Department of Spatial Sciences

Estimating Above Ground Biomass using Remote Sensing in the Sub-Tropical Climate Zones of Australia

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This thesis is presented for the Degree of Doctor of Philosophy of Curtin University

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Declaration

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgment has been made.

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

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Abstract

The state of Western Australia covers approximately one third of the total land mass of Australia and rangelands constitute 87% of the land area. Remote sensing can be used as an aid in assessing and mapping of total standing above ground biomass. This in turn provides producers with information concerning availability of feed in pastures and potentially optimal stocking rates. Efforts have been made previously to come up with above ground biomass assessment tools using destructive (clipping quadrats) and non-destructive methods (pasture height, visual estimates, remote sensing). Indirect methods are faster and minimise on sampling time when compared to direct methods and can be easily scaled from the site to the landscape scale. However, current methods to measure above ground biomass do not deliver adequate results in relation to the extent and spatial variability that characterise rangelands.

In this context, the thesis focused on assessing total standing above ground biomass for rangeland stations in Northern Western Australia. The study area was Liveringa station in the Kimberleys. The research investigated both empirical and semi-empirical approaches in combination with remote sensing and environmental data. Model calibration and validation was done using field collected data as a function of the land system to optimise grazing management. Field based measurements were obtained during an extensive field campaign covering two growing seasons.

Remotely sensed data were obtained from medium and coarse resolution satellites. The starting point was to develop a field data collection protocol suitable for heterogeneous environments using a combination of field data from visual estimates, rising plate meter and a hand held radiometer (Crop Circle). The protocol provided accurate assessments of total above ground biomass for sites dominated by Bunch grass and Spinifex vegetation ("Leave-Site-Out" Q^2 values of 0.70-0.88). Assessment of green above ground biomass was accurate for all vegetation types ("Leave-Site-Out" Q^2 values of 0.62-0.84). The protocol described could be applied at a range of scales while considerably reducing sampling time.

Single and multiple regression relationships between single date vegetation indices from Landsat ETM+ and green or total above ground biomass were developed. The cross-validation results for green above ground biomass improved for a combination of indices for Open plains and Bunch grass sites, but not for Spinifex sites. When rainfall and elevation data were included, cross validation results improved slightly with a Q^2 of 0.49-0.72 for Open plains and Bunch grass sites respectively. Cross validation results for total AGB were weak (Q^2 of 0.41) for Open plains but absent for other site groups despite good calibration results.

Multi-temporal vegetation indices were also investigated. Time-series of 16-day NDVI values were interpolated and smoothed with a Savitzky-Golay filter using TIMESAT software for the years 2010 to 2013. Sites dominated by annual, Spinifex or Bunch grass clearly differed in variation and amplitude range of multi-temporal NDVI patterns. Landsat NDVI correlated to Crop Circle NDVI (R^2=0.6), indicating that atmospheric noise is substantial. NDVI explained up to 96% of variation in the fraction of green AGB of the aggregated vegetation types, while relationships for individual sites were not significant. Strong relationships between cumulative NDVI and amounts of green AGB were found (R^2=0.89) for combined Open plains and Bunch grass groups. The time series of MODIS-NDVI is a useful indicator for green biomass assessments in areas dominated by annual or bunch grass, but not when dominated by Spinifex.

In conclusion, the work carried out in this research demonstrates the potential to use remote sensing to retrieve estimates of biomass for certain vegetation types of the Kimberley region of Western Australia. This study adds knowledge on the monitoring and managing of grazed arid rangelands.

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Terms and Symbols

AGB	Above Ground Biomass
AG	Asymmetric Gaussian
APAR	Absorbed Photosynthetic Active Radiation
APSIM	Agricultural Production Systems Simulator
AussieGRASS	Australian Grassland and Rangeland Assessment by Spatial Simulation
AVHRR	Advanced Very High Resolution Radiometer
BOM	Bureau of Meteorology
CC NDVI	Crop Circle NDVI
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CV	Coefficient of variation
DAFWA	Department of Food and Agriculture, Western Australia
DEM	Digital Elevation Model
DL	Double Logistic
DM	Dry Matter
ENVI	Environment for Visualising Images
fAPAR	fraction of Absorbed Photosynthetic Active Radiation
FOO	Food On Offer
GC	Ground Cover
GI	Growth Index
GPS	Global Positioning System
GPP	Gross Primary Production
GRASP	Grass Production Model
HB	High Biomass quadrat
ISPRS	International Society for Photogrammetry and Remote Sensing
Landsat ETM+	Landsat Enhanced Thematic Mapper
LAI	Leaf Area Index
LAD	Leaf Area Distribution
LB	Low Biomass quadrat
LI	Light Index
LOO	Leave-One-Out
LSO	Leave-Site-Out

LUE	Light Use Efficiency
MI	Moisture Index
MODIS	Moderate Resolution Imaging Spectroradiometer
NDVI	Normalised Difference Vegetation Index
NDWI	Normalised Difference Weighted Index
NDSVI	Normalised Difference Senescent Vegetation Index
NIR	Near-Infra Red
NPP	Net Primary Productivity
OLI	Operational Land Imager
PAR	Photosynthetic Active Radiation
PFS	Pastures from Space
PGR	Pasture Growth Rate
PH	Pasture Height
RMSE	Root Mean Square Error
RPM	Rising Plate Meter
SATVI	Soil Adjusted Total Vegetation Index
SAVI	Soil Adjusted Vegetation Index
SRTM	Shuttle Radar Topography Mission
STVI-1	Stress-related Vegetation Index 1
STVI-3	Stress-related Vegetation Index 3
SLC	Scan Line Corrector
SG	Savitzky-Golay fit
TI	Temperature Index
UAV	Unmanned Aerial Vehicles
USGS	United States Geological Survey
VE	Visual Estimates
VI	Vegetation Index
VIS	Visible wavelengths of the eletro-magnetic spectrum
WA	Western Australia
WALIS	Western Australia Land Information System
WDVI	Weighted Difference Vegetation Index

1 Introduction

Plate 1: Cows grazing at Liveringa Station.
Photograph by Michael Schaefer (University of New England).

1.1 Background

Natural rangelands form an extensive part of the Earth's surface. They extend across low rainfall and variable climates, arid, semi-arid and include ecosystems such as tropical savannahs, woodlands, shrublands and grasslands (DOE 2014). They are complex environments with large spatial variation in vegetation composition and structure, soil type, topography, precipitation and ecological processes (Gerber 2000). Vegetation comprises living and dead plant material in proportions that vary strongly within relatively short distances (Huete and Jackson 1987). They are primarily dominated by native vegetation rather than cultivated pasture. Vegetation ground coverage is low with a mixed species composition resulting in high spatial and temporal variability of Above Ground Biomass (AGB) components (O'Neill 1996). The flora may be made up of a hundred or more species of grasses, forbs, shrubs and trees (Heinisch 1962). Variability of spatio-temporal dynamics in growth and decomposition results in complex canopies, with large differences in dead and green AGB.

Rangelands cover approximately 75% of the Australian continent (Figure 1.1). They are a significant part of the Australian economy and are second only to mining in terms of gross domestic product (RDL 2011). Livestock grazing has been the dominant land use of the world's rangelands (Vavra and Brown 2006). In the state of Western Australia (WA) alone, rangelands occupy 87% of the total land area (2.5 million square kilometres) and comprise 460 pastoral stations (comprising 518 leases) (DAFWA 2014). Pastoralism under extensive grazing is the dominant land use. Livestock grazing uses 42% (910,000 km^2) of the total rangeland area (Bright and Dalton 2002). The primary outputs of pastoral stations are (mostly yearling) cattle for live export. The operational cycle followed by most pastoral properties starts with a wet season grazing (December - May). Mustering and drafting for export occurs in the critical phase of the season (June - November) and followed by a return to the paddocks (October - November). During the dry season there is no supplemental feeding and the rangeland manager needs to ensure that forage from the wet season can sustain stock throughout the dry season without the need for additional feed.

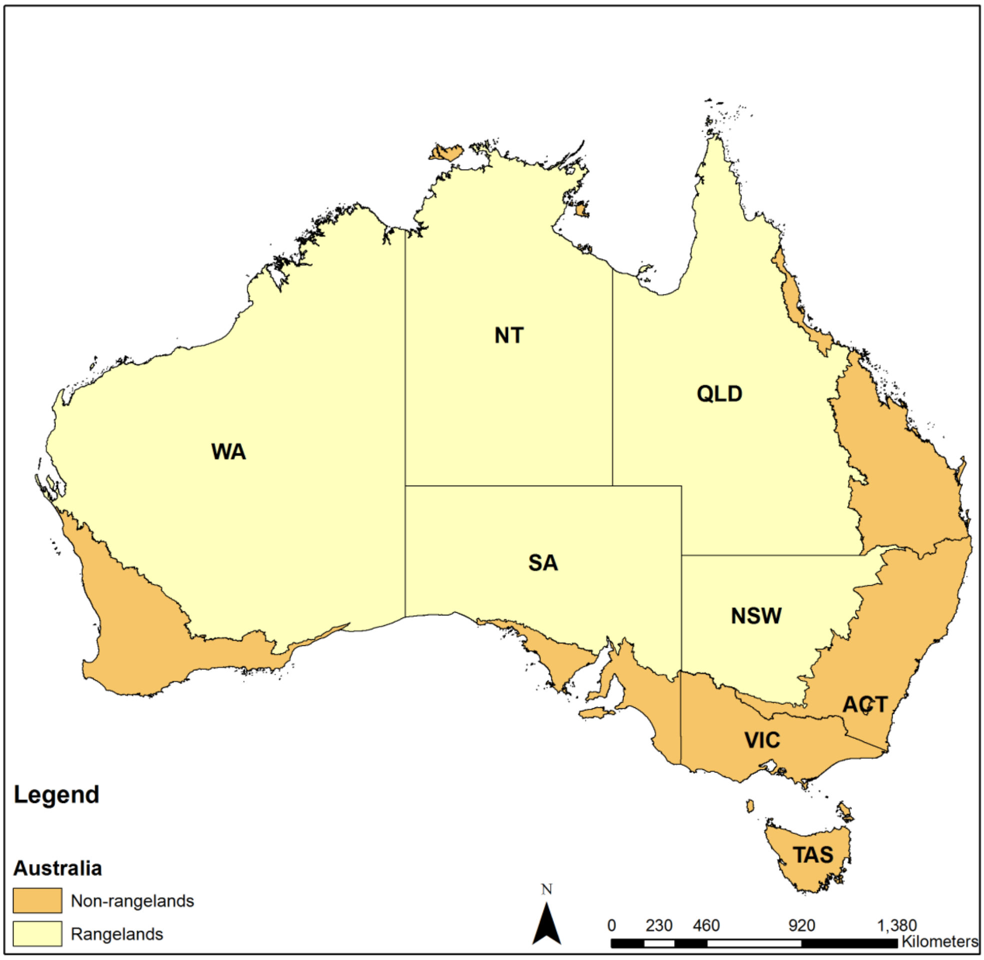

Figure 1.1: Rangeland areas in Australia: (WA - Western Australia, NT - Northern Territory, SA - South Australia, QLD - Queensland, NSW - New South Wales, VIC - Victoria, ACT - Australia Capital Territory and TAS - Tasmania). Source: (DOE 2014).

The state's pastoral leases are located in the Kimberley, Pilbara, Gascoyne, Murchison, Goldfields, Nullarbor and Desert rangelands regions (Figure 1.2). The pastoral region where the study area (Liveringa Station) is located is the Kimberley. Pastoral leases allow for commercial grazing of stock and in the 2008-09 seasons the value of pastoral production was estimated at $240 million (RDL 2011). In the southern regions, the emphasis is on wool production while in the northern regions the emphasis is on cattle production mainly for live export. As crown lease holders, rangeland managers, need to balance between the number of animals on their properties to maximise short term profitability and maintaining the land in an ecologically sustainable manner.

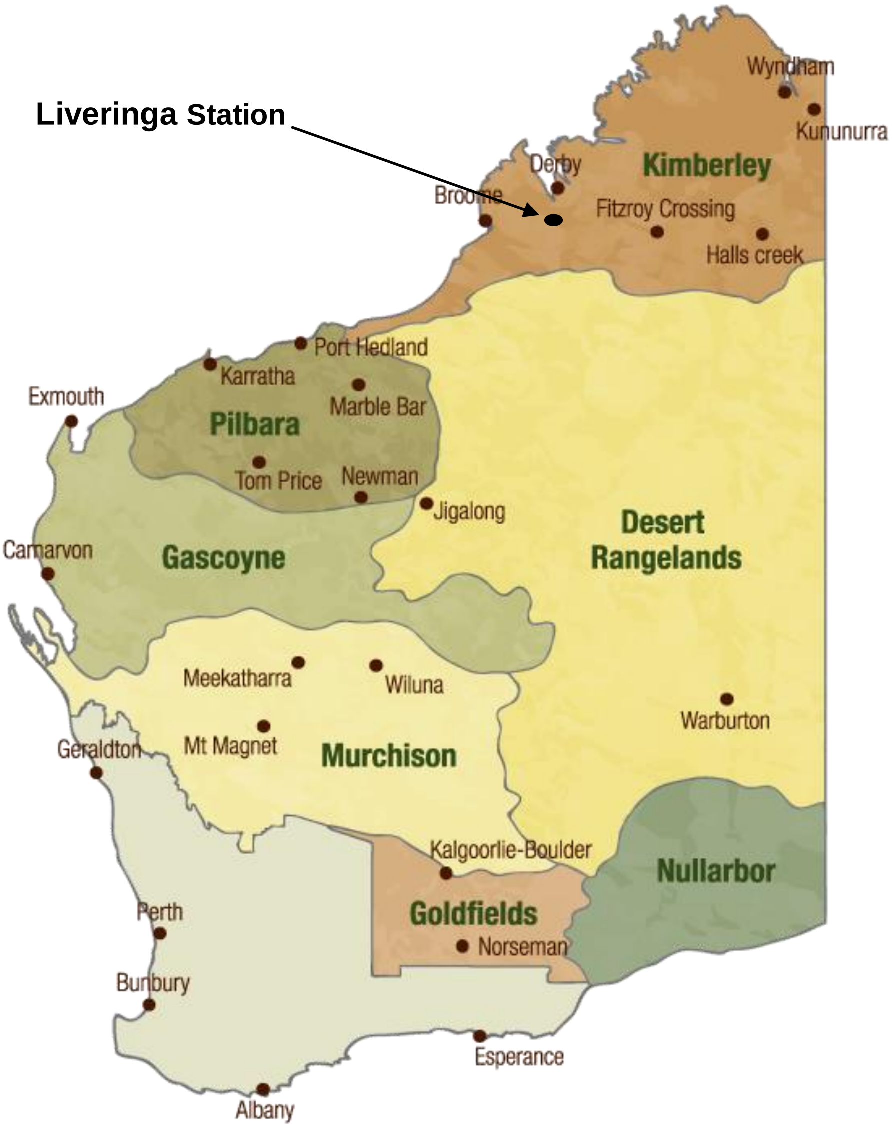

Figure 1.2: Pastoral regions in WA (Kimberley, Pilbara, Gascoyne, Murchison, Goldfields, Desert Rangelands and Nullarbor regions) (Source: (Rangelands 2015)).

In Australian semi-arid shrublands, rangeland degradation has been a major issue (Curry *et al.* 1994; Stafford *et al.* 2007). The Department of Food and Agriculture, Western Australia (DAFWA) estimated that stocking rates recommendations have aimed at a broader scale and require customisation to the local farmer level. A higher financial return, improved sustainability and animal welfare can be accomplished when stocking rates are optimised. Livestock productivity and ecological health are driven by cover and composition of the perennial grass component of pastures (RDL 2011). Knowledge of forage availability helps to assess carrying capacity. Total and green AGB estimates can provide an important indication of feed availability and monitoring growth dynamics may provide clues to the vegetation condition (Reeves *et al.* 2001). As a result, total and green AGB assessments can enable an optimisation of stocking rate adjusted for dynamic growing conditions such as fire regimes.

1.2 Problem statement

An optimized and balanced grazing system is vital for long-term sustainability and productivity (Ritchie and Anderson 1996). Traditional grazing management is generally 'set-stocking' based on the defined carrying capacity of land systems or pasture types (Fisher 2004). However, grazing management focused solely on animal numbers or performance leads to high grazing pressures and may result in grassland degradation (Laca 2009). Pastoralists are interested in knowing the amount of feed available to determine carrying capacity and must balance an economically viable stocking rate while ensuring sustainable land management, ecosystem function and adherence to government policy (McKeon *et al.* 1990). Matching animal numbers to forage supply is the most critical management decision and optimising grazing pressure via timely de-stocking is the key element in achieving this. Decisions to move animals are usually made by driving around paddocks and visually checking pasture growth.

The standard method to estimate AGB is destructive sampling. Over large areas, and in particular areas with considerable spatial and temporal variability in plant morphology and species composition, the process is very time consuming and labour intensive. The current methods used to measure AGB in rangelands rely mostly on calibrated relationships between dry weight and plant attributes such as height, greenness, resistance, and density as they can cover larger areas at low costs. However, these methods do not deliver satisfactory results for extents and spatial variability that characterise rangelands.

Recent studies in remote and proximal sensing-based AGB estimation methods and agro-meteorologic models which make use of plant growth and climate variables in combination with remote sensing have shown potential (Donald *et al.* 2010; Edirisinghe *et al.* 2012). Remote sensing provides temporal and spatial information on feed resources and makes measurements at large extents possible by reducing laborious field sampling and sample processing procedure (Starks *et al.* 2006). Well-known plant growth models for rangeland environments include the Australian Grassland and Rangeland Assessment by Spatial Simulation (AussieGRASS) and Grass Production (GRASP) models (Carter *et al.* 2000). However, deterministic plant growth models include processes that need to be parameterised, and they require extensive parameter calibration. Without detailed knowledge of local conditions (soil, water availability, plant species characterisation) accuracy of these models to predict total and green AGB is often limited.

There is a pressing need to accurately estimate AGB in northern WA at spatial scales which encourage better rangeland management. Most of the work that has been done for development of forage assessment tools has only been calibrated for small parts of Australia. Efforts that have been made in the past to come up with forage assessment tools were concentrated on the temperate pastures of southern WA (Hill *et al.* 2004; Donald *et al.* 2010) as a result, there are knowledge gaps. Northern WA has been specifically targeted since it is a prime beef production region and Liveringa station provided an opportunity for a pilot study.

The study site also corresponded with the current Department of Agriculture and Food Western Australia (DAFWA) rangelands monitoring site field survey, which monitors rangeland condition. WA rangeland managers are now expected to monitor the condition of their pastures via a Rangeland Condition Monitoring (RCM) process that has been approved by the Pastoral Lease Board. The RCM process is at lease level and monitoring is performed at fixed points. The data is collected from soil and plant indicators of range condition. This further presents opportunities in this research or in the future to investigate tools for rangeland condition monitoring from a satellite platform thus significantly improving the monitoring process.

Little is known on the feasibility of the use of available tools for biomass estimation. Remote sensing or modelling approaches may fill this need, but require reliable ground observations for calibration and validation purposes at appropriate scales. The field measured parameters must be linked to what the remote sensing systems actually measure; namely top of atmosphere spectral reflectance characteristics and their derived spectral indices. In this context, there is a need to explore and verify how AGB can be effectively measured from the ground and correlated with satellite data in order to derive predictive models.

1.3 Research objectives

The main aim of the study is to explore and develop total and green AGB assessment tools using remote sensing for the Kimberley region of WA. Total AGB in this context refers to the total amount of edible vegetation (including dead and green components) available to grazing cattle, excluding woody vegetation while green AGB refers specifically to green components. Specific objectives are:

1. Develop a total and green AGB field measurement protocol for calibration and validation that suits a range of scales;
2. Identify vegetation indices that may be used for accurate direct assessment of total and green AGB using high spatial resolution remote sensing data; and
3. Explore and evaluate the robustness of multi-temporal analysis of coarse resolution remotely sensed vegetation indices to improve total and green AGB estimates.

1.4 Significance of the research

It is anticipated that the tools developed in this study can aid accurate prediction of total and green AGB in rangeland areas. Productivity estimates can provide a practical measure of vegetation vigour, seasonality, and growth capacity in rangeland management and assessment (Schut *et al.* 2009). The provision of forage assessment tools in a timely manner to rangeland managers thus provides a means that can be used in the calculation of the viable number of stock from the dry to wet season resulting in sustainable management. Access to total and green AGB information on a regular, timely basis, and in a readily accessible form, would enable more widespread adoption of practices to improve the management of the feed supply (Hill *et al.* 2004), and result in increased productivity thereby allowing producers to boost their income.

1.5 Organisation of the thesis

The thesis is divided into seven chapters. Chapter 2 describes the study area and study sites in detail. The study area (Liveringa Station) is located in the north western part of the state of WA. Detailed descriptions of Liveringa station's characteristics are given in terms of climate, vegetation, land systems, topography and soils. An in-depth description of the botanical composition of the study area sites including their estimated carrying capacity is also presented.

Chapter 3 presents current field data collection methods and outlines an optimised ground data collection protocol. The traditional destructive method is described followed by an explanation and comparison of non-destructive methods. Data collection and processing at the study site is described in detail. Statistical analysis methods and results are presented to show the relationship between AGB and non-destructive measurements for different vegetation types. All non-destructive methods are combined into a single multiple regression model versus the destructive method and evaluated for their effectiveness in site AGB estimation.

Chapter 4 presents a literature review of remote sensing approaches to above ground biomass estimation for Chapters 5-6. It provides in detail, the modelling approaches used and challenges of above ground biomass estimation using higher and coarser resolution remote sensing satellites in rangeland environments. A comprehensive overview on the different biophysical models and spectral indices for above ground biomass and their applicability to the study is presented.

Chapter 5 explores and develops assessment tools that can be used to infer grazable or utilisable AGB. These are based on development of relationships between single image remotely sensed vegetation indices and direct assessment of total and green AGB. The remotely sensed data is obtained from the Landsat ETM+. The vegetation indices suitability is tested using linear and multiple regression approaches.

Chapter 6 evaluates the accuracy of green and total AGB monitoring in grazed rangeland pastures using freely available imagery for savannah conditions typical for the wider Kimberley of Western Australia. To this end, relationships between green and total AGB, Crop Circle NDVI, and Landsat ETM+ and MODIS NDVI values were evaluated and compared with relationships based on MODIS NDVI time-series.

The thesis is concluded in Chapter 7 by with a general discussion focusing on the conclusions drawn from the research. Findings from the previous three chapters on data analysis (ground data collection, mono-temporal indices and multi-temporal indices) are restated and discussed. Gaps identified in the research as well as the application of the methodology to other rangeland areas worldwide are discussed in-depth linking back to previous research. The chapter ends with recommendations for future research.

2 Study area*†

Plate 2: Site 2, recovering after a fire, Liveringa Station.
Photograph by Adam Rosher (Curtin University).

* Parts of this chapter have been published in the Rangeland Journal (Mundava *et al.* 2015) and in the International Society for Photogrammetry and Remote Sensing (ISPRS) annals (Mundava *et al.* 2014).

† Pictures used in this chapter were taken by: Richard Stovold (Landgate, WA), Dr. Waqar Ahmad (CSIRO) and Dr. Brendon McAtee (Landgate, WA).

2. 1 Abstract

This chapter contains an in-depth description of the study area (Liveringa station) including the associated climate and geography. The land systems which characterise the study area are presented. The 19 study sites that were used in this study are discussed in-depth including justification for their selection. This is followed by an in-depth review of the site description and detailed vegetation composition.

2. 2 Introduction

The Kimberley region located in north WA is famously known as "The Kimberleys". It is a tropical savannah area with rugged landscapes and a diversity of native flora and fauna. It extends northwards from the red dune fields of the Great Sandy Desert to the uplands, rugged escarpments and coastal islands of the sub-humid Kimberley Plateau and east to the Northern Territory border (DEC 2009). The region comprises approximately 330,070 km^2 (DAFWA 2014) land area (roughly the size of Great Britain) lying between 14°S and 19°S latitude, and 125°E to 130°E longitude (Petheram and Kok 1983). It has three administrative regions namely, West Kimberly, East Kimberley and North Kimberley and is defined by the boundaries of the Shires of Broome, Derby - West Kimberley, Halls Creek and Wyndham - East Kimberley (Collins 2008).

According to the Department of Water, WA, the region has approximately 30 major rivers with the Fitzroy River being the largest. The catchment area of some of the rivers are: Ord River (53,500 km^2), Drysdale River (15,670 km^2), Carson River (1,288 km^2) and the Fitzroy River (90,000 km^2). The major industries of the Kimberley are agriculture, tourism, mining and pearling. The study area is located at Liveringa Station (124°09'E and 18°02'S) including approximately 2 630 km^2 of leased pastoral land within the Derby - West Kimberley shire (Figure 2.1). The Fitzroy River borders the station to the south for approximately 70 km. According to a description by Shilling (1948), Liveringa Station may be divided into two distinct land types – "Pindan" and "Frontage". "Pindan" applies to areas away from the Fitzroy River, while the "Frontage" is a belt of finely grassed plains including numerous creeks and gullies. The main land use at Liveringa is pastoral farming and the station has an estimated 25,000 breeders with a total dry season staff of 35 people.

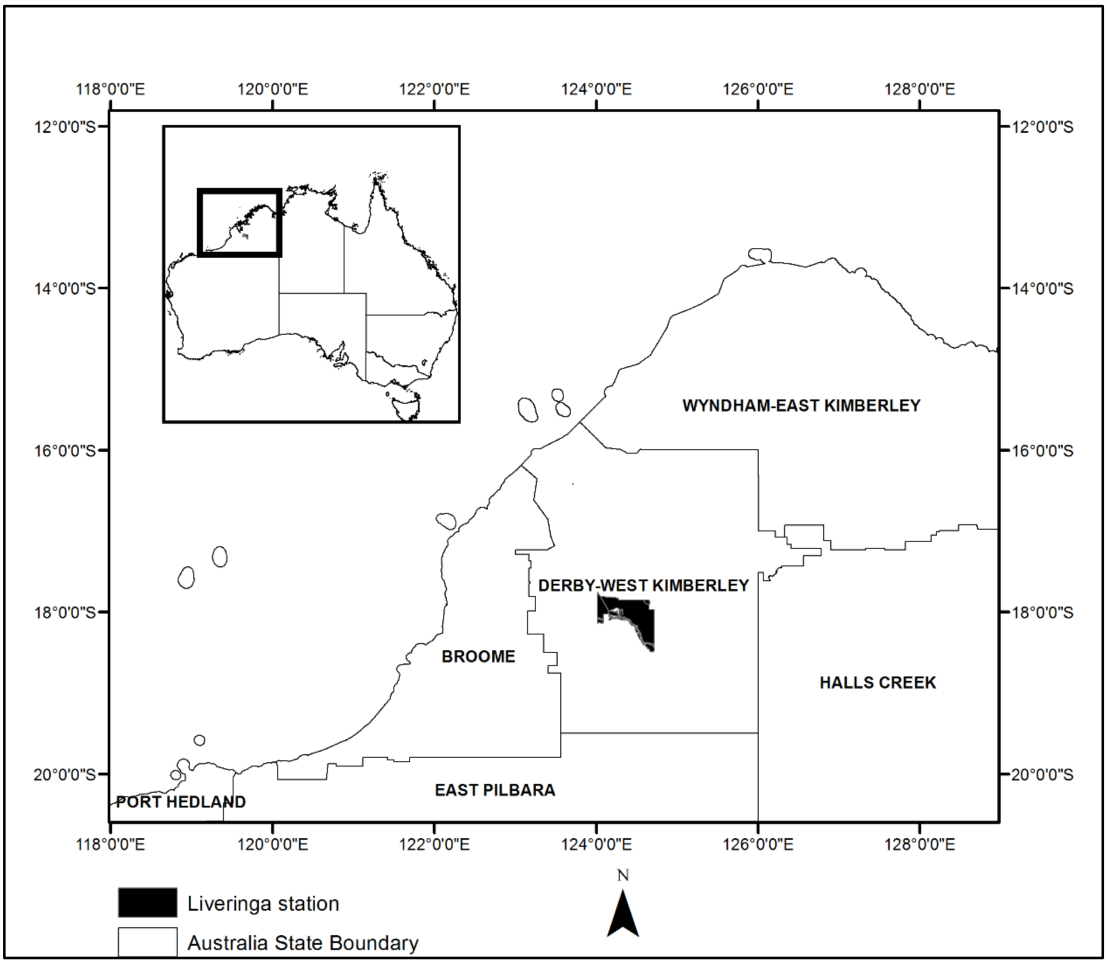

Figure 2.1: Liveringa Station in the West Kimberley area of WA.

2. 3 Climate

The Kimberley region is located in a tropical or monsoonal climate according to the Köppen climate classification (Köppen 1923) with two distinct seasons, a wet and a dry season. The wet season (November - April) is characterised by low atmospheric pressure systems, while the dry season (May - October) is characterised by very high temperatures. The region is among the hottest in Australia. Historical records from the Australian Bureau of Meteorology (BOM) indicate that mean annual rainfall, mean maximum and minimum temperature close to Liveringa are 615 mm, 36°C and 20°C, respectively, averaged across the years (1958/2013) at Camballin (124°19' E and 17°99' S) approximately 5 km from the station. Figure 2.2 shows the mean rainfall for the years 1981 – 2010 for the Camballin weather station with a comparison from the 2011 rainfall when the fieldwork was conducted.

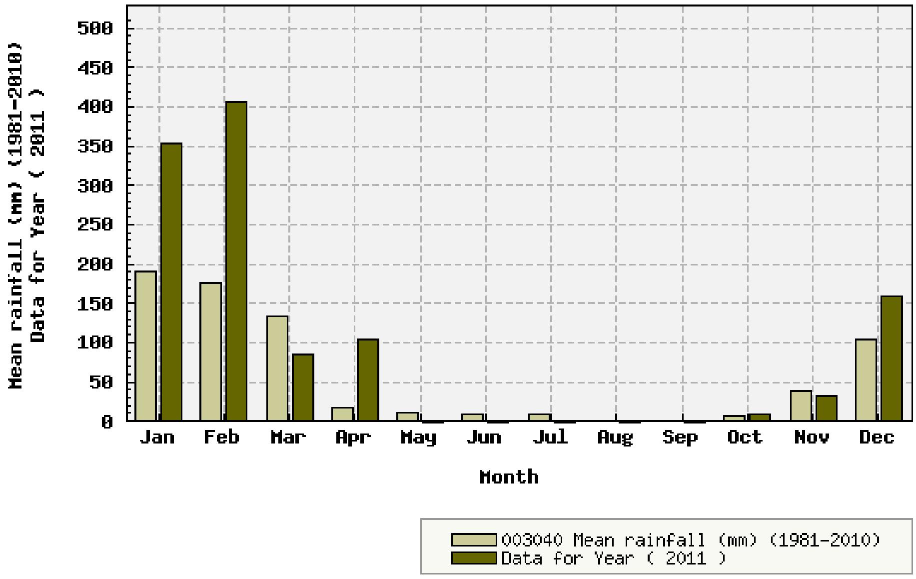

Figure 2.2: Mean rainfall for the years 1981 – 2010 for the Camballin weather station (nearest to Liveringa Station) with a comparison of the mean rainfall for 2011. (Source: BOM, 2015)

The monthly recorded mean rainfall maximum is in January 176.3 mm and the maximum temperature mean is 33°C. Evaporation rates range from 1000 to 2500 mm per year with the highest evaporation rates at the peak of the dry season, while pasture growth duration ranges from 19 weeks in the North-West Kimberley to 10 weeks at Hall's Creek (Petheram and Kok 1983). However, the pasture growing season is directly related to the amount and duration of rainfall (Rye *et al.* 1992).

2. 4 **Land systems**

A land system is defined as "an area or group of areas through which there is a recurring pattern of topography, soils and vegetation" (Christian *et al.* 1953), and these patterns can be readily seen and delineated by stereoscopic examination of aerial photographs. Across the Kimberley area, 111 land systems have been mapped and the three largest land systems are Buldiva (45,841 km²), Yeeda (21,308 km²), and Camelgooda (17,826 km²), (DAFWA 2014). Liveringa Station has varied land systems with different pastoral value as classified according to numerous Kimberley Rangeland surveys conducted since the 1940s (Payne and Schoknecht 2011; DAFWA 2014). In total, 11 land systems (Figure 2.3) which have been mapped in more detail recently at Liveringa (DAFWA 2014) were used in the study. Productivity, species composition, land condition and carrying capacity of land systems varied strongly. The most dominant land systems are Djada, Egan, Calwynyardah, Myroodah, Luluigui, Camelgooda and Wanganut which comprise >50% of the land area. The overview of the location of the sites versus the respective land systems are shown in Figure 2.3 and a detailed description of the land systems is given in Table 2.1. The locations of the sampled sites as accessed by a motor vehicle (four wheel drive) are shown in *Appendix B*.

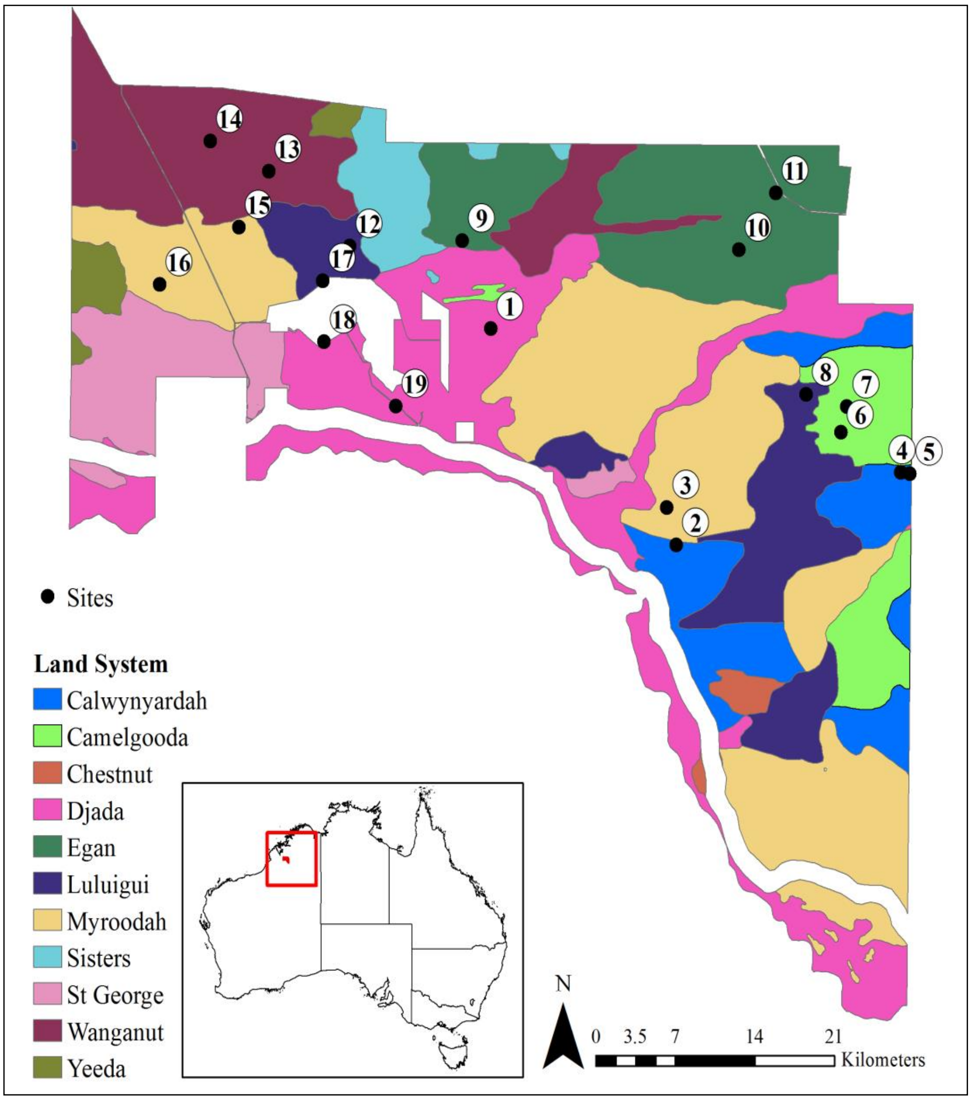

Figure 2.3: Land systems and sampling site locations on Liveringa Station (DAFWA 2014), reprinted with permission under a Western Australia Land Information System (WALIS) data transfer license).

Table 2.1: Selected land systems at Liveringa Station with indication of pastoral value

Land system	Description	Estimated capacity *(cu/km^2)	Pastoral value
Djada	Active flood plains with extensive black plains of cracking clays, grasslands and woodlands	>8	High
Egan	Outcrop plains with low lateritic rises, grassy woodlands and Spinifex. Restricted cracking clay plains	4-8	Moderate
Calwynyardah	Alluvial plains downslope from lateritic remnant yellowish loamy soils, beefwood grassy woodlands	4-8	Moderate
Sisters	Low sandy plateaux and sand plain with through-going drainage, deep red sands and yellow loamy soils, Pindan and tall woodland	4-8	Moderate
Myrooda	Outcrop plain, with extensive scalded surfaces, Spinifex and very low open woodlands	2.5-4	Low
Luluigui	Sand plains and dune fields with stony surfaces and scalded plains. Spinifex and low open grassy woodlands	2.5-4	Low
Camelgooda	Extensive dune fields, Pindan and other low woodlands	2.5-4	Low
Wanganut	Low lying sand plains and dune fields with through-going drainage supporting Pindan acacia shrub lands with emergent eucaplyt trees	2.5-4	Low
Chestnut	Restricted stable flood plains above the level of the active flood plains, sandy to loamy reddish soils with soft Spinifex grasslands with scattered trees	2.5-4	Low
St George	Sandstone plateau and hill lands with open Spinifex and stunted trees, and Pindan on the intervening sand plain	Unsuitable	Unsuitable
Yeeda	Sand plains with deep red and yellow sands, supporting Pindan acacia shrub lands with emergent eucalypt trees	2.5-4	Unknown

* cu/sq. km refers to cattle units (cu) / km^2 (Source: DAFWA). Estimated carrying capacity is defined in cattle units whereby a cattle unit represents a steer older than 2 years or a non-lactating cow.

2. 5 Vegetation

The Kimberley region's vegetation is predominantly grassland with varying degrees of tree cover. Areas with mean annual rainfall of: a) 700 mm are characterised by savannah woodland with tall grasses; b) between 400-700 mm by a tree savannah with scattered trees, and c) less than 400 mm are covered by grass savannah or grass steppe vegetation (Beard 1990). The pastures are native, dominated with perennial remnant vegetation and highly heterogeneous grasses. According to Petheram and Kok (1983) and Speck *et al* (2010), Kimberley pasture species vary with soils, rainfall and grazing pressure, and can be grouped according to their method of survival. These groups include: 1) perennial drought-evading species (e.g. *Astrebla*, *Dicanthium, Sehima)*; 2) drought-resistant sclerophyllous grasses in which vegetative parts remain green in dry periods, mainly Spinifex grasses (e.g. *Triodia* and *Plectrachne*); and 3) short grasses and succulents, mainly annual drought-evading plants, or short lived perennials as well as some coastal pasture (e.g. *Sporobolus)*. Common grasses specific to Liveringa Station include *Chrysopogon fallax* (Ribbon grass), *Eriachne obtusa* (Wire grass), *Aristida holathera* (Erect kerosene grass), *Triodia spp*. (Spinifex grass), *Astrebla elymoides* (Weeping mitchell grass) and *Iseilema vaginiflorum* (Flinders grass). The dominant tree species include *Lysiphyllum Cunninghamii* (Bauhinia), *Eucalyptus coolabah* (Coolabah), *Grevillea striata* (Beefwood), *Atalaya hemiglauca* (Whitewood) and some *Acacia eriopoda* (Broome pindan wattle).

2. 6 **Soils**

Four major groups of soils of importance in this region are (Petheram and Kok 1983):

1. Stony skeletal soils of the ranges and deep sandy soils in the valley floors. These soils have low pastoral values and generally support Spinifex grass;
2. Grey and brown heavy soils, mainly found in the savannahs and grasslands of the plains and support productive grass species such as Mitchel (*Astrebla*), Flinders (*Iseilema* spp) and Bundle bundle (*Dicanthium fecundum*);
3. Brown soils of the river flood plains, mainly found on river fringes and support trees and edible grass; and
4. Deep-reddish sandy soils support small trees and have low palatability value to grazing animals. Dominant trees are *Acacia* and *Eucalptus* and dominant grasses include *Aristida* spp, Spinifex and Sorghum.

2. 7 Topography

Rocky and precipitous hills form two ranges – the Grant range and the Erskine range, with a variety of creeks, billabongs swamps and water holes (Shilling 1948). The lower lying areas are on the river frontage and follow the course of the Fitzroy River. The highest elevation areas are the mountain ranges (~300 m) (Figure 2.4), which are located on the western end of the station and represented with the brown colour. The one-second (30 m) Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) with a horizontal resolution equal to or greater than one arc second of latitude and longitude was obtained from Geoscience Australia. The DEM was produced in 2009.

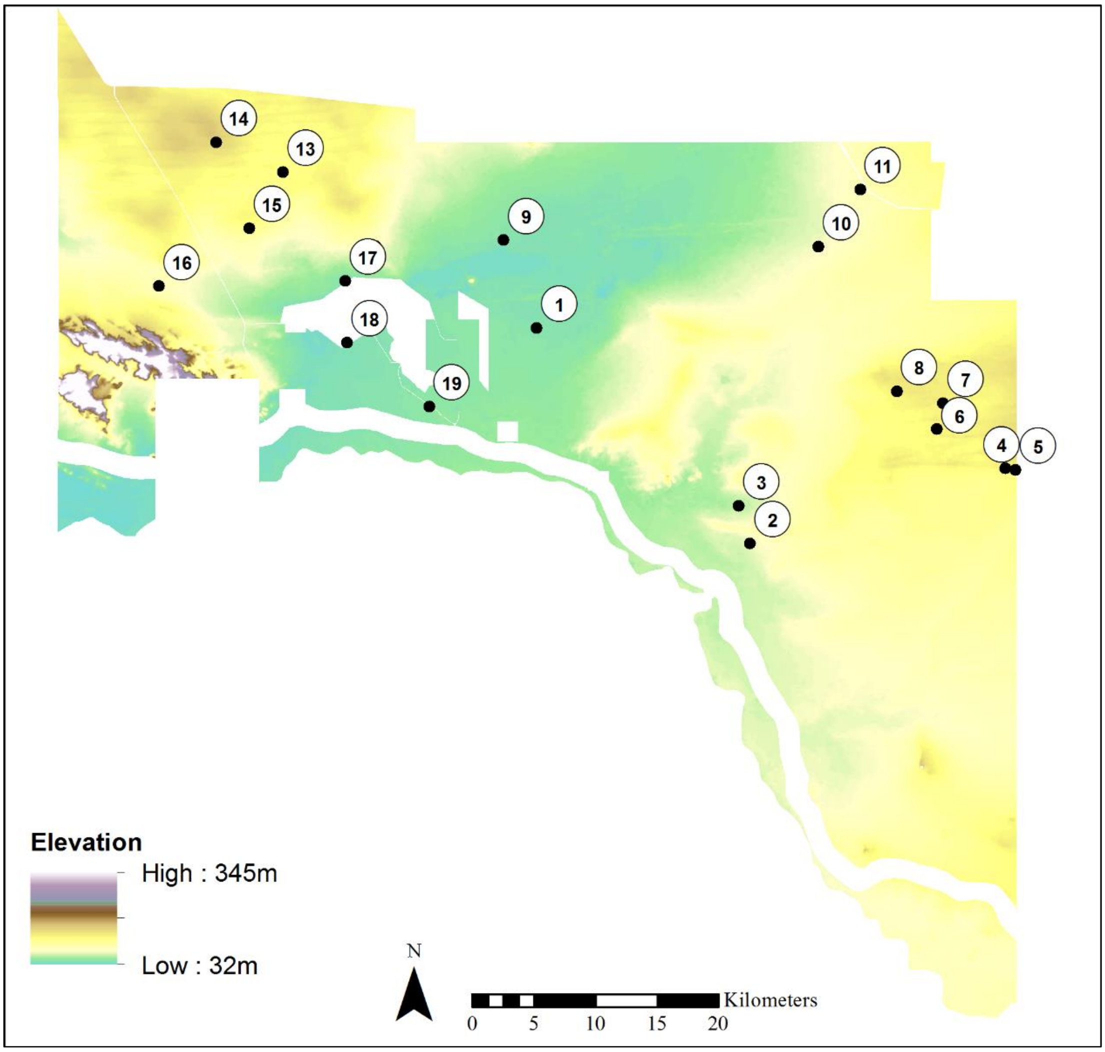

Figure 2.4: A Digital elevation model of Liveringa Station obtained from the SRTM at 30 m resolution (Source: Geoscience Australia).

2. 8 Study area sites

A total of 19 sites were selected on the basis of their pastoral value from seven of the most 'productivity-relevant' land systems in this study (Table 2.2). The size of each site was 100 m x 100 m. The selected sites represented most of the variability that was found within the land systems and could be adequately sampled with the available resources. This resulted in three sites for five land systems (Djada, Calwynyardah, Myroodah, Egan and Camelgooda) and two sites for the two least productive land systems (Luluigui and Wanganut) (Table 2.2). The basis of site selection included: (1) closeness to access roads and accessibility by car and helicopter; (2) a low tree and shrub cover; and (3) presence of a borehole which grazing animals frequent within a 5 km radius.

Table 2.2: Site descriptions at Liveringa Station in the West Kimberley area of Western Australia.

Site	Land system	Topography	Soil type	Paddock	Easting (m)	Northing (m)
1	Djada	Flat	Black clays	Big farm	644542	8010350
2	Calwynyardah	Undulating	Red loamy sand	River Flats	660877	7992811
3	Myroodah	Flat plains	Brown/red clays	Duchess	660028	7995870
4	Calwynyardah	Flat ridge	Red sandy soil	Hardmans	680646	7998702
5	Calwynyardah	Flat	Red sandy loam	Hardmans	681429	7998589
6	Camelgooda	Flat	Sandy loam	Four Mile	675389	8001950
7	Camelgooda	Flat	Red sandy loam	Four Mile	675890	8004023
8	Camelgooda	Undulating	Sandy loam	Four Mile	672311	8005025
9	Egan	Sandy ridges	Red sands	Big Hansens	642727	8017466
10	Egan	Flat	Grey clays	Big Hansens	666376	8016753
11	Egan	Undulating	Sandy loam	Big Hansens	669635	8021346
12	Luluigui	Gentle slope	Red loam	Boab	632122	8017045
13	Wanganut	Undulating	Sandy loam	Bush	625012	8023092
14	Wanganut	Flat	Red sandy loam	Bush	619865	8025538
15	Myroodah	Flat	Clayey red loam	Forest	622371	8018562
16	Myroodah	Flat	Red sandy loam	Forest	615380	8013921
17	Luluigui	Flat	Sandy loam	Forest	629757	8014246
18	Djada	Floodplain	Cracking clay	Rose Hill	629869	8009286
19	Djada	Floodplain	Cracking clay	River Flats	636189	8004077

Figure 2.5 shows the photographs of the sampling sites selected in this study, highlighting the spatial variability and heterogeneity present within the selected land systems. The sites represent different vegetation structure ranging from homogenous Open plains with no trees to mixed sites with interspersed grass and trees. Some of the sites were dominated by shrubs and contained mixed dead and green components of AGB. At any sampling time, sites were always a mixture of dead and green material. Some sites, for example Figure 2.5(b) - Site 12 and Figure 2.5(d) - Site 5 were characterised by bare portions with predominantly red soil. Figure 2.5(c) - Site 17 was dominated by shrubs and with grass understory. A homogenous site, e.g. Figure 2.5(a) - site 10 was located on the River Frontage, where the alluvial deposits were present while site Figure 2.5(e) - Site 19 was characterised by presence of native perennial trees. Figure 2.5(f) - Site 8 was characterised by presence of Hard spinifex grass.

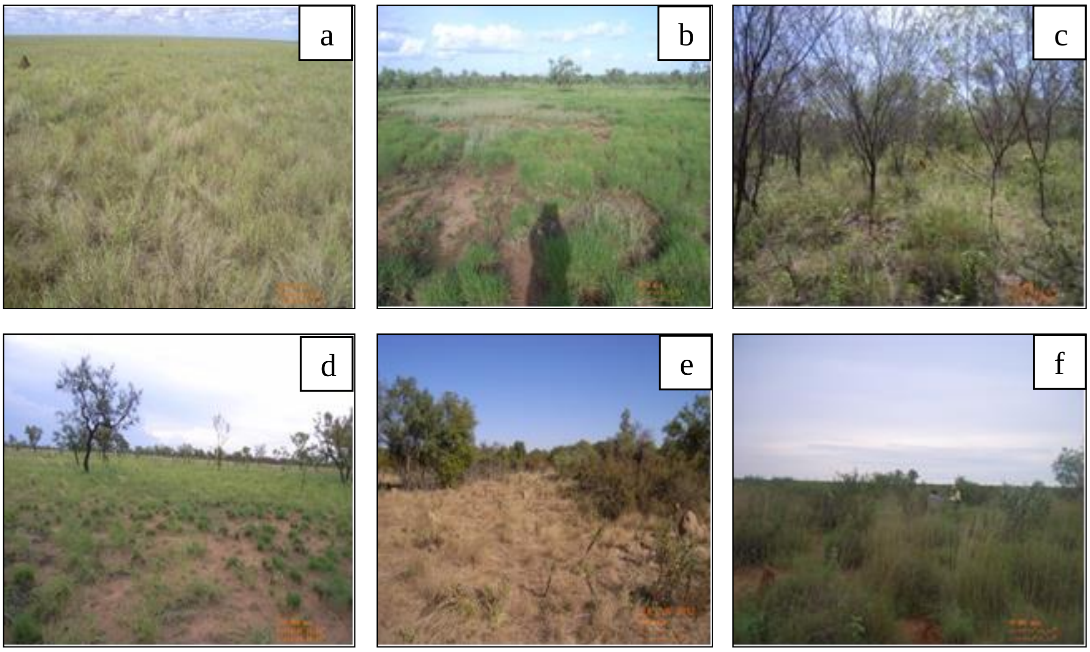

Figure 2.5: Some of the sites used in the study (a) - (Site 10), Bundle bundle grass (b) - (Site 12), young Spinifex grass mixed with some bare ground (c) - (Site 17), predominantly bushy site with some grass understory (d) - (Site 5), young regrowth after a bush fire (e) - (Site19), river flats sites with some trees and (f) - (Site 8), mixture of Spinifex and Ribbon grass.

2.8.1 Summary

Range condition, which is the state of “health” of a given range assessment site may vary within a tract of a few hundred acres and the flora may be made up of a hundred or more species of grasses, forbs, shrubs and trees (Gibbons and Freudenberger 2006). The summary of the dominant grasses, land condition and presence or absence of trees per site is presented in Table 2.3. Good condition indicates dominant grass species expected are present and erosion was absent while bad condition is vice versa. Fair condition meant that the natives species expected are present or recovering but dominated with other grass species while soil erosion is moderate.

Table 2.3: Summary of the grass and tree composition per site for all the 19 sites.

Site	Dominant grasses	Land condition	Trees
1	*Eriachne obtusa* (Wire grass).	Poor	No
2	*Triodia intermedia* (Hard spinifex) and *Cymbopogon nardus* **(**Citronella grass).	Fair	No
3	*Eriachne obtusa* (Wire grass) and *Chrysopogon fallax* (Ribbon grass).	Fair	No
4/5	*Aristida holathera*, (Erect kerosene grass), *Chrysopogon fallax* (Ribbon grass).	Fair	Yes
6	*Chrysopogon fallax* (Ribbon grass), *Eriachne obtusa* (Wire grass) and *Sehima nervosum* (White grass).	Fair	Yes
7	*Eriachne obtusa* (Wire grass), *Chrysopogon fallax* (Ribbon grass), *Aristida inaequiglumis* (Feathertop three awn).	Fair	Yes
8	*Sehima nervosa* (White grass), *Triodia intermedia* (Hard spinifex) and *Chrysopogon fallax* (Ribbon grass).	Good	Yes
9	*Triodia epactia* (Soft spinifex), *Eragrostis* (Love grass).	Fair	No
10	*Dichanthium fecundum* (Bundle bundle), *Chrysopogon fallax* (Ribbon grass) and *Eriachne obtusa* (Wire grass).	Good	No
11	*Chrysopogon fallax* (Ribbon grass).	Good	Yes
12	*Triodia intermedia* (Hard spinifex), *Eriachne obtusa* (Wire grass) and *Aristida holathera* (Erect kerosene grass).	Good	Yes
13/14	*Triodia bitextura* (Curly spinifex) and *Chrysopogon fallax* (Ribbon grass).	Good	Yes
14	*Aristida holathera* (Erect kerosene grass), *Eriachne obtusa* (Wire grass).	Good	Yes
15	*Corchorus sidoides* (Flannel weed).	Poor	Yes
16	*Eriachne obtusa* (Wire grass), *Sehima nervosum* (White grass) and *Chrysopogon fallax* (Ribbon grass).	Poor	Yes
17	*Triodia intermedia* (Hard spinifex), *Eriachne obtusa* (Wire grass) and *Aristida holathera* (Erect kerosene grass).	Good	Yes
18	*Brachyachne convergens* (Kimberley couch), *Iseilema vaginiflorum* (Flinders grass) and *Astrebla elymoides* (Weeping mitchell grass).	Poor	No
19	*Iseilema vaginiflorum* (Flinders grass) and *Astrebla squarrosa* (Bull mitchell grass).	Poor	Yes

Botanical composition and vegetation condition for all the 19 sites sampled in the study was determined with the aid of a local rangeland vegetation expert (Bob

McCartney, from DAFWA). He had extensive knowledge of land systems, vegetation types and plant species found in the wider Kimberley region. The condition scores were based on an assessment framework from Gibbons and Freudenberger (2006). The detailed vegetation and species description for each site including pictures are given in section 2.8.2. For the remainder of this thesis narrative, grasses will be referred to by their common names.

2.8.2 Detailed site descriptions

Site 1

General Description: Site was located in an open plain with black soils. Wire grass was present in smaller percentages. The expected dominant grasses (Ribbon and Bundle bundle) were absent (Figure 2.6).

Grass Composition: 80% *Xerochloa laniflora* (Rice grass) and 20% *Eriachne obtusa* (Wire grass).

Tree Cover: There were no trees present at this site.

Land Condition: Very poor condition because the grass species expected to be dominant like Ribbon and Bundle bundle grass were rare. The main reason was that the site has not been allowed to recover over time due to successive grazing.

Figure 2.6: Site 1 photographs showing an overgrazed Open plain in the wet season (left) and in the dry season (right). Annual grass is dominant due to overgrazing.

Site 2

General Description: The pastures on this site had a low palatability value to cattle. The expected dominant grass (Hard spinifex) was present (Figure 2.7).

Grass Composition: 85% *Triodia intermedia* (Hard spinifex) and 15% other grasses.

Tree Cover: It was approximately 15%.

Land Condition: Fair, the dominant native grass Hard spinifex expected was present.

Figure 2.7: Site 2 photographs showing Hard spinifex grass clumps with isolated bushes and bare areas.

Site 3

General Description: The site was located in the Myroodah land system with black soils. The expected dominant grass (Bundle bundle) was absent (Figure 2.8).

Grass Composition: 80% *Eriachne obtusa* (Wire grass) and 20% *Chrysopogon fallax* (Ribbon grass)

Tree Cover: There were no trees at this site.

Land Condition: Poor land condition because the expected dominant grass species were absent. The main reason could be overgrazing and the site has not recovered over time.

Figure 2.8: Site 3 photographs (left and right) showing sparse coverage of Wire grass in an Open plain. Site was overgrazed and needed time to recover.

Site 4/5

General Description: Sites were located in the Calwynyardah land system which had black soils. Fire had recently passed through the site in November 2011. The expected dominant grass (Erect kerosene grass) was present (Figure 2.9).

Grass Composition: 60% *Aristida holathera* (Erect kerosene grass), 20% C*hrysopogon fallax* (Ribbon grass) and 20% other grasses (Wire grass, Curly spinifex).

Tree Cover: 15% tree cover. The trees present were: *Corymbia collina* (Silver leaf bloodwood), *Corymbia zygophylla* (Broome bloodwood), *Acacia ancistrocarpa* (Fitzroy wattle) and *Grevillea pyramidalis* (Caustic bush).

Land Condition: Fair condition because erosion was moderate and expected grass species were present though not in abundance.

Figure 2.9: Site 4 (left) and Site 5 (right) photographs showing sparse coverage of Ribbon grass. The sites were recovering from a fire.

Site 6/7

General Description: These sites were located in the Camelgooda land system. The expected dominant grass (Ribbon) was present (Figure 2.10).

Grass Composition: 60% *Chrysopogon fallax* (Ribbon grass), 25% *Eriachne obtusa* (Wire grass) and 5% *Sehima nervosum* (White grass).

Tree Cover: 10% tree cover. The trees that were found at these sites were: A*cacia Holosericea* (Candelabra wattle), *Eucalyptus grandifolia* (large leaf Cabbage gum), *Grevillea striata* (Beefwood), *Atalaya hemiglauca* (Whitewood) and *Carissa lanceolata* (Conkerberry).

Land Condition: Fair condition for both sites because Ribbon grass was dominant.

Figure 2.10: Site 6/7 photographs showing dense green coverage of Ribbon grass during the greening period (left) and dried Ribbon grass during the senescence period (right).

Site 8

General Description: This site was located in the Luigui land system. The expected dominant grass (Hard spinifex) was present (Figure 2.11).

Grass Composition: 70% *Triodia intermedia* (Hard spinifex), 25% *Sehima nervosa* (White grass) and 5% *Chrysopogon fallax* (Ribbon grass).

Tree Cover: 5% tree cover and dominant species were: *Grevillea pyramidalis* (Caustic bush) and *Corymbia perfoliata* (Twin leaf bloodwood).

Land Condition: Good condition as the expected dominant grass in the landsystem (Hard spinifex) was abundant.

Figure 2.11: Site 8 photographs showing clumps of Hard spinifex grass with bare ground in some parts (left) and heavily lodged White grass on another section (right).

Site 9

General Description: This site was located close to the Erskine dam. There was an abundance of Soft spinifex. There were some flannel weeds (*Corchorus sidoides*) and Corkscrew grass/bush (*Aristida hygrometrica*). These normally appear after a fire. The expected dominant grass (Soft spinifex) was present (Figure 2.12).

Grass Composition: 80% *Triodia epactia* (Soft spinifex), 20% other grasses – *Eragrostis* (Love grass) and *Whitechloa cymbiformis* (Native panic).

Tree Cover: Tree cover was 5%. These were: *Eucalyptus coolabah* (Coolibah) and *Senna notabilis* (Coakroach bush).

Land Condition: Fair condition because Soft spinifex which was expected was present.

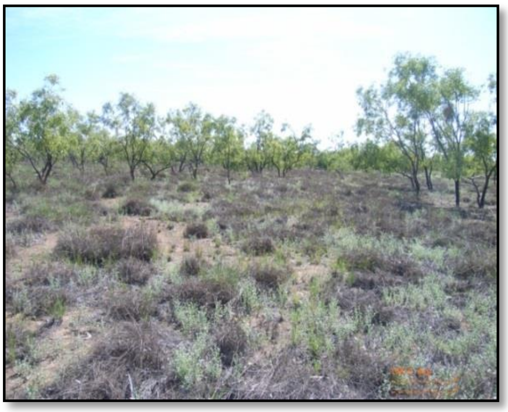

Figure 2.12: Site 9 photographs showing Soft spinifex grass with scattered bushes after a fire (left) and after recovery from the fire (right).

Site 10

General Description: This site was located in Egan land system. The expected dominant grasses (Bundle bundle and Ribbon) were present (Figure 2.13).

Grass Composition: 80% *Dichanthium fecundum* (Bundle bundle)

15%, *Chrysopogon fallax* (Ribbon grass) and 5% *Eriachne obtusa* (Wire grass).

Tree Cover: It was an Open plain with no tree cover.

Land Condition: Good land condition because expected grasses were present.

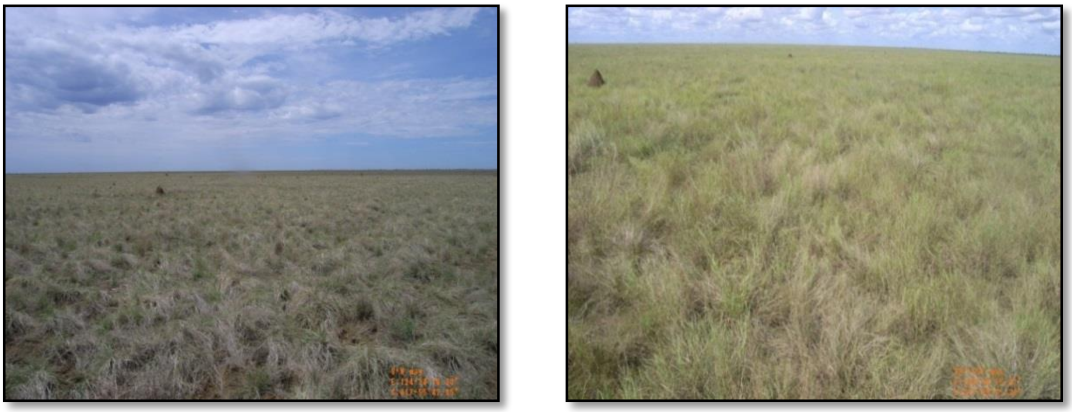

Figure 2.13: Site 10 photographs showing an Open plain dominated by Bundle bundle grass with heavy lodging (left) due to waterlogging and standing Bundle bundle grass (right).

Site 11

General Description: This site was in Egan landsystem. The site had a mixture of grass and trees. In early June 2012, fire had passed through the site before the last field visit. The expected dominant grass (Ribbon) was present (Figure 2.14).

Grass Composition: 90% *Chrysopogon fallax* (Ribbon grass) and 10% other grasses: (White grass, Bundle bundle, Silky brown top, Three awn grass).

Tree Cover: Tree cover was 10% and the dominant species were: *Acacia* rapita (Wattle), *Corymbia collina* (Silver leaf bloodwood), *Corymbia zygophylla* (Broome bloodwood) and *Hakea lorea* (Corkwood).

Land Condition: Good condition because expected dominant grasses were present.

Figure 2.14: Site 11 photographs (left and right) showing a mix of Ribbon grass clumps in the foreground with a sparse coverage of Acacia trees in the background.

Site 12

General Description: The expected dominant grass (Hard spinifex) was present (Figure 2.15).

Grass Composition: 80% *Triodia intermedia* (Hard spinifex), 15% *Eriachne obtusa* (Wire grass) and 5% *Aristida holathera* (Erect kerosene grass).

Tree Cover: 20% tree cover. Trees that were found at this site were: *Acacia holosericea* (Candelabra wattle), *Acacia lysiphloia* (Miniritchie), *Atalaya hemiglauca* (Whitewood) and *Carissa lanceolata* (Conkerberry).

Land Condition: Good condition because Hard spinifex which was expected was abundant.

Figure 2.15: Site 12 photographs showing dense coverage of Acacias with understorey Hard spinifex grass (left) and uniform Hard spinifex grass cover (right).

Site 13/14

General Description: The sites were located in the Wanganut land system with an even mix of trees and grasses. The expected dominant grasses (Curly spinifex and Ribbon) were present (Figure 2.16).

Grass Composition: 50% *Triodia bitextura* (Curly spinifex), 40% *Chrysopogon fallax* (Ribbon grass) and 10% other grasses.

Tree Cover: There was approximately 15% tree cover on the site and these were: *Brachychiton viscidulus* (Kurrajong), *Eucalyptus grandifolia* (Cabbage gum), *Corymbiasetosa* (Bloodwood roughleaf), *Acacia eriopoda* (Broome pindan wattle), *Grevillea dimidiata* (Caustic bush), *Acacia lysiphloia* (Miniritchie), *Terminalia canesens* (Bendee) and Corkybark.

Land Condition: Good because expected grasses were abundant.

Figure 2.16: Site 13/14 photographs showing sparse tree coverage with clumps of Hard spinifex grass (left) and a Ribbon grass dominated section (right).

Site 15/16

General Description: Site 15 was very similar to Site 16. The expected dominant grass (Ribbon) was absent (Figure 2.17).

Grass Composition: 60% *Aristida holathera* (Erect kerosene grass), 30% *Eriachne obtusa* (Wire grass) and 10% other grasses (Curly spinifex and Citronella).

Tree Cover: Tree cover at this site was 10% and these were: *Atalaya hemiglauca* (Whitewood), *Acacia lysiphloia* (Miniritchie), *Grevillea pyramidalis* (Caustic bush), *Corchorus sidoides* (Flannel weed), *Acacia lysiphloia* (Miniritchie), *Terminalia canesens* (Bendee) and Corkybark.

Land Condition: Poor condition because Ribbon grass was absent.

Figure 2.17: Site 15/16 photographs. Sparse cover of Erect kerosene grass (Site 15-left) and Ribbon grass with a dense coverage of Miniritchie trees (Site 16-right).

Site 17

General Description: The expected dominant grass (Hard spinifex) was present (Figure 2.18).

Grass Composition: 80% *Triodia intermedia* (Hard spinifex), 15% *Eriachne obtusa* (Wire grass) and *5% Aristida holathera* (Erect kerosene grass).

Tree Cover: 10% tree cover and these were: *Acacia holosericea* (Candelabra wattle), *Acacia lysiphloia* (Miniritchie), *Atalaya hemiglauca* (Whitewood) and *Carissa lanceolata* (Conkerberry).

Land Condition: Good condition because Hard spinifex which was expected was present.

Figure 2.18: Site 17 photographs showing a heavily eroded Hard spinifex site with Miniritchie trees in the background (left) and eroded open spaces with thicker Hard spinifex clumps and fewer trees (right).

Site 18

General Description: This might have been a Mitchell grass plain a long time ago but was now dominated by an annual grass. The expected dominant grass (Mitchell) was absent (Figure 2.19).

Grass Composition: 60% *Sporobolous spp* (annual grass which maybe the River couch grass or the *Brachyachne convergens* (Kimberley couch), 20% *Iseilema vaginiflorum* (Flinders grass), 15% *Romulea rosea* (Onion grass) and 5% *Astrebla elymoides* (Weeping mitchell grass).

Tree Cover: This was an Open plain with no tree cover.

Land Condition: Poor condition because Mitchell grass, the expected dominant grass was absent. The land has not been given enough time to recover after overgrazing.

Figure 2.19: Site 18 photographs showing good coverage of Flinders annual grass in both set of pictures. The right picture demonstrates the susceptibility of the grass to lodging.

Site 19

General Description: This might have been a Mitchell grass plain a long time ago. It was dominated by an annual grass which invades swampy areas. The expected dominant grass (Mitchell) was absent (Figure 2.20).

Grass Composition: 80% *Iseilema vaginiflorum* (Flinders grass), 15% Astrebla *squarrosa* (Bull mitchell grass with seeds) and 5% *Romulea rosea* (Onion grass).

Tree Cover: This was an Open plain with some trees. Tree cover was 15% and these were: *Acacia Victoria* (Brumble wattle) and *Vachellia nilotica* (Prickly acacia).

Land Condition: Poor condition because Mitchell grass was supposed to be dominant.

Figure 2.20: Site 19 photographs showing parts of an Open plain that had been overgrazed and colonised by Wattle trees (left) and Flinders grass dominated section of the site with isolated tree cover (right).

3 Ground data collection and prediction of site above ground biomass [‡§]

Plate 3: Cattle mustering at Liveringa Station.
Photograph by David Lamb (University of New England).

[‡] Parts of this chapter have been published in the Rangeland Journal (Mundava *et al.* 2015) and in the International Geoscience & Remote Sensing Symposium (IGARSS) proceedings (Mundava *et al.* 2013).
[§] Pictures used in this chapter are taken by: Richard Stovold (Landgate, WA), Dr. Waqar Ahmad (CSIRO) and Dr. Brendon McAtee (Landgate, WA).

3. 1 Abstract

This chapter documents the current field data collection methods that are reported in literature for the determination of total AGB including their strengths and weaknesses. In order for remote sensing based approaches to work effectively in the Kimberley area, field data collection methods need to be accurate as they are used in the calibration of satellite derived models. The objective of this chapter is to present an optimised field data collection protocol for the assessment of AGB that enables calibration and validation of remote sensing imagery or plant growth models at suitable scales. The data collection sites were already introduced in section 2.8. The protocol combines a limited number of destructive samples with non-destructive measurements including NDVI, pasture height and visual scores of AGB sampled over 2 years (section 3.3). The model calibration is presented in section 3.4 and the results are discussed extensively in section 3.5 ending with a summary in section 3.6.

3. 2 Methods of determining above ground biomass

AGB estimates may range from local, paddock, landscape to global scales. Tothill *et al* (1998) suggested that techniques and tools that are developed for rangeland monitoring should be objective, provide useful information for decision making, be repeatable over time and be adaptable to a range of situations. A number of factors influence the type of methodology that is used and these include the size of area to be assessed, costs, accuracy and labour requirements (Catchpole and Wheeler 1992). Destructive (direct) and non-destructive (indirect) sampling methods are used in literature for total AGB assessment and estimation. Destructive sampling involves the clipping and harvesting of quadrats while non-destructive sampling involves calibration with the harvested samples. Destructive sampling is considered the most accurate way of AGB estimation at a local level (Lu 2006). However, it is labour intensive (Tothill and Partridge 1998). As a result, extensive research has been undertaken in finding non-destructive methods in AGB assessment. The methods used are visual estimations, manual and electronic pasture meters, capacitance probe, hand held spectro-radiometers and remote sensing. Both destructive and non-destructive methods are discussed below:

3.2.1 Destructive methods

Traditional assessment of total AGB at site scales is through destructive sampling, i.e. clipping all total AGB within defined quadrats (Haydock and Shaw 1975). Total AGB is cut directly to the ground (Figure 3.1) and the cut sample is harvested, sorted and dried in an oven at a defined temperature. The Dry Matter (DM) of the cut sample is then calculated after oven drying. DM yield refers to the dry weight of the fractions of green and dead material after oven drying. Though destructive in nature, clipping total AGB in quadrats is an accurate method provided that enough quadrats are cut to reflect the spatial variability (Lu 2006). However, cutting total AGB in quadrats is time-consuming (locating, cutting, sorting, drying and weighing of samples) and labour-intensive (Marsett *et al.* 2006). The accuracy of estimation decreases with increasing spatial variability (Catchpole and Wheeler 1992; Ritchie and Anderson 1996; Psomas *et al.* 2011). In heterogeneous rangeland ecosystems, a large number of destructive samples are required even when using double-sampling techniques (Laca 2009). At a local scale, total AGB can be estimated with reasonable accuracy but it is impractical and very difficult to extrapolate this information to the landscape level ('t Mannetje and Haydock 1963). In practice, destructive sampling is employed for the calibration of non-destructive measurement techniques (Lu 2006).

Figure 3.1: A field AGB 50 × 50 cm quadrat before (left) and after harvesting a cut sample (right).

3.2.2 Non-destructive methods

Non-destructive methods to estimate total AGB relying on calibrated relationships between dry weight and plant attributes such as height, greenness, resistance and density are promising as they can cover larger areas at low costs. Currently available non-destructive methods for total AGB assessments include: 1) visual estimates (VE) (Harmoney *et al.* 1997); 2) pasture height (PH) (sward stick/rising plate/disc plate meter (Whitney 1974; Earle and McGowan 1979; Sharrow 1984; Gourley and McGowan 1991; Huete *et al.* 2002); 3) remote sensing (field radiometers/active optical sensors/leaf canopy analysers/airborne satellites (Schut and Ketelaars 2003; Trotter *et* *al.* 2010); and 4) capacitance probes and conductivity meters (Sanderson *et al.* 2001). Non-destructive methods still require destructively measured samples though fewer than if the destructive method was used alone, often referred to as dual sampling techniques. This effectively reduces cost and time required for sampling and sample processing while increasing the number of samples obtained. However, non-destructive methods are associated with some level of error, and particular methods maybe site, climate, soil and or species specific thus localised calibrations are necessary. Some of the widely used non-destructive techniques in literature are discussed below.

3.2.2.1 Visual estimates

Visual estimation provides quick estimates of total AGB (Catchpole and Wheeler 1992). This is achieved by weighing representative units of a plant and establishing an ‘eye’ for different amounts of total AGB (Huete 1988). Available total AGB assessment techniques to collect ground data on site scales are based on dry weight ranking for species composition (‘t Mannetje and Haydock 1963), plant frequency sampling, comparative yield (Haydock and Shaw 1975) or combinations thereof. Examples are BOTANAL (Tothill *et al.* 1992), comparative yield, plant basal area, step point and ground cover assessments (Ritchie and Anderson 1996). The dry-weight-rank method developed by ‘t Mannetje & Haydock (1963) is based on the proportion of DM of different species in a grass sward. The comparative yield method uses a scoring system (e.g. 1 for low AGB, 10 for high AGB). These scores are calibrated by means of regression with cut quadrat samples (Haydock and Shaw 1975). 't Mannetje (2003) reports that the comparative yield method is widely used in combination with the dry-weight-rank method in the computer programme BOTANAL (Tothill *et al.* 1992) achieving success in rapid DM yield assessment of small plots and large areas. However, they require an expert with knowledge about local plants, are subjective and prone to error as accuracy of measurements is dependent on vegetation type, experience and ability of the observer ('t Mannetje and Jones 2000).

3.2.2.2 Pasture height

Pasture height has been successfully used in the monitoring of pasture yield with reasonable accuracy though different calibrations are required at different growth stages (Correll *et al.* 2003; Li *et al.* 2003). The ability of the vegetation to repel compression or compaction when force is placed upon it is measured with a rising plate meter (Harmoney *et al.* 1997). The Rising Plate Meter (RPM) measures PH by downward pressure of the plate and gives more accurate estimates where resistance to compression is higher (Heinisch 1962). In spatially heterogeneous areas, PH measurements with a disk plate meter have outperformed other methods over a wide range of forage species (Harmoney *et al.* 1997; Correll *et al.* 2003), but accuracy varies with growth stage (Correll *et al.* 2003; Li *et al.* 2003), forage type and pasture species (Harmoney *et al.* 1997). The main limitation with the approach is that; the plate is less reliable where pasture has been trampled by cattle or has lodged and is more suited to some pasture types than others.

3.2.2.3 Hand held radiometers

Proximal sensors are another method of measuring AGB, the most common one being the hand held radiometers (Tucker *et al*. 1979). The main advantage is that they contain their own light source allowing for measurements to be performed under any condition of ambient illumination, including at night (Schaefer 2012). Hand held radiometers are popular in measuring agricultural productivity (Tucker *et al*. 1979) and in obtaining quick and reasonably accurate estimates for green AGB (Hanna *et al.* 1999). Starks *et al* (2006) used a portable ASDInc FieldSpec spectro-radiometer in the collection of canopy reflectance data to develop real time algorithms for prediction of Bermuda grass total AGB. They concluded that total AGB production could be predicted throughout the growing seasons using two waveband reflectance ratios.

3.2.2.4 Comparison of non-destructive methods

Comparisons have also been made across above mentioned methods (Harmoney *et al.* 1997; Ganguli *et al.* 2000; Schut *et al.* 2003; Martin *et al.* 2005). Schut *et al* (2003) concluded that an experimental ground-based imaging spectroscopy system performed significantly better than the disk plate meter and 8-band radiometer. Martin *et al.*

(2005) concluded that results at individual sites and dates were very variable and no single method was effective in all the experimental conditions. Trotter *et al* (2010) concluded that the integration of a Global Positioning System (GPS) unit with the hand held Crop Circle sensor makes it possible to map the quantity, spatial and temporal variability of total AGB across paddocks without the need for full paddock surveys. It may provide insights into factors that limit pasture productivity. Harmoney *et al* (1997) observed that accuracy of indirect methods is dependent on forage type and species.

3.2.3 Methods used in Australia

At paddock or landscape scales, contemporary techniques of ground data collection based on VE, including BOTANAL and drive-by methods (Hassett *et al.* 2000), have been used extensively in numerous grazing experiments across Northern Australia (O'Reagain *et al.* 2009; Orr and O'Reagain 2011; Orr and Phelps 2013). Rapid assessment techniques which use VE have been employed in the northern part of Australia. Hassett *et al* (2000) used a technique called 'spider mapping' in their work to assess pasture AGB for the calibration and validation of a state wide model in Queensland on a 5 km grid basis. Spider mapping involves rapid visual assessment of AGB from transacts while in a moving vehicle at uniform intervals. The advantage with this approach is that it provides quick reliable estimates of AGB; however, it is most suited to large spatial scale data collection.

The potential of photographic biomass guides as a management tool has also been investigated. Anonymous (2013) concedes that, in rangelands, point scale monitoring systems are inadequate for broad scale land condition assessment hence the need for assessments that function at the paddock scale. The Stocktake package is a paddock-scale land condition monitoring and management tool, which provides a systematic way for assessing land condition and long term carrying capacity including the calculation of forage budgets (Anonymous 2013). Data in Stocktake is collected on a paddock by paddock basis. Setting up of monitoring sites involves identification of paddocks plus their size. A key process in the process is the selection and the setting up of photo sites. Two photographs are taken per site at a fixed location. Data recorded for each site includes soil condition, pasture condition, tree basal area, pasture yield and percentage unpalatable yield (Anonymous 2013). These assessments are done once a year and the change over the years is then used in the condition assessment. While this tool is good in detailing the land condition over time, the data collected is not sufficient to calculate how much forage is available at any given time throughout the year.

3.2.4 Summary

As previously discussed, individual relationships based on available non-destructive methods are limited to specific sites or seasons and at times require the use of experts in the case of VE. However, point-based sampling methods provide poor representation of heterogeneous landscapes through time (Reeves *et al.* 2001) and lack precision due to sward heterogeneity ('t Mannetje and Jones 2000). Cheaper yet representative ground data collection approaches are required that are scalable from site to paddock scales, providing means to monitor total and green AGB with remote sensing or modelling tools. Remote sensing methods require calibration and validation but current field data collection methods imply "a high fixed cost to prepare an image" (Marsett *et al.* 2006, p. 539). Non-destructive measurements on their own are site-, species- and date-dependent (Harmoney *et al.* 1997; Martin *et al.* 2005; George *et al.* 2006).

Consequently, there is a desire for measurement techniques that are time-, labour- and cost-effective (Catchpole and Wheeler 1992) regardless of seasonal conditions and observers. One of the aims of this study is to develop a total and green AGB assessment protocol that can be used at site to paddock scales in rangelands regardless of seasonal conditions and observers, while strongly reducing sampling and sample processing time. The accuracy of relationships between destructively sampled total and green AGB and non-destructive measurements from an active canopy sensor, a rising plate meter, VE and combinations thereof was compared in this analysis. It is hypothesised that a combination of various non-destructive methods is more accurate than any of the techniques separately and will provide an accurate estimate of total and green AGB in all seasons. Table 3.1 shows a summary of the research that has been conducted in Australia with respect to total AGB assessments at different scales and their related accuracies.

Table 3.1: Destructive and non-destructive total AGB assessment methods and their related accuracy in Australia. *H represents high and M represents moderate accuracy.

Scale	**Destructive**	***Accuracy level**	**Non-destructive**	***Accuracy level**	**Temperate examples**	**Tropical examples**
Plot	Quadrats	**H**				
Paddock	Quadrats	**H**	Rising plate meter	**M**	Correll *et al* (2003)	
			Crop Circle	**M**	Trotter *et al* (2010)	
Landscape	Transects	**M**	Remote sensing	**H**	Donald *et al* (2010) Edirisinghe *et al* (2011)	GRASP Rickert *et al* (2000)
			Modelling	**H**	Smith *et al* (2011) Hill *et al* (2004),	

3. 3 Dataset

3.3.1 Sampling strategy

An extensive field campaign spanning two seasons was carried out at Liveringa Station. The selection of the sampling dates was on the basis of a historical MODIS NDVI time series (Figure 3.2). As observed, the 2013 MODIS NDVI time series runs until August since the last sampling date was set in June. The annual temporal profiles of NDVI exhibit differences between years that may be related to vegetation phenology and climatic influences. These differences in pattern may be used to approximately identify the start and end date of the annual growing seasons. This choice of sampling dates meant that the growth of the AGB components could be measured from the onset of growth until the senescence phase.

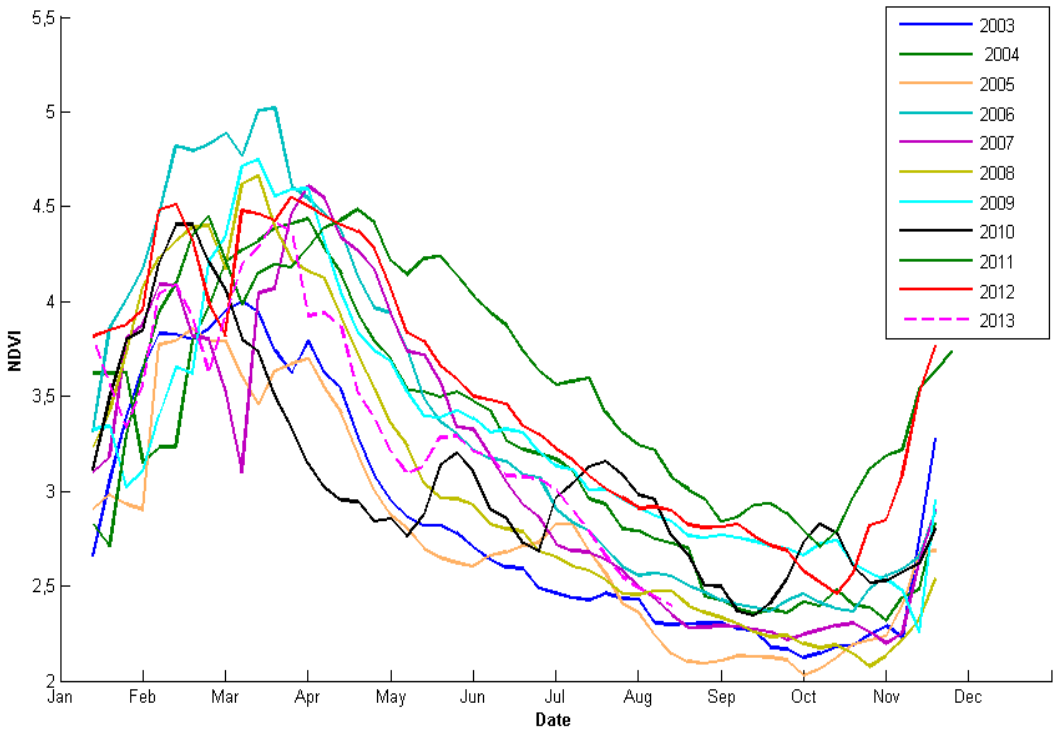

Figure 3.2: Historical MODIS NDVI time series of Liveringa Station from 2003-2013 (Source: Satellite Remote Sensing Services, 2013).

3.3.2 Above ground biomass field data collection

Field data were collected between December 2011 and June 2013, which included two growing seasons. Destructive and non-destructive measurements of AGB were collected at four field visits per growing season. The first visit was made just before the start of the wet season (December), two visits in the wet season (February and March/April) and the final visit just after the start of the dry season (June) to coincide with the senescence phase. Each site included transects along the north, south, east and west radials extending to a distance of 50 m from the centre (Figure 3.3a -covering an area of 0.785 ha). Quadrats of size 50 × 50 cm were located 25 m from the centre of the site in the direction of a radial: only the east and west radials were used in the first season, but all four cardinal radials were used in the second season. At each sampling time, unique quadrat locations were moved so as to avoid previously sampled locations. Additionally, quadrats with, the highest and lowest visually determined amounts of AGB (HB and LB, respectively) within the site were also sampled. This resulted in four quadrats per site for the 2011–2012 growing season and six quadrats per site for the 2012–2013 growing season.

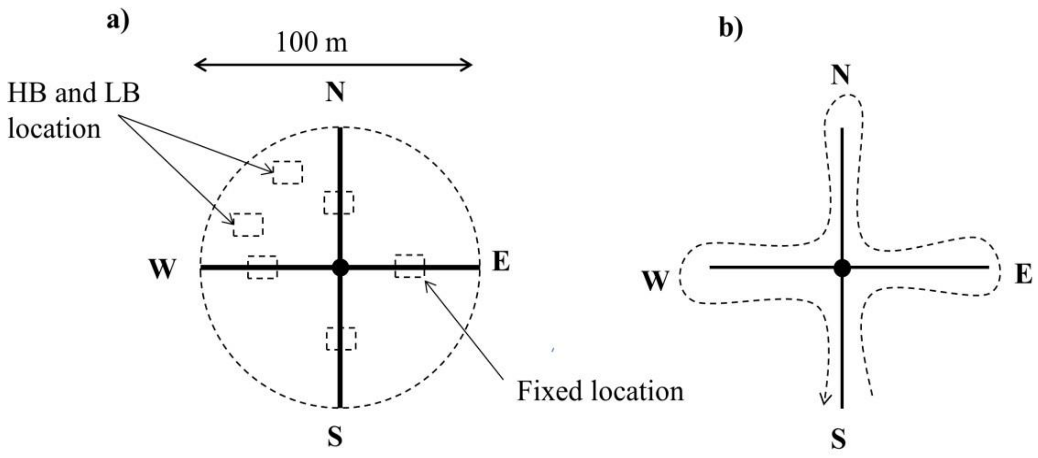

Figure 3.3: Vegetation sampling design: a) for quadrats, sampled at a location with high and low AGB (HB and LB, respectively) that were visually determined at the time of the site visit and two or four quadrats sampled 25 m from the centre along the cardinal radii; and b) for sites, tracks where recordings of crop reflection were taken continuously while walking and where disk plate meter readings and comparative yield scores were recorded at regular intervals.

3.3.3 Non-destructive sampling

Before clipping quadrats, recordings from non-destructive measurements including VE, PH and canopy reflectance were taken. Second, VE and rising plate meter recordings were taken along the north, south, east, and west radials at 2.5 m intervals to capture all variation present within sites (Figure 3.3b). VE were conducted by two observers at any given sampling time, using the comparative yield approach (Haydock and Shaw 1975). Each observer estimated AGB using values between 0 and 10, adjusted according to the lowest and highest AGB quadrats within each site. A rising plate meter with a 0.6 kg disk and a diameter of 53 cm (Figure 3.4b) was used to measure PH. The Holland Scientific Crop Circle ACS210 sensor was used to obtain red (650 nm) and Near-infrared (NIR) (880 nm) reflectance to calculate normalised difference vegetation index (NDVI) values. Recordings were made continuously while walking at a steady pace (Figure 3.4c). The Crop Circle is an active sensor and has its own light source, which ensures that measurements can be taken at any time of the day. Reflectance was recorded at a consistent height of 1 m above the plant canopy. The sampling protocol that was used is presented in *Appendix A*.

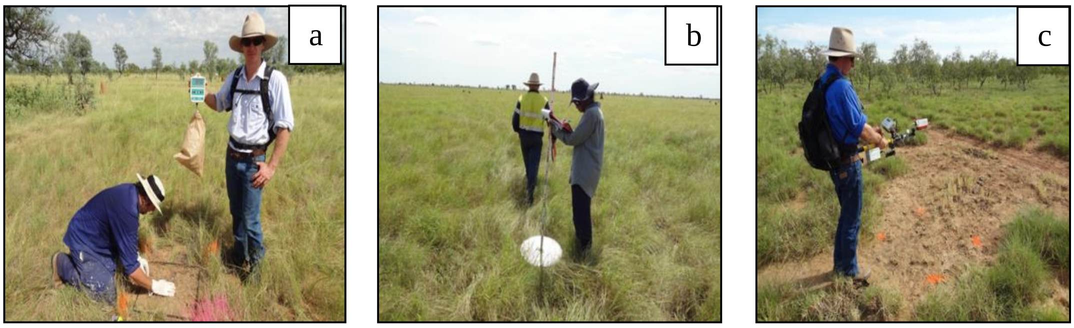

Figure 3.4: (a) Clipping of AGB, (b) measuring PH and (c) canopy reflectance measurements within a quadrat.

3.3.4 Destructive field sampling and sample processing

High and low AGB samples were included to ensure a wide range of AGB values. This was needed for the calibration of the VE per site. A 50 × 50 cm quadrat was used for clipping AGB to ground level (Figure 3.4a). Clipped standing and senescent material within the quadrat was bagged taking care to avoid litter, leaves and sticks. Fresh weight of the bagged material was recorded with a digital scale in the field. Samples were refrigerated when possible to ensure that the samples did not deteriorate before they were dried. For each site, the material of all quadrats was composited and thoroughly mixed before subsamples were taken. These subsamples were dissected into fractions of green and dead material and oven-dried at 60°C for 72 hours to determine their dry weight and the fraction of green AGB and the DM content of total and green AGB. Total AGB of DM per quadrat was determined using the field recorded fresh weights of AGB and DM content of AGB in the subsample. The AGB of green DM per quadrat was calculated by multiplying the green DM fraction and the total AGB.

3.3.5 Data available for analyses

The number of samples collected in quadrats and measurements recorded in quadrats and along radials within sites for each field visit are shown in Table 3.2. At the site scale, means of all non-destructive measurements were determined.

Table 3.2: Number of samples obtained at point locations and along radials for each site at each field visit.

Sampling	**Numbers of samples recorded per site per visit**	
	Quadrat locations (reference)	
	First year	**Second year**
AGB	4	6
PH	4	6
VE	4	6
Crop Circle	100 recordings (x 4)	100 recordings (x 6)
	Radials (observations)	
PH	80 (20 per radial)	
VE	80 x 2 (20 per radial and based on two observers)	
Crop Circle	Depending on walking speed (1000+ recordings per radial)	

The total number of quadrats measured is shown in Table 3.3. The high (HB) and low (LB) AGB quadrats were excluded from further analysis whenever the VE was selected as the predicting variable to ensure that only fully independent data were used to evaluate model performance. Not all quadrat observations were available for modelling because samples for determination of DM content from one visit in the second season were lost due to a malfunctioning oven. The number of green AGB quadrats in Open plains sites (see Section 3.3.2 for description) was limited because vegetation material was fully senesced at several field sampling dates. Bush fires removed standing material at some sites in two seasons and these observations were excluded from the statistical analysis.

Table 3.3: Number of samples collected in quadrats over two seasons and the number of quadrat observations available for modelling, differentiated for models including or excluding VE for total AGB and green AGB (gAGB). When VE was included in the model, the samples from high and low AGB quadrats were excluded.

Group	Reference samples		Observations including VE		Observations Excluding VE	
	2011-12	2012-13	AGB	gAGB	AGB	gAGB
Open plains	96	108	108	98	191	173
Bunch grass	128	174	147	146	249	250
Spinifex	80	90	96	94	162	158
Total	**304**	**372**	**351**	**338**	**602**	**581**

3. 4 Methods

3.4.1 Calibration of visual estimates

Comparative yield scores from the VE of each observer were converted to DM estimates using simple linear calibrations, based on the measured DM yields in the high (HB) and low (LB) AGB quadrats, collected at the sampling time for each site. The accuracy of these VE was assessed using the DM yields that were determined in the other quadrats collected on the same date at the same site, and average absolute and relative errors were determined. Finally, means of the visual DM yield estimates from the two observers were determined per quadrat.

3.4.2 Statistical analysis

All data collected in various visits were adjusted coefficient of determination. This was to (1) allow a comparison of performance across dates, (2) to make available a sufficient number of observations for a multiple regression model, and (3) enable prediction of AGB for lost quadrat samples in a later stage. Multiple regression models ($\boldsymbol{Y}_{vt}, s, q, t = \boldsymbol{A}_{vt}\boldsymbol{X}_{vt}, s, q, t + e_{vt}$) were developed using MATLAB (version 2013) where: *q* is quadrat measurement, *s* is site, *t* is time and *vt* vegetation type. Models were calibrated and validated with quadrat (*q*) measurements made on all sites (*s*) at various visits (*t*) for a specific vegetation type (*vt*). Several stratifications were compared for model development, combining sites with the same land-use system, the same soil types or the same vegetation type. Only vegetation type was statistically important and resulted in an improvement of results. Three vegetation types reflecting Open plains, Bunch grass and Spinifex sites were defined (Table 3.4). Predictability of AGB with non-destructive measurements differed strongly between vegetation types, for example; for sites with sturdy Spinifex and Bunch grass, PH is far more important than for annual grass that occurred in the Open plains site.

Table 3.4: Vegetation types used for the statistical analysis, the numbers for included sites refer to the sampling locations as indicated in Figure 2.3.

Vegetation type	Sites	Occurrence
Open plains	1, 3, 10, 11, 18, 19	Egan and Djada land systems including flood plains or high groundwater tables.
Bunch grass	4, 5, 6, 7, 13, 14, 15, 16	Yellow or red sandy soils dominated by *Chrysopogon spp.* (ribbon grass) with a mixture of trees and grass.
Spinifex	2, 8, 12, 17, 9	High abundance of *Triodia* spp. (Hard spinifex) grass.

3.4.2.1 Selection of independent variables

Independent variables considered in the model were PH, VE and NDVI, with quadratic and interaction terms. If VE were included, all data from HB and LB quadrats that were used to calibrate the VE were excluded, reducing the number of quadrats available (Table 3.3). The relative importance of an indirect measure is a function of phenology and hence may differ during the season. Therefore, sampling period (sampling number), reflecting sampling in the green or dry period of the year, was considered as an interaction term. This allowed the model to give different weights to measurements collected at various sampling dates. The independent variable was either the measured green AGB or total AGB.

3.4.2.2 Outlier Handling

The three best independent variables were selected in a stepwise regression approach with a forward selection procedure. When a quadratic or an interaction term was selected, the underlying terms were also included. All selected terms were then fed into a multiple regression model to identify outliers (Student distribution with $P < 0.01$). The procedure to identify outliers was firstly used to rigorously evaluate if errors were made in the process of field-data recording. Secondly, remaining outliers were labelled but not excluded from the analysis. Two datasets were defined, one including all available quadrats and one excluding outliers in order to allow a comparison between them. Also HB and LB quadrats were excluded from both datasets when VE was selected as a model term. Predictions of green and total AGB at the site scale were based on multiple regression models calibrated on the dataset excluding the identified outliers. Outliers were excluded in order to develop a model as robust as possible to accurately predict AGB at the site level. A single extreme observation can strongly influence the selection of model terms and model calibration. This is undesirable as model performance may then be less robust for normal observations. Outliers (extreme observations) that were encountered within quadrats are unlikely to occur at the site scale as these are based on means of all measurements collected along the radials. To get an indication of model performance at the site scale, extreme observations should, therefore, be also excluded from the datasets used for validation. Predictions of green and total AGB at the site scale were based on means of non-destructive measurements (PH, VE and Crop Circle NDVI) collected along the radials, to ensure accurate representation of within-site variation.

3.4.3 Validation

Structural redundancy (Golbraikh and Tropsha 2002) could be expected due to strong correlations between values measured on an individual site, requiring validation with an independent dataset (Golbraikh and Tropsha 2002). In order to test the robustness of the calibrated relationships based on the quadrat measurements, a 'Leave-One-Out' (LOO) and a 'Leave-Site-Out' (LSO) cross-validation approach was carried out (Schut *et al.* 2009). This procedure includes a model calibration step and a model validation step to predict values of data left out when calibrating the model. The calibration model was based on values measured at all sites excluding site *k* to predict all values for site *k* (Schut *et al.* 2009). The outcome from the cross-validation procedure was evaluated with the Q^2 statistic (Golbraikh and Tropsha 2002), equivalent to the 'modelling efficiency' originally proposed by (Loague and Green 1991).

$$Q^2 = 1 - \frac{\sum_i (y_i - \hat{y}_i)^2}{\sum_i (y_i - \bar{y})^2} \quad (1)$$

where y is the measured value for observation i, $\hat{y}$ the predicted value and $\bar{y}$ the mean of all measured values. The Q^2 is used as a criterion of both robustness and predictive ability of the model (Golbraikh and Tropsha 2002). It can be likened to an R^2 value, but can become negative when there is a strong bias in the predictions. Only models including the best performing independent variables, selected for the datasets without outliers, were used for validation. A separate calibration and validation was performed for datasets including and excluding outliers as described above. The model was considered successful when the R^2_{adj} and LOO-Q^2 values were at least 0.5 and LSO predictions fulfilled all four conditions as defined by Golbraikh and Tropsha (2002) and further discussed in Tropsha (2010).

3. 5 **Results**

3.5.1 Destructive total above ground biomass samples

Spinifex sites had a much higher total AGB (6245 kg DM ha^{-1} and 7446 kg DM ha^{-1}) than the Open plains (3629 kg DM ha^{-1} and 2888 kg DM ha^{-1}) and Bunch grass (4121 kg DM ha^{-1} and 2886 kg DM ha^{-1}) sites in both years although large differences between sites were observed (Table 3.5). The mean AGB in the 2011-2012 growing season for the Open plains and Bunch grass sites were higher than for the 2012-2013 growing season, in contrast to the Spinifex sites. The coefficients of variation (CV) were large in both sampling seasons ranging from 40-150%. The means of CV% of quadrats over all sampling dates within sites ranged widely with values typically well above 50% for total AGB, especially for the Spinifex and Bunch grass sites. The large standard deviation of the quadrat means also reflect large differences between dates. Spinifex sites had the highest mean AGB per site for the sampling years at 6 245 kg DM ha^{-1} for green and 7 446 kg DM ha^{-1} for total AGB.

Table 3.5: Means (± standard deviations of mean) in the temporal domain (indicating variation between sampling dates) of total AGB in 2011-2012 and means (± standard deviations of mean) in time of the coefficients of variation (CV%, mean divided by the standard deviation in the spatial domain) of quadrat AGB measurements within sites in 2012-2013.

Site	Total AGB in 2011-2012 (kg DM ha^{-1})	CV (%)	Total AGB in 2012-2013 (kg DM ha^{-1})	CV (%)
		Open plains sites		
1	3028 ±3170	90±30	2670±1458	110±30
3	2370±315	70±20	2064±1126	120±30
10	4481±2765	70±10	4129±2565	70±40
11	5790±648	80±10	2489±333	60±60
18	2548±975	60±10	3525±1560	100±20
19	3558±1426	40±20	2449±160	110±0
Mean	3629	70	2888	90
		Bunch grass sites		
4	2344±708	100±40	_	_
5	2144±543	110±30	2958±1382	90±30
6	5838±910	90±20	4820±1643	110±20
7	2732±567	80±30	2510±161	110±30
13	5169±1140	100±10	3594±933	90±90
14	4663±1245	60±20	1089±945	90±10
15	6027±5847	80±20	2139±326	60±50
16	4050±1644	120±30	4000±2766	101±30
Mean	4121	90	2886	90
		Spinifex sites		
2	10057±6592	80±20	5510±1836	100±90
8	8230±3211	100±10	8586±1565	90±30
9	1676±714	70±20	6820±4020	70±10
12	6215±4557	130±30	11882±1838	100±10
17	5045±2795	100±10	4430±938	150±30
Mean	6245	70	7446	100

3.5.2 Calibration of multiple regression models

Vegetation type sites provided sufficient measurements for the establishment of relationships between AGB measurements in quadrats and a combination of non-destructive measurements. This allowed identification of outliers (Figure 3.5). The adjusted coefficients of determination (R^2_{adj}) for relationships for total AGB were 0.65 for Open plains, 0.77 for Bunch grass and 0.90 for Spinifex sites. For green AGB, the R^2 values ranged from 0.67 to 0.88 (Table 3.6). Step-wise regression results show that the most significant dependent variables for annual grass-dominated Open plains sites were VE and NDVI, whereas PH and VE were most important for Bunch grass and Spinifex sites. The Crop Circle NDVI responded strongly to green AGB for the Open plains and Bunch grass sites and was included as a model term for both vegetation types for total AGB. As can be seen in some models, for example, for total AGB for the Open plains sites, VE and NDVI are used for both significant terms 1 and 2. These terms as included in the model are independent although correlated with AGB and this is tested with validation in the next section. A summary of these results is given in Table 3.6.

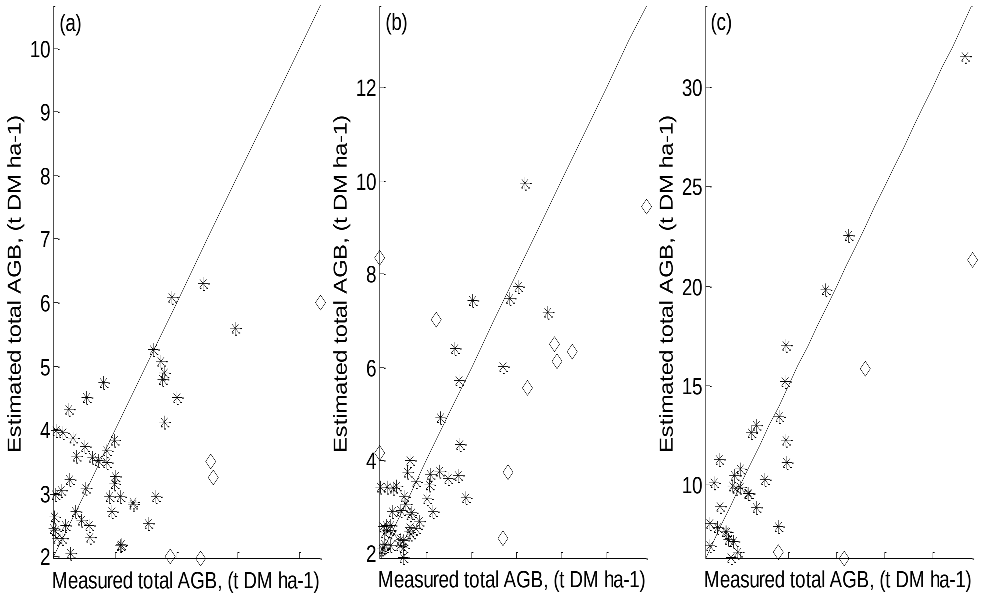

Figure 3.5: Measured total AGB values (X-axes) for the three vegetation types at sites - (a) Open plains sites, (b) Bunch grass sites and (c) Spinifex sites, versus estimated total AGB (Y-axes) obtained from calibrated multiple regression models. The adjusted R^2 indicates the explained variation for relationships excluding the identified outliers, (◊) represents outliers outside the 95% confidence interval.

Table 3.6: Model terms and calibrated relationships between predicted and measured total and green AGB (AGB, t ha^{-1}), excluding outliers. Selected independent variables in the calibrated multiple regression models included VE, PH or NDVI.

Vegetation Type	Model Equations	$R^2_{Adj.}$	Selected independent variables*
	Total AGB		
Open plains	$Y = 0.094 + 0.997X_1 + 0.100X_2 - 0.001X_3 + 0.070X_4 + 0.259X_5$	0.65	VE*NDVI, PH, PH^2, VE, NDVI
Bunch grass	$Y = -0.117 + 0.007X_1 - 0.905X_2 + 0.390X_3 + 0.067X_4 + 3.529X_5 + 0.424X_6$	0.77	PH^2, VE*NDVI, PH*NDVI, PH, NDVI, VE
Spinifex	$Y = -1.4364 + 0.012X_1 + 0.348X_2 - 0.700X_3 + 0.044X_4 + 9.216X_5$	0.90	PH*VE, PH, PH*NDVI, VE, NDVI
	Green AGB		
Open plains	$Y = 0.119 + 1.215X_1 + 0.008X_2 + 4.299132X_3 + 0.137X_4\ 1.517X_5 + 0.008X_6$	0.88	VE*NDVI,NDVI*PH, NDVI*NDVI, VE, NDVI, PH
Bunch grass	$Y = -0.284 - 0.001X_1 + 1.855X_2 + 0.001X_3 + 0.291X_4 + 0.010X_5$	0.67	VE*PH, NDVI, PH*PH, VE, PH
Spinifex	$Y = -0.694 + 0.014X_1 + 0.100X_2 - 0.242X_3 + 0.081X_4 + 3.942X_5$	0.88	PH*VE, PH, PH*NDVI, VE, NDVI

*suffixes of X refer to the sequence of variables below

3.5.3 Validation of multiple regression models

The LSO-Q^2 values for Spinifex sites were 0.80 and 0.88 for green and total AGB, respectively (Table 3.7 and Figure 3.6). The models resulted in weak to strong relationships (LSO-Q^2 >0.24) when excluding identified outliers for both green and total AGB for all vegetation types (Table 3.7). A total of 19 quadrat observations were considered outliers for green and total AGB. For datasets including outliers, the LSO-Q^2 values ranged between 0.17-0.80. These were generally lower when compared to excluding outliers which had a LSO-Q^2 range of 0.24-0.88. The Q^2 values for total AGB in the LOO-validation were 0.59, 0.73 and 0.88 and for LSO 0.24, 0.70 and 0.88 for Open plains, Bunch grass and Spinifex sites, respectively. For models calibrated with datasets excluding outliers, the differences between the LOO and LSO validations were reasonably small. The models predicting green AGB of quadrats can be considered predictive for all three vegetation types, as all conditions as defined by

Tropsha (2010) were met. This is also true for models predicting total AGB for Bunch grass and Spinifex site quadrats. The model for total AGB of Open plains sites failed one out of the four of Tropsha's conditions, as one quadrat was predicted poorly in the LSO validation.

Table 3.7: Leave-One-Out (LOO) calibration and Leave-Site-Out (LSO) validation results using Q^2 statistic including and excluding outliers for green and total AGB for vegetation types where *N* is the total number of observations.

Vegetation Type		**Green AGB**			**Total AGB**	
	N	LOO-Q^2	LSO-Q^2	*N*	LOO-Q^2	LSO-Q^2
			Including Outliers			
Open plains	98	0.75	0.72	108	0.50	0.17
Bunch grass	146	0.47	0.33	147	0.59	0.53
Spinifex	94	0.69	0.68	96	0.80	0.80
			Excluding outliers			
Open plains	92	0.84	0.75	103	0.59	0.24
Bunch grass	135	0.59	0.62	137	0.73	0.70
Spinifex	91	0.85	0.84	92	0.88	0.88

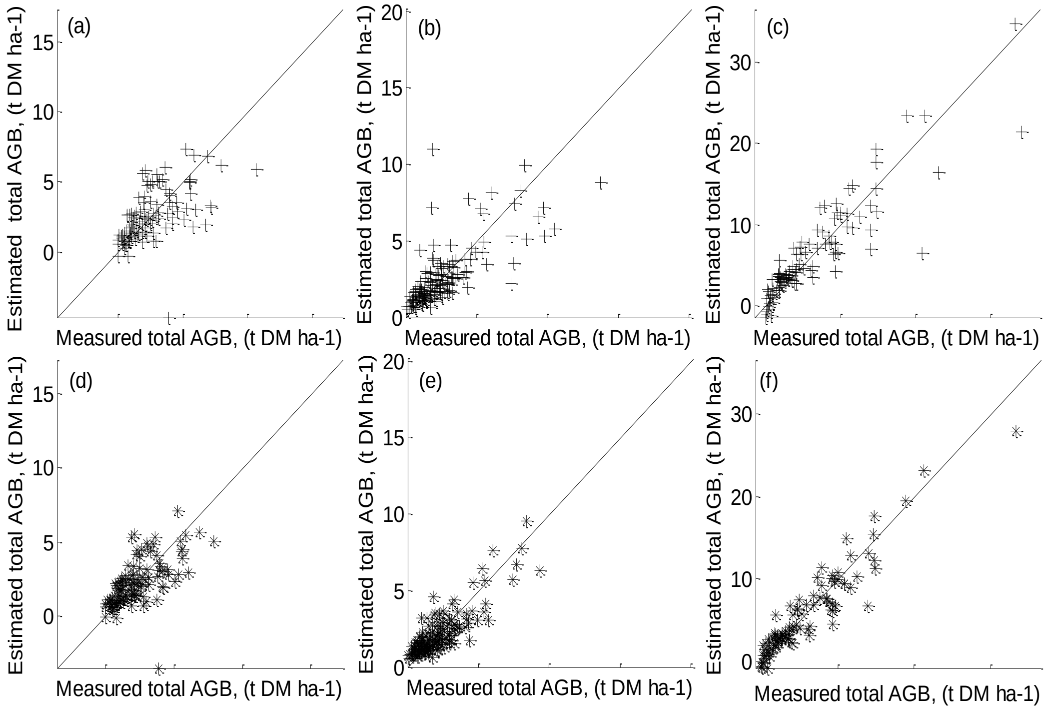

Figure 3.6: Measured total AGB (AGB: tonnes DM ha^{-1}) versus predicted total AGB for the leave-site-out validation using calibrated relationships based on datasets of (a) Open plains sites, (b) Bunch grass sites and (c) Spinifex sites including (Q^2in) and (d) Open plains sites, (e) Bunch grass sites and (f) Spinifex sites excluding (Q^2ex) outliers.

3.5.4 Predicted above ground biomass at the site scale

Predicted AGB values, derived from the calibrated equations using site mean values for indirect measurements, across sampling seasons are shown in Figure 3.7. Sites with Spinifex grass had large amounts of green AGB where variation within and between sites was very high. Site 12, dominated by *Triodia pungens* (Soft spinifex) species and site 17 had an average AGB slightly lower when compared to sites where *Triodia intermedia* (Hard spinifex) species were abundant (site 2). Predicted green AGB increased as the growing season progressed, even though grazing was occurring simultaneously, but decreased during the senescent stage. This trend was observed across all the sites, but Spinifex sites exhibited more spatial variability than Bunch grass or Open plains sites, as indicated by the large error bars.

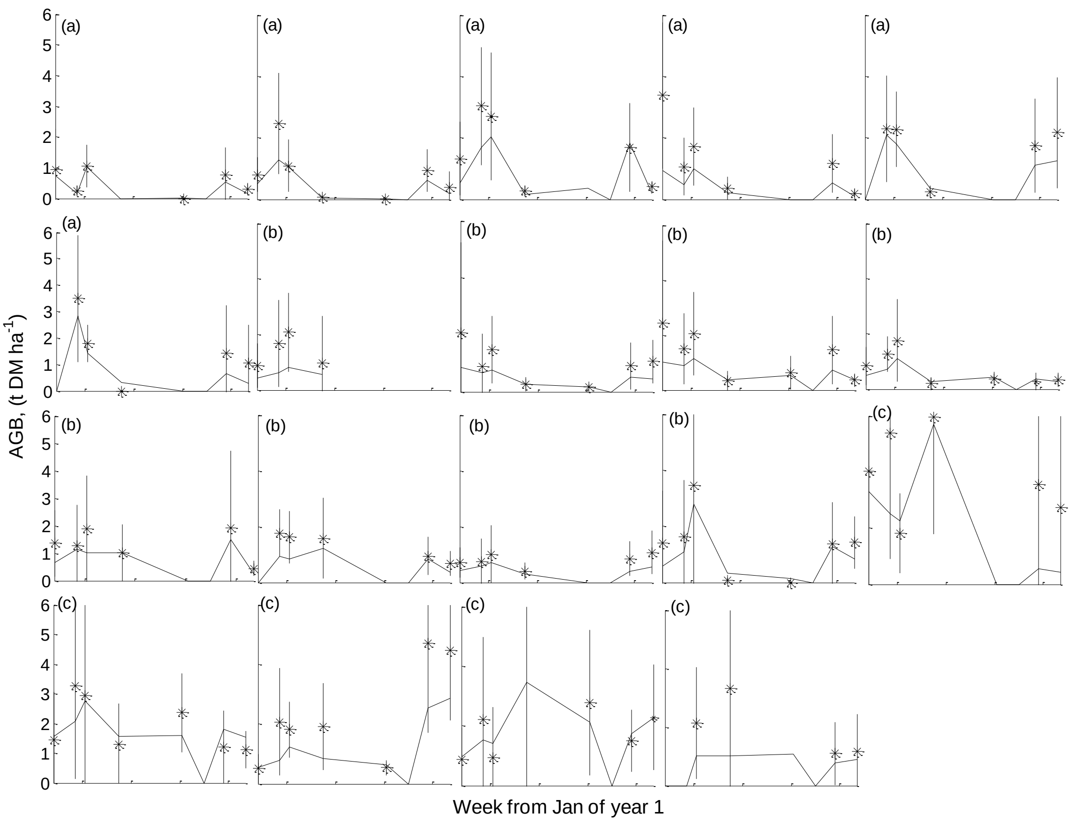

Figure 3.7: Predictions of green AGB (black line) compared with means of quadrat cuts (*) per site and Jan (January). The graphs of (a) Open plains sites in descending order refer to sites 1, 3, 10, 11, 18 and 19; (b) Bunch grass sites in descending order refer to sites 4, 5, 6, 7, 13, 14, 15 and 20; and (c) Spinifex sites in descending order refer to sites, 2, 8, 9, 12 and 17. The error bars indicate the 95% confidence interval around the mean (P<0.05, student t distribution).

3.6 Summary

Reliable field data is the foundation of any assessment in the field of remote sensing or modelling. The proposed methodology is based on upscaling destructive measurements in small quadrats by combining three indirect AGB measurement methods (active canopy sensor, a rising plate meter and VE) that can be replicated many times within a site to address the large spatial variation present. This strongly reduces the number of required cuts, especially as calibrations can be based on vegetation types with similar vegetation composition. The ability to further increase the number of indirect measurements also enables upscaling of the methodology to larger scales relevant for collection of ground data, for example, in the calibration and validation of satellite imagery. This improved data collection protocol developed in this research was necessary because of the high number of samples required, site accessibility and the high heterogeneity of the vegetation. When compared to traditional ground based data collection our technique was unique in that it could provide rapid measures of AGB in the field at a range of scales while considerably reducing sampling time. The main advantage is that field data can be collected at all times during the growing season. If PH does not work due to lodging or flooding, then VE prove useful. As previously noted, several methods exist in literature to estimate fresh and dry biomass in the field. However, none of the methods are expected to be accurate, as they are associated with a certain degree of error and may be favourable to specific situations.

4 Literature review of remote sensing approaches to above ground biomass estimation**

Plate 4: Hills close to Liveringa Station.
Photograph by Mick Schaefer (University of New England).

**Parts of this chapter have been published in the International Society for Photogrammetry and Remote Sensing (ISPRS) annals (Mundava *et al.* 2014).

4.1 Abstract

This chapter reviews the role of remote sensing in AGB estimation in rangeland environments. It focuses on static evaluation approaches versus multi-temporal approaches which are ideal for long term monitoring. The first section explores the vegetation indices that have been used in rangeland environments using higher resolution satellites. The second section reviews biophysical models which are used in Australia for AGB estimation. Some of the models are looked at in-depth including their strengths and weaknesses. The third and final section reviews the long term analysis of AGB suitable for monitoring with coarser resolution multi-temporal satellites. LiDAR another form of active remote sensing that utilises reflected radiation from the target is not discussed in the context of this thesis.

4.2 Above ground biomass estimation: A remote sensing approach

The spatial heterogeneity of rangelands pose challenges in sampling methodologies, demanding a large number of replicate measurements that are expensive and labour intensive when working on the scale of pastoral stations. Satellite remote sensing has made the acquisition of information over large extents possible and enables timely information delivery to rangeland managers. Remote sensing can be used as an aid in assessing and mapping of total standing AGB and plant growth rates in rangelands (Donald *et al.* 2010). It provides temporal and spatial information on feed resources and makes measurements at large extents possible by reducing laborious field sampling and sample processing procedures (Starks *et al.* 2006).

Remote sensing data from airborne and satellite platforms has been used with varying accuracy in mapping water stress, AGB monitoring (Cho and Skidmore 2008), mapping natural vegetation, drought monitoring as well as mineral mapping and estimation of primary productivity (Tothill *et al.* 1992; Schut *et al.* 2009). It has also been used in the derivation of biophysical and biochemical parameters based on the spectral radiance reflected by the plant canopy e.g. retrieval of chlorophyll and nitrogen content (Clevers and Kooistra 2012), Leaf Area Index (LAI) (Wylie *et al.* 2002; Zheng and Moskal 2009) and water content (Clevers *et al.* 2010).

Remote sensing based approaches are spatially explicit and dynamic, offer synoptic metrics, and are potentially transferable across regions and seasons (Reeves *et al.* 2001; Starks *et al.* 2006; Marsett *et al.* 2006). Non-destructive AGB estimation methods in combination with remote sensing data have an added advantage in that they can rapidly provide AGB estimates non-destructively on a large scale with an increased temporal frequency. AGB estimation from remote sensing is generally based on either empirical or biophysical models. Calibration and validation of empirical models involve establishing and testing of direct relationships between spectral reflectance (via vegetation indices) and observed AGB, sampled at the same scale (Tothill *et al.* 1992; López Díaz and González-Rodríguez 2003; Marsett *et al.* 2006). On the other hand, biophysical models relate spectral reflectance to light absorption i.e. fraction of Absorbed Photosythetically Active Radiation (fAPAR) (Hanan *et al.* 1998). The differences in the approaches are summarised in Table 4.1.

Table 4.1: Comparison of empirical and physical based parameter retrieval approaches using remote sensing

Empirical/Statistical approach	**Bio-physical approach**
• Parameters are related to the spectral behaviour of spectral bands	• Describes the causal physical relationship between radiation interaction and canopy properties
• Based on statistical techniques	• Based on physical laws
• Simple to implement	• Complex to implement, allocates huge computation power
• Sensor and canopy specific	• Universal, independent from sensor, canopy, and study site
• Transferability is limited, requires training on new data	

4.2.1 Empirical models

Based on the direct empirical approach, remotely sensed vegetation indices represent an integrative measure of both vegetation photosynthetic activity and canopy structural variation that is useful in monitoring, time series analysis, and change detection studies (Huete *et al.* 2002). A vegetation index's main intention is to enhance the vegetation signal while minimising solar irradiance and soil background effects (Jackson 1991). For healthy green vegetation, the selective absorption of solar radiation by the leaves and the high absorption of visible and red light rather than infrared light makes it possible to generate vegetation indices which are usually calculated as a combination of NIR and red reflectance (Figure 4.1).

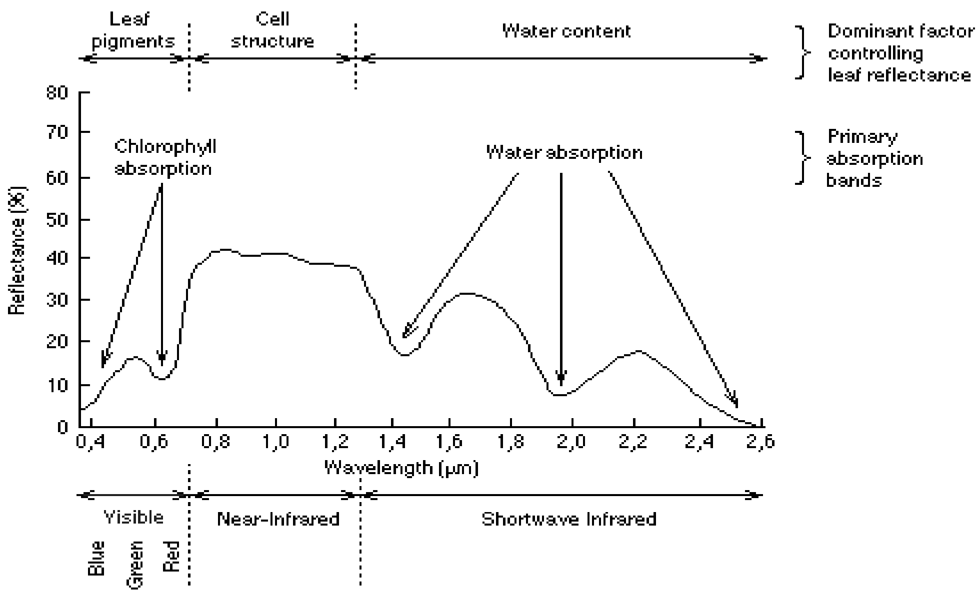

Figure 4.1: Typical spectral response characteristics of green vegetation (Hoffer 1978).

4.2.2 Biophysical models

Remote sensing based biophysical models rely on two key vegetation parameters the Absorbed Photosynthetic Active Radiation (APAR) and the efficiency of the plant to utilise the APAR for photosynthesis. Monteith and Moss (1977) proposed the Light-Use Efficiency (LUE) model (equation 2). LUE indicates the efficiency of the photosynthetic apparatus to use the fraction of APAR (fAPAR) for photosynthesis. fAPAR is the proportion of the incoming solar radiation in the photosynthetically active spectral region (400-700 nm) effectively absorbed by plants for photosynthesis. In other words, biological production is directly proportional to fAPAR (Monteith and Moss 1977). The LUE model is commonly used to estimate the Net Primary Productivity (NPP) (Wu *et al.* 2009), as they are based on the proportionality between NPP and APAR (Monteith and Moss 1977). fAPAR is then directly related to ground cover and LAI. Monteith's model can be calculated using the following equation:

$$GPP = PAR \times fAPAR \times LUE \quad \textbf{(2)}$$

where: *GPP* - the Gross Primary Production
PAR - Photosynthetic Active Radiation.
fAPAR - fraction of Absorbed Photosynthetic Active Radiation
LUE - Light-Use Efficiency

4.3 Biophysical models and above ground biomass estimation in Australia

Across Australia, deterministic plant growth models have been developed for AGB estimation. These are mainly driven by meteorological variables and are used to assess the influence of weather and climate on pasture/grass production and variability. Recent studies have shown that agro-climatic models combining descriptive or deterministic plant growth models with remote sensing are promising (Lamb 2000; Hill *et al.* 2004; Donald *et al.* 2010; Trotter *et al.* 2010; Edirisinghe *et al.* 2011; Smith *et al.* 2011; Edirisinghe *et al.* 2012). Well-known plant growth models for rangeland environments include AussieGRASS and GRASP (Carter *et al.* 2000) as well as Pastures from Space model (CSIRO 2011), the GrassGro decision support system which is a component of the GRAZPLAN (Moore *et al.* 1997), the GROWEST model and the Agricultural Production Systems Simulator (APSIM). Some of the models that are available for use in Australia are summarised in the next section.

4.3.1 GROWEST

The GROWEST plant growth index simulation model (Fitzpatrick and Nix 1970) is a simple model that combines climate and plant growth. The GROWEST model calculates three primary output indices that characterise relative plant growth in response to light, temperature and soil moisture. These indices are combined to generate a fourth index, the growth index (*GI*), which is the product of the light (*LI*), moisture (*MI*) and temperature (*TI*) indices (Fitzpatrick and Nix 1970). The values of all of these indices vary between zero and one. The GROWEST PLUS is a modification developed by Laughlin *et al* (2007).

4.3.2 AussieGRASS

AussieGRASS (Carter *et al.* 2000) is a simulation model that was developed to monitor historical grass production and land cover in all Australian regions. As the model can be used nationally, it can therefore provide alerts, as well as providing an equitable and objective assessment of pasture status in different Australian regions. The model has been validated for major pasture communities and operates on both a regional and national scale. Principal input to the AussieGRASS model are past daily rainfall, historical climatic data, soil type, tree density, stocking rate and seasonal climate forecasts (Carter *et al.* 2000). A central feature of the model is the GRASP pasture production model. AussieGRASS is, essentially, a spatial implementation of the GRASP model. Within the AussieGRASS framework, GRASP is run daily on a 5 km x 5 km grid.

4.3.3 GRASP

GRASP (McKeon *et al.* 2000) is a dynamic, deterministic, point-based model that simulates soil moisture, pasture growth and animal production from daily inputs of rainfall, temperature, humidity, pan evaporation and solar radiation (Pahl *et al*. 2011). GRASP is therefore the pasture growth model within AussieGRASS. The GRASP model is reliant on data collected in the semi-arid Northern Territory state but has not been calibrated for the Kimberley area.

4.3.4 GRAZPLAN

The GRAZPLAN decision support project for temperate Australian grazing lands (Moore *et al.* 1997; Donnelly *et al.* 2002) is a suite of models, which include the pasture growth model GrassGro. GrassGro, requires multiple parameters related to pasture species phenology, soil characteristics and animal physiology (Moore *et al.* 1997). GrassGro is a discrete computer package, developed for Microsoft Windows™ which combines the pasture growth module with a module for predicting the intake of herbage of ruminants and their productivity. It can be used to examine the effects of farm profitability, climatic variability and management.

4.3.5 APSIM

APSIM (McCown *et al.* 1996) is a crop production model that requires detailed descriptions of soil and crop data. The initial stimulus to develop APSIM came from a perceived need for modelling tools that provided accurate predictions of crop production in relation to climate, genotype, soil and management factors, whilst addressing long-term resource management issues in farming systems (Keating *et al.* 2003). This model is more focused on crop production.

4.3.6 Pastures from Space

The Commonwealth Scientific and Industrial Research Organisation's (CSIRO) Pastures from Space (PFS) project provides information at whole farm and/or paddock basis but has been focused primarily on the Mediterranean and temperate zones (CSIRO 2011). PFS provides estimates of pasture growth rate (PGR) and Food On Offer (FOO) for south-west Western Australia and selected parts of south eastern Australia. The PGR tool provides quantitative estimates of PGR as kg/ha/day (CSIRO 2011). The PFS model uses the GROWEST and a LUE model.

4.3.7 Summary

Standing AGB cannot be measured at all times of the year as satellite signals respond weakly to dead plant components making deterministic models ideal. However, little information is available for the northern parts of WA as most available models have not been applied and no similar studies have been conducted for this complex environment. Some of the tools that have been developed for the Kimberley area, for example the Grazing Land Management tools may provide estimates for selected Kimberley pasture types. At the moment, the GRASP model (Rickert *et al.* 2000) is reliant on data collected in the Northern Territory but has not been calibrated for the Kimberley area. The CSIRO Pastures from Space (PFS) project provides information at whole farm and/or paddock basis but has been focused primarily on the Mediterranean and temperate zones. The GrassGro decision support system, a component of the GRAZPLAN as previously discussed can be used to examine the effects of farm profitability, climatic variability and management decisions is developed for temperate Australian grazing lands only (Moore *et al.* 1997).

A disadvantage is that deterministic plant growth models include processes that require extensive parameter calibration and are complex to implement. Collection of the necessary ground data for model calibration and validation given the spatial variability of rangelands while including dynamics such as fire regimes and seasonal variation is a major challenge. At the same time, the natural rangeland environment is very heterogeneous and complex with large variation in the grazing intensity, vegetation cover, soil types and presence of native vegetation. Little is known on the feasibility of these models for AGB estimation in the tropical rangelands of WA as models have many assumptions based local conditions which might confound the model accuracy and reliability.

4. 4 The use of spectral reflectance indices to determine above ground biomass

Remote sensing derived ratio-based vegetation indices have been in use for a long time in AGB estimation (Lu 2006). Vegetation indices can be calculated by transforming (tasselled cap and perpendicular indices.), rationing (e.g. simple ratio vegetation index), differencing (e.g. difference vegetation index), adding (e.g. Land Monitor and Green+Red indices) and forming linear combinations of spectral band data (Huete and Jackson 1987; Jackson 1991; Silleos *et al.* 2006; Chen and Gillieson 2009; Viña *et al.* 2011). The visible wavelengths of the eletro-magnetic spectrum (VIS) reflection most strongly responds to the visible amount of chlorophyll/m, whereas the near-infrared (NIR) responds to the total number of water to air transitions/m^2 as typically found in healthy leaves. As a result, vegetation indices respond to chlorophyll content, the fraction of ground covered with healthy leaves (*GC*), the density of leaves (*LAI*) and the orientation and distribution of leaves (*LAD*). Therefore, vegetation indices are not directly related to AGB but are correlated with biophysical parameters. These can be used to estimate the primary productivity such as Leaf Area Index (*LAI*) (defined as the one-sided green leaf area per unit ground surface area), fraction of intercepted radiation and leaf chlorophyll concentration.

4.4.1 Mono-temporal models

The most widely used indices include various ratios of the NIR and red wavebands such as NDVI (Tucker *et al.* 1983), Normalised Difference Weighted Index (NDWI) (Gao 1996), Weighted Difference Vegetation Index (WDVI), (Zhou *et al.* 1998) and the Soil Adjusted Vegetation Index (SAVI) (Whitney 1974). The most widely applied index in AGB estimation has been the NDVI (Anderson *et al.* 1993; Todd *et al.* 1998). Although the NDVI has been useful in many studies, it has clear limitations. It is most sensitive to ground coverage with chlorophyll containing leaves (Purevdorj *et al.* 1998) as present in the vegetative growth phase (Donald *et al.* 2010), but the response saturates before the ground is completely covered, typically at a LAI of 2 to 3 (Baret and Guyot 1991).

Previous studies have identified strong relationships between vegetation indices and AGB for grassland ecosystems (Wylie *et al.* 2002). For instance, Dancy *et al* (1986) reported an R^2 of 0.72 when deriving ground cover in Botswana rangelands and Beeri *et al* (2007) reported a prediction error of 18% for total AGB in moderately grazed pastures due to overestimation by NDVI. However, Beck *et al* (1990) found no correlation between green or total AGB and ground derived NDVI. The most probable reason was the spatially-variable soil background and the contribution of senescent material.

In the Australian context, relationships between AGB and vegetation indices have been successfully developed for the Mediterranean and temperate zones (Donald *et al*. 2010). However, little information is available for the north western tropical zone as many vegetation indices have not been extensively tested. Commonly used indices are not suitable as rangelands are dominated by perennial vegetation which does not have a strong response in the NIR region (Jafari *et al.* 2007) but only responds to the green component (O'Neill 1996). Pixel heterogeneity poses a problem as pixels may encompass green and senescent vegetation including soil. Todd *et al* (1998) pointed out that soil-vegetation spectral mixing distorts AGB estimation in semi-arid environments. Senescent material can have a profound effect on the net spectral response of plant canopies (Todd *et al.* 1998). There is need for novel AGB estimation approaches with higher accuracy levels.

Red soils characterising the Australian rangelands have a great influence on the red reflectance. Indices that incorporate a soil background adjustment factor (Ahamed *et al.* 2011) enhancing the vegetation signals over high AGB areas while reducing atmospheric influences (López Díaz and González-Rodríguez 2003) are worth considering. Examples of soil adjusted indices include SAVI (Huete 1988), and Soil Adjusted Total Vegetation Index (SATVI) (Marsett *et al.* 2006). Stress related indices have also been found to be good predictors of ground cover. O' Neill (1996) working in semi-arid shrub land in western New South Wales (Australia) found that the stress related vegetation indices are strongly related to total vegetation cover in both summer and winter. In the southern rangelands of South Australia Jafari *et al* (2007) reported that stress related indices 1 and 4 (STVI-1, 4) were good predictors of perennial vegetation and of total ground cover at the landscape scale. This implies that both near and middle infrared wavelengths are useful in monitoring vegetation in semi-arid environments.

In summary, relationships between vegetation indices and AGB are often species and location specific (Eisfelder *et al.* 2011), hence difficult to infer to different site locations than where they were developed and perform poorly in different biomes and climatic conditions (Schut *et al.* 2009). Commonly used indices are not suitable as rangelands are dominated by perennial vegetation which does not have a strong response in the NIR region (Jafari *et al.* 2007). As a result, vegetation indices need to be extensively tested to evaluate their effectiveness and applicability in this particular rangeland environment. Robinson *et al* (2012) have tested some vegetation indices in this region for their potential to discriminate between “poor” and “good” range condition. The indices evaluated in the work are based on his findings in the “Pastoral Lease Assessment using Geospatial Analysis project” (Table 4.2). Limited research has been done on estimating AGB using high spatial resolution satellites in North Western WA. As a result all the indices will be evaluated for Liveringa Station.

Table 4.2: Vegetation indices to be tested (adopted from the Pastoral Lease Analysis using Geospatial Analysis (PLAGA) from (Robinson *et al.* 2012).

Vegetation Index	Example studies	Equation[1,2]
Normalised Difference Vegetation Index (NDVI)	Tucker *et al* (1983)	(B2-B1)/(B2+B1)/
Soil Adjusted Vegetation Index (SAVI)	Washington-Allen *et al* (2006)	(B2-B1)/(B2+B1+Lx(1+L)
Soil Adjusted Total Vegetation Index (SATVI)	Marsett *et al* (2006)	(B6-B1)/(B6+B1+L)x(1+L))-(B7x0.5)
Land Monitor	Curry *et al* (2008)	B3+B5
Normalised Difference Senescent Vegetation Index (NDSVI)	Dean (2005)	(B6-B1)/(B6+B1)/
Stress-related Vegetation Index (STVI1)	O'Neill (1996) Jafari *et al* (2007)	(B6XB1)/B2
Stress-related Vegetation Index (STVI3)	O'Neill (1996) Jafari *et al* (2007)	B2/(B6+B3)
Green +Red	Wallace and Thomas (1998)	B4+B1

1: B- Band
2: L-Soil Adjustment factor

4.4.2 Multi-temporal models

With rapid developments in the field of remote sensing and ease of access to satellite data, a lot of effort has gone into developing AGB monitoring tools from paddock to landscape scale. At the landscape level different satellite data sources have been used in the derivation of AGB estimates in past research, AVHRR (Hill *et al.* 2004), Landsat (Sharrow 1984; 't Mannetje 2003), SPOT-VEGETATION and MODIS (Gerber 2000; Cho and Skidmore 2008). In rangeland conditions, the presence of native/non-grazable vegetation can affect remotely sensed signals and as such distort AGB estimation. Empirically derived AGB estimates are strongly affected by vegetation spectral properties, pixel heterogeneity, background reflectance, solar zenith and view zenith angle, vegetation shadow fractions, atmospheric scattering and BRDF effects (López Díaz and González-Rodríguez 2003). They are always soil type and vegetation type specific due to the sensitivity for ground cover especially bare soil (Gao *et al.* 2000), leaf angle distribution, leaf area index (Gao *et al.* 2000; Pettorelli *et al.* 2005) and the ratio between dead and green components.

AGB estimation at rangeland scale is practically impossible with daily visits and keeping track of plant growth realised in the previous season can give an indication of available AGB. As a result multi-temporal models may be able to take into account the AGB growth of the previous seasons. Multi-temporal imagery provides information about phenology and can be used to e.g. evaluate fire frequency, vegetation monitoring etc (Hill *et al.* 2004, Tuanmu *et al.* 2010; Schmidt *et al.* 2012). Phenological development gives an indication of changes in seasonal dynamics over time (Reed *et al.* 1994; Hill and Donald 2003; Fensholt *et al.* 2009; Yin *et al.* 2012; Horion *et al.* 2014). In Australia, time series of vegetation indices has been used in understanding land cover and condition monitoring over time (Pickup *et al.* 1994; Caccetta *et al.* 2000; Hill and Donald 2003; Wallace *et al.* 2006). It provides information about the timing and length of the season and the total productivity within the growing period. The amplitude of the seasonal signal may provide an approximation of landscape greening and indicate the maximum amount of AGB accumulation (Hill *et al.* 2004). Combining phenological information with vegetation indices may provide means to more accurately estimate AGB (Zhu and Liu 2014).

AGB accumulation is a cumulative function of the net production over time and can be linked to the total amount of APAR from the start of season which can be linked to accumulated NDVI (le Maire *et al.* 2011). As a result, satellite based NDVI can provide an objective assessment and multi-temporal NDVI models may be able to take into account the AGB growth of previous seasons. Multi-temporal analysis is only useful when done for low resolution imagery (MODIS/AVHRR) with high temporal resolution. However, when focusing on standing material using a single date image, higher spatial and temporal resolution imagery may be more useful e.g. RapidEye and DigitalGlobe satellites.

As previously mentioned medium spatial resolution sensors like MERIS and the Advanced Very High Resolution Radiometer (AVHRR) are suitable for vegetation monitoring. However, satellite data are notoriously noisy due to the disturbing effects of the atmosphere. The noise distorts the subsequent interpretation and calibration of derived vegetation indices. MODIS data are noisy on pixel level, mainly due to atmospheric disturbances and maximum value compositing over e.g. a period two weeks. Noise may be reduced by filtering in the spatial or temporal domain with filter kernels or curve-fitting procedures. The latter has the advantage that interpolations are possible, providing the best estimate for a sampling date in-between composite periods. Noise smoothing algorithms which have been used in literature include Savitsky-Golay, Gaussian and Logistic algorithms from TIMESAT software (Jönsson and Eklundh 2004; Heumann *et al.* 2007; Tuanmu *et al*. 2010; Tan *et al*. 2011; Palacios-Orueta *et al.* 2012; Gao *et al.* 2013), PHENOLO (Ivits *et al.* 2009), TIMESTAT (Udelhoven 2011) and threshold based fourier fitting (Cihlar 1996).

4. 5 **Summary**

As noted in this chapter, over large areas the most feasible and practical way to measure biomass is through remote sensing. However, direct empirical relationships of biomass with vegetation indices are difficult to transfer to new areas. As a result there is a need to evaluate which vegetation indices work in this environment. The following chapter will explore and verify the use of vegetation indices derived from remote sensing data (Landsat) as well as elevation and rainfall data for the estimation of AGB in the Kimberley region of WA.

5 Vegetation indices for above ground biomass estimation[††]

Plate 5: Fitzroy River Barrage at Liveringa Station, the source of irrigation water.
Photograph by Waqar Ahmad (CSIRO).

[††] Parts of this chapter have been published in the International Society for Photogrammetry and Remote Sensing (ISPRS) annals (Mundava *et al.* 2014).

5.1 Abstract

The objective of this chapter is to test relationships between green and total AGB and remotely sensed vegetation indices. Single and multiple regression relationships were calibrated and validated using a "leave site out" cross validation. The sites were divided into three groups (Open plains, Bunch grass and Spinifex) based on similarities in dominant vegetation types. Four tests were compared and results indicate that relationships based on single vegetation indices are moderately accurate for green AGB in wide Open plains covered with annual grasses. The cross-validation results for green AGB improved for a combination of indices for the Open plains and Bunch grass sites, but not for Spinifex sites. When rainfall and elevation data are included, cross validation improved slightly with a Q^2 of 0.49-0.72 for Open plains and Bunch grass sites respectively.

5.2 Dataset

The dataset include field collected data used as reference data (Chapter 3), remotely sensed data and additional data which comprised of a Digital Elevation Model (DEM) and rainfall data. Remotely sensed data was obtained from the Landsat ETM+ (http://earthexplorer.usgs.gov/). For the Landsat 7 ETM+ imagery, atmospheric correction with an estimate of transmissivity was performed using the Landsat calibration module in the Environment for Visualizing Images (ENVI) software (version 5.0, 2013). The ETM+ comprises 8 bands with a spectral range varying from 0.45 – 12.5 µm; the spatial resolution at nadir is 30 m. The swath is 183 km x 170 km with a temporal resolution of 16 days. The sampling dates and corresponding images used in this analysis are shown in Table 5.1. Some of the Landsat pass dates fall just before and after sampling because of unavailability of images due to presence of cloud and the satellite revisit time.

Table 5.1: Sampling dates and Landsat passes dates as used in the analysis *72/73 refers to the Landsat 7 ETM+ rows.

Sampling Date	Year	% Cloud *72	% Cloud *73	Landsat 7 pass
11-18 December	2011	0	6	23 December
18-25 February	2012	7	6	25 February
19-26 March	2012	0	3	29 March
16-23 June	2012	8	0	16 June
30 November - 7 December	2012	1	0	10 December
15-22 February	2013	3	0	9 February
12-19 April	2013	0	0	13 April
15-22 June	2013	0	-	2 June

The Landsat 7 ETM+ has a Scan Line Corrector (SLC) failure, which causes some areas to be imaged twice while no data is recorded for others (Figure 5.1). The SLC error affected 13 sites over the two seasons. If a site was affected, bilinear interpolation was used to approximate the required image information from adjacent pixels. If all adjacent pixels around the site had no data, the particular site was excluded from the evaluation process. The Landsat 7 ETM+ path 109 and rows 72 and 73 covered the study area. Daily gridded total rainfall (mm) data corresponded to the sampling dates and was obtained from the Australian Bureau of Meteorology website (http://www.bom.gov.au/). The spatial resolution of the grids was 5 km x 5 km. The positional accuracy of the observational stations on which the grids are based was approximately 1 km. In addition, elevation readings were obtained from the DEM provided by Geoscience Australia (refer to section 2.7).

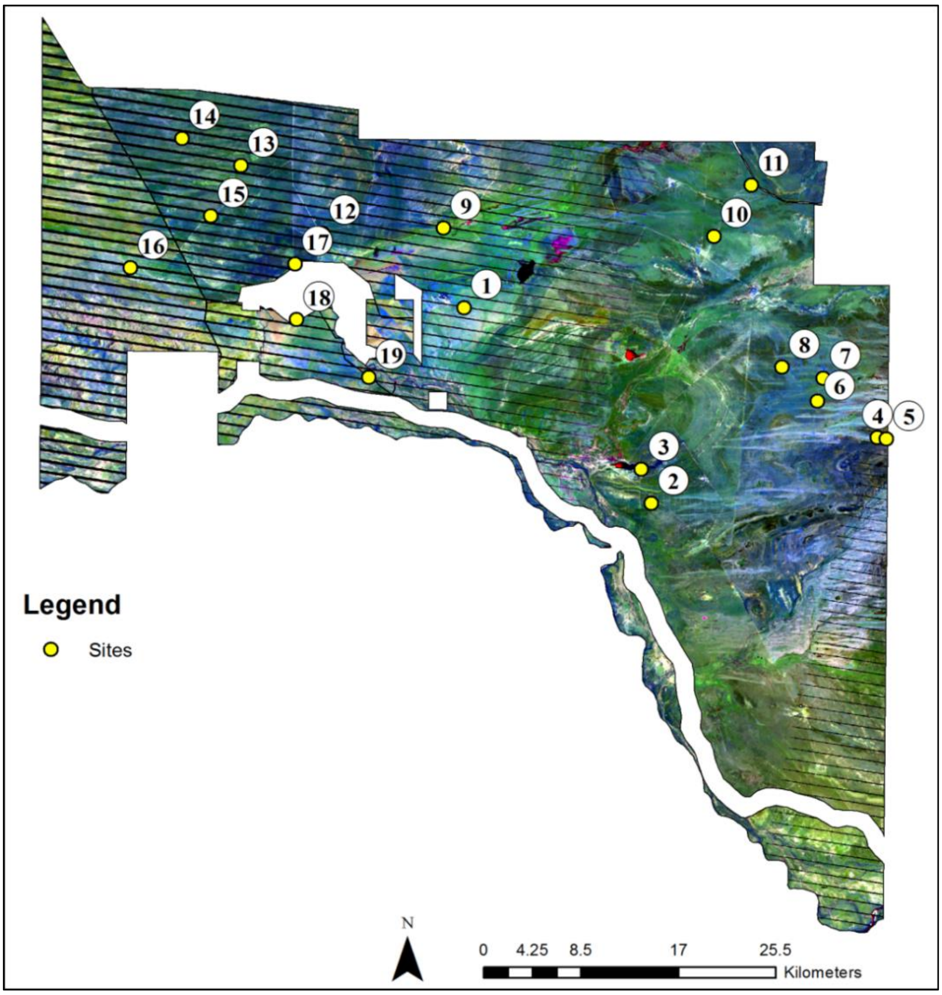

Figure 5.1: Landsat ETM+ false colour image including an RGB combination of bands 6, 5 and 4 with site locations at Liveringa Station for 23 December 2011.

5. 3 Methods

All the vegetation indices (Table 4.2) were derived from eight Landsat ETM+ scenes, covering wet and dry seasons using ESRI ArcMap software model builder tool (version 10.2). In order to match the image pixels to the size of the ground represented in the sample sites, vegetation indices' values were bi-linearly interpolated from adjacent cells with valid values using a weighted distance method under the assumption of linearity. This step was required because the study sites covered a circular area with a 50 m radius, equivalent to four Landsat pixels. In order to test the robustness of the relationships between AGB and the vegetation indices four tests were compared: 1) relationships between AGB and vegetation indices combining all sites; 2) separate relationships per site group; 3) multiple regressions including selected vegetation indices per site group and 4) same as 3 but including rainfall and elevation data. The details of the tests are given in-depth in the following sub-sections:

Bivariate regression (Test 1)

Separate linear regression models were developed for each vegetation index and total or green AGB measured at all sites. The independent variables were the derived vegetation indices while the dependent variables were the total or green AGB. The coefficient of determination R^2 was used to test the robustness of the model.

Bivariate regression by vegetation type (Test 2)

Sampling sites were further merged into three main groups according to the vegetation types defined previously (Table 3.4); Open plains (6 sites), Bunch grass (8 sites) and Spinifex (5 sites). The relationships between the site groups and single vegetation indices were established using bivariate regression relationships.

Multiple regression (Test 3)

In this test, relationships for a combination of indices for each site group versus the measured green and total AGB were evaluated using a multiple regression model. The dependent variables were green and total AGB and the independent variables considered were all the vegetation indices derived from the Landsat ETM+ data.

Multiple regression with environmental variables (Test 4)

The fourth test is similar to the third test but elevation and rainfall are included as additional independent variables in the multiple regression model.

Validation

Single and multiple regression relationships between vegetation indices and green and total AGB were calibrated and validated using a 'Leave-Site-Out' (LSO) cross-validation approach. All the tests are summarised in Table 5.2. The left column represents the test number, the middle column the test configuration and the right column, the number of data samples available for each test.

Table 5.2: Overview of the processed tests where O=Open plains, B=Bunch grass and S=Spinifex. Sampling was done 8 times during the data collection.

Test no.	Name	Number of data samples
1	Single vegetation indices for 19 sites in a simple linear regression model	152
2	Single vegetation indices for three site groups in a simple linear regression model	O=48, B=64, S=40
3	Combined vegetation indices for three site groups in a multiple regression model	O=48, B=64,S=40
4	Combined vegetation indices and additional data for three sites groups in multiple regression model	O=48, B=64, S=40

5. 4 **Results**

5.4.1 Bivariate regression

In the first test, when all sites were included, relationships between total or green AGB and selected vegetation indices resulted in consistently weak relationships with R^2 values below 0.2. The results of the correlations are summarised in Table 5.3 and in Figure 5.2 for total AGB and Figure 5.3 for green AGB. Figure 5.3 and 5.4 represent the following vegetation indices: (a) NIR, (b) Green+ Red, (c) STVI3, (d) STVI1, (e) NDSVI, (f) SAVI, (g) NDVI and (h) Land Monitor. Relationships remained far below the defined threshold of 0.5 and were therefore not useful in the assessment of AGB when all the sites were combined together.

Table 5.3: Regression results (R^2) for green and total AGB with vegetation indices. *RMSE indicates the Root Mean Square Error

Vegetation Index	Total AGB		Green AGB	
	R^2	RMSE	R^2	RMSE
NIR	0.00	0.21	0.00	0.21
Green + Red	0.00	0.04	0.00	0.04
STVI3	0.00	0.13	0.16	0.12
STVI1	0.00	0.05	0.15	0.05
NDSVI	0.00	0.04	0.00	0.04
SAVI	0.00	0.05	0.10	0.05
NDVI	0.00	0.09	0.13	0.08
Land Monitor	0.00	0.07	0.15	0.07

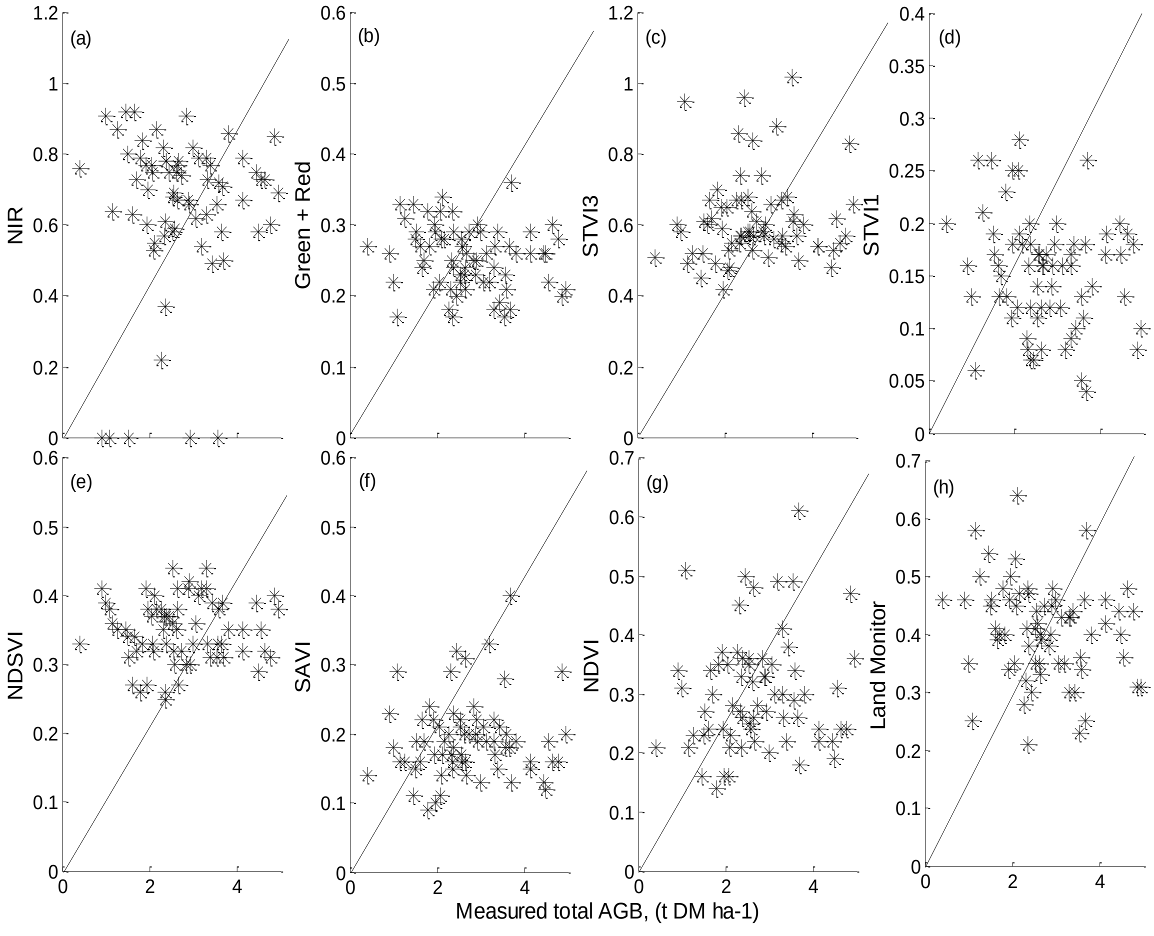

Figure 5.2: Measured total AGB values (X-axes) versus estimated total AGB (Y-axes) for 8 vegetation indices.

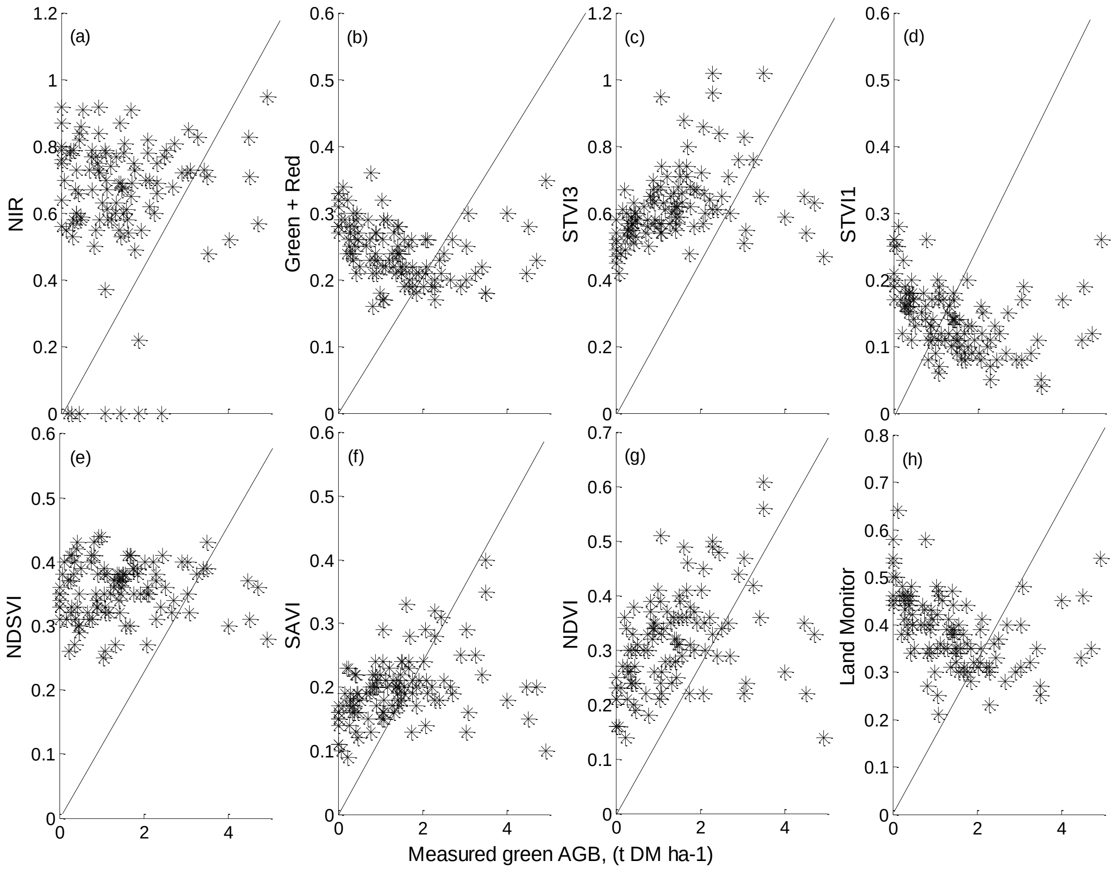

Figure 5.3: Measured green AGB values (X-axes) versus estimated total AGB (Y-axes) for 8 vegetation indices.

5.4.2 Bivariate regression by vegetation type

When sites were grouped according to vegetation types in test 2, relationships did not improve for total AGB as indicated by a maximum R^2 value of 0.3 for some indices for Open plains and Bunch grass vegetation groups (Table 5.4). The relationships between Spinifex and total AGB were non-existent with R^2 values of below 0.2 for all vegetation indices. However, there was an improvement in correlation with green AGB for Open plains, with R^2 values of between 0.4 and 0.6, occasionally achieving the required threshold value of 0.5. For Open plains, green AGB had a moderate correlation with the vegetation indices STVI1, SAVI and NDVI with an R^2 of 0.6 and 0.5 for the Land Monitor. Bunch grass had a low correlation with green AGB for all the vegetation indices with R^2 values ranging from 0.0-0.4. Similar results were obtained for Spinifex (R^2 values between 0.0-0.2) for green AGB. The correlation of the indices with total AGB was low for all sites with R^2 values of between 0.0 and 0.3. Figure 5.4 and Figure 5.5 show the scatter plots of the vegetation groups versus the measured total and green AGB. Figure 5.4 and 5.5 represented the following vegetation indices: (a) NIR, (b) Green+ Red, (c) STVI3, (d) STVI1, (e) NDSVI, (f) SAVI, (g) NDVI and (h) Land Monitor.

Table 5.4: Coefficients of determination for vegetation indices with green and total AGB where O=Open plains, B= Bunch grass and S= Spinifex. Values equal or above 0.5 are highlighted (Test 2).

Index	Total AGB R^2			Green AGB R^2		
	O	**B**	**S**	**O**	**B**	**S**
Green + Red	0.3	0.3	0.2	0.4	0.4	0.1
STVI3	0.2	0.2	0.0	0.4	0.4	0.0
STVI1	0.3	0.3	0.2	**0.6**	0.4	0.0
NDSVI	0.0	0.2	0.2	0.0	0.2	0.0
SAVI	0.3	0.2	0.1	**0.6**	0.4	0.0
NDVI	0.3	0.2	0.1	**0.6**	0.4	0.1
Land Monitor	0.3	0.3	0.2	**0.5**	0.4	0.1
Red	0.0	0.0	0.0	0.0	0.0	0.0

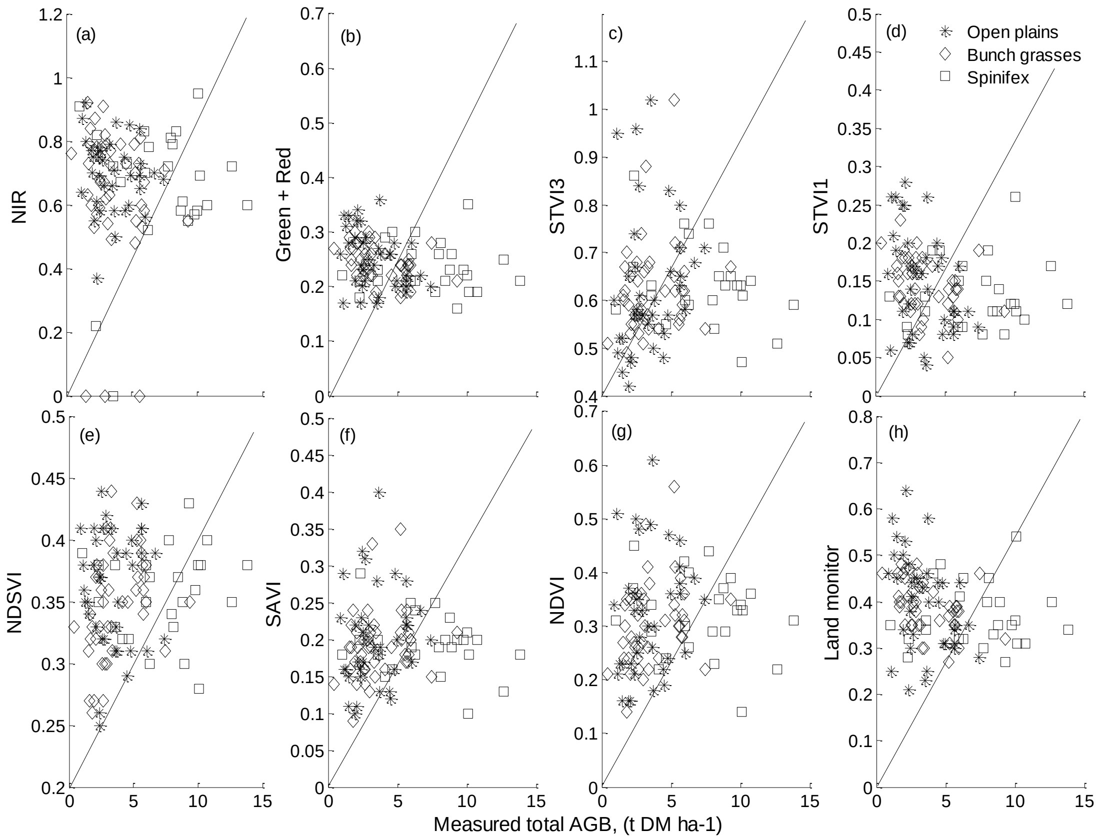

Figure 5.4: Measured total AGB values (X-axes) versus estimated total AGB (Y-axes) for 8 vegetation indices (Test 2).

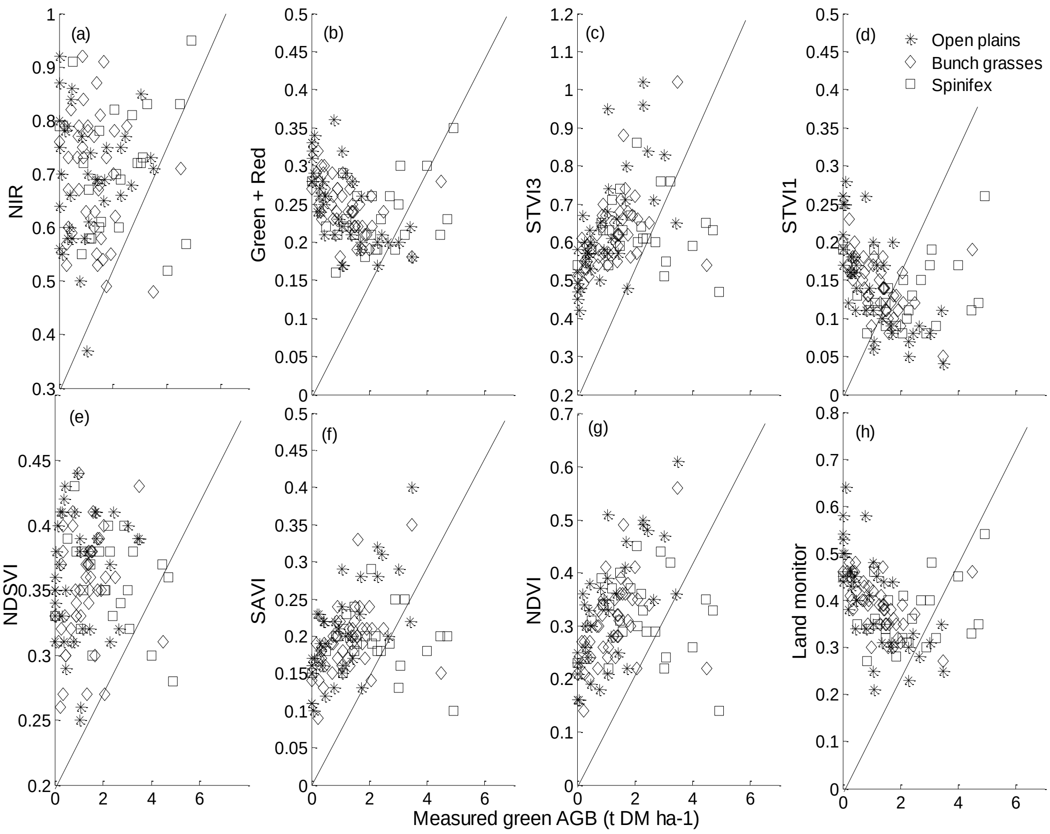

Figure 5.5: Measured green AGB values (X-axes) versus estimated total AGB (Y-axes) for 8 vegetation indices (Test 2).

5.4.3 Multiple regression

When all indices were combined together in a multiple regression model in test 3, there was no correlation found for total AGB (Table 5.5-top left). The adjusted coefficient of determination is a statistical measure that shows the amount of variation explained by the predicted regression line. The adjusted coefficient of determination (R^2_{adj}) was 0.26 for Open plains, 0.33 for Bunch grass and 0.39 for Spinifex. For green AGB, the calibration of the multiple regression model indicated better fits than the simple linear regression model with an adjusted coefficient of determination (R^2_{adj}) of 0.60 for Open plains, 0.56 for Bunch grass (Figure 5.6). The most significant term for the Open plains was STVI3 while for Bunch grass it was STVI1. However, the validation for total AGB was poor with Q^2 values of -0.05 for Open plains, -0.09 for Bunch grass and -1.74 for Spinifex. For green AGB, Open plains and Bunch grass had LSO-Q^2 values of 0.53 and 0.42. Spinifex had poor Q^2 values at -0.22.

Table 5.5: Adjusted R^2 and 'Leave Site Out' Q^2 values for the multiple regression Test 3 and Test 4.

Site	Total AGB		Green AGB	
	R^2Adj.	**LSO Q^2**	**R^2Adj.**	**LSO Q^2**
		Test 3		
Open plains	0.26	-0.05	**0.60**	**0.53**
Bunch grass	0.33	-0.09	**0.56**	0.42
Spinifex	0.39	-1.74	0.19	-0.22
		Test 4		
Open plains	**0.58**	0.41	**0.78**	**0.72**
Bunch grass	0.37	0.17	**0.57**	0.49
Spinifex	0.40	-1.14	0.44	-0.21

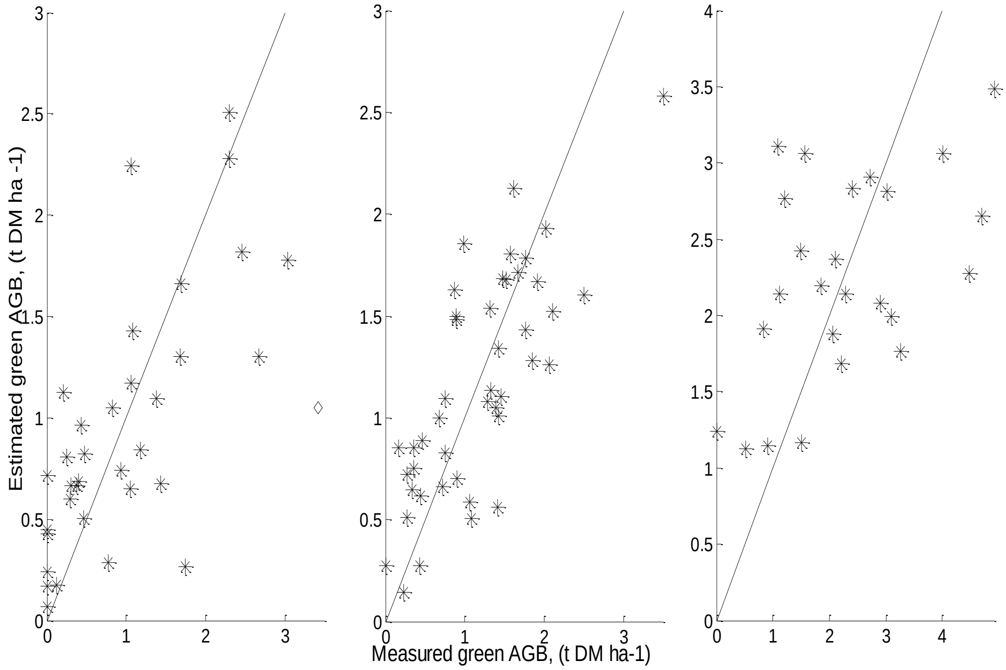

Figure 5.6: Measured green AGB values (X-axes) for the three vegetation types at sites - (a) Open plains sites, (b) Bunch grass sites and (c) Spinifex sites, versus estimated total AGB (Y-axes) obtained from calibrated multiple regression models. The adjusted R^2 indicates the explained variation for relationships excluding the identified outliers, (◊) represents outliers outside the 95% confidence interval (Test 3).

5.4.4 Multiple regression with environmental variables

When elevation and rainfall information are added to the analysis in test 4, results slightly improved (Table 5.5-bottom) for total AGB for Open plains 0.58 (instead of 0.26). However, the Bunch grass and Spinifex values still fell below the defined threshold at 0.37 and 0.40 respectively. For green AGB, the Open plains improved from 0.60 to 0.78 (Figure 5.7) while for Bunch grass and Spinifex there was only a slight improvement. Open plains are located in areas of high groundwater tables hence would have higher rates of greening. For all the site groups, the most significant terms are the plant water sensitive indices in combination with rainfall and elevation. The validation for total AGB had Q^2 values of 0.41 for Open plains, 0.17 for Bunch grass and -1.14 for Spinifex. For green AGB, Open plains and Bunch grass had LSO-Q^2 values of 0.72 and 0.49. Spinifex had very low Q^2 values at -0.21. The cross validation results for this test were comparable to test 3 with significant improvement for Open plains. This indicates that this more complex model did not significantly improve results for Bunch grass and Spinifex.

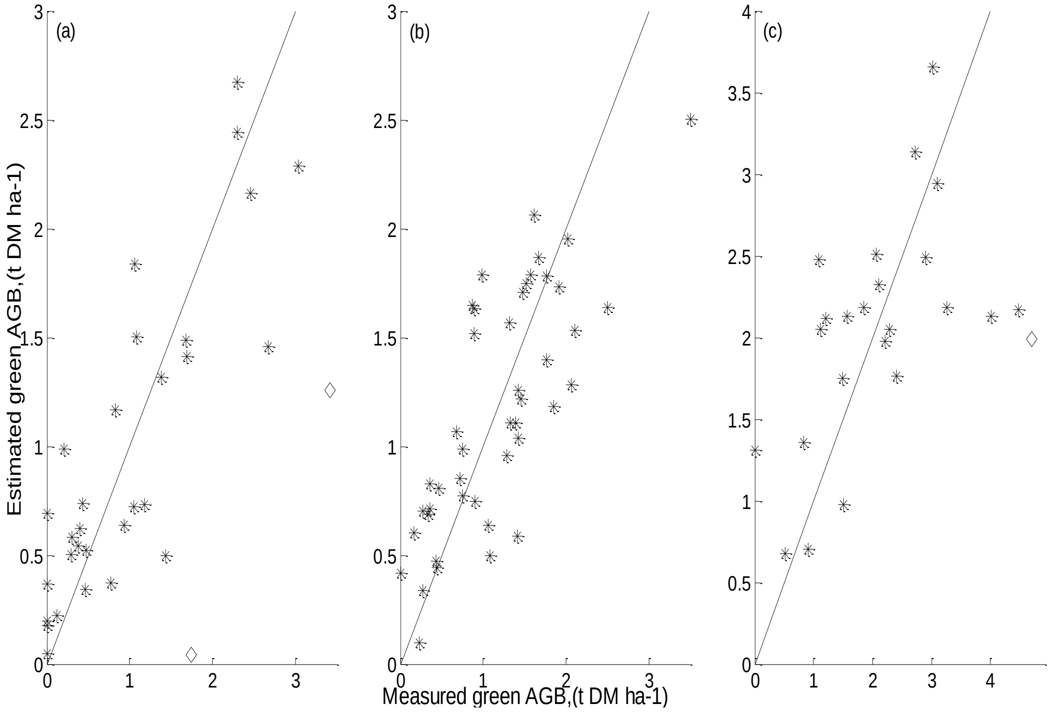

Figure 5.7: Measured green AGB values (X-axes) for the three vegetation types at sites - (a) Open plains sites, (b) Bunch grass sites and (c) Spinifex sites, versus estimated total AGB (Y-axes) obtained from calibrated multiple regression models including elevation and rainfall. The adjusted R^2 indicates the explained variation for relationships excluding the identified outliers, (◊) represents outliers outside the 95% confidence interval (Test 4).

5.5 Summary

In comparing vegetation indices derived from Landsat ETM+ imagery and AGB, in heterogeneous rangeland environments in the Kimberley region of WA, there was low correlation between vegetation indices and green or total AGB when combining all sites and samples in one single relationship. This could indicate that vegetation indices have a temporal effect and may work for some stages in the growing season; as a result combining all sites and all sampling times produced non-robust relationships. This could also be an indication of strong spatial heterogeneity within the sampled sites. However, results improved for green AGB when sites were grouped in terms of similar botanical composition, i.e. Open plains, Bunch grass and Spinifex in a multiple regression model, but not for total AGB. Open plains had a correlation of 0.60 while Bunch grass had 0.56. Spinifex, which is predominantly perennial, had a very low correlation of 0.19 for green AGB. When using the multiple regression approach, calibration results slightly improved for Open plains green AGB to 0.78 and validation results to 0.72 when elevation and rainfall information is added to the model. However, validation results did not improve for Bunch grass and Spinifex. Again, for total AGB models no robust estimates could be made when validated using the leave site out validation (Q^2 values ranged from -1.14 to 0.41).

A combination of vegetation indices provided robust estimates for green AGB Open plains and Bunch grass groups; for total AGB only the Open plains group showed robust estimates. The introduction of environmental information did not further improve validation results. Again, spatial scale could explain the non-correlation with AGB as the sampled areas were quite diverse in terms of vegetation composition. In future studies, stratification based on land units may give favourable results. There were also some strong correlations observed when groups were split on a sampling date basis, but when using only one season data the numbers of points are statistically low. Increasing the size of the sites to match the size of the satellite pixels in future can help in capturing the variation present within the sampling sites.

In summary, the results indicate the capacity of Landsat vegetation indices to be useful in mapping green AGB across the most important grazing areas including the defined vegetation groups Bunch grass and Open plains. However, relationships were not robust for Spinifex and perform poorly for total AGB despite moderately strong calibrations. As a result, multi-temporal indices may reflect both standing green and senesced components of AGB. To this end, relationships between green and total AGB, Crop Circle NDVI, and Landsat ETM+ and MODIS NDVI values were evaluated and compared with relationships based on NDVI time-series in the following chapter.

6 Multi-temporal indices for above ground biomass estimation

Plate 6: Anthill at Liveringa Station.
Photograph by Mick Schaefer (University of New England).

6. 1 Abstract

The objective of this chapter is to test the potential of using cumulative, temporally smoothed MODIS NDVI for the cost-effective monitoring of green AGB in rangeland environments at larger scales. The 16 day 250m resolution NDVI MOD13Q1 product from MODIS was compared with Landsat and Crop Circle NDVI to assess influences of spatial resolution and atmospheric conditions. Time-series of NDVI were interpolated and smoothed with a Savitzky-Golay filter using TIMESAT software for the years 2010 to 2013. Sites with vegetation types Spinifex, Bunch grass and Open plains clearly differed in their multi-temporal NDVI patterns. They show a limited range in amplitude for sites with Spinifex vegetation. The largest range in amplitude was for Open plains sites that senesce earlier than sites with Bunch grass. Both MODIS and Landsat NDVI correlate moderately strong to Crop Circle NDVI (R^2=0.6). NDVI explained up to 89% of variation in green components of the vegetation; however relationships were only significant when aggregating to vegetation types.

6. 2 Dataset

6.2.1 Remote sensing data

Remotely sensed data was sourced from EarthExplorer (http://earthexplorer.usgs.gov/). This included MODIS NDVI data (code: MOD13Q1) (http://reverb.echo.nasa.gov/) and Landsat 7 ETM+ and Landsat 8 Operational Land Imager (OLI) data. The OLI sensor is comparable to the ETM+ but includes two additional spectral bands in blue and infrared wavelengths. The spatial resolution was 25 m and images were recorded in June 2013, at the end of the wet season. Orthorectified aerial photographs were sourced from the Satellite Remote Sensing Services WA (Landgate). The aerial RGB photographs, with a spatial resolution of 0.8 m were recorded on 10 November in 2007.

The MODIS NDVI product (code: MOD13Q1) is produced over land at 250 m resolution globally and is cloud composited for every 16 days. The technical specifications of the 36 band MODIS sensor on-board Terra and Aqua satellites are: spectral range for channel 1 and 2 (0.6 µm - 0.9 µm), 3 to 7 (0.4 µm - 2.1 µm), channel 8 to 36 (0.4 µm - 14.4 µm), a spatial resolution of 250 m (bands 1-2), 500 m (bands 3-7), 1000 m (bands 8-36) with swath dimensions of 2,330 km (cross track) by 10 km (along track at nadir). Centre coordinates used were latitude 18 and longitude 124. Overpass dates of MODIS Imagery corresponding to field sampling dates are shown on Table 6.1.

Each MODIS pixel contains the best possible surface "maximum compositing" reflectance observation during a 16-day period as selected on the basis of high observation coverage, low view angle, the absence of clouds or cloud shadow, and aerosol loading. The downloaded subsets were reprojected to the Geocentric Datum of Australia (GDA) 1994 with the MODIS re-projection tool. Subsequent processing was carried out in IDRISI Taiga software (version 16.05).

Table 6.1: Dates of field sample collection and available MODIS fortnightly composites.

Year	Field sampling	MODIS composite
2011	11-18 December	19 December
2012	18-25 February	18 February
2012	19-26 March	22 March
2012	16-23 June	25 June
2012	30 November - 7 December	3 December
2013	15-22 February	18 February
2013	12-19 April	23 April
2013	15-22 June	25 June

6.2.2 Field data

A detailed description of the field data collection protocol can be found in Chapter 3. Site level estimates of green and total AGB (kg DM ha^{-1}) were derived from a combination of disk plate meter height, Crop Circle NDVI, using calibrated relationships per vegetation group based on a large number of destructive quadrat cuts. Field AGB measurements were collected between December 2011 and December 2013, including both wet and dry seasons. Field measured data included total and green AGB values and Crop Circle NDVI readings. The fraction of green AGB refers to the percentage of green AGB per quadrat calculated by multiplying the green DM fraction with the total AGB.

6. 3 **Methods**

Temporally filtered MODIS NDVI values enable the development of green and total AGB assessment tools based on remote sensing. In order to infer the grazable portion from the green AGB, the MODIS NDVI time series can be used to create aggregate indices that measure the temporal sum of NDVI over a growing season. This may be a better indicator of green and even total AGB than single date NDVI. However, corrections need to be done on the MODIS time series in order to deal with sources of errors and biases. The detailed methodology investigating: 1) pixel misregistration and spatial resolution, 2) noise contribution due to the atmospheric influences and 3) development of relationships between components of AGB with temporally filtered cumulative MODIS NDVI is shown in Figure 6.1. In order to carry out the data analysis, raw MODIS NDVI values were smoothed with a Savitzky-Golay filter using TIMESAT software (section 6.3.1).

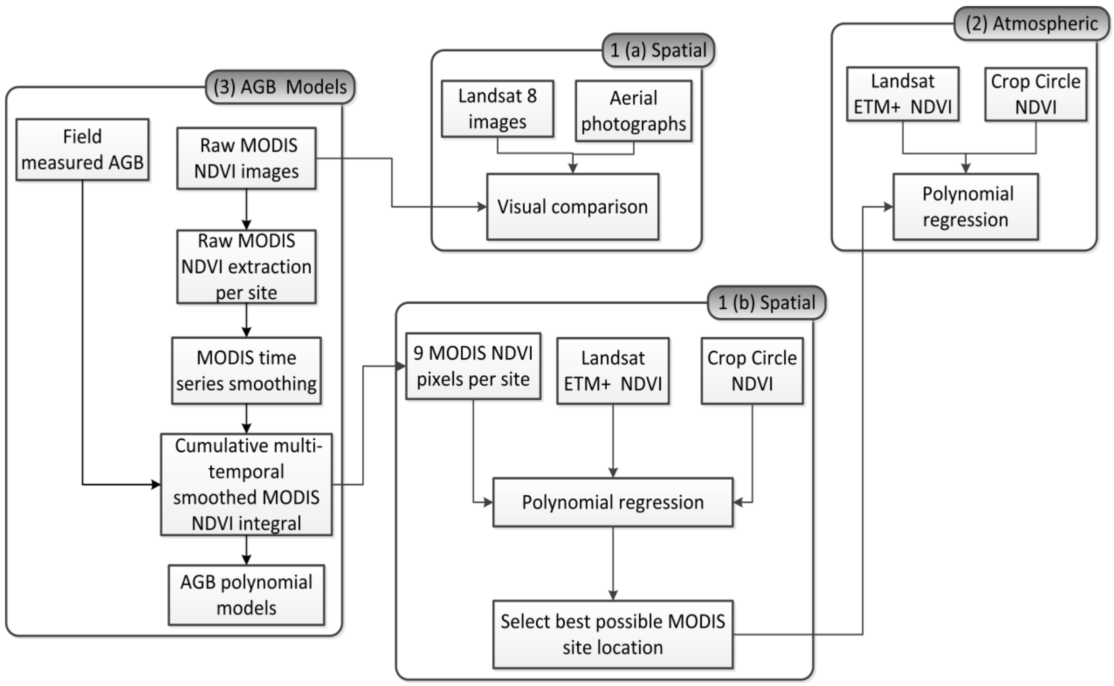

Figure 6.1: The data analysis flowchart.

6.3.1 Interpolation of raw MODIS values

For each of the 19 sites, the MODIS NDVI pixel centroid nearest to site centre was extracted using ArcMap 10.2. The noisy composited NDVI values were smoothed with TIMESAT, developed by Jönsson and Eklundh (2004) for curve fitting and interpolation. TIMESAT implements three processing methods based on least-squares fits to the upper envelope of the vegetation index data. Using a set of user defined settings, TIMESAT will fit a smooth continuous curve using Savitzky–Golay filtering

(SG), asymmetric Gaussian (AG), or double logistic (DL) functions to the time series and an adaptive upper envelope to account for negatively biased noise such as cloud (Jönsson and Eklundh 2004). The SG filter uses local polynomial functions while the AG and DL uses ordinary least squares method (Jönsson and Eklundh 2004).

In order to characterise this seasonal curve interpolation methods often give similar results which need careful examination. For noisy time-series the SG method sometimes yields undesirable results and the DL or the AG may be optimal (Jönsson and Eklundh 2004). All three processing methods use a preliminary definition of seasonality (uni-modal or bi-modal) along with approximate timings of the growing seasons. The SG filtering technique was selected for this analysis because of its close resemblance to the raw NDVI curve (Figure 6.2). The least squares DL and AG smoothing functions tend to over-fit the data in some sections. As a result, the specifications for the SG filter settings that were adopted in TIMESAT were as follows: Number of envelope iterations=1, Adaptation strength=2, Force minimum value=0, Savitsky-Golay window size=3, Spike Method=median filter, Seasonal parameter=1, Start of season method=1 and value of season start/stop=1.

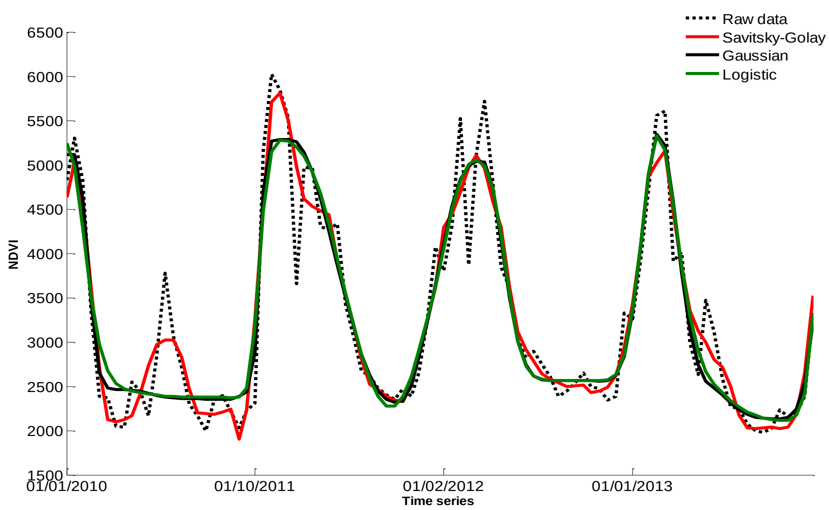

Figure 6.2: Comparison of three interpolation methods in TIMESAT (Savitsky-Golay, Gaussian and Logistic).

6.3.2 Statistical analysis

Sites were grouped together into vegetation types on the basis of similarity of soil and vegetation characteristics, Open plains, Bunch grass and Spinifex (see Table 3.4). The influence of the uncertainty in the exact location sampled by a MODIS pixel was evaluated by comparing relationships between Crop-Circle NDVI, Landsat 8 OLI NDVI and MODIS-NDVI in a 3 x 3 window (Figure 6.3). As a result 9 raw NDVI and TIMESAT temporally filtered MODIS NDVI values were obtained for each of the 19 site locations. Effects of spatial resolution and atmosphere were evaluated by evaluating relationships between NDVI derived from MODIS, Landsat OLI and Crop Circle. The Landsat and MODIS pixels are sampled from top of the atmosphere while the Crop Circle radiometer RED and NIR reflectance were recorded at a consistent height of 100 cm above the plant canopy (Section 3.4).

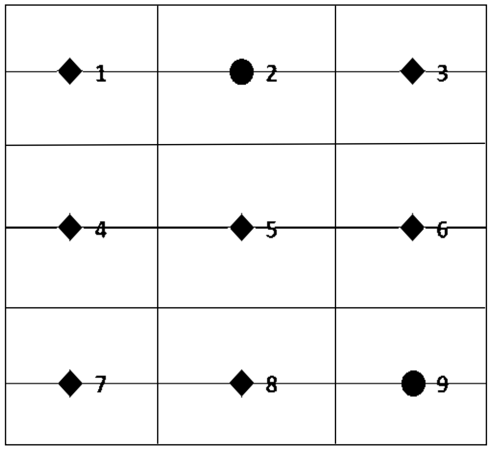

Figure 6.3: 3 x 3 window with numbers representing pixel centres. Due to geometric inaccuracies pixel 2 is the originally selected site location while pixel 9 is the field sampled site location.

Second order polynomial models $Y_{SG} = a_{SG} + b_{SG} \times X_{SG} + c \times X^2{}_{SG}$, were used to describe relationships for each site group (SG) between temporally filtered values of NDVI, measured fraction of green material and amounts of green and total DM. To account for differences in background, a 12 month rolling minimum was used as base value that was subtracted from all NDVI values (dNDVI). NDVI relates directly to the ground cover of green material, and is an indicator of the amount of light intercepted. Following from concepts around radiation use efficiency (Sinclair and Muchow 1999), total amount of light intercepted is a good indicator of variation in growth. Therefore, it is expected that integrating minimum dNDVI (MdNDVI) from the start of the season would explain more variation in total DM than NDVI. All the models developed were split on the basis of vegetation type (Table 6.2). Statistics (R^2 and RMSE) were determined from the regression models. For the evaluation of all the models, a successful correlation was considered when the adjusted R^2 value obtained had a value of at least 0.5. This implies that 50% of the variance in the dependent variable is accounted for by the model.

Table 6.2: Polynomial regression models developed in the analysis. Calibrated datasets were split on a vegetation type basis

Test	Independent variable	Dependent variable
1	MODIS NDVI	Landsat NDVI
2	MODIS NDVI	Crop Circle NDVI
3	Fraction green AGB	MdNDVI
4	Total AGB	Cumulative MdNDVI
5	Green AGB	MdNDVI

6. 4 **Results**

Results are presented in this section summarising the key outcomes from regression models developed between the temporally filtered NDVI and the cumulative MdNDVI, further details are presented in *Appendix C.*

6.4.1 Spatial resolution

The assumptions made were that pixel 2 was the originally selected site location on the map while pixel 9 was the field sampled site location due to positional inaccuracies. As a result raw and temporally filtered MODIS NDVI values were obtained for the Open plains, Bunch grass and Spinifex sites using pixel 9 as reference and correlations investigated. For all sites, linear regression relationships showed very strong correlations with coefficient of determination values ranging from 0.6-0.9 (Table 6.3).

Table 6.3: Correlation coefficients for the 9 pixels for all sites of MODIS raw values compared to the TIMESAT temporally filtered NDVI values. Values below 0.9 are highlighted in bold.

Site	Pixel 1	Pixel 2	Pixel 3	Pixel 4	Pixel 5	Pixel 6	Pixel 7	Pixel 8	Pixel 9
1	0.92	0.92	0.94	0.95	0.94	0.93	0.93	0.94	0.90
2	0.96	0.96	0.92	0.96	0.92	0.96	0.94	0.95	0.94
3	**0.82**	0.93	**0.85**	0.91	0.94	**0.88**	0.93	**0.86**	0.96
4	0.95	0.96	0.92	0.91	0.93	0.94	0.95	0.96	0.95
5	0.95	0.93	0.95	0.94	0.96	0.96	0.95	0.96	0.96
6	0.96	0.96	0.91	0.94	0.93	0.96	0.95	0.94	0.94
7	0.95	0.96	0.94	0.95	0.96	0.96	0.95	0.96	0.95
8	0.92	0.93	0.93	0.91	0.93	**0.81**	0.92	0.95	**0.83**
9	**0.70**	**0.59**	**0.76**	**0.89**	**0.89**	**0.58**	**0.80**	**0.84**	0.48
10	0.95	0.96	0.96	0.97	0.95	0.95	0.96	0.96	0.96
11	0.94	0.93	0.92	0.93	0.95	0.94	0.95	0.92	0.93
12	0.93	0.92	0.90	0.91	0.90	0.90	0.93	0.92	0.93
13	**0.82**	**0.81**	**0.71**	**0.83**	**0.86**	**0.81**	0.92	**0.86**	0.91
14	0.95	0.91	0.94	0.9	0.92	0.93	**0.86**	**0.87**	0.95
15	**0.80**	**0.77**	0.94	**0.83**	**0.83**	0.93	0.93	**0.88**	0.92
16	0.91	0.94	0.93	0.93	0.94	0.92	0.94	0.95	0.92
17	0.94	**0.77**	0.91	-	**0.87**	0.93	-	-	0.90
18	**0.85**	**-**	**-**	**-**	**0.81**	**0.86**	**0.88**	0.90	0.94
19	0.91	0.9	0.94	0.92	**0.8**	**-**	**0.80**	-	0.92

The correlation coefficients were above 0.9 for most of the 9 pixels indicating a strong agreement between the TIMESAT temporally filtered values and raw values. Some pixels had correlations below 0.9 (indicated in bold) which could indicate strong atmospheric influences. Site 9 (Spinifex site) had all the values below 0.9. Another example of a Spinifex site (Site 17) confirmed the raw NDVI as generally variable as shown in Figure 6.4. All the pixels behaved independently of each other due to the huge spatial heterogeneity that characterised the Spinifex sites. The curves were very noisy depicting the nature of the Spinifex grass which has a senescent top and a green bottom (Figure 7.1). This could also be attributed to bare soil differences within the neighbouring pixels as the Spinifex cover is unevenly spread. Similar site comparisons for Open plains and Bunch grass vegetation type groups are shown in *Appendix C.*

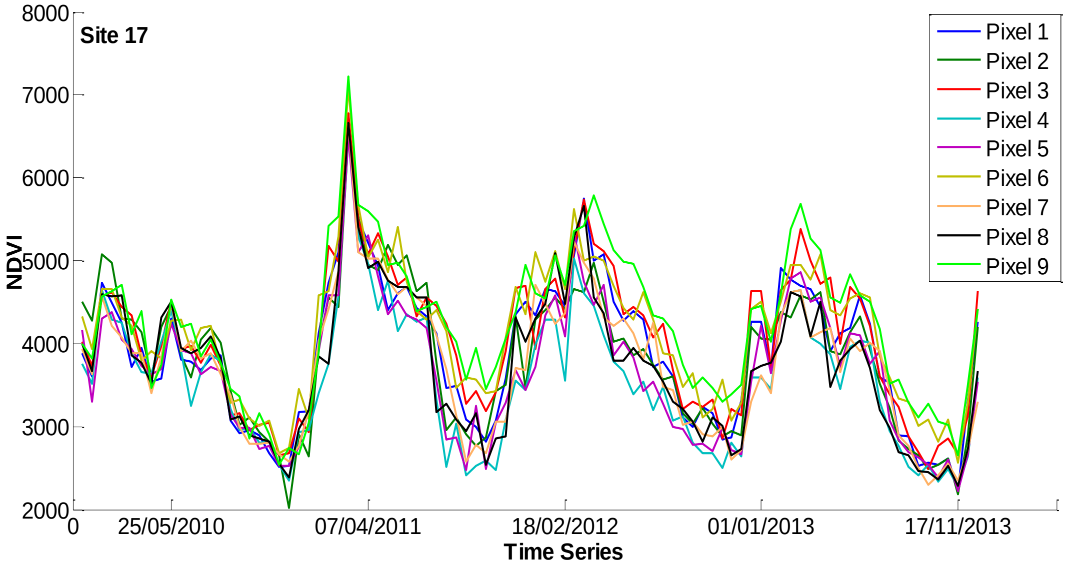

Figure 6.4: Pixels in a 3 x 3 window showing importance of pixel selection (Site 17).

The coefficients of determination values (R^2) and RMSE for all the sites for 9 pixels are presented in Table 6.4. For the Landsat ETM+, the raw values ranged from an R^2 of 0.4-0.6 while the temporally filtered NDVI values ranged from 0.5-0.6 (Figure 6.5). This indicates a reasonable agreement in spatial resolution between MODIS and Landsat ETM+ NDVI. As expected, the temporally filtered NDVI R^2 values were slightly higher than the raw values. When MODIS NDVI was compared with Crop Circle NDVI a slight correlation was obtained for the temporally filtered NDVI with a maximum correlation of 0.6 (Figure 6.6). The range of the temporally filtered MODIS NDVI was 0.3-0.6 compared to the raw NDVI which has a range of 0.3-0.5. Pixel 8 which was correlated with Landsat and the Crop Circle NDVI at an R^2 of 0.6 was chosen as the "actual" site location and would be used in future regressions as the MODIS site location. Figure 6.5 and Figure 6.6 show the respective scatter plots. It should be noted that the NDVI range is scaled from 0-1 for Landsat and Crop Circle while for MODIS NDVI the values are scaled from 0-10 000.

Table 6.4: Correlations coefficients of 9 pixels for raw and temporally filtered MODIS NDVI (X-axes) values compared to Crop Circle (Y-axes) and Landsat (Y-axes) NDVI data and the RMSE of the estimate.

Pixel	**Raw**				**Temporally filtered**			
	Landsat		**Crop Circle**		**Landsat**		**Crop Circle**	
	R^2	**RMSE**	R^2	**RMSE**	R^2	**RMSE**	R^2	**RMSE**
1	**0.5**	657	0.3	909	**0.6**	587	0.4	642
2	**0.5**	625	0.4	694	**0.6**	541	**0.5**	559
3	**0.5**	643	0.3	722	**0.5**	632	0.4	657
4	**0.6**	1125	0.4	1518	**0.6**	1439	**0.5**	1203
5	**0.6**	574	**0.5**	632	**0.6**	507	**0.5**	566
6	**0.5**	638	0.4	679	**0.5**	572	0.4	630
7	**0.5**	598	0.4	653	**0.6**	540	**0.6**	1173
8	**0.6**	1101	0.4	1126	**0.6**	1076	**0.6**	1144
9	0.4	662	0.3	703	**0.5**	580	**0.5**	658

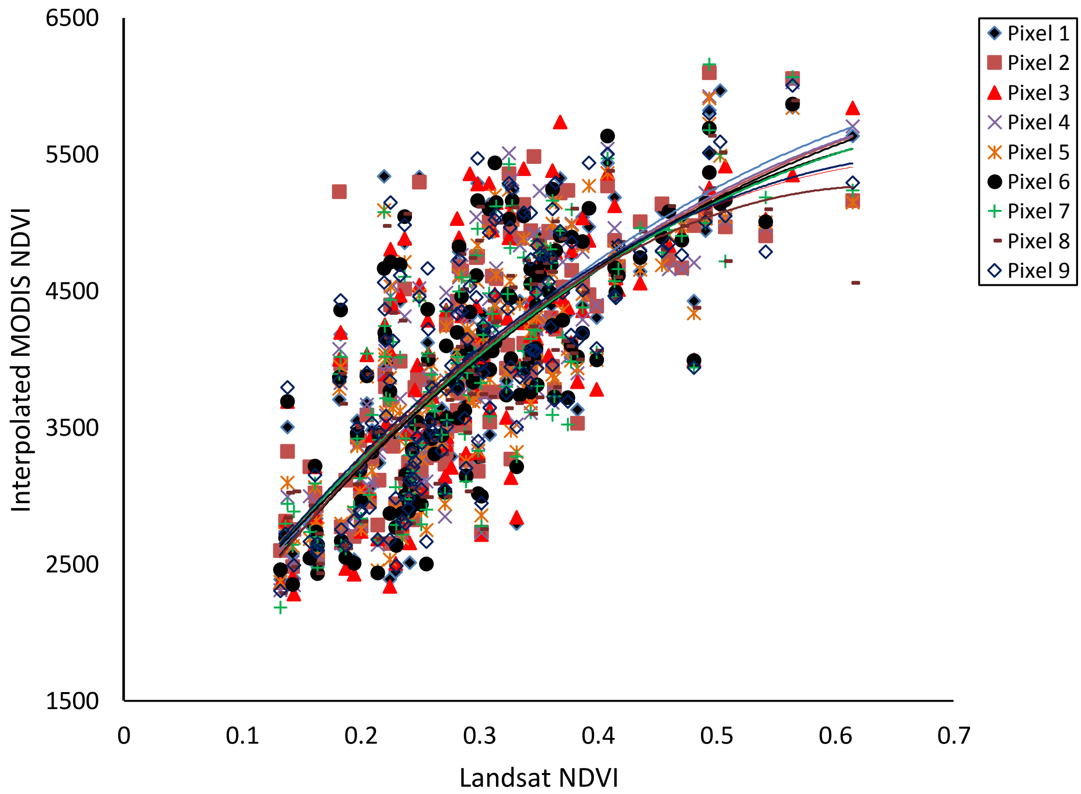

Figure 6.5: Temporally filtered MODIS NDVI compared to Landsat ETM+ NDVI.

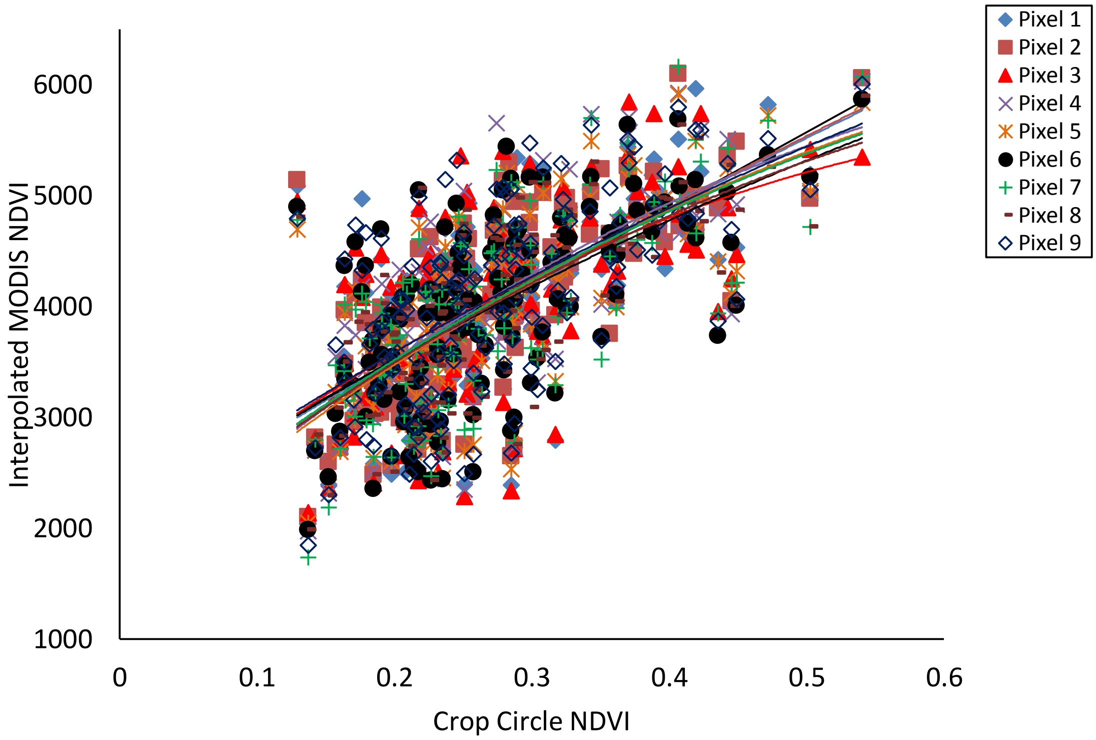

Figure 6.6: Temporally filtered MODIS NDVI compared to Crop Circle NDVI.

6.4.2 Atmosphere influences

Landsat NDVI correlated moderately strongly with Crop Circle NDVI (R^2=0.6 not shown). Distinct temporal differences are exhibited in the temporally filtered MODIS to Landsat NDVI relationship (Figure 6.7) which may influence the calibrated relationships. Sampling points are clustered together depending on the time of sampling. Samples that are collected in the peak of the growing season (February and March) have higher NDVI values while those collected at the start and end of season (December and June) have lower NDVI. This indicates that temporal differences are important in the derivation of NDVI relationships.

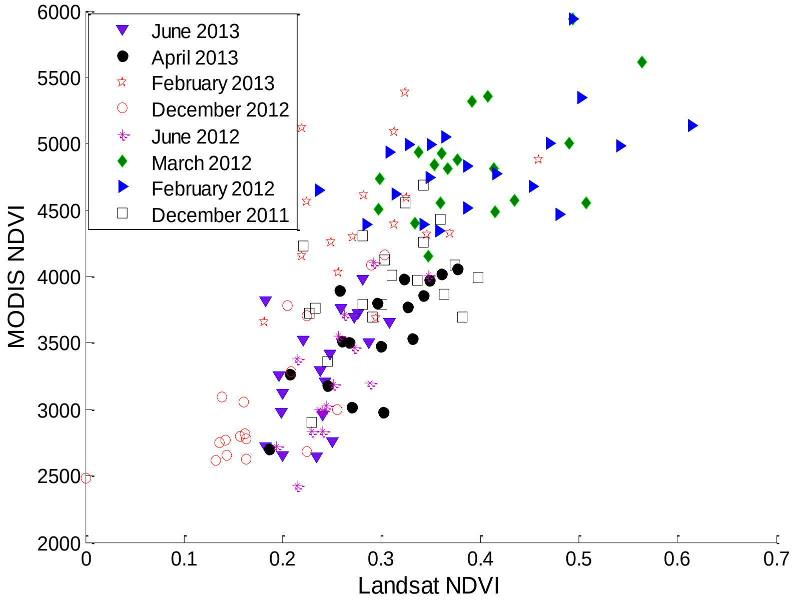

Figure 6.7: MODIS vs Landsat NDVI scatter plots for the sampling duration.

6.4.3 Polynomial models

Site-equivalent green AGB values for the corresponding sampling dates were compared with temporally filtered MODIS NDVI values (Table 6.2: Test 1 and 2). The relationship of Landsat and MODIS for the Open plains was moderate with an R^2 of 0.6 with an error of approximately 700 kg DM ha^{-1}. It was not robust for Bunch grass and Spinifex at 0.3 and 0.2 respectively Table 6.5. For the Bunch grass and Spinifex groups there was no correlation for the Crop Circle NDVI with green AGB. The highest RMSE values ranged from 1204 kg DM ha^{-1} for Landsat NDVI to 1966 kg DM ha^{-1} for Crop Circle NDVI.

Table 6.5: Statistical description of polynomial relationships between green AGB and Landsat, Crop Circle and MODIS SG-NDVI values for pixel 8.

	R^2	RMSE (kg DM ha^{-1})	R^2	RMSE (kg DM ha^{-1})	R^2	RMSE (kg DM ha^{-1})
	Open plains		*Bunch grass*		*Spinifex*	
Landsat	**0.6**	669	0.3	746	0.2	1204
Crop Circle	0.4	827	0.3	753	0.3	1966

Polynomial models that were developed in the analysis (Table 6.2: Test 3, 4 and 5) with NDVI explained up to 96% of variation in green components when plotted against the fraction of green AGB, however relationships were only significant when aggregating to vegetation types (Open plains and Bunch grass) (Table 6.6). Strong relationships were obtained for both fraction green AGB (R^2=0.96 for Open plains to 0.89 for the joint groups of Bunch grass and Open plains) (Figure 6.8) and green AGB (R^2=0.94 for Open plains to 0.89 for the joint groups of Bunch grass and Open plains). For total AGB, there were no robust relationships obtained for the Open plains, Bunch grass and Spinifex groups with R^2 values of 0.4 and 0.3 and 0.0 respectively (Table 6.6).

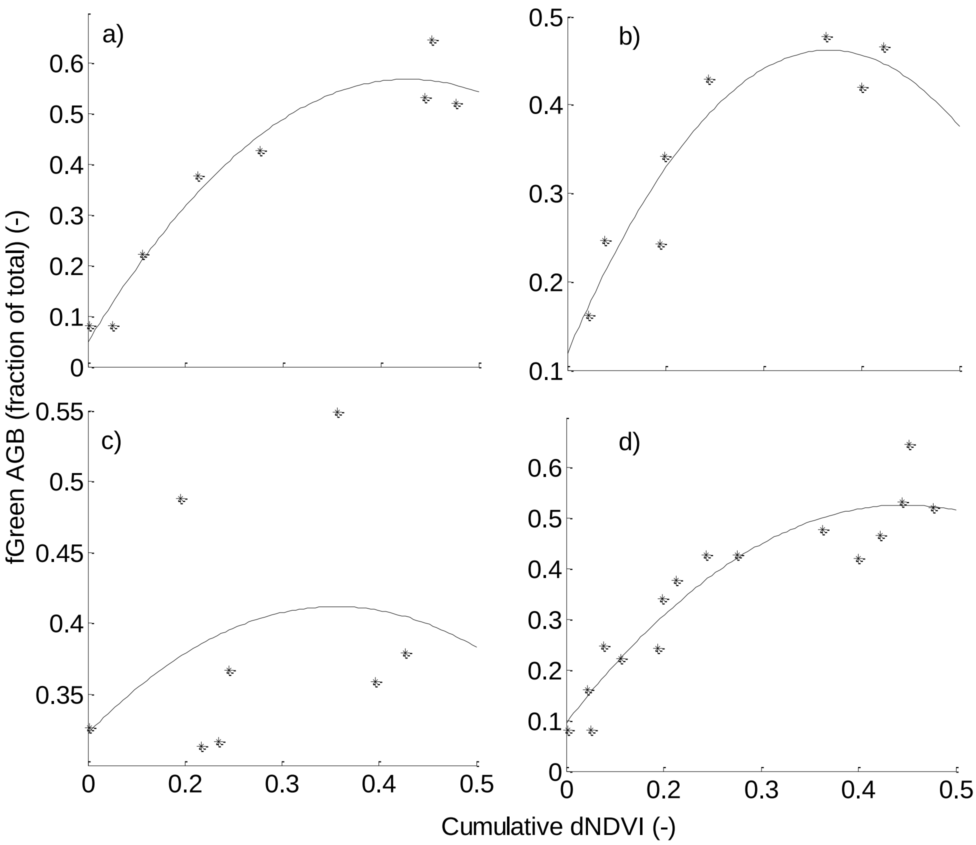

Figure 6.8: Fraction of green DM versus cumulative dNDVI for the polynomial relationships based on datasets for a) Open plains, b) Bunch grass, c) Spinifex and d) combined Open plains and Bunch grass.

The relationships between accumulated NDVI with green fraction and green (dry) AGB demonstrate that accumulated NDVI rises with increasing green fraction (Figure

6.8) but around a value of 0.5 green fraction, accumulated NDVI continues to rise without a change in fraction. This means that the first response is expanded green cover, and the second response is increased NDVI within the expanded green cover. This potentially suggests outgrowth of crowns and development of new shoots that expands the spatial cover of green material.

Table 6.6: R^2 values of relationships between fraction of green AGB, green AGB versus MdNDVI, and total AGB versus cumulative MdNDVI for the polynomial relationships based on datasets of Open plains, Bunch grass, Spinifex and combined Open plains and Bunch grass.

	Open plains	**Bunch grass**	**Spinifex**	**Open plains +Bunch grass**
1. Fraction of green AGB	**0.96**	**0.89**	0.1	**0.89**
2. Green AGB (kg DM ha-1)	**0.94**	**0.8**	0.0	**0.89**
3. Total AGB (kg DM ha-1)	0.40	0.40	0.0	0.40

6. 5 **Summary**

Green AGB can be monitored accurately with cumulative, temporally smoothed MODIS NDVI for Open plains and Bunch grass sites, but not for Spinifex sites. Strong quadratic relationships between cumulative NDVI and cumulative green AGB were found (R^2=0.89) for site groups but showed much stronger scattering for individual sites, with only very weak relationships (R^2=0.1). This was likely due to the small sampling area compared to the large MODIS pixels and considerable uncertainty due to geometric errors in pixel location. As a result, the sample may not represent the reality well for individual pixels especially the dead fraction. Responses of cumulative NDVI for Bunch grass and Open plains sites were similar and could be combined.

In order to estimate AGB at any given time, a single date NDVI can be used. However when it is spread through the growing season which relates better to the carrying capacity, then accumulated NDVI or Time-integrated NDVI (TINDVI) is a good measure. However, Spinifex still presented challenges as none of the methods worked. This is because of the nature of the Spinifex grass which hides its green under dry sclerophyllous leaves resulting in a small fraction of green cover in a pixel. For the selected 9 pixels scatter plots of time series for MODIS NDVI illustrated the importance of pixel selection on the surrounding landscape, MODIS NDVI correlated strongly with the Landsat NDVI (R^2=0.6), for the pixel located at the centre of the sites (pixel 8). Geometric accuracy of Landsat ETM+ was higher than MODIS. Correlations with Landsat NDVI and Crop Circle NDVI improved when selecting the neighbouring pixel rather than the pixel above the sites. This indicates problems with geometric accuracy of MODIS imagery, further evidenced by stronger relationships for Landsat NDVI with green AGB and Crop Circle NDVI.

Standing green AGB was correlated to NDVI and relationships were weak, especially when green AGB was mixed with larger amounts of dead AGB. Cumulative NDVI is accounting for the build-up of AGB over time. At the last phase of the growing season, grazing becomes more important. Cumulative NDVI also correlated moderately with accumulated green AGB, although the last sampling dates of the season showed the effect of grazing and/or decomposition clearly. The atmosphere also affected satellite imagery, adding large amounts of scatter to relationships between Crop Circle NDVI and Landsat or MODIS NDVI. Atmospheric effects were reduced when MODIS NDVI values for individual pixels were temporally filtered with the Savitzky-Golay filtering method, evidenced by a reduction in RMSE in the relationships with Crop Circle NDVI for nearly all pixels considered.

In conclusion, the strong relationships between cumulative MdNDVI for site groups and green AGB are suitable for paddock assessments, the scale relevant for pastoralists. However, Spinifex infested areas need to be masked out and excluded as relationships are significantly different when compared to the Open plains and Bunch grass. Cumulative NDVI values are indicative of the cumulative amount of radiation intercepted by green plant parts in the growing season. Therefore, it is expected that plant growth models that are driven by the intercepted amount of radiation will be able to predict plant growth in these environments, and may enable modelling of the fraction of dead material.

7 General Discussion and Conclusion

Plate 7: Baobab tree at Liveringa Station.
Photograph by Adam Rosher (Curtin University).

7. 1 Abstract

The thesis provides novel research contributing to use of remote sensing to retrieve estimates of AGB in the Kimberley area of WA. A summary of the three objectives highlighting these main contributions and recommendations for future research are presented in this chapter. This general discussion integrates the most significant findings of this thesis in the context of recent research on AGB estimation in the WA rangelands and past international research in retrieval of AGB from MODIS and other sensors. For instance, it is discussed in-depth how successful the research was in addressing the estimation of AGB using remote sensing including how the field protocol developed can be applied to other locations outside the study area. Gaps that were discovered and new issues that were raised in the course of the research are also highlighted.

7. 2 General Discussion

Approximately 81% land area of the Australian continent is dominated by rangelands covering a huge environmental range (Rangelands 2015). In order to sustainably manage pastoral properties, rangeland managers require accurate estimates of AGB. Remote sensing for the mapping and assessment of total AGB provides an advantage in that it can rapidly provide AGB estimates non-destructively on a large scale with an increased temporal frequency. However, while methods are in place for southern WA, there is a lack of models calibrated specifically for the Kimberley region in northern WA. The research carried out in this thesis focused on the Kimberley region of WA and was divided into three objectives that could be used to aid AGB estimation: (1) a ground data collection protocol for field measured AGB estimation in heterogeneous rangeland environments which is important for the development of assessments based on remote sensing or growth modelling; (2) AGB estimates based on regression models relating indices derived from medium resolution satellite imagery to ground data and (3) AGB estimates obtained from temporally filtered vegetation indices from low resolution satellite imagery that can be used for monitoring of larger areas and paddocks on rangeland stations. The three objectives are discussed in detail below.

7.2.1 Field AGB estimation from ground data collection protocol

Remote sensing for assessment and mapping of total standing AGB relies on accurate ground data for calibration and validation. The requirements of the number of samples increases with spatial variability and size (Muir 2011) and sampling challenges include costs, site access and labour requirements. The Kimberley rangeland area has high spatial variability and vegetation includes alluvial plains dominated by annual and perennial grass species with heterogeneous tree cover. In the study area in the Kimberleys (heterogeneous savannah environment with green and senesced vegetation components), the main vegetation areas could be separated into Open plains, Bunch grass and Spinifex. Similar to the other rangelands, the Kimberley vegetation growth is rainfall dependent with short periods of lush green vegetation (Al-Bakri and Taylor 2003). However, traditional survey methods require numerous sample points to represent highly diverse savanna landscapes resulting in limited number of points that are incorrectly interpolated or extrapolated to the landscape level (Moleele *et al.* 2001). Given the size and scale of Australian pastoral stations such as Liveringa station (263,000 ha) the following challenges exist: a) collection of sufficient number of AGB measurements on the ground to represent the spatial variation present; b) lag times between date of sampling and image acquisition; and c) spatial mismatches at pixel level (Gao 2006).

The combinations of VE and PH have been discussed before (e.g. (GabriËLs and Van Den Berg 1993; George *et al.* 2006)), however, the developed protocol is novel as it successfully combines various indirect measurements in one predictive model, a first in Australian rangeland environments. The protocol is suited to addressing large spatial variability at the site scale, especially where variation is not known beforehand or when the required number of samples exceed the suggested 16 quadrat samples (Muir 2011). It was found that responses of Crop Circle NDVI, PH and VE were similar for sites with comparable vegetation types, enabling calibration of relationships that can be used within specific vegetation types. In addition, the protocol can be used at a range of scales, specifically addressing spatial variability as additional indirect measurements can be collected with only a limited need for additional destructive samples.

The research showed that all individual relationships based on available non-destructive methods were limited to specific sites or seasons, due to dynamics in the ratio of dead and green material, large differences in vegetation composition and grazing intensity between sites confirming the work of Murphy *et al.* (1995); Zhou *et al.* (1998) and Martin *et al.* (2005). The issue is overcome by including multiple non-destructive measures as mentioned in López Díaz and González-Rodríguez (2003). The advantage of the non-destructive measures lies in the ability to add measurements without much extra time, strongly increasing accuracy at sites with large spatial variation. Also, measurements can easily be extended to a larger scale with a limited number of additional quadrat cuts. This is of particular importance when collecting ground data to match spatial resolution of satellite imagery. After establishing robust relationships between AGB in quadrats and indirect measurements, there is only a limited need to collect additional quadrats. Additional sites can be sampled with only a destructive sample required for low and high AGB quadrats to calibrate the comparative yield scores. Existing sites that are revisited can be sampled with a reduced number of destructive samples, only required to account for new conditions not encountered before or temporal changes due to for example sensor drift at a new field visit. However, ultimately real-time monitoring of AGB at the landscape scale needs to rely on remote sensing technology.

The proposed protocol offers an approach to quantifying available AGB for grazing animals and is useful for ground-data collection. It can be applied in the extended Kimberley region as well as other rangeland areas across the world with typically strong spatial variability, mixtures of dead and green AGB and diverse species composition. Nevertheless, extrapolation of this protocol to other regions should not be done directly without the necessary calibration as different regions may have different vegetation and environmental dynamics (Oesterheld *et al.* 1998). In other areas with different vegetation types, the selection of indirect measurements may need to be adjusted, for example, including radiometric measurements (Starks *et al.* 2006). In future research, the recommended frequency for ground data collection should be seasonal so as to cater for the ever changing seasonal conditions and unpredictable fire regimes.

7.2.2 AGB estimation from single image vegetation indices

Arid land AGB estimation with a VI is typically dependent upon the strength of reflectance signal received from the vegetation, reflectance properties of the background and the fraction of ground coverage and the sensitivity of the VI for these factors (Beck *et al.* 1990). Some of the research has also focused on the empirical estimation of relationships of AGB in the savannahs in Africa (Prince and Tucker 1986; Moleele *et al*. 2001; Sannier *et al*. 2002). The complicated interactions between sources of variation, associated with the grassland vegetation and their different spatial and morphological properties, makes it challenging to derive AGB estimation models using remote sensing indices alone. Results reported in this thesis were consistent with other studies using empirical approaches in the estimation of AGB in semi-arid rangeland environments (Eisfelder *et al.* 2011). The spatial scale of the study area could also attribute to the non-correlation between vegetation indices and total AGB. Initial site selection, as defined by a rangeland expert, was based on a stratification based on land systems, but selected sites within one land-use system were spatially too heterogeneous to achieve a robust correlation between total AGB and all selected vegetation indices. This indicates a strong variability within the sampled sites as also reported elsewhere (Anderson *et al.* 1993; Kurtz *et al.* 2010).

The fractional cover of photosynthetic vegetation, non-photosynthetic vegetation and bare soil plus litter is crucial in its influence on the effectiveness of the NDVI as an indicator of green and total AGB. The more bare soil and non-photosynthetic vegetation is present the poorer NDVI will be, since less of the signal within a pixel is coming from the cover fraction for which the indicator is sensitive (Hobbs 1995). There is evidence to suggest any one index will not characterise AGB at all times during the season as there is a lot of variability of AGB (Silleos *et al.* 2006). NDVI was correlated moderately strong to green AGB, but weakly to total AGB. Robust relationships could be found for the site groups Open plains and Bunch grass but not for Spinifex. This indicates a very strong influence of site-specific factors. It implies that a horses for courses strategy is required, i.e. different approaches for different site groups in order to estimate AGB.

For example, Spinifex tends to maintain attached dry sclerophyllous leaves whilst generating green leaves in response to rainfall. Its clumping behaviour interleaved with bare soil makes it difficult for a nadir viewing to detect green AGB change due to shading and low fractional cover. This could be attributed to the senescent AGB and dominance of soil background in sparsely vegetated areas as established in previous research (Beck *et al.* 1990; Robinson 2012; Horion *et al.* 2014). Spinifex grass (Triodia spp) (Figure 7.1) mainly comprises of a green base and a senescent top part which may block the satellite signal to the green response (Figure 7.1). As a result, another approach for estimating Spinifex AGB might be needed e.g. some kind of morphological model might help in generating estimates for Spinifex dominated areas. However, in providing any model for AGB assessment in rangelands many assumptions have to be accepted which may alter the reliability of data. The study showed that the division of sites into vegetation types is based on land systems which are mapped at a broad scale. In future, land unit scale (which is more detailed) may provide better stratification if this data is available.

Figure 7.1: Clumps of Spinifex grass. Photo by Richard Stovold (Landgate, WA).

Using NDVI as a measure of productivity in rangeland areas is also not without controversy. As has been demonstrated in this research, NDVI was more sensitive to green AGB within the Open plains and Bunch grass groups but less sensitive to total AGB and the Spinifex dominated sites which have considerable bare ground portions. However, some studies suggest that EVI is potentially more sensitive in arid lands since NDVI shows great potential to quantify AGB only in the rainy season (Beck *et* *al.* 1990; du Plessis 1999). EVI is a ratio of the red to near infrared reflectance bands which aids in the removal of soil–brightness induced variations (Potter 2014). The use of improved indices such as EVI has been proven to enhance vegetation signal over high biomass areas thus reducing atmospheric influences and improving AGB estimation (Hilker *et al.* 2008; Potter 2014). For example, in tropical areas with high biomass densities and frequent fires, EVI has been proven to be better than NDVI (Huete 2002). However, previous studies in savanna areas have mainly used NDVI (Prince and Tucker 1986; du Plessis 1999). In future research it may be worth comparing NDVI and EVI in this environment.

The main limiting factor for point based estimation is accurate pixel to sample point registration and physical factors within the environment (Lu 2006). Higher resolution satellites maybe more useful when focusing on standing material using a one-off image for example new constellations providing high spatial and temporal resolution RapidEye (Chander *et al.* 2013), DigitalGlobe's WorldView-2 (Anderson and Marchisio 2012) and Sentinel (Showstack 2014). Nonetheless, at the scale of rangelands the cost of image acquisition normally outweighs the benefit of monitoring (Schellberg *et al.* 2008). At the same time sensors and analytical techniques continue to improve so there is room for future affordable monitoring with high resolution imagery. In future studies, additional data may be collected to ensure a wider range of predictors from within the same pixel. For instance, combining multiple indices or phenological characteristics included in times-series imagery may provide means to more accurately estimate AGB (Zhu and Liu 2014).

7.2.3 AGB estimation from temporally filtered vegetation indices

At the landscape level different satellite data sources have been used in the derivation of AGB estimates in past research, e.g. AVHRR (Prince and Tucker 1986; Hill *et al.* 2004), Landsat (Steininger 2000; Todd *et al.* 1998), SPOT-VEGETATION and MODIS (Kawamura *et al.* 2005; Smith *et al.* 2011). Some of the work has also focused on the empirical derivation of AGB in the savannahs in Africa (Prince and Tucker 1986; Moleele *et al.* 2001; Sannier *et al.* 2002). Many problems have been associated with AGB estimation in these previous studies. This is because empirically derived

AGB estimates are strongly affected by vegetation spectral properties and pixel heterogeneity (Hilker *et al.* 2008). As a result, it is imperative that work targeted in AGB estimation using remote sensing in rangelands should focus on multi-temporal data. Total AGB accumulation reflects the radiation use efficiency (Sinclair and Muchow 1999) and the total amount of APAR from the start of season (le Maire *et al.* 2011), directly linked to the density of chlorophyll m^{-2}. In this work, green AGB could be monitored accurately with cumulative, temporally smoothed MODIS NDVI for the Open plains and Bunch grass, but again not for Spinifex.

Some studies have proved that temporal analysis can be improved by an integration of sensors for example Landsat and MODIS (Potter 2014). At smaller scales (small paddock) the Landsat ETM+ sensor is a good estimator of productivity, however it is not suitable at the landscape scale (Paruelo *et al.* 2000). The fusion of remotely sensed data from different satellite systems allows for exploitation of their different spectral, spatial, angular (viewing and solar geometry), and temporal sensing characteristics (Roy *et al.* 2008; Zurita Milla *et al.* 2008). Integration of remote sensing sensors makes the information extraction process easier and takes advantage of the strengths of the different image data thus improves visual interpretation and quantitative analysis (Lu 2006). As a result the integration of multi-source data (multi temporal and high spatial resolution) could improve AGB estimation and monitoring in rangeland environments in future research (Paruelo *et al.* 2000).

Temporal sums of NDVI for primary production assessments may be erroneous in arid landscapes of Australia because satellite derived estimates of length of growth season may be wrong due to plant phenology, season and high tree and shrub cover on NDVI (Hobbs 1995). According to Schut *et al* (2015), other alternative metrics of productivity which can be explored in further research besides the annual NDVI sums as used in this research include maximum LAI values (Cook and Pau 2013), phenology derived integrals (Ivits *et al.* 2013) and residual trends after regression with rainfall amounts based on seasonal sums for dryland areas (Fensholt *et al.* 2013).

Plant growth rates are linearly directly related to the fraction of light intercepted (Goudriaan and Van Laar 1994; Sinclair and Muchow 1999) and total AGB accumulation is governed by the period of growth, light extinction coefficient and LAI (e.g. (Goudriaan and Van Laar 1994). From strong relationships between light interception and NDVI, it can be understood that accumulated NDVI is a good indicator of the total amount of light intercepted and accumulated AGB. In the green phase of the season, a positive relationship can be expected between cumulative NDVI and green AGB, that starts to plateau or decline when new growth is contributing more to non-leaf plant organs and older leaves start senescing. Spinifex responded differently, as this vegetation type has abundant dead material present all-year round, contrasting with the vegetation in the other two site groups. Plant senescence with dead leaves at the top of the canopy strongly reduces NDVI, and accumulation rates of NDVI decline at this stage. It is expected that dynamic modelling can explicitly account for these factors and thus would enable further improvements of these relationships.

7. 3 Directions for future research

The capacity to estimate AGB in the Kimberley area of WA has been developed in this study. The ability to predict available AGB aids in sustainable pasture management. This enables the farmer to calculate stocking rates which are essential in determination of culling numbers and live export to overseas markets (Oesterheld *et al.* 1998). Satellite based estimates gives Kimberley farmers an opportunity to know the temporal dynamics rangeland pastures and this is useful for determining start and stop of season pasture growth cycles. Further improvement in their operation is added by the ability to check the pasture condition using remote sensing aiding in sustainable management. The study provides detailed knowledge of the potential to retrieve estimates of AGB using remote sensing. A ground data collection protocol has been developed and numerous vegetation indices have been tested for their capacity to estimate AGB. Limitations in the ability to measure AGB have also been presented in relation to the phenological cycles of the different vegetation classes. Despite the limitations, this work is applied and adds incrementally to knowledge and methods for monitoring and managing grazed arid rangelands.

Complex system modelling such as a dynamic, deterministic models which include weather effects may also be potential replacements for empirically based approaches, for example GRASP (McKeon *et al.* 2000). However, growth models need to be able to handle seasonal variation and vegetation composition, presence of natural vegetation and variable ground cover (Moore *et al.* 1999; Hill and Donald 2003). Incorporation of ground cover estimates with green material would improve intercepted light, the main driver of growth. As a result, generic models are required that are less sensitive to species composition but capture the main seasonal response and are able to include effects of grazing. Other type of deterministic models such as agent based on neural networks (Almeida *et al.* 2009) may also be considered as well as other approaches for example, the fusion of remotely sensed data from different satellite systems (Roy *et al.* 2008).

Furthermore, another recommendation for future work is that simultaneous grazing on sites during the study should not be conducted as it could influence the results (Hiernaux 1998). Rangeland's productivity is strongly affected during a drought and grazing pressure which has been found to have the greatest effects remain an unknown for modelling accurately (Hein 2006). Animals are selective grazers, removing most palatable parts of plants first and this affects the discussed relationships between total AGB and vegetation indices. The total amount of grazing was not accounted in this study and for future studies it is recommended to account for grazing in model development.

Advances in agricultural research, for example Unmanned Aerial Vehicles (UAV) and drones in combination with precision agriculture approaches, are a possible future for monitoring rangelands (Schellberg *et al.* 2008). Precision management by definition requires precise and accurate information or data at a spatial scale that captures variability with a temporal frequency that delivers continuous information (Schellberg *et al*. 2008). UAV systems may be suitable for monitoring vast tracts of WA rangelands. UAV-based precision agriculture and smart farming remote sensing offers various advantages to farmers if adopted (Jensen *et al*. 2011). An ideal UAV based remote sensing system should be cost-effective easy to operate with good geometric accuracy (Rokhmana 2015). Compared to traditional methods based on imagery obtained from aerial or satellite platforms, UAV systems lead to improved cost savings in this task without losing accuracy (Mesas-Carrascosa *et al*. 2014). They also offer an advantage in that they can monitor vast tracts of land at higher temporal resolution in less time and using less manpower (Mesas-Carrascosa *et al.* 2014). In previous studies near-infrared (NIR) images acquired with UAV have been used to develop relationships between vegetation indices and field measured parameters (Lelong *et al.* 2008; Laliberte *et al.* 2011).

In future a combination of UAV with MODIS offers the rangeland manager a powerful combination for monitoring rangelands. However, links need to be established between the ground collected samples, the UAV data and remote sensing data. In previous research, van der Heijden *et al*. (2007) successfully combined a close-range sensing equipment (Imspector Mobile) with remote sensing data in order to develop models for spatial extrapolation of DM yield and DM content to large grassland areas. They used destructive measurements to calibrate the close-range sensing device, which in turn was used to calibrate remote sensing data. They concluded that this two-step calibration allows for a much more cost effective approach than direct calibration (van der Heijden *et al.* 2007). This two-step calibration can also be implemented in rangelands environments to improve AGB estimation. UAV high spatial resolution also offers the ability to distinguish vegetation groups instead of the use of local knowledge as done in this study. Another promising approach is on-tractor sensors which have been successfully trialled in many grazing experiments (Trotter *et al.* 2010). However, precision agriculture approaches need farmer training and some farmers are reluctant to change their mode of operation. For UAV-based approaches, one main disadvantage could be the size rangeland stations which might be too big for effective monitoring with UAV alone.

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Appendix A: Liveringa sampling protocol

This is an excerpt taken from the protocol that was implemented during the field data collection.

Sampling locations

- There are 5 ‘principle’ land systems; DJA, MYR, LUI and EGN.
- Each land system has three sampling locations (with exception of the ‘most productive’ land system DJA, which has five).
- At 5 locations, 10 × 10 m fences / exclusion cages are placed to determine grazing effect. Sample as for sites but then at smaller scale.
- Each sample location is configured for sampling along N, E, S, W radials extending a distance of 100 m from the site’s central GPS location according to Figure 1.

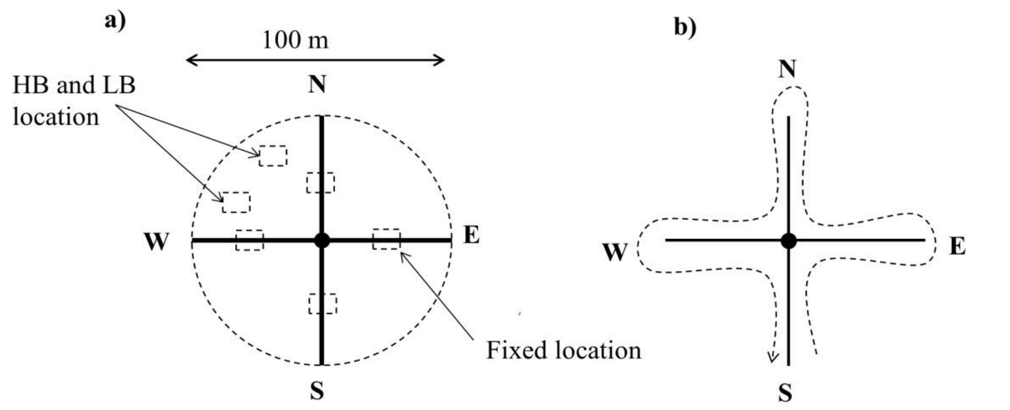


Figure 1: Vegetation sampling design: a) for quadrats and b) for sites.

Onsite sampling (19 sites + 5 exclusion areas): **two people’s** job

- **Step #1**: When you first arrive at the sample location, use your compass to identify each of the principle compass radials- i.e. N, S, E, W.
- **Step #2**: **(End of wet season sampling only)**. Walk around ~ 100 m radius of the centre location and do a visual assessment of the type and relative proportion of key pasture species present within the entire 100 m radius, e.g. 20% wild sorghum:30% Spinifex:50% Mitchell grass.
- **Step #3: (All sampling times)** Also do a visual assessment of the relative ground cover (easiest to do a relative bare soil- e.g. 20% soil = 80% ground cover.
- **Step #4:** Also do a visual assessment of the relative remnant vegetation cover (e.g. 20% eucalypt).
- **Step #5: Ensure you take photos of your site**. Use GPS enabled camera.
- **Step #6**: Conduct a moving Crop Circle survey of the grass canopy along the full radial arms placing equal emphasis along each radial arm.

- Measure while moving. Ensure you move at a constant speed. As the instrument simply records a rapid stream of continuous measurements you need to move such that the recorded points are distributed evenly along the radials. This will ensure the average and standard deviation values are a true reflection of the average and standard deviation values of the radial arms without bias towards those segments where you moved slower over hence collected larger volumes of recorded data.
- Ignore any shrubs/trees in your path and dodge around them as best as you can.
- A suggested method is as follows: Ensure the Crop Circle head is maintained at a 'consistent' vertical distance from the top of the plant canopy. This MUST be in the range 50-100 cm (note: ensure you do not hold the sensor head closer than 50 cm from the top of the canopy as this will degrade the instrument reading).

- **Step #7: Person A and B:** along the full radial arms, take a visual estimate of biomass and a disk plate meter reading of canopy height at 5m intervals .
- **Step #8**: **Persons A and B**: At one location with low biomass, one location with high biomass and two RANDOM locations within the circle, drop the 50 cm quadrat onto the ground.
  - **Take both a nadir, using a tripod at fixed height, and oblique photo of the in-situ quadrat.**
  - Using the disk plate meter, record thee average height of the grass and **both persons** make a visual estimate.
  - Take a Crop Circle recording for this location.
  - Using secateurs/shears, remove and 'bag' all grass down to a height of 3 cm above the soil. Include both green and senescent <u>standing</u> material. Ignore litter such as sticks, bark and severed/broken grass. Ignore trees and shrubs. Place material of all four quadrat harvest into a single bag.

<u>Back at Base Camp</u>

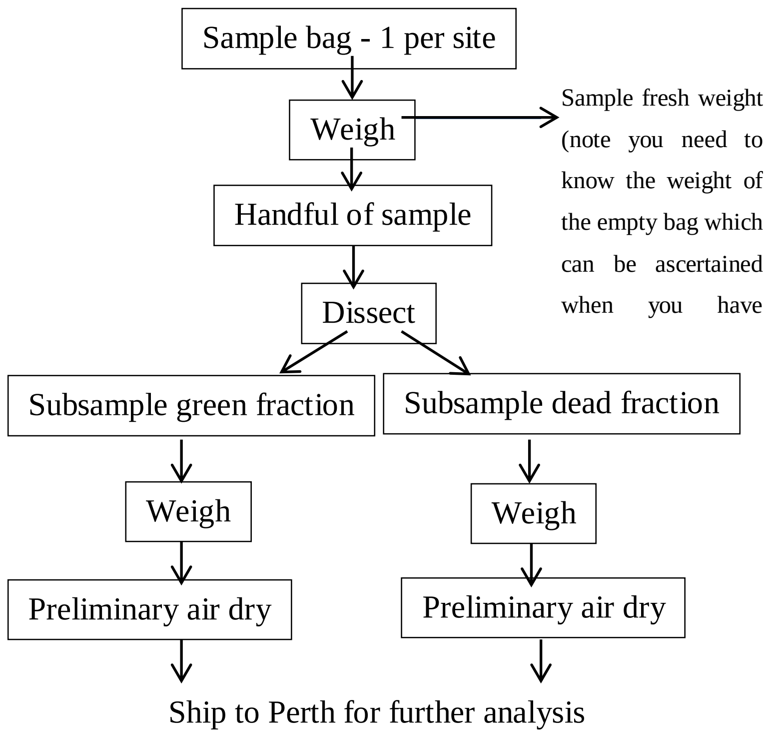
- Store sample bags in the refrigerator in-between site heli-visits if possible.
- Take sub-samples ASAP when using 4WD and store small bags in cooler box.
- Sub-sampling:
  - Weight the empty standard sample bags to determine average weight/bag.
  - Weight the full sample bag for each site.
  - Reach into each sample bag and carefully but thoroughly 'mix' the sample - ensure you minimise breaking the pasture strands.

- Remove a handful of the composite subsample from the bag and carefully dissect into green and dead fractions - bag each subsample (green and dead).
- Weigh each bag carefully, should have 150-200 gram fresh material, this should give more than 20-40 gram dry material.
- Preliminary air dry the subsamples to avoid decomposition when shipping to Perth.
- These bags will be returned to Perth for further analysis.

Back in Perth (Laboratory)

- Oven dry (**70**°C, 2 days as per standard protocol) all subsample fractions for each site.
- Mill and store all ground subsamples for possible digestibility assay.

Summary of the field protocol



Appendix B: Site access

Site access

When the weather conditions were favourable, all the sites were accessed by car as shown in Figure 2. The GPS device was used in track mode to record all the movements as the sites were visited. Field sampling for all the sites was one week duration due to the size of Liveringa Station, for example sites 4, 5, 6, 7 and 8 were located over 60 km away from the homestead.

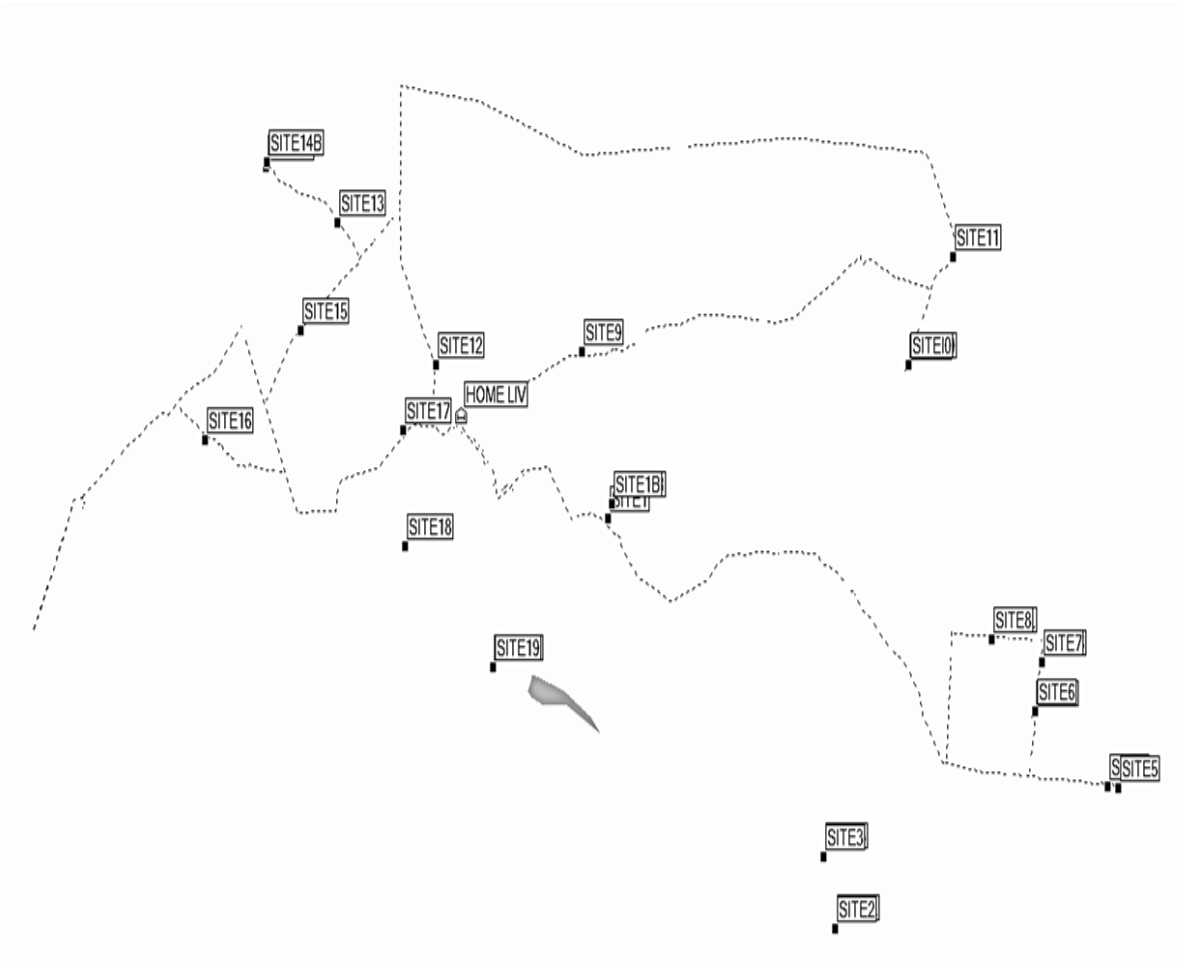


Figure 2: GPS in track mode (---) showing the trails made when visiting the sites by car at Liveringa station, HOME LIV was the location of the Liveringa homestead which was the base camp.

Appendix C: Multi-temporal indices

Comparison of raw and temporally filtered MODIS images

Using the selected Savitzky-Golay filter, temporally filtered images were compared. A comparison of the raw MODIS NDVI images versus the TIMESAT temporally filtered NDVI images were created in Arcmap for a visual comparison. The TIMESAT temporally filtered NDVI had a less paper and salt effect as compared to the raw NDVI values indicating a reduction in noise in the temporally filtered image (Figure 3).

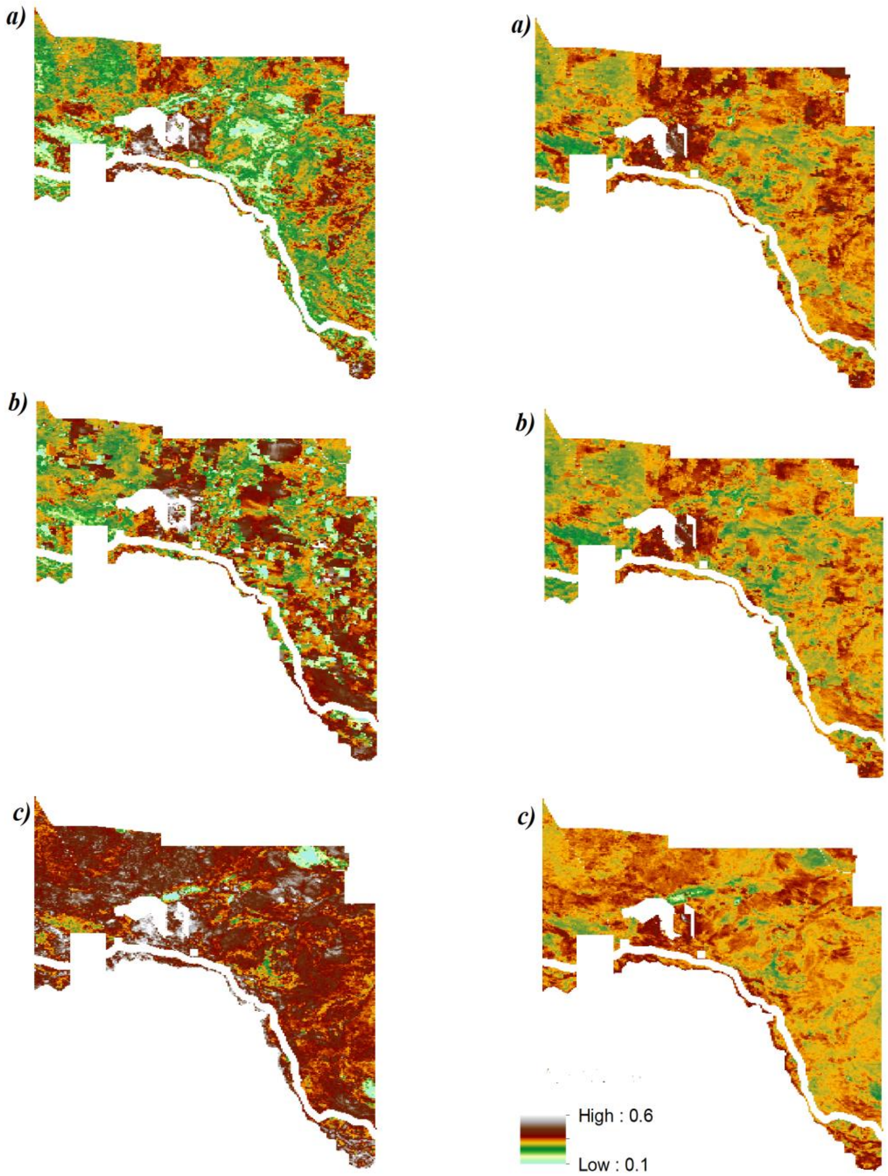


Figure 3: Seasonality fitted metrics during the peak growing season of February-April 2012. Left are the raw values and right are the SG temporally filtered values.

Open plains

Open plains sites exhibited the most homogeneity of the groups and were generally greener as they were located in the alluvial floodplains. The raw time series plot for site 10 compared the differences within neighbouring pixels (Figure 4). The NDVI as observed had a huge range from 0.2 (lowest) to 0.6 (highest).

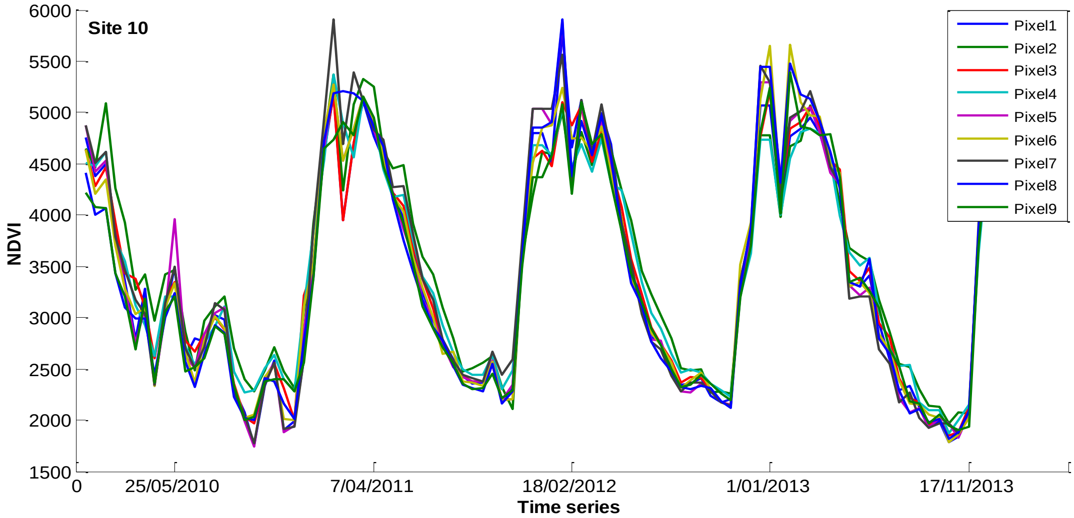


Figure 4: 9 pixels in a 3 x 3 window showing the importance of pixel selection for site 10.

Bunch grass

Bunch grass showed some differences within the neighbouring pixels (Figure 5) but not as variable as compared to the Spinifex group. Bunch grass are relatively uniform with marked differences in percentage soil cover which could cause the differences that were observed in the neighbouring pixels especially on the curve peaks.

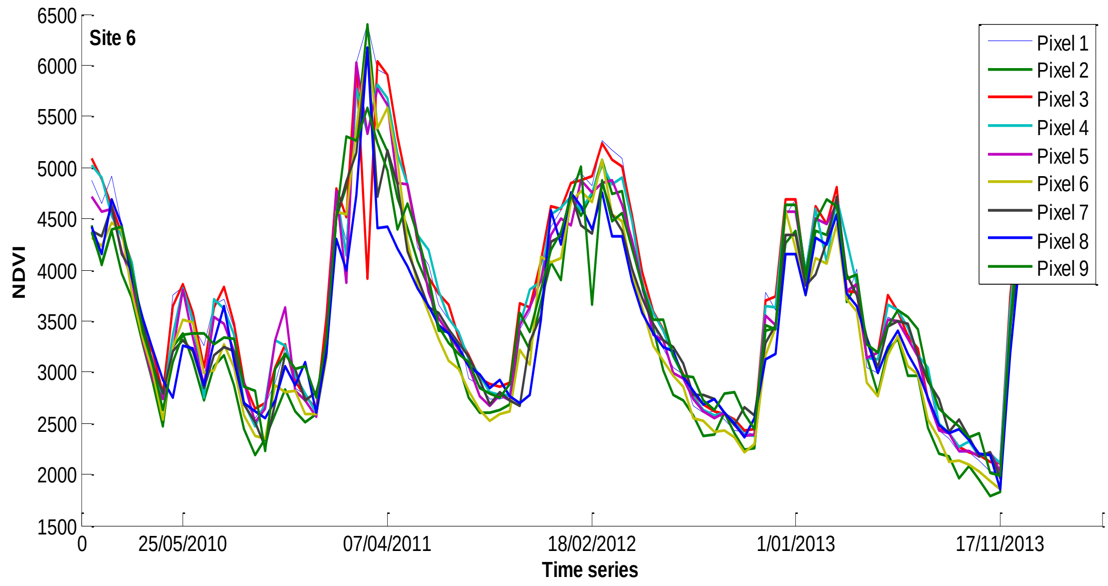


Figure 5: 9 pixels in a 3 x 3 window showing the importance of pixel selection for site 6.

Spatial Resolution

Figure 6 shows the scatter plot of site 10 as an example of the correlation that existed between the temporally filtered NDVI values and the raw MODIS NDVI data. All the site 10 pixels had correlations of above 0.9. This shows that there was a strong sensitivity between the raw and smoothed data as expected.

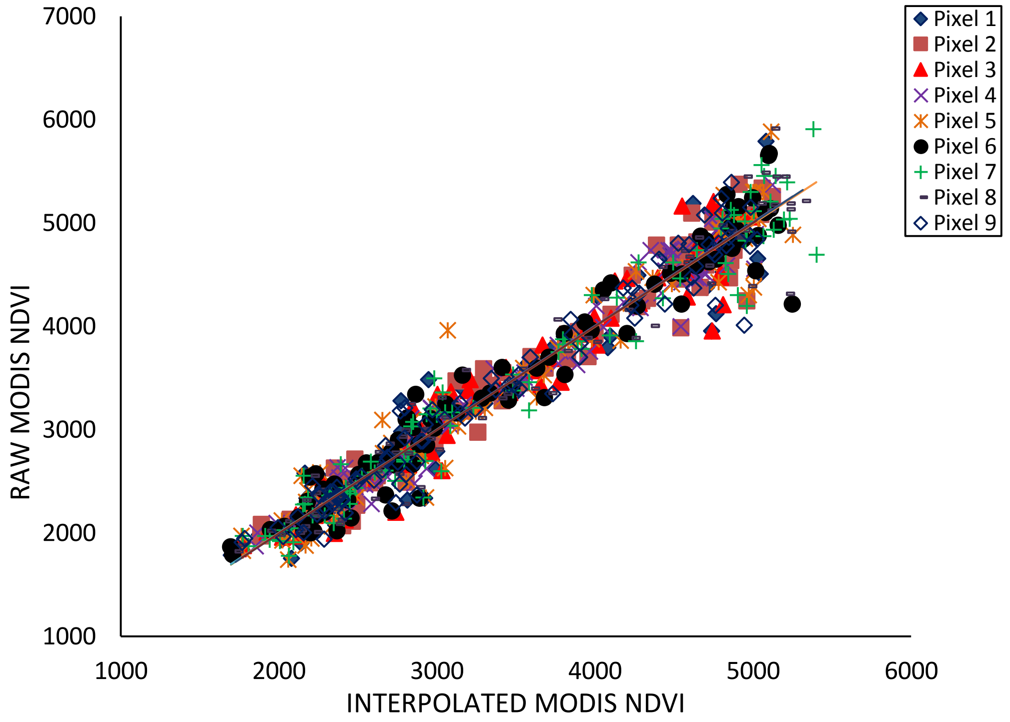


Figure 6:.Comparison of 9 pixels of site 10 TIMESAT temporally filtered MODIS values versus the MODIS raw values.

An interesting result obtained was that variations in the site groups make the combination of all sites into one plot less robust as they were distinct temporal differences exhibited by the MODIS NDVI and Landsat NDVI relationship (Figure 7). Temporal differences could also contribute to the no correlation hence regression for respective sampling periods as well vegetation groups might improve results in future. With the temporally filtered NDVI values data there was a reduction in the scatter in the range of values Figure 8. The TIMESAT temporally filtered range of NDVI values was lower than the MODIS raw values. This is because TIMESAT deals with outlier peaks in the time series as compared to the raw values.

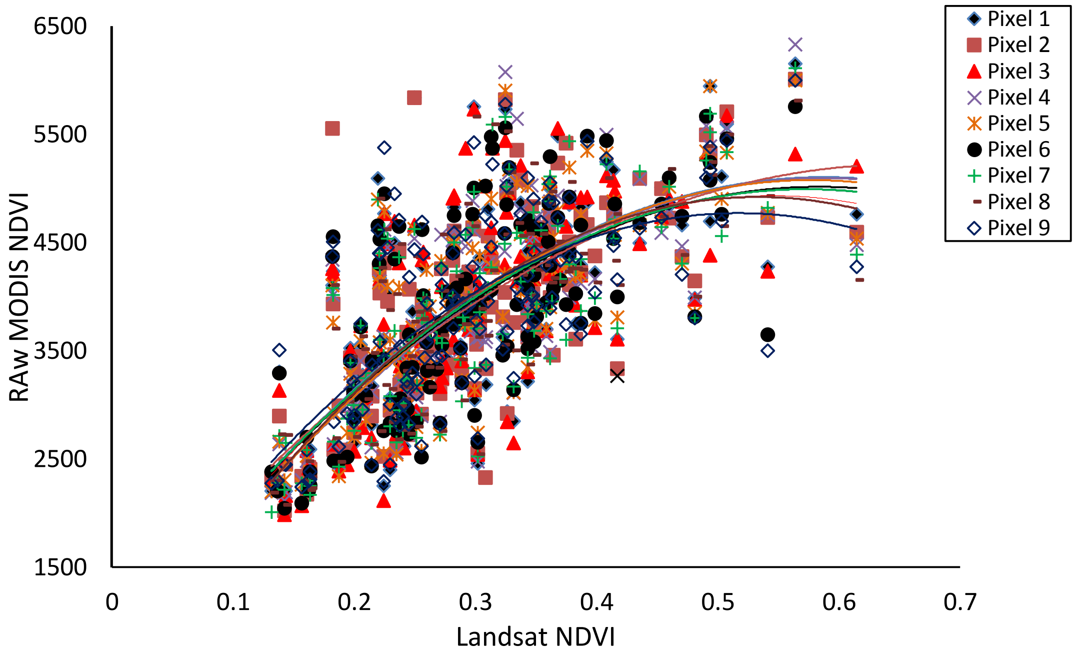


Figure 7: Raw MODIS data versus Landsat data.

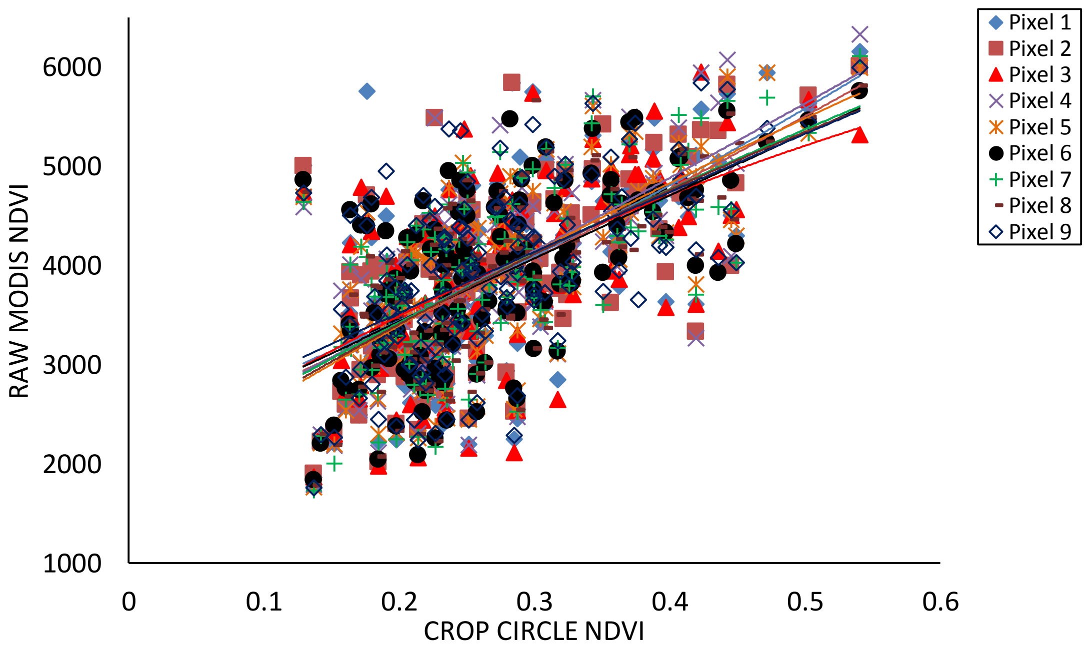


Figure 8: Raw MODIS data versus the Crop Circle NDVI.

i) Raw MODIS

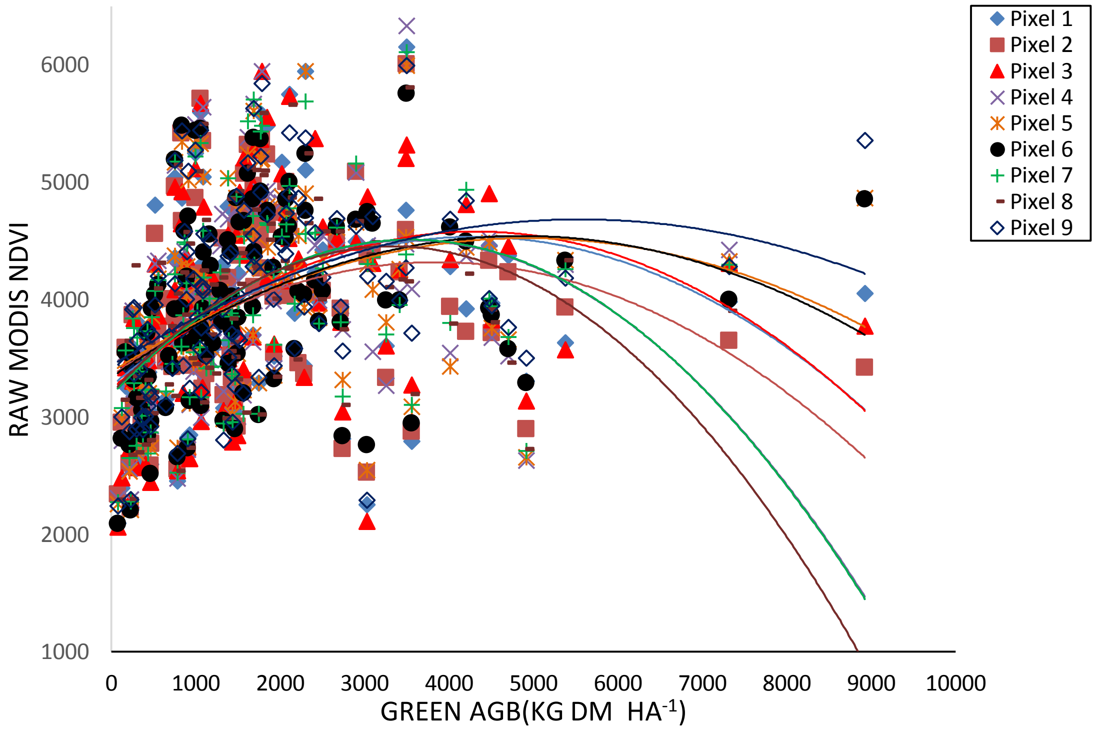


Figure 9: Raw MODIS NDVI with the green AGB.

Predictive models comparison with green AGB

Figure 10 shows the relationships between green AGB and raw MODIS NDVI. Various percentages of green AGB (50%, 60% and 70%) were plotted against the MODIS, Landsat and Crop Circle NDVI. This meant if 50% was used the assumption was that 50% of the AGB is green. Table 1 summarises the results.

Table. 1: Summary of the various green AGB percentages correlations with Landsat, MODIS, Landsat and Crop Circle NDVI.

Group	Crop Circle	Landsat	MODIS
		50%	
Open plains	0.3	0.4	0.1
Bunch grass	**0.5**	**0.5**	0.0
Spinifex	0.3	0.4	0.4
		60%	
Open plains	0.3	0.4	0.0
Bunch grass	0.3	0.3	**0.9**
Spinifex	**0.9**	**0.9**	**0.7**
		70%	
Open plains	0.0	0.4	0.1
Bunch grass	**0.6**	**0.6**	**0.9**
Spinifex	**0.9**	0.1	**0.9**

When the AGB percentages were increased, relationships significantly improve for the Spinifex and Bunch grass groups which previously did not have robust correlations with green AGB. However the relationships became poorer for the Open plains which previously had better correlations with AGB when plotted against all green AGB. The scatter plots for the Open plains and Spinifex groups as described in Table 1 are shown in Figure 10 and Figure 11 respectively. The scatter plot for the MODIS relationship is shown in Figure 13.

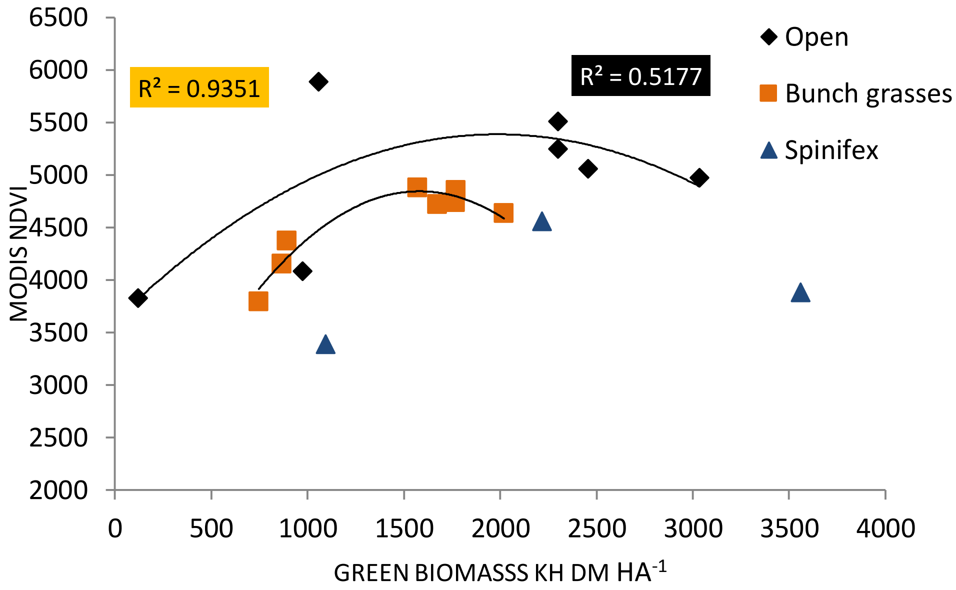


Figure 10: Plot for vegetation groups when greenness is greater than 0.65.

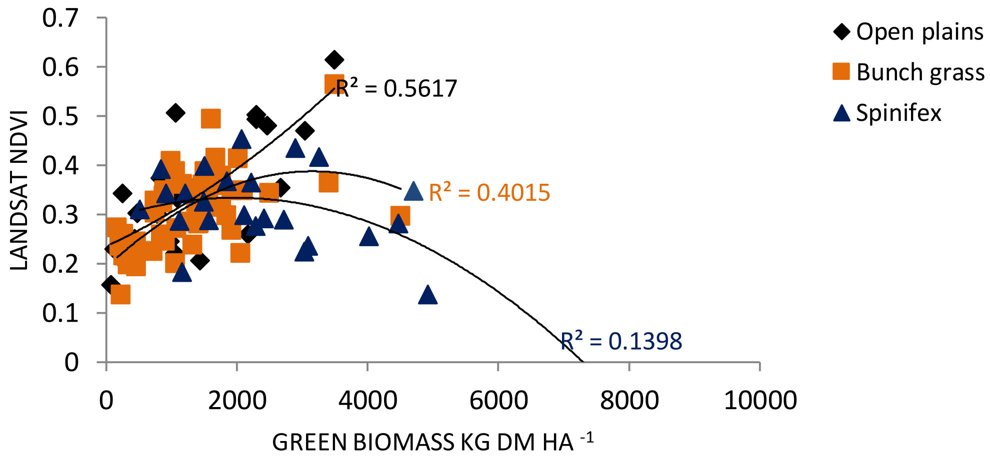


Figure 11: Green AGB for the different vegetation types compared with Landsat NDVI at 70% green AGB.

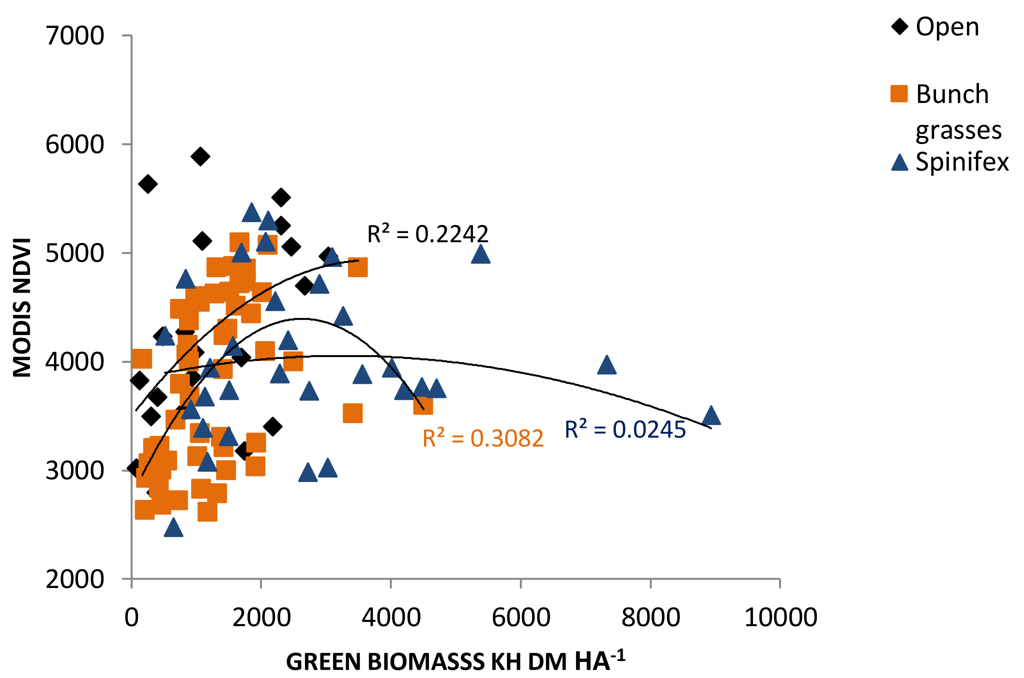


Figure 12: Green AGB for the different vegetation types compared with MODIS NDVI.

The time series for the Open plains group (sites 1, 3 and 10) Bunch grass group (Sites 6, 7 and 13) and Spinifex group (Sites 2, 9 and 12) were compared in order to help understand if the TIMESAT temporally filtered values would improve. The time series for Open plain (green), Spinifex (blue) and Bunch grass (pink) sites are shown in Figure 13. The NDVI curves show some distinctive trends within similar vegetation types. Open plain sites curves are evenly clustered together indicating lower spatial variability. This could be attributed to the annual grasses which are dominant in this group while the other groups do not have one dominant species. Bunch grass sites exhibit the same curves as the Open plains which showed low variability. For the Spinifex group, the curves show a lot of variation and this can be explained by the huge spatial heterogeneity within the group. This indicates that the different sites have similar behaviour within their groups and analysing the site groups might give worthwhile results as compared to all the sites combined together.

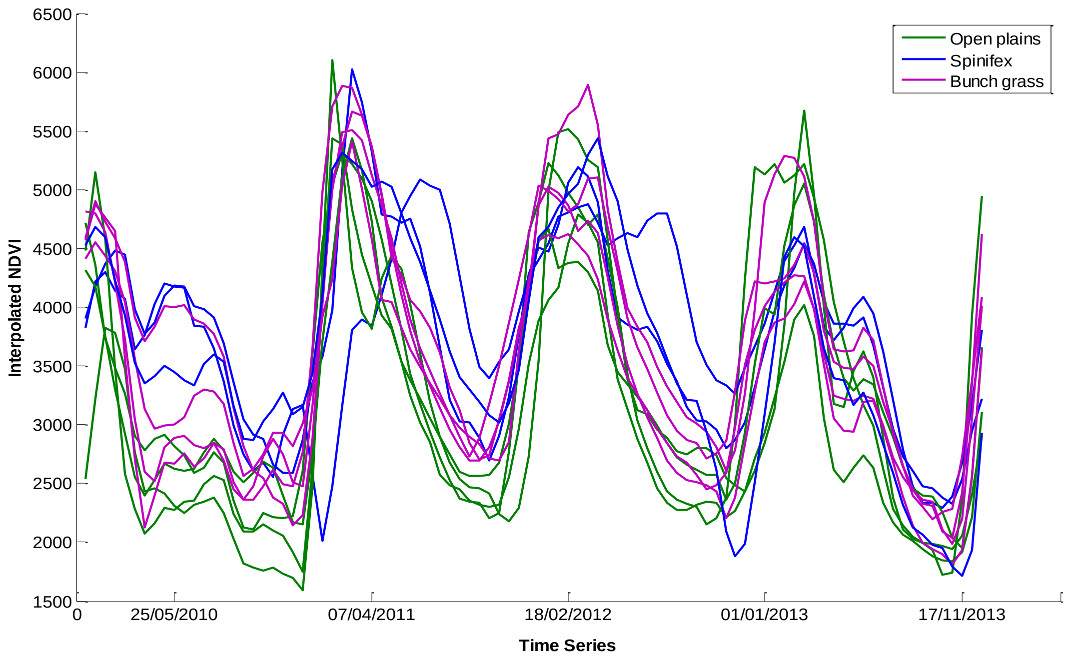


Figure 13: Differences of temporally filtered MODIS time series between crop types.

Since the Open plains sites had a reasonable relationship with green AGB, two sites were selected for the Open plains (site 3 and 10) and plotted against green AGB. The results indicated a strong correlation with green AGB as already shown on Figure 14. Site 3 had an R^2 value of 0.9 and site 10 had 0.8.

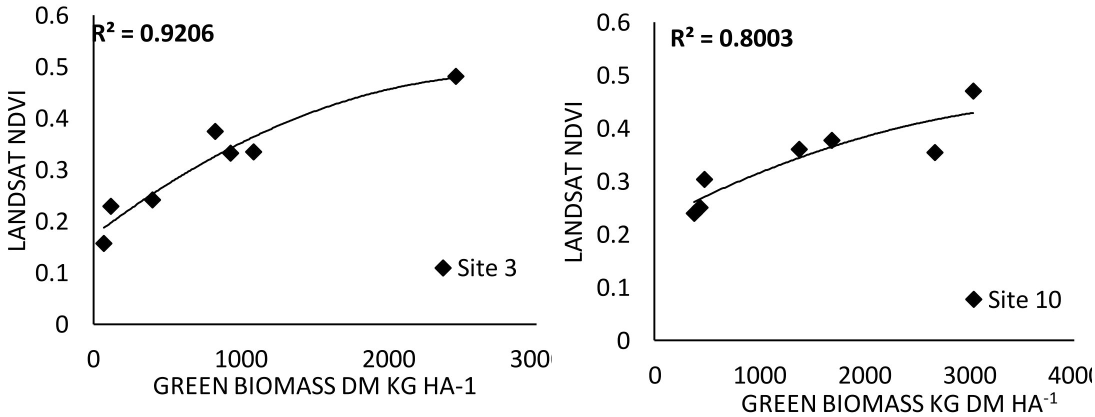


Figure 14: Site 3 and 10 (Open plains) versus green AGB.