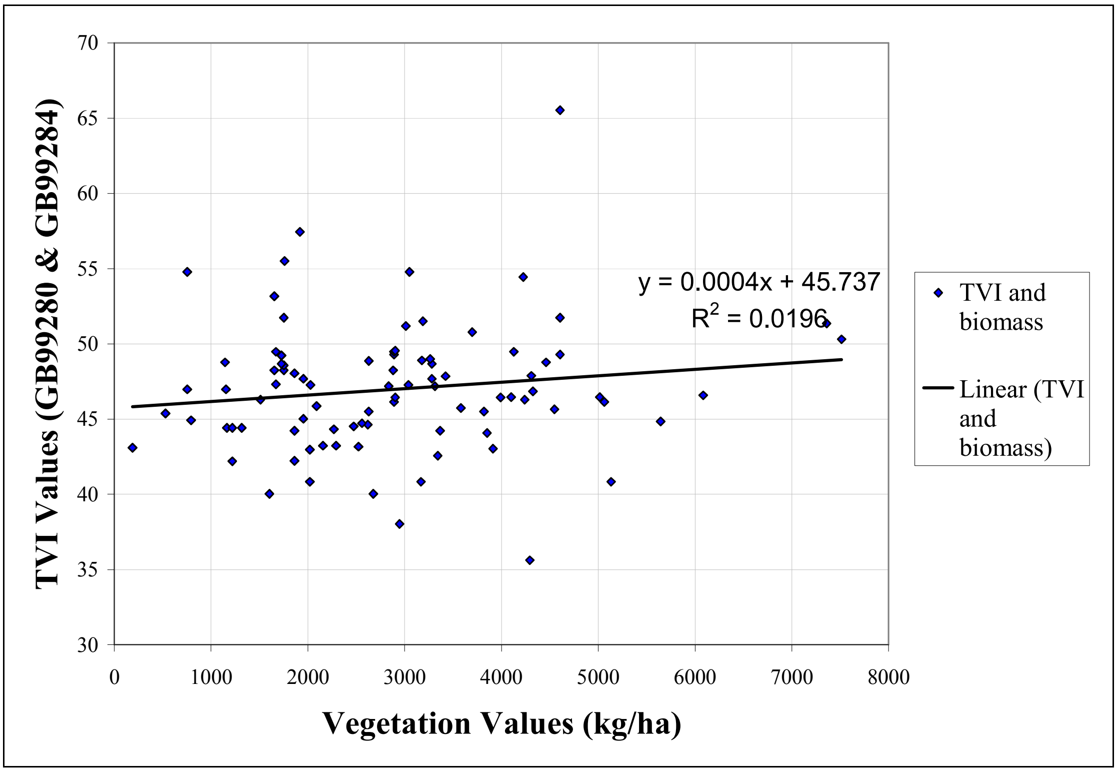

Figure 3.2: X-y scatter plot graph with linear regression line between the TVI values of GB9280 and GB99284 and the ground vegetation biomass points.

Visual inspection of the graph indicates of both graphs reveal that the majority of the points of the x-y scatter plots fall within a small range of each other along the regression line. This is despite the equation of the regression line indicating a very weak gentle slope with almost no correlation of the data points. Conversely, both x-y scatter plots (Figure 3.1 and Figure 3.2) have many other points that are randomly scattered on the graph. These outliers will have an effect on the correlation between the two data sets.

The remaining ASTER image GB68186 (collected on 28th December 2005 in the wet season) returned weak correlations with the vegetation standing crop biomass values for both the NDVI and TVI values. The NDVI and vegetation standing crop biomass values x-y scatter plot returned a poor R^2 value of 0.053 (Figure 3.3) and the TVI and vegetation standing crop biomass values returned an equally as poor R^2 value of 0.048 (Figure 3.4).

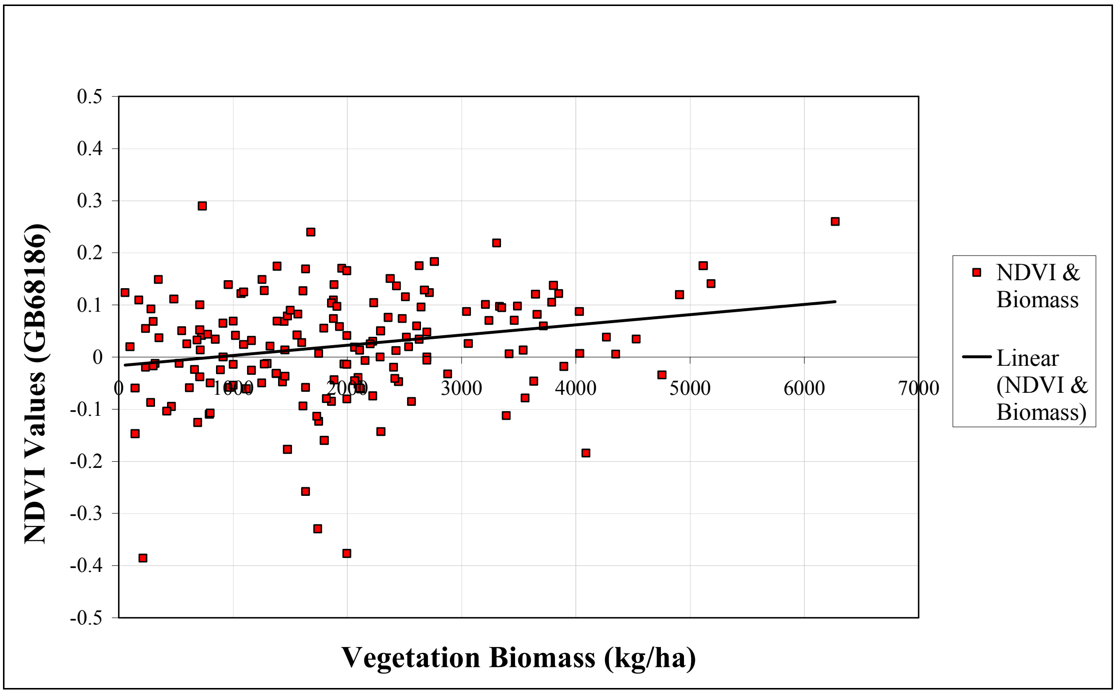

Figure 3.3: X-y scatter plot graph with linear regression line between the NDVI values of GB68186 and the ground vegetation biomass points.

Visual inspection of the x-y scatter plots revealed the same grouping of points along the regression line (Figure 3.3 and Figure 3.4). As with the results for the ASTER images GB99280 and GB99284, a portion of the points fall outside of the general distribution of a group of points on the plots.

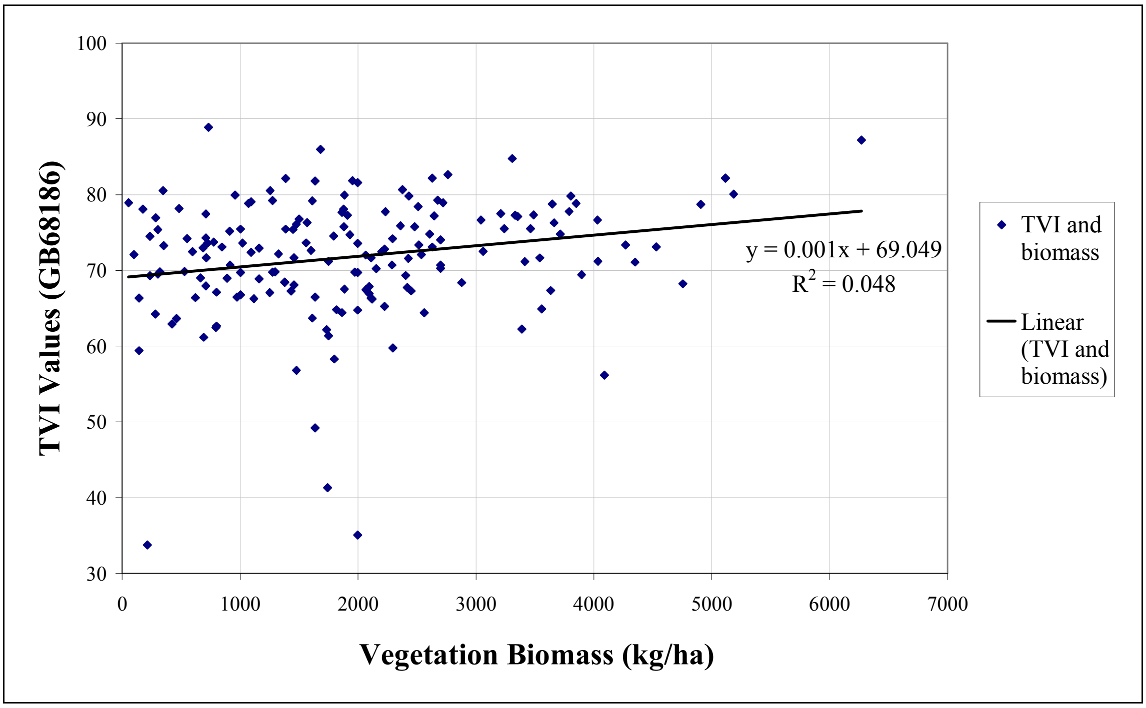

Figure 3.4: X-y scatter plot graph with linear regression line between the TVI values of GB68186 and the ground vegetation biomass points.

MAS data

The correlation between the MAS images (both collected on 7th September 2000 in the dry season) were almost as weak as with all the ASTER images and vegetation standing crop biomass values. The R^2 values on the linear regression line for the NDVI and ground vegetation standing crop biomass graph was 0.075 (Figure 3.5) and 0.073 for the TVI and ground vegetation standing crop biomass graph (Figure 3.6).

Visual inspection reveals that while the linear regression of the data points is very weak, the scatter plot displays the same visual trend as with the ASTER images (Figure 3.5 and Figure 3.6). A portion of the points on the graphs deviate from the general clustering of the points on the plots (Figure 3.5 and Figure 3.6).

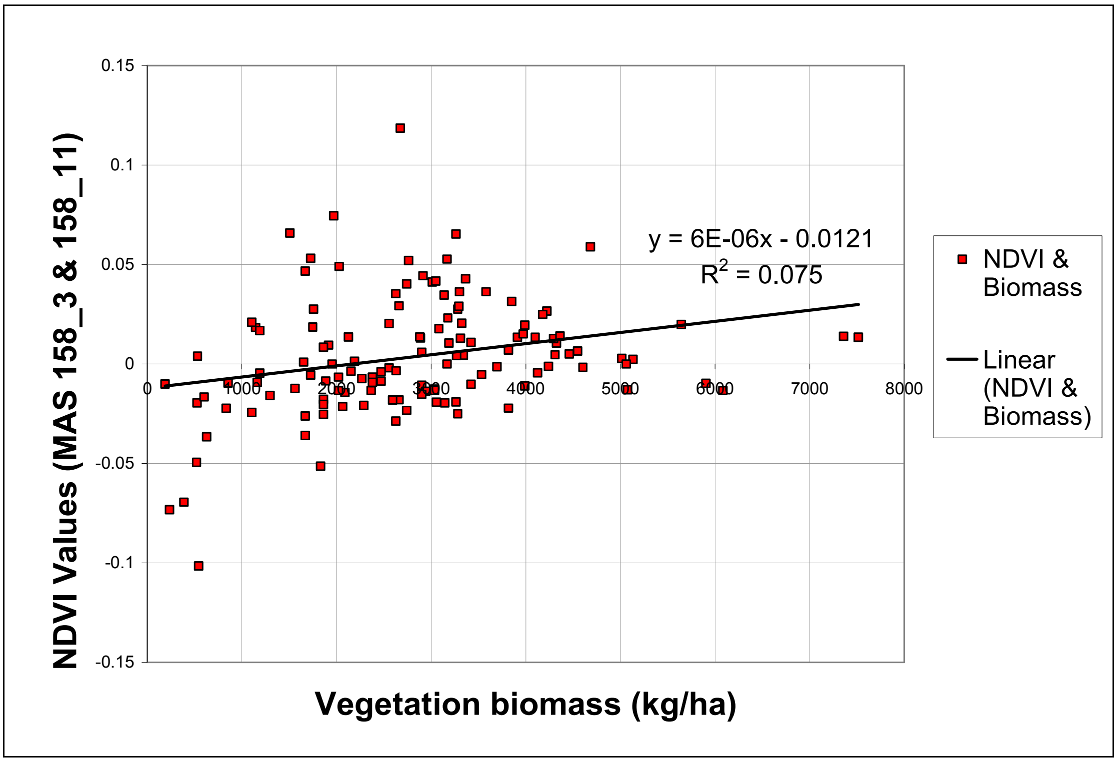

Figure 3.5: X-y scatter plot graph with linear regression line between the NDVI values of MAS 158-3 and the ground vegetation biomass points.

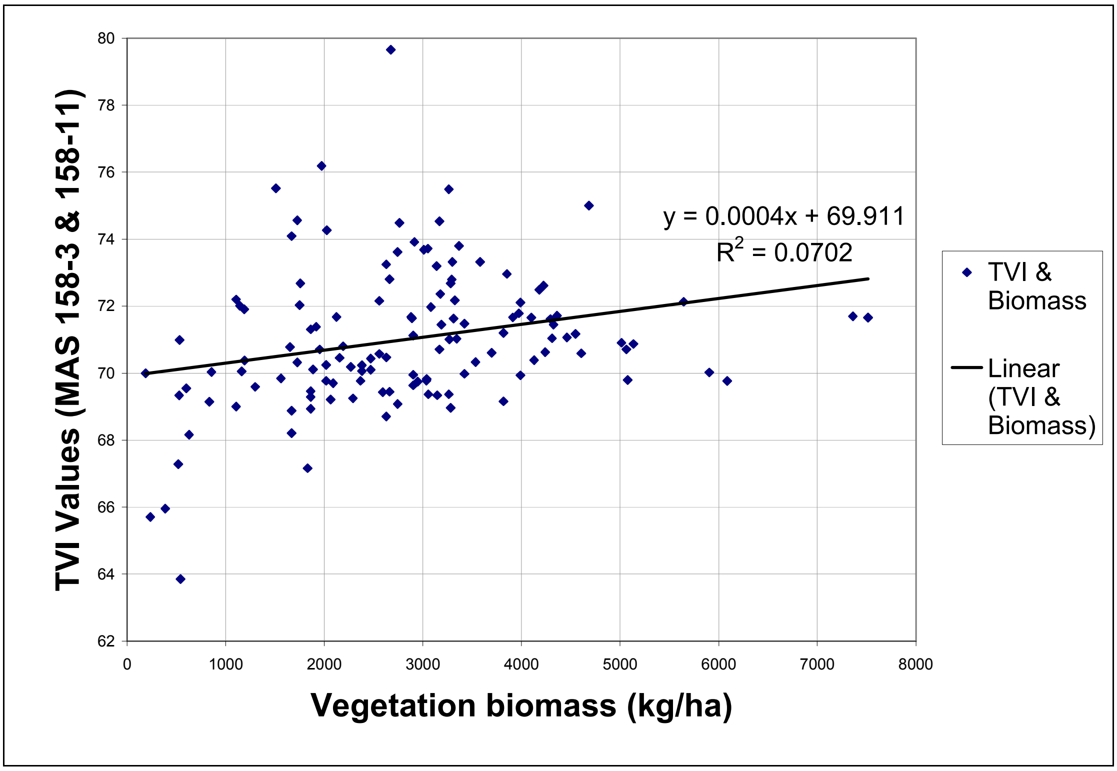

Figure 3.6: X-y scatter plot graph with linear regression line between the TVI values of MAS 158-11 and the ground vegetation biomass points.

Results for 'Brown' or Dry Vegetation Detection

A variety of ratios were calculated using the spectral response signatures and the corresponding image bands, as described in chapter 2. Representative results are presented below.

A weak correlation exists between the above ground standing crop biomass and the ratios for detecting brown vegetation. The best calculated R^2 values were 0.13 for the VNIR/TIR ratio (Figure 3.7) and 0.16 for the MIR/TIR ratio (Figure 3.8).

Visual inspection of the x-y scatter plots for the VNIR/TIR and MIR/TIR ratios revealed that the points on the plots exhibited a more random scatter. The points are further apart and more dispersed across the graph indicating a large prevalence of noise and little correlation or trend in the data points (Figure 3.7 and Figure 3.8). A conspicuous absence of data points is present in the lower diagonal of this figure.

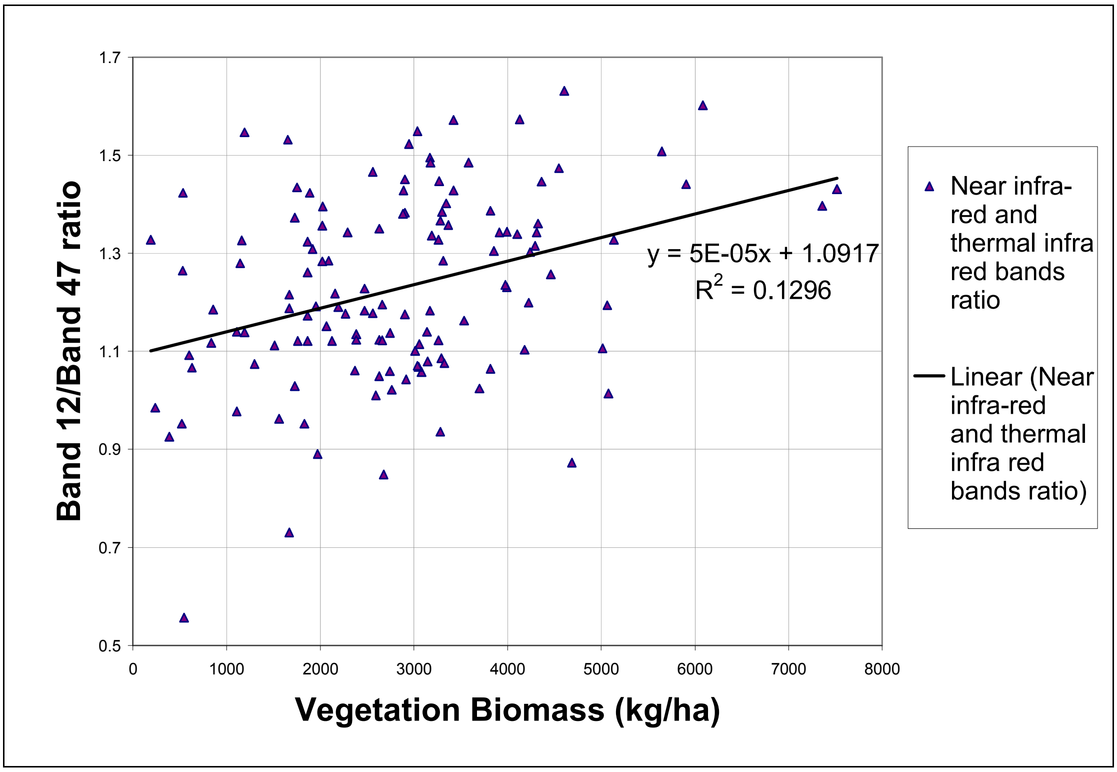

Figure 3.7: Best x-y scatter plot graph with linear regression line between the mid infra-red (band 12) and thermal infra-red (band 47) of the MAS imagery.

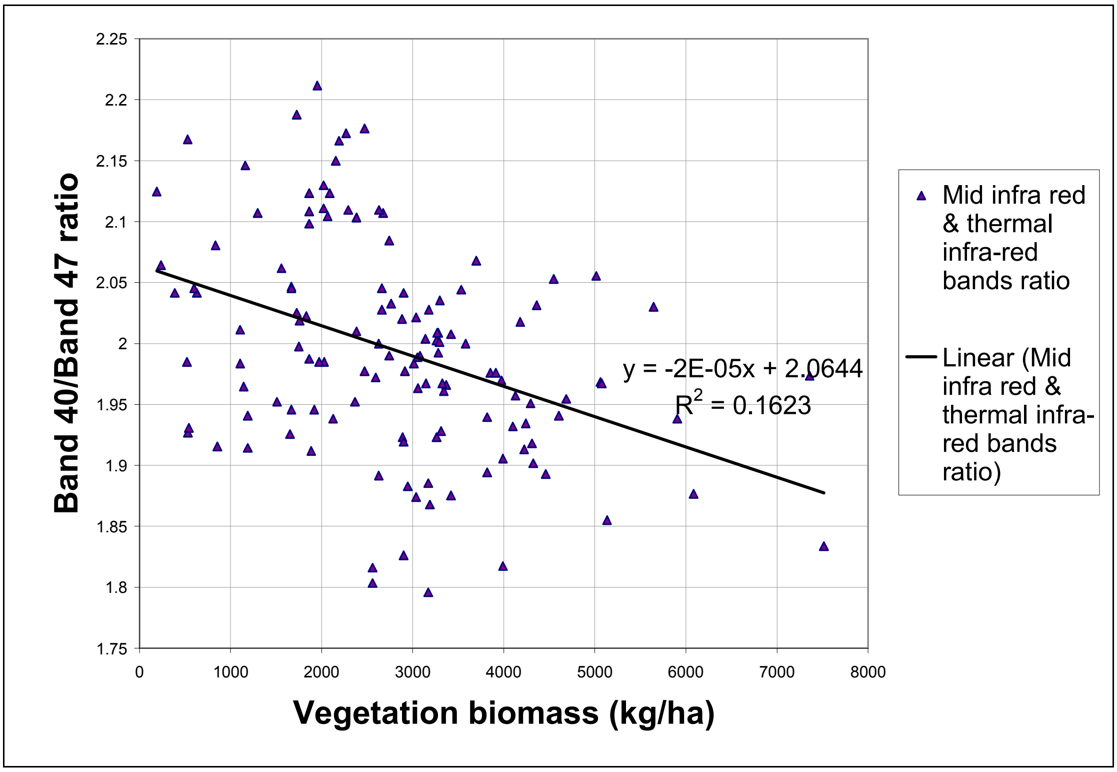

Figure 3.8: Best x-y scatter plot graph with linear regression line between the mid infra-red (band 40) and thermal infra-red (band 47) of the MAS imagery.

No meaningful correlations were identified between the mid-infrared bands, thermal infra-red bandwidths and the visual/near infra-red bands of the MAS imagery, which had been identified as possible bands that might indicate brown vegetation.

Investigations to detect brown vegetation using the ASTER data yielded similar results as that as described in the MAS data. The ASTER made use of a ratio between the MIR (Band 5) and TIR (Band 14) (Figure 3.9), and a ratio between the TIR bands (Band 13 and 10) (Figure 3.10). The similarities are found in the low R^2 values with many points randomly dispersed across the image.

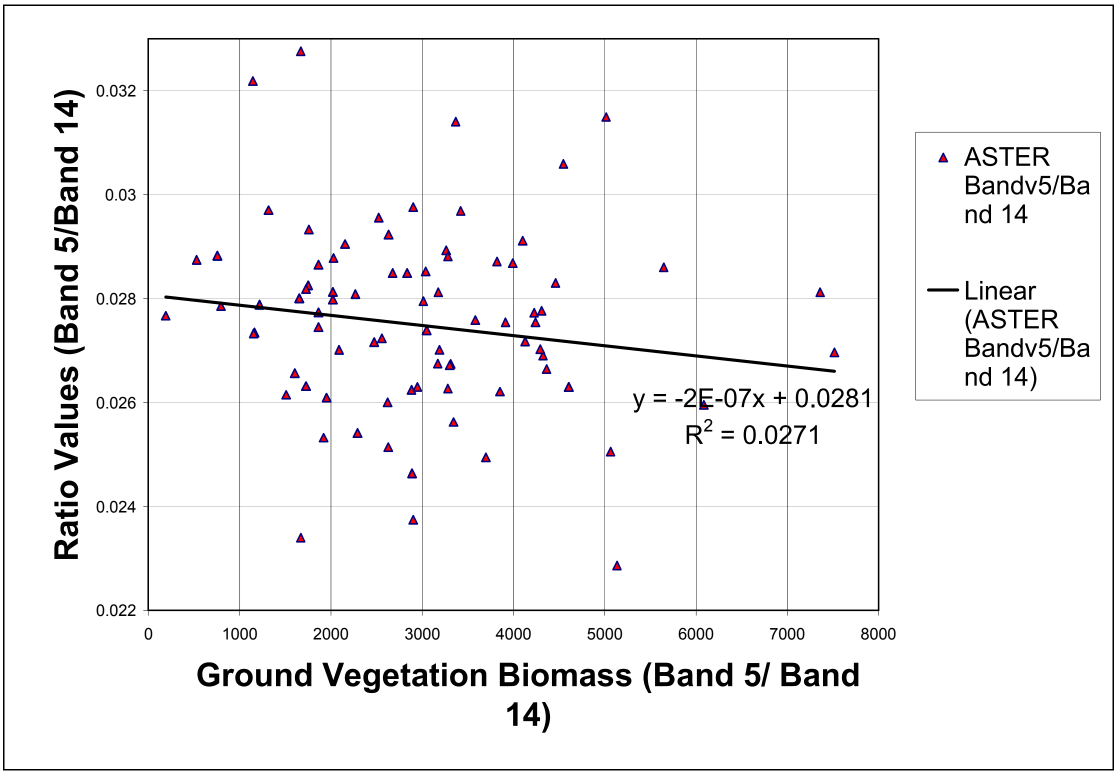

Figure 3.9: X-y scatter plot graph with linear regression line between the ratio of GB99280 and GB99284 Bands 5 (SWIR) and 14(TIR) and the ground vegetation biomass points.

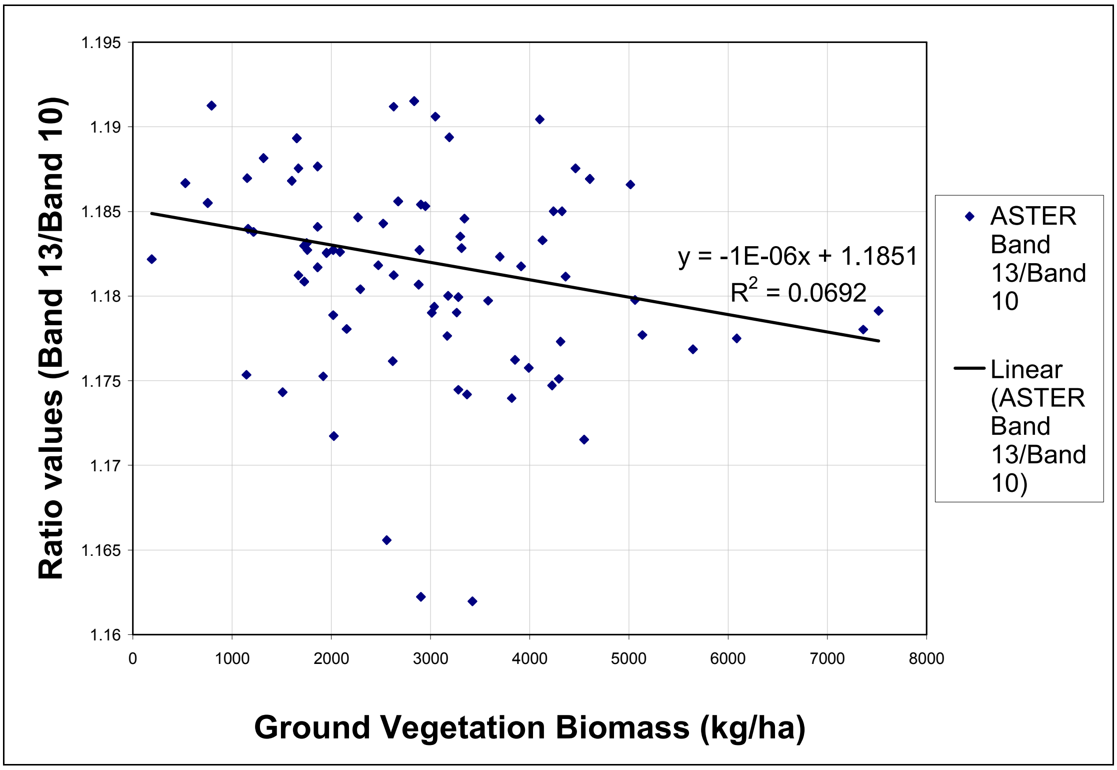

Figure 3.10: X-y scatter plot graph with linear regression line between the ratio of GB99280 and GB99284 Bands 13 (TIR) and 10 (MIR) and the ground vegetation biomass points.

Discussion of Vegetation Indices and Linear Regression

Vegetation Indices and Ground Vegetation Biomass Data

Both vegetation indices yielded statistically weak correlations with vegetation standing crop biomass values. It is apparent from biomass values recorded that standing crop biomass in the study area has moderately high vegetation biomass. This is confirmed by the NDVI scenes for the GB99284 (Figure 3.11) and GB99280 (Figure 3.12) ASTER images. The areas where live vegetation is indicated are due to forestry (south east corner of Figure 3.11), agriculture (south central area of Figure 3.11), and river lines (eastern portion of Figure 3.11) and trees (speckled green dots dispersed throughout Figure 3.11).

Even though these scenes were collected towards the end of the dry season, the images exhibited green vegetation over large portions of the study areas. The GB68186 scene, collected during the wet season, depicted higher green vegetation presence over the study area than the winter scenes, which is to be expected (Figure 3.13). The correlation between the vegetation indices values and vegetation biomass however failed to exhibit the increase in green vegetation in the correlation between the NDVI values and vegetation biomass expected.

The weak trend lines of the linear regressions for the x-y scatter plots indicate that the ASTER vegetation indices values do not statistically correlate with the vegetation biomass values. The same results were found for the MAS vegetation indices and the vegetation biomass values. These weak correlations are not in line with the results of similar studies (Moreau *et al.*, 2003).

Visual inspection of the graphs indicates that some points were grouped together along the regression line while conversely others were randomly dispersed across the graph. There are sufficient points providing good representation and relationships to homogenous pixels providing a basic relationship in the results indicated by the visual trends. However, there are sufficient sample points not meeting these criteria and negatively influencing the ability to draw conclusions.

The different land uses in the areas are expected to have varying impacts on the vegetation biomass. The two primary land uses take place in the area are herbivory in the communal areas and game farming/reserves. The communal areas can primarily be seen in the central to central eastern portion of GB99284 (Figure 3.11) and in Mozambique located in the north eastern portion of GB99280 (Figure 3.12). In contrast, the private game reserves, which can be seen more clearly in the eastern and northern portion of GB99284 (Figure 3.11) and throughout the majority GB9920 (Figure 3.12). The various land uses are more clearly visible in Figure 2.3 (page 28).

The communal areas have lower biomasses. No references could be found as to the cause of this lower biomass. A lesser danger from wildfires exists in the communal areas as there is insufficient fuel to maintain a large fire.

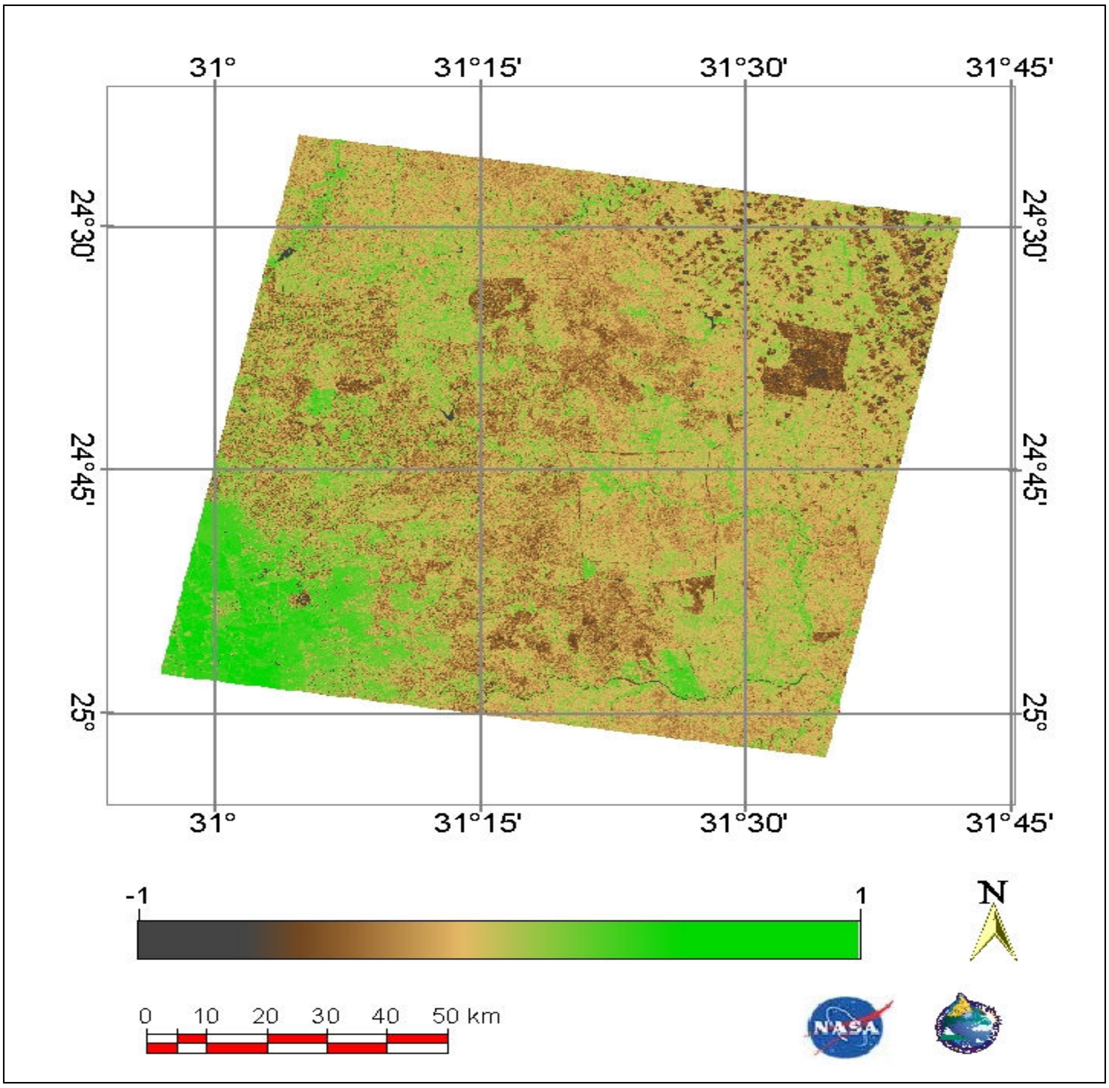

Figure 3.11: NDVI for the ASTER image GB99284.

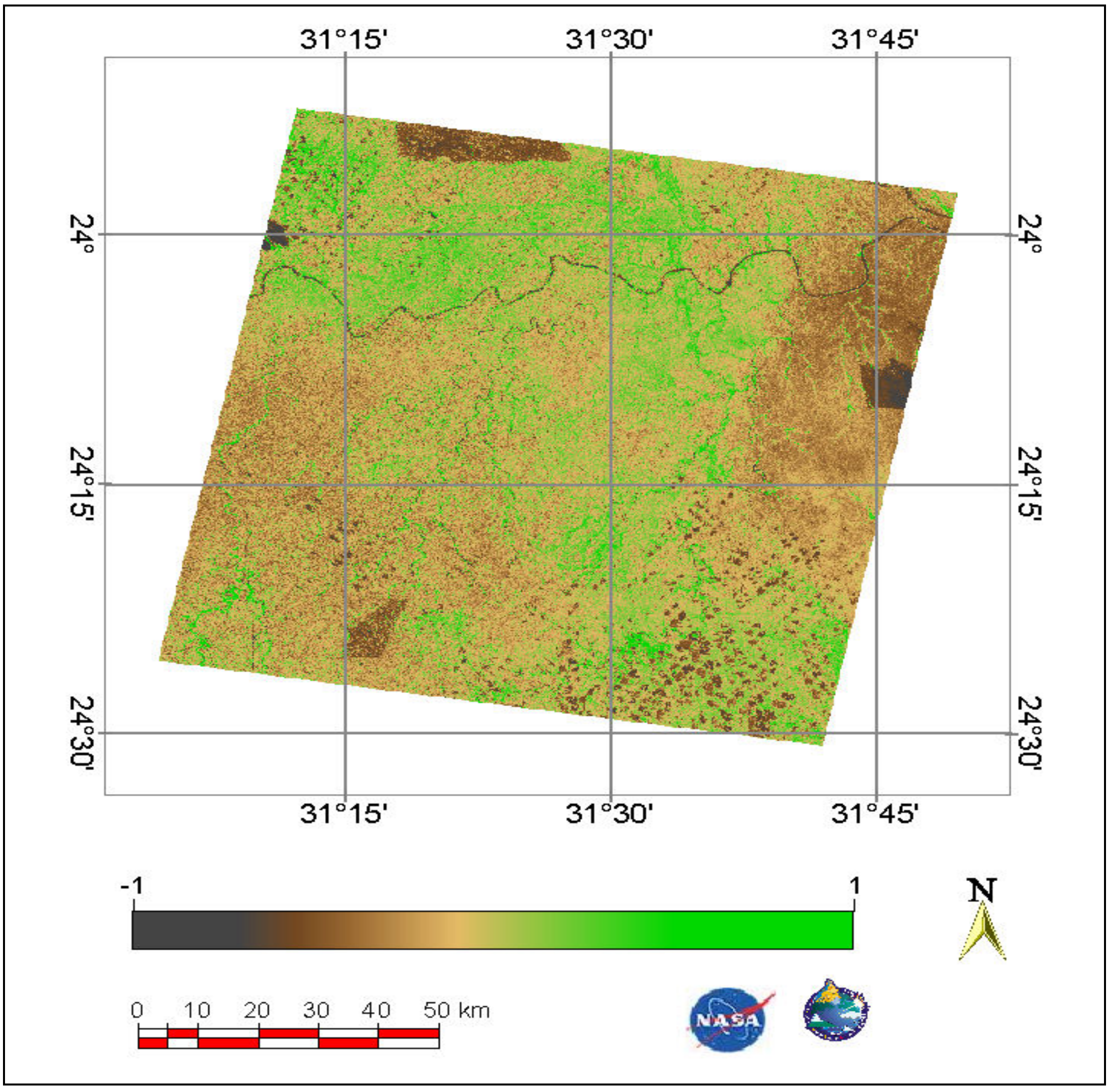

Figure 3.12: NDVI for the ASTER image GB99280.

The game farm/reserves are more stringently managed in order to allow for a sufficient vegetation carrying capacity for the game. Some of the game farms/reserves are over stocked, which results in lower biomass due to the over consumption of vegetation by the animals. The resultant effect is less of fire risk due and less efficient spreading of fire through the ground cover to a drop in available fuel for burning. Fire management takes place in the game farms/reserves with measures such as controlled burning. This is necessary to maintain a healthy ecosystem and to ensure that animals are not burnt since the game farms are fenced off and in the event of large fires, animals can be trapped and burnt.

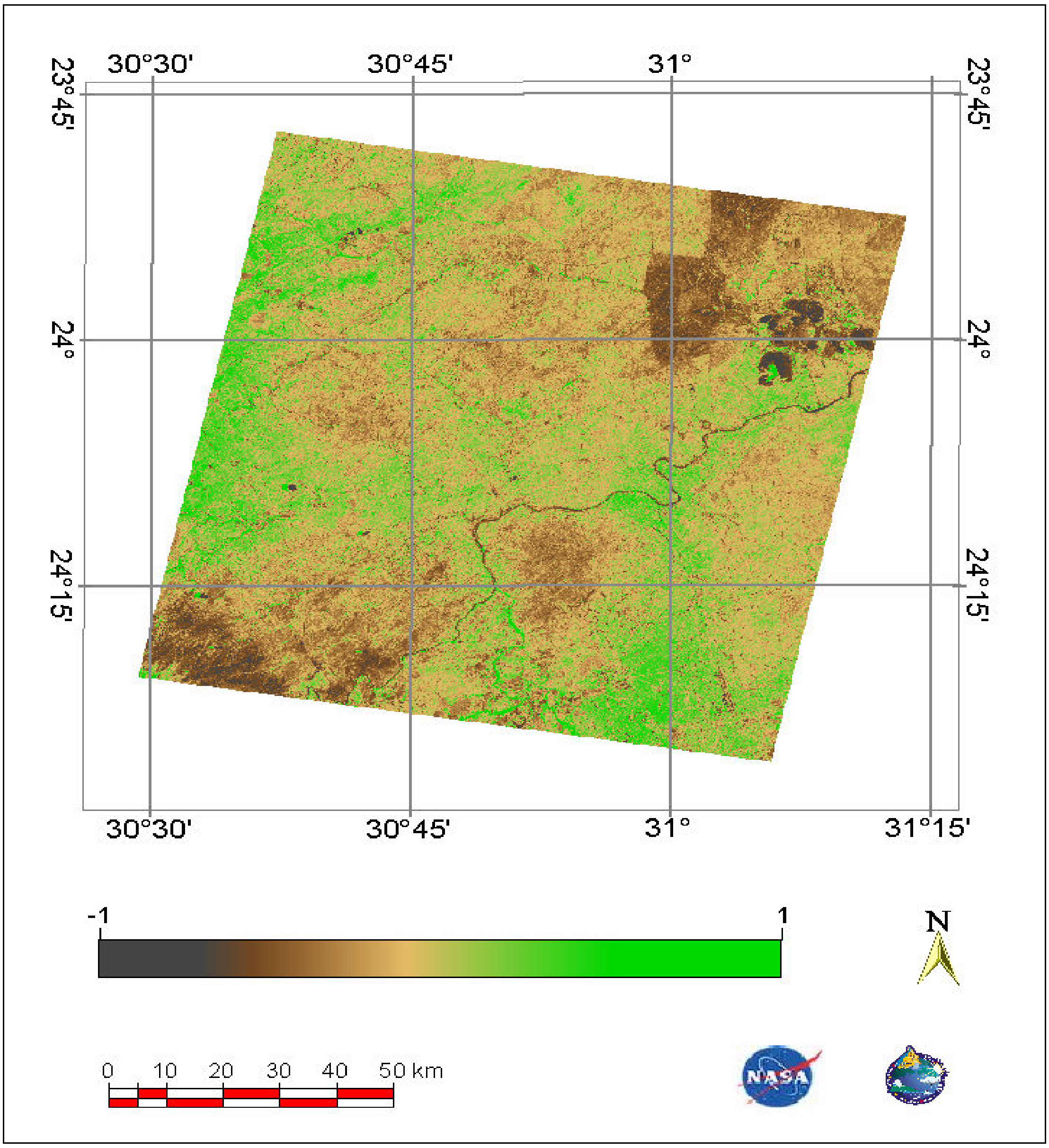

Figure 3.13: NDVI for the ASTER image GB68186.

Other areas in which fire is a risk are agricultural areas, especially forestry. The savannahs are less susceptible to canopy fires since the trees are fire resistant and difficult to ignite and they are not close enough together for fires to spread through the canopies. Forest fires pose large risks to commercial forestry and fire preventative measures are undertaken. Cultivated fields also experience fires and fire preventative measures are employed by the farmers.

Ground biomass measurements were taken with a disc pastural meter, which only merasures grass biomass. This data therefore did not take into account the woody biomass. The NDVI however collects data on the standing vegetation over the surface of the land, including both grassy and woody biomass. The vegetation cover of the study area in question is savanna, consisting of both grassy and woody biomass. As a result, the NDVI values and grass biomass, as recorded by the disc pastural meter, are bound to differ due to this limitation in the ground vegetation biomass data.

Results of "Brown Ratios" and Vegetation Biomass

The "brown'' ratios exhibited weaker statistical relationships and visual trends with the ground biomass than the vegetation indices. The visual trend on the scatter plots indicated a weaker visual trend than those noted on the vegetation indices.

Traditional vegetation indices are effective at detecting green vegetation. Vegetation indices are able to detect increasing quantities of green vegetation, as a portion of the electromagnetic energy is able to penetrate the top of the vegetation canvas so that the lower layers of the green vegetation also reflect electromagnetic energy that is detected by the sensors. If this were not the case, plants would only have one layer of leaves at the top of the vegetation canvas in order to photosynthesis to take place.

In the case of brown vegetation, the leaves are dead so photosynthesis is no longer taking place. Since the vegetation is a similar colour to the soils, it is difficult to separate the reflectance values of the brown vegetation from the soils below the vegetation. In order for this to be achieved, a method, which takes into account background signal from the soils, would be required to remove the interference of the soil layer.

Possible Improvements to the Data and Research Methodology

Even though the statistical results in the study were not convincing, a visual trends indicates that there may be a relationship between the ground vegetation biomass and vegetation utilised. The ability to remove the background noise, particularly the soil reflectance, may provide promising results for both dry vegetation and ground biomass detection (Kasturirangan, 1996).

The following improvements to ground biomass collection criteria for specific use to this application are recommended:

- Ground biomass should be collected within one week or as close as possible of the satellite passing overhead. For the testing of the time series scenario, four data collection dates, one at the end of each season, are recommended.

- The data should be collected over an area with a variety of land use changes in close proximity to one another. This will allow for a greater variety of different land uses to be collected during the data collection period within the limited timeframes.
- Sufficient data points for pixels are required for meaningful statistical analysis on the satellite data.
- More recently, remote sensing data are becoming readily available on finer temporal and spatial scales (Singh, 1989; Avitabile *et al.*, 2005; Kusangaya, *et al.*, 2005; Mohamed *et al.*, 2005; Thompson *et al.*, 2005). With availability of more frequent images at higher resolution, detection of dry vegetation may not be a requirement for wildfire prediction, as it can be in indirectly calculated from the amount of biomass determined during the growing season, and the curing rates of different plant species within the biomes. It is therefore recommended that if feasible, the direct detection of dry vegetation by satellite imagery as well as the indirect detection through time series imagery be tested. This would require the acquisition of a collection of suitable time series of images for analysis.
- The data collected should not only include the biomass but should also include soil and weather data. The collection of soil data will allow for the removal of background soil reflectance and allow for the testing of the PD54 dry vegetation index (Richardson and Wiegand, 1977; Qi *et al.*, 1994). The collection of weather data would allow for a greater scope of work and application to wildfire products such as the testing for fuel moisture content from the same imagery (Chuvieco *et al.*, 2000; Chuvieco *et al.*, 2003; Verbesselt *et al.*, 2002).

If time series analysis of the imagery is to take place, the collection of the ground and satellite data must coincide. The collection of ground biomass over such a large area within close proximity to the satellite image being recorded will prove to be difficult for one person to achieve. A team of data collectors will most likely be required for the task. This may prove to be costly and difficult to organise, especially since the team will have to be familiarised with the data collection techniques. Multiple sets of instrumentation will also be required. Multiple collection dates will further complicate the issue, as it would be preferable for the same persons to collect the data from the same points. The feasibility of this will depend on the availability of resources.

The collection of the satellite and ground data over a period of at least a year will allow for one full season of data. Collection of this data on a monthly basis will allow for a temporal comparison of the effectiveness of different vegetation indices in detecting ground biomass in various seasons. Multiple images will also allow for better knowledge of the temporal resolution of satellite data required for accurate ground biomass detection. For more information on the collection of ground data for use with vegetation indices, refer to Kasturirangan (1996).

Spatial accuracy of the satellite imagery is of vital importance. It is recommended that better referencing sources be used such as cadastral surveying data. This would be reliant on the available maps and funds for the area.

The accuracy of the GPS is also importance to ensure to be able to reference the ground based measurements with the correct pixels on the satellite. Currently the most accurate GPS is a Phase Differential GPS, which provides accuracy of the order of millimetres and centimetres (Trenor, 2005). This however is also very costly. The differential GPS provides an accuracy of 0.5 to 5 m, depending on the receiver (Trenor, 2005). Autonomous or "stand alone" GPS receivers provide an accuracy of 15 m, which is currently the general purpose GPS utilised today. Base stations can be used to eliminate some of the accuracy errors experienced with GPS receivers.

CHAPTER 4: CONCLUSIONS

The aim of this research was to determine if it is feasible to use ASTER and MAS remote sensing data to estimate brown and green biomass for wildfire prediction purposes. The aim was investigated by:

- Assessing and evaluating the ASTER and MAS data against the above ground biomass.
- Utilising dry vegetation spectral response signatures to detect ‘brown’ vegetation using ASTER imagery.

The findings of this study are that it is not feasible to use ASTER and MAS remote sensing data to estimate brown and green biomass for wildfire prediction purposes using the same applied datasets and research methodology applied in this study.

The statistical relationships between the vegetation indices calculated on the ASTER and MAS imagery and the above ground biomass were very weak. All of the correlations between the vegetation indices and ground vegetation yielded R^2 values less than 0.1. Visual trends were identified on the x-y scatter plots however, these trends were relatively weak and no conclusion could be drawn from the results.

The use of dry vegetation response signatures in an attempt to detect ‘brown’ vegetation was unsuccessful. The correlation between above ground biomass and dry vegetation ratios were weak with the correlation analysis returning the same weak R^2 values and x-y scatter plots and showing a large amount of random noise in the data. The dry vegetation ratios showed less of a visual trend the vegetation indices.

The recommended improvements to the data and research methodologies may prove to be difficult to coordinate and costly. The ability to remove background noise, in particular soil reflectance, would most likely provide better results by removing some undesired reflectance values from the satellite data. The rapidly changing environment of the field of remote sensing is resulting in time series remote sensing data being more readily available. Time series patterns of green vegetation indices would most probably sooner become a more effective and less costly technique than calibrating a multi-spectral dry vegetation index for fire fuel load predications to feed into fire danger rating systems.

Satellite imagery is currently be used to collect data on other parameters of fire danger rating systems. These include the majority of the weather parameters such as wind speed and direction, temperature, rainfall and relative humidity. The use of satellite data means that this data can be continually updated leading to a more effective fire danger rating system. Scope exists to use satellite imagery to add continually updated information on biomass characteristics such as fuel load, distribution and heterogeneity, and moisture content.

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