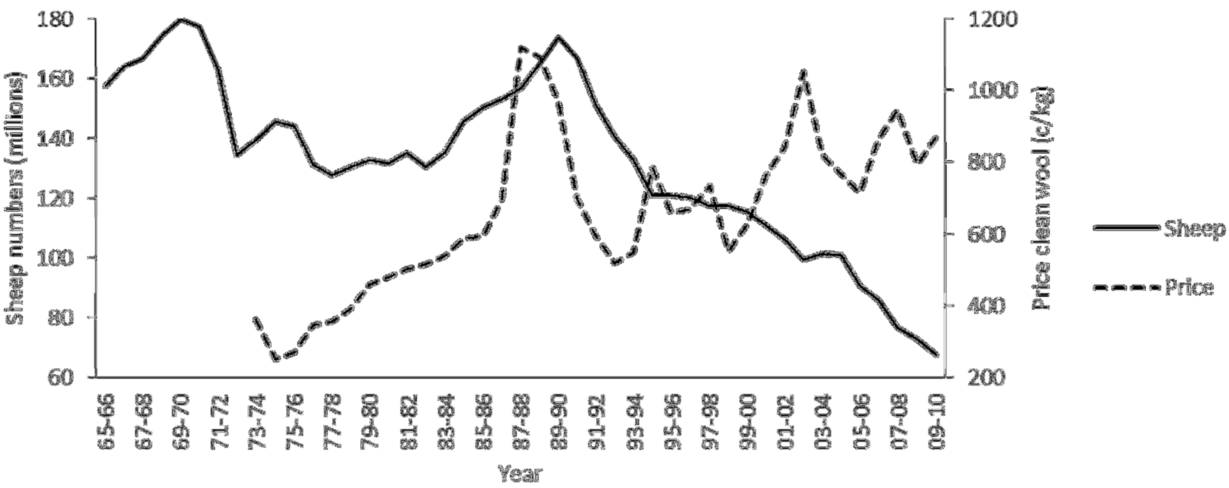
Chapter 1

Introduction

The wool industry is one of the oldest agricultural industries in Australia. In 1796 Macarthur introduced Merino sheep into Australia from South Africa. From this early base the industry grew until the phrase “Australia rides on the sheep’s back.” was heard in the 1940s (Munz, 1950) and 50s (Cottle, 2010). The largest number of sheep in Australia was recorded in 1969-70 (179.8 million) and a secondary peak was reached in 1989-90 (ABARE, 2010) due mainly to an inflated price (via a floor price scheme) paid for wool by the Australian Wool Corporation (Richardson, 2001) (Figure 1.1). Since the collapse of the floor price for wool in 1990-91 (Richardson, 2001) there has been a significant contraction of the industry (Perry, 2005). The number of sheep in Australia fell along with the number of mixed farms with sheep and enterprises that had in the past grown wool turned towards prime lamb production (ABARE, 2005). Wool, although in decline, still contributed \$3.8 billion in export income in 2002-3 (Barrett *et al.*, 2003) but had fallen to \$2.3 billion in 2009-10 as the wool price fell (ABARE, 2010).



(Source: ABARE, 2005; ABARE, 2010).

Figure 1.1: Sheep numbers (1966-2010) and wool price (1974-2010).

The Australian Bureau of Agricultural and Resource Economics (ABARE, 2006) and Australian Wool Innovation (AWI, 2008) have stated that the viability of the sheep industry would depend on the new farming techniques that lead to productivity gains. Nix (1981) separated the pathways to achieving goals in agriculture into four phases, including trial and error, transfer by analogy, statistical, multivariate analysis and systems analysis and simulation. Trial and error is a system that is still used in farming communities but if the errors outweigh the successes the consequences may be negative. Information at the farm level could reduce the risk of errors and Nix (1981) states that remote sensing can be integral in providing this information. Transfer by analogy relies on the principle that a system that works on one property will work on the next property. For this to work either the new technology must be transferable from one environment to another or uniformity of the farms is required. Transfer by analogy benefits from classifying agricultural areas into similar types, based on environment and management. Systems analysis and simulation requires proof of the relevance and accuracy of the simulation models. *"Effective control of a complex system requires feedback about the current state of that system."* (Nix, 1981).

The focus of AWI funded research is for graziers to use their pasture resources more efficiently (AWI, 2005). Sustainable use of pastures is vital to the long-term viability of the sheep industry. However, pasture resources in a grazing system are an integral component of a very complex system. To utilize pastures efficiently, and ensure sustainability, graziers need to manage their pasture resource and, to do so, they need to monitor the quantity and quality of pasture available. Remotely sensed data can be used to map the quantity of pasture available (Hill and Donald, 1997; Edrisinghhe *et al.*, 2000; Henry *et al.*, 2002; Hill, 2004; Hill *et al.*, 2004; Trotter *et al.*, 2010a; Edirisinghe *et al.*, 2011; Smith *et al.*, 2011).

In the present study the use of remotely sensed data to improve the efficiency of pasture utilisation by defining sheep grazing environment is explored. Feed quality (digestibility) (Reid, 1994) and quantity (kg DM/ha) will normally define the nutritional environment for grazing sheep, as per GRAZPLAN (Freer *et al.*, 2006). For the purposes of the present study sheep grazing environment is defined as the quantity (green dry matter (kg/ha)) and quality (digestibility) of pasture available to sheep. Nix (1981) has indicated that information at the farm level will reduce risk of errors. However, the accuracy of the information is critical (Sanderson *et al.*, 2001). Improving the accuracy and ease of collecting data that defines pasture resources will underpin any improvement in monitoring. The approach taken in the present study was to examine the application of remotely sensed data at different scales. There is large variation in pasture resources and pasture utilization within a paddock (Bailey, 1999) and producers want to be able to measure pasture resources at a scale relevant to their day–to-day management and, thus led to the development of the first hypothesis.

1.1 Hypothesis 1

Remotely sensed data could be used to map within paddock variation in pasture biomass in Mediterranean and temperate environments.

Pasture monitoring on a large property is difficult to sustain using traditional methods (House *et al.*, 2002). Many attempts have been made to develop inexpensive and accurate methods to measure pasture availability with limited success (Morley *et al.*, 1964; Earle and McGowan, 1979; Laca *et al.*, 1989; Gourley and McGowen, 1991; Mata *et al.*, 2002). Satellite and airborne remote sensing techniques have the ability to estimate quantity and quality of pasture over large areas (Henry *et al.*, 2002; Hill, 2004). However, the biggest limitation to the use of satellite and airborne systems remain the spatial and/or temporal resolution and/or user flexibility (Trotter *et al.*, 2010a). In addition, the spectral resolution of satellite systems may limit reliability (Roberts *et al.*, 1993; Numata *et al.*, 2007; Numata *et al.*, 2008). The present study is unique because the evaluation of a hand-held sensor, which could be used by farmers in the field, was conducted at two different environments over three years.

1.2 Significance of Hypothesis 1 to the Australian sheep industry

Development of a technique using a hand-held sensor that can accurately and precisely map the amount of green dry matter (GDM) in a paddock:

- will provide producers with a tool that can be used to monitor the amount of pasture available to stock,
- will enable producers to use pasture resources more efficiently, and
- could be used in grazing experiments to define grazing conditions.

The ability to predict GDM within a paddock will be useful for day-to-day management of pasture resources. However, pasture resources need to be managed to optimise meat and wool production on the whole property. One advantage of satellite data over a hand-held device is that the data are collected in a systematic way over a large area (Allan, 1990) and it has the potential to be used to predict meat and wool production for individual paddocks and the whole property. To improve confidence in the use of remotely sensed data there needs to be an established relationship between animal performance and remotely sensed data at a property scale and this led to two additional hypotheses. The second and third hypotheses were developed to explore the relationship between remotely sensed data, collected via satellite, and liveweight change and wool parameters.

1.3 Hypotheses 2 and 3

Remotely sensed data could be used to differentiate the grazing environment and monitor liveweight change of sheep grazing in different environments. (Hypothesis 2)

A vegetation index derived from satellite data could be used to monitor seasonal changes in wool fibre diameter. (Hypothesis 3)

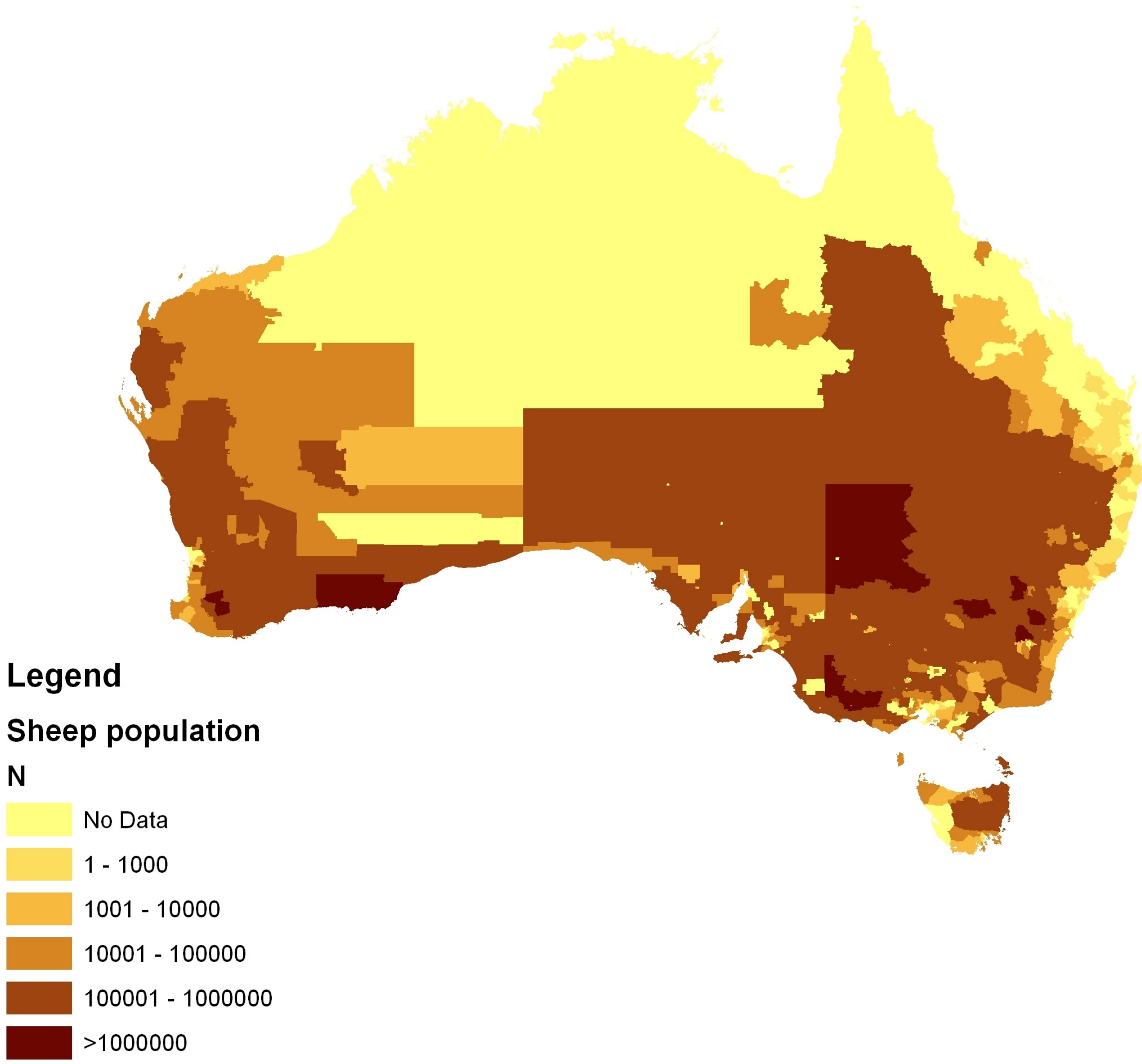
It is well established that there is a relationship between the quantity of pasture available and wool production and liveweight changes (Freer, 2002). However, measuring the quantity of pasture on a farm is time consuming. Many methods of estimating the pasture biomass have been developed but most are not accurate (Martin *et al.*, 2005) and there is evidence that farmers are reluctant to use skills they have acquired through training (Sneddon *et al.*, 2000). Although satellite-derived estimates of pasture availability have many advantages (e.g. systematic, can be retrospective, available at a variety of scales), producers need to be confident that the estimates are linked to animal production. Establishing relationships between animal production and remotely sensed data, collected via satellite, in Queensland, NSW, Victoria, Tasmania, South Australia and Western Australia has not been attempted.

1.4 Significance of Hypotheses 2 and 3 to the Australian sheep industry

Establishing a link between remotely sensed data and animal production:

- will enable growers to manipulate feeding to avoid tender wool,
- will provide a systematic approach to pasture monitoring in grazing experiments,
- has the potential to replace traditional methods of monitoring pasture resources,
- has the potential to improve wool production forecasting, and
- has the potential to assist the industry to adapt to climate change.

Sheep production in Australia is dependent on sheep grazing pasture (Cottle, 2010) and the sheep industry extends over a large proportion of Australia (Figure 1.2). As a consequence, sheep graze in vastly different environments from semi-arid environments in Queensland and western New South Wales (NSW) to temperate environments in Tasmania. Viewing the industry at a continental scale (Figure 1.2) it was clear that there needed to be a better definition of grazing environments. Grazing environments are presently divided into three very broad (High Rainfall, Wheat-sheep and Pastoral) zones (ABARE, 2006). Although environments that influence beef production (Bertrand *et al.*, 1985) and dairy production (Weigel and Rekaya, 2000) have been classified, there has been no attempt to develop a meaningful and robust classification of sheep grazing environments in Australia. The concept that remotely sensed data could be used to classify grazing environments led to the development of the fourth hypothesis.



(Source: Australian Bureau of Statistics, 2001)
Figure 1.2: Distribution of sheep population throughout Australia.

1.5 Hypothesis 4

Remotely sensed data and temperature could be combined to produce a meaningful and robust classification of the sheep grazing environments of Australia.

To be meaningful the classification needed to take into consideration the temporal and spatial variation of the grazing environment. The parameters used to derive the classification must be driving factors of animal production. The quantity and quality of pasture available to sheep are the major factors that limit production.

1.6 Significance of Hypothesis 4 to the Australian sheep industry

A meaningful and robust classification of sheep grazing environments would:

- enable producers to differentiate environments when selecting sires,
- have the potential to improve wool production forecasting, and
- have the potential to quantify changes in sheep grazing environment due to climate change.

For a classification to be considered robust there must be evidence that differences between classes reflect real differences in animal production, which led to the fifth, and final, hypothesis.

1.7 Hypothesis 5

The classification of sheep grazing environments could be used to detect genotype by environment interactions between linked flocks.

1.8 Significance of Hypothesis 5 to the Australian sheep industry

To use pasture resources efficiently graziers need to select sheep that are best suited to the quantity and quality of pasture available throughout the year on their property (Woolaston, 1985). With increasing sheep-meat prices, breeders select for carcass characteristics and reproductive characteristics important to prime lamb production whilst trying to maintain wool quality (Safari *et al.*, 2005). Breeders can select rams from a large area within Australia using a nationally recognised breeding value (Brown *et al.*, 2009) but the performance of the sire's progeny will be affected by the environment. In a survey of 436 Victorian wool producers 78% believed that the ranking of a sire would change in a different environment (Kaine *et al.*, 2002). Thus, breeders may overestimate the impact of genotype by environment interaction (GxE) and select sires from the local area in preference to superior sires from other regions. If a GxE is increasingly expressed as environments diverge (Carrick, 2005) then being able to differentiate environments will be a valuable tool to assist breeders select sires.

At present GxE is identified by year x flock effects in models (Brown *et al.*, 2009). No attempt has been made to differentiate environments on any quantitative measure (Woolaston, 1987; Carrick, 2005) but bioeconomic modelling shows that it is important (Young *et al.*, 2010). A robust classification of grazing environments can be used to quantify the potential GxE and put it into perspective. Breeders will be able to select sires with greater confidence knowing that the GxE would not be significant between similar grazing environments or they can avoid paying a premium for a sire whose progeny will not perform as expected. Although the sheep industry extends across a large proportion of the continent (Figure 1.2), there has not been an attempt to incorporate location into the Sheep Genetics database.

1.9 Overview of methodology

To determine whether remotely sensed data could be used to improve the efficiency of pasture utilisation in Australia, remotely sensed data at four scales were used. First, a comparison was made between pasture measurements at two sites (New England Tablelands, NSW and the Barossa Valley, South Australia) using a hand-held active optical sensor to determine the accuracy of the sensor for measuring within paddock variation of the amount of pasture available (to test Hypothesis 1). Secondly, satellite data were used as an estimate of the amount of pasture available in individual paddocks at four properties used by the Sheep CRC Information Nucleus Flock. The satellite-derived data were compared with liveweight change (to test Hypothesis 2). Thirdly, satellite data (NDVI) from properties throughout Australia were compared with fibre diameter profiles for the flocks to determine if remotely sensed data could be used to monitor the nutritional status of the flocks (to test Hypothesis 3). Finally, sheep grazing environments were defined at a continental scale. All sheep grazing areas of Australia (Figure 1.2) were classified into sheep grazing environments using satellite-derived normalised difference vegetation index (NDVI) and average monthly temperature data. The classification was compared with an existing zones used by (ABARE), results from a simulated grazing experiment and a survey of Weddin Shire, in NSW, to determine if it was meaningful to the sheep industry (to test Hypothesis 4). The Sheep Genetics database was used to verify that the classification was robust and sheep grazing environment classes (SGEclasses) could be used to detect GxE (to test Hypothesis 5).

1.10 Thesis structure

The thesis consists of a short introduction chapter (Chapter 1) followed by a literature review addressing areas relevant to the five hypotheses (Chapter 2). The following five chapters (Chapters 3 to 8) are draft publications that present a brief introduction, a description of the methods used, results and discussion section. The titles and authorship of each publication is presented in Table 1.1. An evaluation of the whole project is discussed in Chapter 8.

Table 1.1: Draft publications presented in Chapters 3 to 7 with the percentage contribution from Michael Whelan.

Hypothesis/ Chapter	Title of publication	Authorship	Whelan contribution
1/3	Active optical sensing and mapping of the green fraction of a pasture sward.	M.B. Whelan, D.W. Lamb, D. J. Cottle & K. G. Geenty	80%
2/4	Differentiating the grazing environment of sheep flocks using satellite remotely sensed data and temperature.	M.B. Whelan, K.G. Geenty, D.W. Lamb and D.J. Cottle	80%
3/5	Relationships between a satellite-derived vegetation index, wool profiles and staple strength in different sheep grazing environments.	M.B. Whelan, K.G. Geenty, D.J. Cottle, D.W. Lamb and G.E. Donald	80%
4/6	Classifying Australian sheep grazing environments using a Normalised Difference Vegetation Index and monthly average maximum temperature.	M.B. Whelan, D.W. Lamb, D. J. Cottle & K. G. Geenty	80 %
5/7	Classifying sheep grazing environments in Australia to quantify genotype by environment interaction using temperature and satellite data.	M.B. Whelan, D.J. Cottle, K.G. Geenty, D.W. Lamb and D.J. Brown	70%

Chapter 2
Literature Review

2.1 Introduction

With the collapse of the floor price for wool in 1990-1 came an exodus of growers from the industry (Richardson, 2001). Between 1992 and 2002 approximately 10,000 producers stopped running sheep. About a third of all farms in Australia produce some wool but 75% of the total wool clip is produced on 40% of those farms running sheep. Many wool growers also run cattle and grow crops (Barrett *et al.*, 2003). As the profitability of wool declined producers reduced their flock size to increase beef cattle numbers and cropping (ABARE, 2006). In addition to a move to cattle and cropping, sheep producers have been turning off more prime lambs because sheep meat exports (predominately lamb to the US market) has increased (Perry, 2005). However, exports to the US have declined recently (ABARE, 2010), probably due to the strong Australian dollar. In 1992 30% of wool producers sold lambs for slaughter but this proportion grew to 47% by 2002 (Barrett *et al.*, 2003). As a consequence, the number of ewes mated to meat breed sires has increased from 15% to 50% between 1990 and 2005 (Banks *et al.*, 2006).

The options of moving into cattle, cropping or turning off prime lambs are not available to specialist wool growers in drier regions of Australia. These producers must improve productivity to remain viable in the long term (ABARE, 2006) and using pasture resources more efficiently has the potential to increase the productivity (Young *et al.*, 2010). AWI has identified that producers need to increase productivity and lower costs and produce environmentally sustainable wool. They have recognised that to achieve this aim they need to adopt pasture technology to increase profit and improving pasture management and agronomy will help the wool industry survive climate change and increased climate variability (AWI, 2008).

The prime lamb industry has grown and the prospects for the near future are promising as there is growing global demand for Australian lamb (MLA, 2007; ABARE, 2010). Like AWI, Meat and Livestock Australia (MLA) recognise that it is vital to build resilience to climate change (MLA, 2007). Efficiency is recognised as the key to long-term prosperity of the meat industry.

New and innovative knowledge platforms will provide solutions to reducing costs and improving productivity. Development of genetic information to enhance flock performance is one strategy MLA identified to improve productivity. Accurate prediction of genetic merit for livestock is seen as a key way of improving productivity (MLA, 2007).

It is predicted that improving pasture utilisation by 1% would increase the value of the sheep meat industry by $35m over the next 25 years (MLA, 2006). The use of remotely sensed data to measure pasture is seen as a way of improving the efficiency of the use of perennial pastures (MLA, 2006).

2.2 Remote sensing

"Remote sensing is the science of drawing information about the Earth's land and water areas from images acquired from a distance." (Campbell, 1987)

Remote sensing has been used for many aspects of land management, (including agriculture, geology, land use planning, forestry and coastal management) (Lo, 1986). Satellite remote sensing is well suited to studies involving agricultural land because it has the capacity to view large areas of land simultaneously (Allan, 1990). Most remote sensing techniques rely on the interpretation of imagery derived from electromagnetic radiation (EMR) received by a sensor.

The electromagnetic spectrum represents the entire range of EMR. The spectrum, while continuous, is divided into spectral bands that share similar characteristics (Avery and Berlin, 1992) (Table 2.1). High-energy EMR (e.g. gamma rays) has very short wavelengths, while low-energy EMR (e.g. radio waves) has long wavelengths. Solar radiation absorbed by the Earth's surface is emitted (re-radiated) as thermal infrared EMR (7-18 µm) (Campbell, 1987). Thermal infrared EMR was not used in the present study.

Table 2.1: Principal divisions of the electromagnetic spectrum.

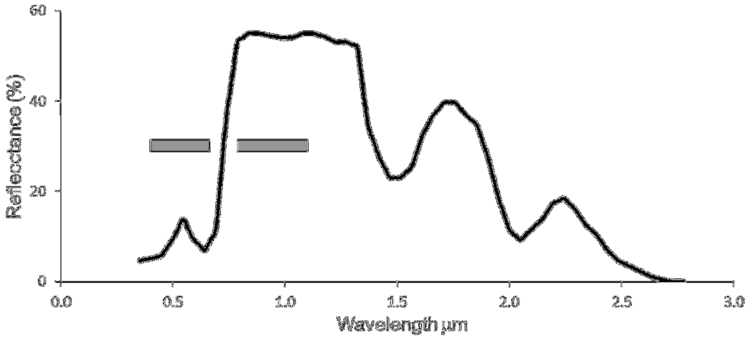
Division	Wavelength µm
Gamma rays and X-rays	<0.01
Far ultraviolet radiation	0.01-0.2
Mid ultraviolet radiation	0.2.0.3
Near ultraviolet radiation	0.3-0.4
Visible (Vis)	0.4-0.7
Near infrared radiation (NIR)	0.7-1.5
Mid infrared radiation (MIR)	1.5-5.6
Far infrared radiation (FIR)	5.6-1000
Microwave and Radio	>1000

(Source: Avery and Berlin, 1992)

The interaction of EMR with the pasture canopy plays an important role in defining grazing environment (the quantity and quality of pasture available to sheep). The response to EMR in the visible portion of the spectrum is dependent on the chlorophyll content of the leaf. Chlorophyll, and other pigments, in the leaf absorb EMR in the blue (0.4-0.5 µm) and red (0.6-0.7 µm) portions of the spectrum for use in photosynthesis (Figure 2.1). The green (0.5-0.6 µm) portion of the spectrum is absorbed to a lesser extent and is reflected. Because green light is reflected leaves appear green (Campbell *et al.*, 2005). Sensors used to map terrestrial areas usually detect EMR in the red and NIR portions of the spectrum to identify vegetation.

Soil background affects the reflectance (EMR bidirectional reflectance from the target) of a canopy. A dark toned soil will absorb red electromagnetic radiation so that as the leaf area of the canopy increases there is little change in the reflectance of red electromagnetic radiation (Figure 2.2). Infrared reflectance is not altered by soil background because it is not absorbed by soil (Curran, 1985). The influence soil background has on canopy reflectance will depend on the spectral properties of the soil and the canopy, solar zenith angle and atmospheric conditions (Huete, 1987).

a)



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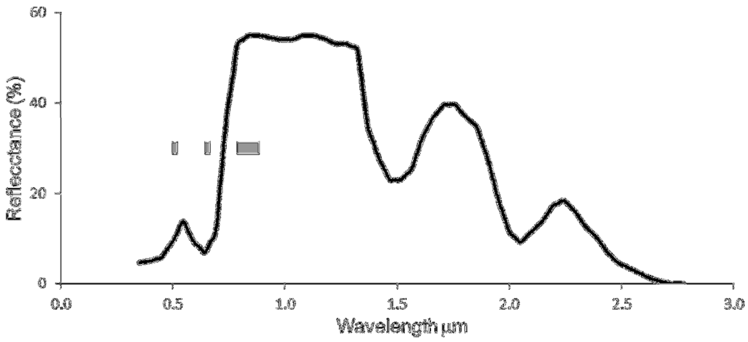

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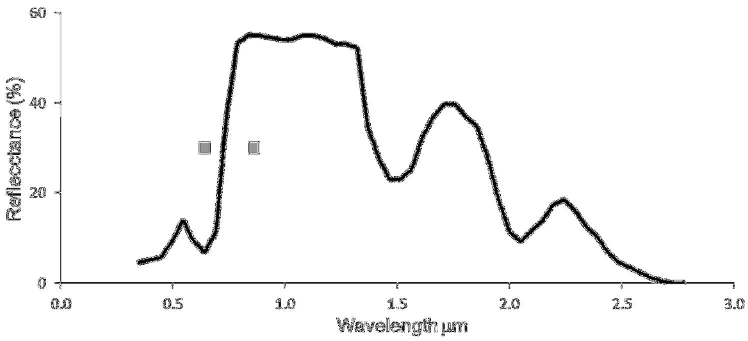

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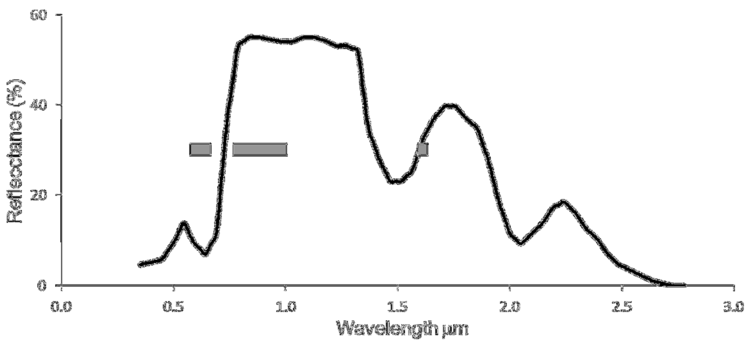
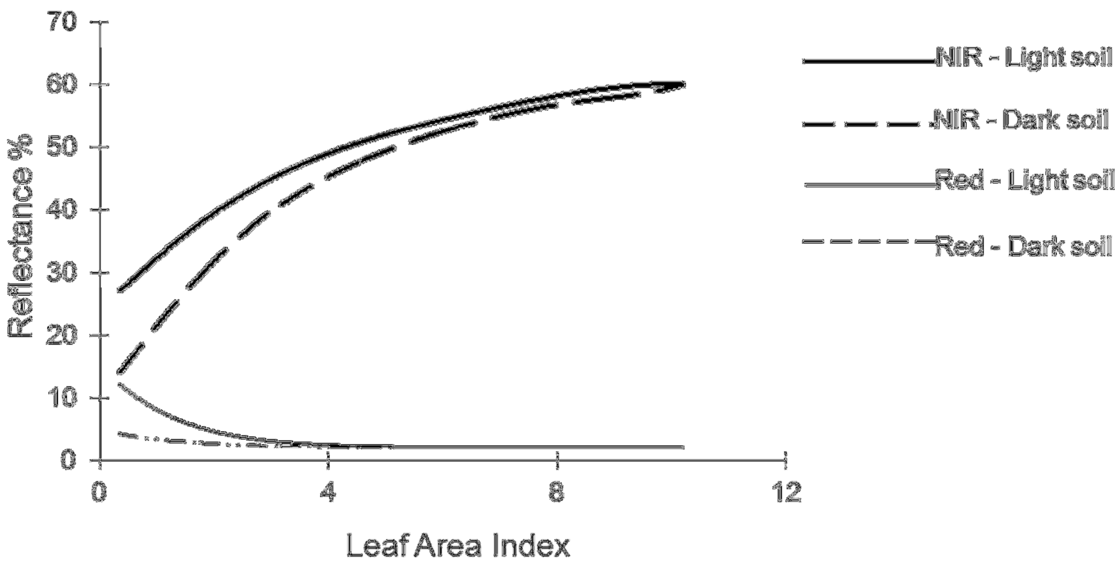


(Source: Knipling, 1970)

Figure 2.1: Spectral reflectance of a tobacco leaf with the spectral resolution of a) Crop Circle™, b) Satellite Pour l'Observation de la Terre (SPOT), c) Moderate Resolution Imaging Spectroradiometer (MODIS), and d) National Oceanic and Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer (AVHRR),



(Source: Curran, 1985)

Figure 2.2: Relationship between leaf area index (LAI) and red and near infrared (NIR) reflectance.

EMR reaches a remote sensor in one of three ways; (1) solar EMR reflected from the Earth's surface, (2) EMR emitted from the Earth's surface, and (3) EMR generated by an active sensor such as radar (Curran, 1985). The Crop Circle™ (used in the present study) is an active sensor that emits EMR in the red and near infrared (NIR) portion of the spectrum (Figure 2.1) (Holland *et al.*, 2004). To be useful in defining grazing environment, remote sensing must be sensitive to changes in pasture biomass. Three factors control the interaction of EMR with a grass canopy; (1) photosynthetic pigments, (2) spongy mesophyll structure, and (3) water content of the leaf (Colwell, 1974). Leaf area has an effect on red, green and NIR reflectance of the canopy (Tucker, 1979; Campbell, 1987).

Leaf area index (LAI), which is the area of leaf surface per unit area of soil surface (Campbell, 1987) is often used to differentiate crops and predict yield. LAI has a positive correlation with NIR reflectance because NIR radiation is scattered by leaves and absorbed by soil. Red light absorption is positively correlated with LAI because it is absorbed by chlorophyll. The changes in NIR reflectance continue as LAI increases long after red absorption has reached an asymptote because NIR radiation is transmitted into, and scattered by, subsequent leaf layers (Bauer, 1975). The relationship between red and NIR reflectance is used by researchers to create vegetation indices, which are used to estimate (Campbell, 1987), and monitor changes in (Justice and Hiernaux, 1986; Coops, 1999), vegetative cover.

2.2.1 Normalised difference vegetation index

Normalised difference vegetation index (NDVI) is the most commonly used vegetation index (Goel *et al.*, 2003). It is calculated using NIR and visible red reflectance values at each image pixel (Equation 2.1). The advantage of using NDVI derived from satellite data is that it makes it possible to make regular synoptic coverage over large areas (Justice and Hiernaux, 1986). NDVI can be calculated at any scale. For example, hand-held sensors (Holland Scientific, n.d.) can be used to calculate NDVI for small (43 by 8 cm) areas in the field. Satellite Pour l'Observation de la Terre (SPOT) data (minimum detection footprint of 20 m x 20 m) can be used to calculate NDVI and National Oceanic and Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer (AVHRR) satellite data, with a minimum detection footprint of 1.1 km x 1.1 km, are used to produce an NDVI map of the entire Australian continent every day (GeoScience Australia, 2009). Regardless of the scale used, mapping pasture biomass using remote sensing techniques that detect optical reflectance from pasture canopies rely on NDVI or a similar index. However, when pasture biomass is high NDVI reaches an asymptote (Hill *et al.*, 1998a; Hanna *et al.*, 1999; Zhao *et al.*, 2007; Smith *et al.*, 2011).

$$\mathrm{NDVI} = \frac{\mathrm{NIR} - \mathrm{R}}{\mathrm{NIR} + \mathrm{R}}$$

Where:

NDVI – Normalised difference vegetation index
NIR – Near infrared reflectance
R – Red reflectance

Equation 2.1: Formula used to calculate normalised difference vegetation index (Rouse *et al.*, 1973).

2.2.2 The concept of scale in remote sensing

Spatial resolution

The scale used to generate a map based on remotely sensed data depends on the spatial resolution of the data collected. Spatial resolution is level of detail depicted on an image (Harrison and Jupp, 1990). The area on the ground viewed by a scanning sensor (e.g. NOAA AVHRR) at any instant in time is an instantaneous field of view (IFOV) (Campbell, 1987). The spatial resolution of an image is defined by the pixel size. Although the pixel size can be changed to suit the application, the dimensions of the IFOV will remain constant. The spatial resolution of an imaging sensor (e.g. MODIS) is defined by the area on the ground represented by a single pixel (Justice *et al.*, 1998).

The spatial resolution of remotely sensed data is important in deciding the suitability of specific data for a particular task. For example, to map pasture biomass within a paddock requires a fine spatial resolution, for example SPOT 20 m x 20 m or a hand-held/vehicle-mounted instrument. To differentiate the grazing environment on one property from the next and to map differences in pasture biomass on a property or between paddocks MODIS data (250 m x 250 m) is suitable. To differentiate environments across the continent the spatial resolution of NOAA AVHRR data (1.1 km x 1.1 km) is ideal. The spatial resolution of common satellite remote sensing systems is presented in Table 2.2.

Table 2.2: Spatial, spectral and temporal resolution of common satellite remote sensing systems.

Sensor	Spatial resolution	Spectral resolution Bands: divisions*	Temporal resolution
Landsat 7 ETM+	30 m	7: Vis, NIR, MIR, FIR (120m)	16 days
Landsat 7 ETM+	15 m	1: Vis	16 days
MODIS	250 m	2: Vis, NIR	Daily
MODIS	500 m	5: Vis, NIR, MIR	Daily
MODIS	1000 m	28: Vis, NIR, MIR, FIR	Daily
NOAA AHVRR	1.1 km	5: Vis, NIR, MIR, FIR	Daily
SPOT	20 m	3: Vis, NIR	26 days

(Source: GeoScience Australia, 2009) *refer to Table 2.1

Spectral resolution

Spectral resolution is the range of wavelength intervals of EMR (Table 2.1) incorporated into each image channel (band) and or the number of channels in an image (Avery and Berlin, 1992; Lamb, 2000). Spectral resolution of common satellite remote sensing systems are presented in Table 2.2 and the spectral resolution of sensors used in the present study are illustrated in Figure 2.1. The sensor data most suitable for an application will be the one that will maximise the contrast between the background and the object of interest (Jensen, 1996). In the present study the object of interest is the quantity and quality of pasture that is available to grazing sheep.

Temporal resolution

Temporal resolution is the interval between successive image acquisitions for a given area (Campbell, 1987). The temporal resolution of the remotely sensed data will determine the suitability for some applications. Obtaining "real-time" data to influence day-to-day management decisions would require daily or weekly images as is available via Pastures from Space (PfS™) (Smith *et al.*, 2004; CSIRO, 2006; Fairport, n.d.). On the other hand, to classify grazing environments at a continental scale the period of data collection must be long enough so that annual patterns can be detected. To classify grazing environments a monthly image would be adequate.

2.3 Application of remote sensing in the sheep industry

To date the exploration of how remote sensing could be useful in the sheep industry has been dominated by the PfS™ group (Smith, 1994; Hill *et al.*, 1998b; Mata *et al.*, 2004; Smith *et al.*, 2004) but much of this research/application has focused on areas in Western Australia (Anderton *et al.*, 2004; Edirisinghe *et al.*, 2004b; Gherardi *et al.*, 2006; Smith *et al.*, 2011). There has been some mapping of land degradation attributed to sheep (Jafari *et al.*, 2008) and mapping grazing gradients in South Australia (Bastin *et al.*, 1993; Bastin *et al.*, 1998). Outside Australia, Posse Cingolani (2000) explored the relationship between NDVI and sheep production in Argentina. Remote sensing has the potential to be beneficial to the sheep industry at a variety of scales.

There is an established link between the amount of pasture available to sheep (pasture biomass) and pasture quality and wool production (Stewart *et al.*, 1961; Williams, 1991; Adams and Briegel, 1998; Doyle *et al.*, 1999; House *et al.*, 2002; Hyder *et al.*, 2002), and meat production (Mulholland *et al.*, 1976; McMeniman *et al.*, 1986; McMeniman *et al.*, 1989; Atiq-ur-Rehman *et al.*, 1999; Dominik *et al.*, 1999; Freudenberger *et al.*, 1999; Adams *et al.*, 2002; Hyder *et al.*, 2002; Robertson, 2006). The present study explores the application of remote sensing to define pasture biomass and quality as the grazing environment at scales from within a paddock to a continental scale. There is potential to improve pasture utilisation by mapping the pasture biomass within a paddock (Laca, 2009). To map at this scale the spatial resolution of airborne, vehicle-mounted or hand-held platforms is required.

2.4 Hypothesis 1

Remotely sensed data could be used to map within paddock variation in pasture biomass in Mediterranean and temperate environments.

There are benefits to the sheep industry if they manage their pastures closely (Trompf *et al.*, 1998; Doyle *et al.*, 1999; Bell and Allan, 2000; House *et al.*, 2002) and factors related to efficient use of pasture (stocking rate, pasture quality, persistence of pastures in dry times, always having sufficient feed) were rated highly by 2016 meat and wool producers for a successful grazing enterprise (Reeve *et al.*, 2000) (Table 2.3). However, “Paddock records” was rated lowest of 16 factors (Table 2.3). An objective method of assessing pasture will be more reliable than producers’ intuition (Hanna *et al.*, 1999) and systems, such as PROGRAZE, are integral to maintaining sustainable wool production (Crosthwaite, 2002). Bell and Allan (2000) recognised that to improve the efficiency and sustainability of grazing systems producers need to be able to assess the quantity (biomass) and quality (species composition and digestibility) of pasture available to sheep. Assessment of the PROGRAZE training revealed that 89% of respondents thought that it increased return and 91% thought that it led to more sustainable practices (Bell and Allan, 2000). However, less than 50% of farmers put pasture estimation training into effect (Sneddon *et al.*, 2000). Estimating pasture biomass on large properties is difficult (House *et al.*, 2002) and using a sampling technique that requires harvesting a small area will be inaccurate because of density variations within the paddock (Hanna *et al.*, 1999).

Table 2.3: Factors regarded by 2016 meat and wool producers as very important in the success of a grazing enterprise.

Factor	Proportion of respondents (%)	Ranking
Stock water supplies	83.5	1
Animal health	83.1	2
Stocking rate	80.3	3
Caring for the land	71.3	4
Pasture quality	71.0	5
Financial management	71.0	5
Persistence of pastures in dry times	69.7	7
Carry out stock husbandry practices on time	69.1	8
Marketing of stock	66.9	9
Always having sufficient feed	65.5	10
Breeding and culling program	64.4	11
Quality stock	64.0	12
Adequate fodder reserves	62.2	13
Method of grazing management	53.9	14
Stock records	40.1	15
Paddock records	28.1	16

(Source: Reeve *et al.*, 2000)

2.4.1 Causes of within a paddock variation of pasture resources

According to Hodgson (1993) variation in the pasture sward is due to the following.

- Distribution of different pasture species.
- Plants at different stages of growth.
- Small scale variation in soil.
- Small scale variation in climate.
- Uneven effects of grazing.
- Uneven effects of treading.
- Uneven distribution of excreta.

The size of the paddock also has an effect on variation (Laca, 2009). For example, if we take two paddocks. On the first 100 sheep graze 100 ha and on the on second 1000 sheep graze 1000 ha. Although the stocking rate is the same, the paddocks are not homogeneous and grazing pressure will vary more in the larger paddock (Laca, 2009). Grazing patterns will depend on abiotic factors (e.g. distance from water and slope), biotic factors (e.g. pasture quality and quantity), social factors (e.g. herding) and other factors (e.g. shade seeking in hot weather) (George *et al.*, 2007). In addition, there are management factors that can influence grazing patterns (e.g. fences, position of tracks, fertiliser application and feeding sites) (George *et al.*, 2007). Laca (2009) recommended measuring at multiple scales in grazing research.

2.4.2 Measuring pasture biomass

Methods used to measure pasture biomass in grazing experiments vary depending on the level of funding for the project and the dependence on reliable pasture estimates to interpret the results. When, for example, strains of sheep are grazed together (Adams and Briegel, 1998) detailed pasture records may not enhance interpretation of the results. On the other hand, when different management options for similar genotypes are being evaluated detailed pasture records are critical to the success of the project (Doyle *et al.*, 1999). The frequency of measurement during the experiment varies from twice in six months (Mata *et al.*, 2002) to weekly (Osoro *et al.*, 1999). A sample of techniques that are used to measure pasture biomass and pasture quality in grazing experiments is presented in Table 2.4.

Table 2.4: Examples of physical and visual methods of pasture assessment/sampling used in grazing experiments.

Study	Measure	Technique
Adams & Briegel (1998)	Pasture quality and pasture biomass	Subjective visual assessment
Doyle*, et al.* (1999)	Green feed on offer	Visual appraisal with calibration
	Species composition	
	Pasture growth rate	Cage measurements
	Dry matter solubility	Quadrat sampling
	Crude protein	
Schlink*, et al.* (1999)	Total dry matter	Quadrat sampling
	Dry matter digestibility	
	N content	
Mata*, et al.* (2002)	Per cent green grass	Quadrat sampling
	Per cent green clover	
	Per cent green other	
	Total dry matter	
Andrew & Lodge (2003)	Per cent green	Quadrat sampling based on
	Species composition	BOTANAL methodology.
	Total dry matter	
	Litter	

It is evident that there is a variety of methods employed in estimating pasture biomass making comparisons difficult (Table 2.4). No single method of measuring pasture biomass and pasture quality has been adopted as "best practice". Andrew and Lodge (2003) used a technique developed by Tothill*, et al.* (1978) to estimate pasture resources in the Sustainable Grazing Systems experiment. Tothill*, et al.* (1978) who developed the BOTANAL methodology have been cited in over 80 articles (ISI Web of Knowledge Cited Reference Search) where pasture measurements were made.

2.4.3 Non-destructive pasture sampling

In a review of methods used to sample biomass, Catchpole (1992) regarded destructive methods (locate, cut, sort, dry and weigh) as accurate at a single point but are expensive techniques in terms of labour. Because of the high cost, few samples can be taken and extrapolating to a whole study is problematic (Haydock and Shaw, 1975). Sampling techniques are of great importance when representing areas with a few samples. Given the spatial variability of the pasture being sampled a larger number of less accurate samples may be a more reliable method of estimating pasture biomass in a paddock (Haydock and Shaw, 1975; Harmoney *et al.*, 1997). In practice farmers would not use destructive sampling because it is time-consuming and would not provide timely results for day-to-day pasture management (Murphy *et al.*, 1995). A non-destructive method is needed to improve pasture management on the farm (Murphy *et al.*, 1995).

Indirect and non-destructive measures have the advantage of reduced labour. Non-destructive methods can provide an estimate where an absolute measure is not required (Frame, 1993). Double sampling methods have been used to quantify the variation that exists within a paddock. Destructive sapling is used to calibrate a cheaper and less accurate method (e.g. raising plate meter, visual assessment). A good double sampling technique is one where the calibration remains constant across a number of factors (e.g. season, year, pasture type, management and species) (Laca *et al.*, 1989). A number of non-destructive methods have been developed to measure green dry matter (GDM) in the sward; visual estimation (Campbell and Arnold, 1973), visual estimation using a standard (Morley *et al.*, 1964; Haydock and Shaw, 1975), rising plate meter that takes into account pasture height and pasture density (Earle and McGowan, 1979), electronic capacitance (Neal *et al.*, 1976) and a falling plate meter (Sharrow, 1984). The reliability of various methods is presented in Table 2.5.

Table 2.5: Reliability (R^2 and root mean square error (RMSE)) of physical non-destructive and non-optical methods of pasture biomass estimation.

Source	Method	Reliability	RMSE (kg/ha)	N
Campbell & Arnold (1973)	Visual assessment	$0.27 < R^2 < 0.86$	NA	11
Haydock & Shaw (1975)	Visual assessment of height and density	$0.96 < R^2 < 1.00$	134-893	5-9
Neal *et al.* (1976)	Electronic capacitance	$0.56 < R^2 < 0.79$	283-974	20
Earle & McGowan (1979)	Automated raising plate meter	R^2 0.97	264	12
Sharrow (1984)	Falling plate meter	$0.70 < R^2 < 0.91$	NA	20-30
Scrivner *et al.* (1986)	Rising plate meter	$0.42 < R^2 < 0.94$	105-239	4-12
Laca, *et al.* (1989)	Visual assessment vs. fresh weight	$0.79 < R^2 < 0.91$	341-986	13-120
Laca, *et al.* (1989)	Raising plate vs. fresh weight	$0.04 < R^2 < 0.82$	250-1364	6-120
Murphy, *et al.* (1995)	Sward stick	$0.10 < R^2 < 0.49$	NA	120
Murphy, *et al.* (1995)	Capacitance	$0.13 < R^2 < 0.42$	NA	120
Murphy, *et al.* (1995)	Raising plate meter	$0.002 < R^2 < 0.52$	NA	120
Harmoney, *et al.* (1997)	Pasture height using Ropel Pole	$0.43 < R^2 < 0.83$	500-1650	7-212
Harmoney, *et al.* (1997)	Raising plate meter	$0.36 < R^2 < 0.84$	292-1739	7-212
Harmoney, *et al.* (1997)	Pasture height using ruler	$0.08 < R^2 < 0.81$	639-1718	7-212
Harmoney, *et al.* (1997)	Leaf canopy analyser based on leaf area index	$0.18 < R^2 < 0.47$	632-2187	7-212
Lokhorst and Kasper (1998)	Raising plate meter	R^2 0.32	NA	99
Sanderson, *et al.* (2001)	Raising plate meter	R^2 0.31	447-653	15
Sanderson, *et al.* (2001)	Capacitance	$0.14 < R^2 <0.19$	535-762	15
Sanderson, *et al.* (2001)	Pasture height	$0.07 < R^2 <0.14$	500-690	15
Correll, *et al.* (2003)	Raising plate meter	$R^2 >0.90$	NA	70
Ehlert, *et al.* (2003)	Pendulum meter	$0.85 < R^2 <0.99$	NA	16-36
Martin, *et al.* (2005)	Visual	$0.03 < R^2 <0.93$	NA	30
Martin, *et al.* (2005)	Raising plate meter	$0.04 < R^2 <0.86$	NA	30
Martin, *et al.* (2005)	Capacitance	$0.07 < R^2 <0.92$	NA	30
Tsutsumi and Itano (2005)	Capacitance	$0.62 < R^2 <0.69$	NA	24

The PROGRAZE system was developed to assist producers to assess pasture resources and animal productivity quickly and easily (Bell and Allan, 2000; MLA, 2009) and, therefore, improve pasture management. PROGRAZE uses pasture height to estimate the GDM (Equation 2.2). Other equations have been published. For example, Equation 2.3 uses pasture height measured using a rising plate meter (Earle and McGowan, 1979) to predict GDM and Harmoney *et al.* (1997) found that the slope and intercept varied depending on the pasture species in the sward (Equations 2.4 and 2.5).

$$\text{GDM kg/ha} = 160.7 * \text{pasture height (cm)} + 722.2$$

Equation 2.2: Equation used to estimate green dry matter (GDM) from pasture height (MLA, 2009).

$$\text{GDM kg/ha} = 155.0 * \text{pasture height (cm)} + 762.0$$

Equation 2.3: Equation used to estimate green dry matter (GDM) from pasture height measured with a raising plate meter (Earle and McGowan, 1979).

GDM kg/ha = (33.6 to 81.0) * pasture height (cm) + -1137.9 to 1987.7

Equation 2.4: Equation used to estimate green dry matter (GDM) from pasture height measured with a pasture stick for a variety of pasture species (Harmoney *et al.*, 1997).

GDM kg/ha = (116.8 to 364.2) * pasture height (cm) + -1037.5 to 2058.9

Equation 2.5: Equation used to estimate green dry matter (GDM) from pasture height measured with a raising plate meter for a variety of pasture species (Harmoney *et al.*, 1997).

In a comprehensive evaluation of non-destructive methods of estimating pasture biomass (Martin *et al.*, 2005) concluded that destructive sampling was the only reliable method. The reliability of non-destructive methods fluctuates wildly (Table 2.5) and some sources quote high R^2 values based on very small sample sizes. Harmoney, *et al.* (1997) compared four non-destructive methods. They found that reliability varied (Table 2.5) and the slope of the line used to estimate biomass fluctuated by a factor of 2.2 - Ropel Pole, 2.4 - pasture height (Equation 2.4), 3.1 - raising plate meter (Equation 2.5) and 5.2 - leaf area index. The variation in slope casts doubt on any non-destructive method of pasture biomass estimation being reliable without calibration. It also illustrates that the relationship between leaf area and biomass may not be reliable enough to be useful for grazing management.

For a non-destructive method to be employed by producers it will need to predict green dry matter (GDM) accurately. Laca *et al.* (1989) found that visual assessment gave better estimations of fresh biomass but commented that per cent DM would be required to make any estimation useful when estimating the value of the pasture sward to grazing stock. Sanderson, *et al.* (2001) reported such low reliability that none of the three methods evaluated could be considered accurate enough to make pasture biomass estimations useful to producers. Local calibration would be necessary for reliable estimates to be made (Earle and McGowan, 1979; Sanderson *et al.*, 2001; Tsutsumi and Itano, 2005). Hodgson (1993) put forward a strong argument when evaluating the differences between techniques used to measure pasture biomass that the differences may well be true biological differences and not inaccuracies in the technique.

Any non-destructive method must be reliable (Sanderson *et al.*, 2001). A methodology relying on remote sensing will need to be as accurate and easy to use as other non-destructive methods, e.g. pasture height, before they will be adopted. Systems such as PROGRAZE have no spatial component but provide paddock or farm averages and variability across the farm or within the paddock cannot be mapped easily. A pendulum-meter that could be mounted to a vehicle and connected to a global positioning system (GPS) has been developed to map biomass (Ehlert *et al.*, 2003).

2.4.4 Mapping within paddock variation in pasture biomass

Mapping pasture biomass over the extent of the farm requires a system that is linked to a GPS to record the geographic coordinates of the sample site. Some attempts have been made to estimate pasture biomass accurately within the entire paddock to find an average for the paddock. These methods attempt to account for the high variability of pasture biomass within a paddock (Earle and McGowan, 1979; Flynn, 2006). Robertson (2006) found that pasture growth varied more within farms on the Mallee than between farms and Hutchings (1991) found that variation in the sward height was dominated by variation within 1 to 2 m of the transects. Within paddock mapping of pasture biomass would have application in strip and rotational grazing systems (Mata *et al.*, 2002). For example, the pasture biomass can be used to graze pastures to a specified residual biomass and manage stock and pasture using quantitative measures (Edrisinghhe *et al.*, 2000). Smith *et al.* (2011) suggested a feed on offer (FOO) trigger value of 500 kg DM/ha to avoid a rapid decrease in wool fibre diameter and weight loss.

Some research has tracked animals with a GPS attached to determine the pasture resources they have grazed (Tomkins and O'Reagain, 2007; Trotter *et al.*, 2010b) and quantify grazing pressure (Kawamura *et al.*, 2005). Tomkins and O'Reagain (2007) considered the technology could be used to better utilise different pasture resources on a property. Grazing animals with GPS fitted combined with near real-time mapping of paddock pasture resources could help to improve pasture utilisation. Research indicates that there is the potential to select animals to improve grazing distribution (Bailey, 1999; Stassen, 2009).

2.4.5 Remote sensing methods of estimating within paddock biomass

For remotely sensed data to be useful to manage pasture resources within paddock it needs to be:

- at spatial resolution fine enough to be able to differentiate areas within the paddock,
- collected at near real-time,
- be a reliable predictor of animal performance, and
- cost effective.

Hill (2004) identified the following 10 structural factors that impact on the interaction of EMR and grassland.

- Height.
- Variation in height.
- Soil coverage.
- Leaf area.
- Leaf orientation.
- Density.
- Proportion of senescent material.
- Moisture content.
- Pigmentation.
- Spatial arrangement of structures.
- Variability due to species diversity.

Colwell (1974) reported that the reflectance of EMR is dependent on the water content of the leaf. As a consequence, NDVI is also sensitive to the water content of the leaf. Lokhorst and Kasper (1998), for example, found a weak (R^2 0.14) negative correlation between NDVI and dry matter per cent in the pasture sward. Monitoring pasture always relies on measuring dry matter content of the pasture (Table 2.5) because water has no nutritional value.

Gitelson *et al.* (2002) found that leaf arrangement in the canopy impacted on the reflectance of NIR. Leaf structure and function also affects reflectance and absorbance in the canopy (Tucker and Sellers, 1986). NIR reflectance has a negative correlation with the percentage of senescent material in the sward and soil moisture (Gitelson *et al.*, 2002).

Hill*, et al.* (1999a) used satellite data to classify pasture type (species composition) within the paddock. The pasture type was then used as a parameter in a simulation model that predicted animal production. It was possible to identify areas within paddocks that have lower than average production that could dictate fertiliser application on the property. However, they did not use the satellite data to predict pasture biomass. A hand-held sensor will be able to detect variation that is below the resolution of satellite systems (Hill, 2004).

The hand-held and vehicle-mounted sensors are able to record reflectance at a very fine spatial resolution (Holland *et al.*, 2004). A clear advantage of remote sensing techniques is that they are non-destructive and acquired rapidly (Di Bella *et al.*, 2004b). Hand-held and vehicle-mounted sensors can be connected to a GPS and as soon as the data are downloaded and incorporated into mapping software the data can be used to generate a near real-time map of the pasture biomass. They are used frequently in cropping enterprises. For example, active sensors connected to GPS have been used to map the density of weeds and the percentage coverage of cotton crops (Sui *et al.*, 2008).

Passive Sensors

The reliability of hand-held and vehicle-mounted passive sensors to estimate pasture biomass is not consistent. For each study that reports reliable predictions another will report poor results. In addition many "successful" experiments rely on hyperspectral data and the authors often optimise the wavelengths used to calculate vegetation indices to get the best results. For example, Steyn-Ross*, et al.* (1998) incorporated green reflectance to improve accuracy. Much of the work by Starks*, et al.* (Starks *et al.*, 2006a; Starks *et al.*, 2006b; Zhao *et al.*, 2007; Starks *et al.*, 2008) optimises band ratios of hyperspectral data to produce reliable predictions of biomass. Lokhorst and Kasper (1998) found very low correlations between pasture biomass and NDVI (R^2 0.07) and biomass and pasture height (R^2 0.32) but concluded that there were "no big differences" between CropScan^{TM} (used to measure NDVI) and the raising plate meter (used to measure pasture height). The results of other studies that used passive sensors, which could be used to map within paddock variation, are presented in Table 2.6.

Table 2.6: Examples of mapping of within paddock variation of pasture resources using passive optical sensors (green dry matter – GDM; total dry matter – TDM; RMSE - root mean square error).

Author	Comment
Lokhorst and Kasper (1998)	CropScan™ (a passive hand-held radiometer) was compared with pasture height to estimate TDM. Reliability was very low (R^2 0.07, RMSE not available).
Hanna, *et al.* (1999)	Combined three bands (NIR, red and green) to predict GDM (R^2 0.93 and RMSE 262 kg/ha). However, these results were achieved after removal of "outliers". Points with either more than 4000 kg/ha, or more than 3000 kg dead material or swards dominated by C_4 plants in the sward.
Ganguli, *et al.* (2000)	A hand-held remote sensing device (LAI 2000) did not perform any better (R^2 0.34 RMSE 613 kg/ha) than home-made devices (R^2 0.37 to 0.85 RMSE 445 to 691 kg/ha) costing less than 1% of the LAI2000 when used to measure TDM.
Schut (2003)	Schut used mini swards to develop methods to estimate TDM using spectroscopy. Relationships were very strong ($0.59 < R^2 < 0.84$, RMSE 163 to 689 kg/ha) and they were considered better than pasture height ($0.55 < R^2 < 0.66$, RMSE 555 to 645 kg/ha). Extending the methodology into a farming context appeared problematic.
Tarr, *et al.* (2005)	Suggested that measurement of pasture LAI with ground based remote sensing would provide quick and non-destructive quantification of TDM. However, the reliability of predictions (using NDVI) of TDM was very low (R^2 0.23, RMSE 768 kg/ha).
Gianelle & Vescovo (2007)	When using a hand-held spectrometer to estimate pasture parameters found that the reliability of estimates of TDM was lower than their estimation of GDM. The most reliable estimates were of the ratio of green biomass in the sward.
Zhao, *et al.* (2007)	Used a hyper spectral scanner to establish whether it was possible to predict quality variables and TDM. They discovered good correlation with crude protein per cent (R^2 0.62) but poor correlations with other parameters. TDM had a low R^2 (0.36 RMSE 1270 kg/ha) but no attempt was made to accommodate for the asymptote of the vegetation index and green biomass.
Cho & Skidmore (2009)	Found good correlation ($0.56 < R^2 < 0.64$, RMSE 2980 to 3490 kg/ha) between NDVI collected from an airborne scanner and GDM.
Fava, *et al.* (2009)	Used hyperspectral data to predict LAI (R^2 0.73), N (R^2 0.73) and GDM (R^2 0.73, RMSE 2350 kg/ha) content of a Mediterranean pastures with reasonable accuracy.

Active Sensors

An active sensor emits EMR that strikes the target and reflected EMR is received by a sensor. The EMR is sent in pulses so that it can be distinguished from ambient light (Henderson and Grafton, 1975). Over a number of decades active sensors were evaluated to predict N stress in corn crops (Middleton *et al.*, 2004). The sensors used in the 1980s were large and cumbersome and needed to be located in a van to be used. The instruments were purpose built for the experiments. In the early 2000s the instrument was bought commercially and hand-held or mounted on a farm vehicle. Light emitting diodes (LEDs) are often used as the source of EMR (Holland *et al.*, 2004; Inman and Khosla, 2005; Flynn *et al.*, 2008) and reduce the weight and power requirements of the active sensor (Kunnemeyer *et al.*, 2001).

The Crop Circle™ (used in the present study) is an active sensor and a full description can be found in (Holland *et al.*, 2004). Holland*, et al.* (2004) reported good correlation with the Crop Circle™ sensor in cornfields between N rate of application and NDVI ($0.72 < R^2 < 0.94$). They have also had good correlation with NDVI and top growth biomass in blue grass (R^2 0.94). Inman and Khosla (2005), has used an active sensor, GreenSeeker™, to determine how much fertiliser to add to a maize crop. Flynn (2006) used an active sensor to predict the GDM in the pasture sward. He used pasture height to calibrate the readings from the GreenSeeker™. He found that pasture height (from a raising plate meter) was much more accurate than the GreenSeeker™. He used a meter connected to a GPS to map variability in the sward. The relationship between GreenSeeker™ readings and pasture height (R^2) was as low as 0.04. Ultra low-level airborne platforms with active sensors have also been used in cropping (Lamb *et al.*, 2009; Lamb *et al.*, 2011).

In a preliminary exploration of the use of the Crop Circle™, Trotter*, et al.* (2008) found that the instrument was reliable predicting total dry matter of crops but it was unreliable when used with pasture (Table 2.7). They also found that the simple ratio of NIR/red was less prone to saturation than NDVI. The poor performance in pasture was attributed to large spatial variability in the pasture sward. There was no attempt to separate dead material from green material and the reliability of crop predictions was lower when there was senescent material present.

Table 2.7: Summary of coefficients of determination of vegetation indices (highest reported) and total dry matter of different agricultural cover types using the Crop Circle™.

Cover type	R^2
Sorghum (Site 1)	0.37
Permanent Pasture	0.17
Native Pasture	0.06
Lucerne	0.06
Sorghum (Site 2)	0.75
Triticale	0.75

(Source: Trotter *et al.*, 2008) Root mean square error not quoted.

Trotter*, et al.* (2010a) used a Crop Circle™ to map the GDM above 4 cm in a study on the New England Tableland. The study evaluated a number of vegetation indices and found that the Soil Adjusted Vegetation Index (SAVI) gave the most reliable predictions of GDM. SAVI was developed by Huete (1988) to adjust for the variation in vegetation indices caused by soil reflectance. The correction factor (L – Equation 2.5) can be optimised for vegetation density

(1 – low density, 0.5 – intermediate density and 0.25 – high density) (Huete, 1988). Trotter *et al.* (2010a) used L of 0.5 (intermediate vegetation density) to reduced noise from soil reflectance. When LAI was above 2.8 there is little reflectance from the soil and the advantage of using SAVI instead of NDVI is lost.

SAVI = [(NIR – red)/(NIR+red+L)] x (1+L)

Where:
NIR – Near Infrared Reflectance
Red – red reflectance
L – soil correction factor

Equation 2.5: Formula used to calculate soil adjusted vegetation index (SAVI) (Huete, 1988)

Trotter*, et al.* (2010a) were able to predict GDM with a RMSE of 288 kg green DM/ha (R^2 0.77). They were able to produce maps of GDM for a paddock and highlight areas that were lower and higher in production within the paddock. However, they cut pasture to a height of 4 cm and on some occasions they were unable to harvest any green material. Using the PROGRAZE equation (Equation 2.2) to estimate pasture biomass from pasture height as much as 1365 GDM kg/ha may have been left uncut.

Although Trotter*, et al.* (2010a) reported high reliability using the Crop Circle™ it is quite common for a method to have a high R^2 values in some experiments only to be followed by very poor relationships in another. For example, Martin*, et al.* (2005) using traditional non-destructive methods, recorded high R^2 in weeks 32 and 33 of an experiment (0.80 and 0.70, respectively) followed by R^2 of 0.03 in week 35 (Martin *et al.*, 2005).

In a study by Flynn*, et al.* (2008) there were quite low R^2 values when NDVI derived from an active sensor and pasture dry matter were compared. However, there were a few problems with the technique described. The pasture was cut to a height of 5 cm and material below 5 cm may have accounted for as much as 1525 GDM kg/ha (Equation 2.2) of biomass and there was no separation of green and dead material and so if there were large amounts of senescent material in the sward this may have impacted on accuracy.

Flynn*, et al.* (2008) found that pasture height was a more reliable predictor of GDM than the active sensor (GreenSeeker^{TM}). On the other hand, Schut (2003) found the opposite. Schut (2003) quoted that the reflectance measurements were more reliable than pasture height. However, the experiment was conducted under controlled conditions using swards grown in pots and stated that NDVI was less sensitive when biomass was above 2000 DM kg/ha, which is consistent with results reported by Smith *et al.* (2011). Kunnemeyer*, et al.* (2001) developed an active sensor to measure green biomass in pasture. They were able to predict GDM with reasonable accuracy (R^2~0.7). However, it is necessary to establish the link between remotely sensed data and animal production. The question then arises "is it possible to monitor animal performance using data derived from a satellite bourn sensor?". Hill *et al.* (1998a) demonstrated that NDVI metrics provide a quantification of seasonal characteristics that could affect animal production.

2.5 Hypothesis 2

Remotely sensed data could be used to differentiate the grazing environment and monitor the liveweight change of sheep grazing in different environments.

Liveweight change is monitored in many experiments; that compare genotypic differences (Morley, 1956; Atkins *et al.*, 1992; Adams and Briegel, 1998; Amores *et al.*, 1999; Adams *et al.*, 2006; Brown *et al.*, 2006; Brown *et al.*, 2009), explore the impact of pasture resources on animal production (Mulholland *et al.*, 1976; McMeniman *et al.*, 1986; McMeniman *et al.*, 1989; Atiq-ur-Rehman *et al.*, 1999; Dominik *et al.*, 1999; Freudenberger *et al.*, 1999; Adams *et al.*, 2002; Hyder *et al.*, 2002; Robertson, 2006) and compare management strategies (Doyle *et al.*, 1999). Liveweight change is also an output from simulation models used to optimise management (Orsini and Arnold, 1986; Whelan *et al.*, 1986; Alcock *et al.*, 1998; Clark *et al.*, 2000; Andrew and Lodge, 2003; Graham *et al.*, 2003; Freer *et al.*, 2006). Decisions are often made in grazing enterprises using subjective assessment of changes in liveweight (Bell and Allan, 2000). Liveweight change is closely related to the grazing environment (i.e. pasture biomass and quality) (Freer *et al.*, 2006).

Alison (1985) quoted four factors that define the nutritional environment of grazing animals; the animal's requirements, nutrient content of the feedstuff, digestibility of the feedstuff and how much the animal will consume. Assessing pasture resources on the farm has been a priority of AWI and MLA for many years (AWI, 2005; MLA, 2006). Recording animal performance (e.g. liveweight change, wool growth, IGF1) at weekly intervals is possible only in intensive grazing experiments or on properties where automated weighing is in use. Pasture biomass is a determining factor in setting stocking rate (Harmoney *et al.*, 1997) and feed intake (Freer *et al.*, 1997). Many decision support tools developed over the decades focus on improved utilisation of pasture to improve lamb production (Whelan *et al.*, 1986; Freer *et al.*, 1997; Andrew and Lodge, 2003). Any technique that improves monitoring of pasture resources has the potential to improve animal production (Henry *et al.*, 2002; MLA, 2004).

Temporal variation in most grazing systems is much greater than spatial variability (Schellberg *et al.*, 2008). For example, changing lambing to take advantage of the spring flush will have a greater impact on lamb production than moving sheep around to take advantage of differences in pasture biomass or identifying patches of pasture that perform below average. Management factors such as, stocking rate, supplementary feeding and parasite control impact on animal production (Denney *et al.*, 1990) but systematic, accurate and timely methods of estimating pasture biomass will assist decision making. Butterfield and Malmstrom (2006), for example, found that managers of large sheep and cattle properties in California saw the potential of satellite data to optimise the use of pasture resources.

Hill *et al.* (2004) highlight the need for graziers in WA to better manage their pasture resource. FOO can be used by producers to manage their pastures and, for example, graze pastures to a specified residual biomass (Anderton *et al.*, 2004) and manage stock and pasture using quantitative measures (Asner, 1998). Monitoring pasture biomass and pasture quality makes it possible to separate pasture resources from other factors impacting on animal production. As a consequence, measuring pasture biomass to define the grazing environment has been an integral part of grazing experiments for decades (Morley *et al.*, 1964; Campbell and Arnold, 1973; Haydock and Shaw, 1975; Earle and McGowan, 1979; Sharrow, 1984; Scrivner *et al.*, 1986; Laca *et al.*, 1989; Gourley and McGowen, 1991; Harmoney *et al.*, 1997; Doyle *et al.*, 1999; Osoro *et al.*, 1999; Mata *et al.*, 2002). Sanderson *et al.* (2001) concluded that estimates of pasture biomass would have to be within 10% of the true value to provide any economic benefit to dairy farmers.

The relationship between remotely sensed data (e.g. NDVI) and the pasture biomass is well documented (Justice and Hiernaux, 1986; Smith, 1994; Hill *et al.*, 1998a; Hill *et al.*, 1999b). This suggests that remotely sensed data, therefore, may provide a reliable method of predicting the pasture biomass and may be used to supplement visual pasture cut measurements in grazing experiments.

2.5.1 Estimating pasture biomass using satellite data

Satellite-derived NDVI has been used for decades to measure green biomass (Kerr and Ostrovsky, 2003) and have been used to provide timely estimates of pasture biomass and pasture growth (Hill *et al.*, 2004). NDVI and similar vegetation indices are used to estimate pasture biomass (Table 2.8) but the satellite systems used to estimate pasture biomass vary. NOAA AVHRR data have been used because the data have been available on a daily basis since 1978 although the resolution of the data is quite coarse (1.1 km x 1.1 km). Landsat Thematic Mapper (TM) and SPOT data have been used because the resolution of the data (30 m x 30 m and 20 m x 20 m, respectively) is finer. However, the temporal resolution is low (Landsat TM – 18 days and SPOT – 26 days). When the Terra Earth Observation Satellite was launched (1999) it provided MODIS NDVI data more frequently (daily) and at a better spatial resolution (250 m x 250 m) than NOAA AVHRR data (Donald *et al.*, 2004a).

When estimating the accuracy of pasture biomass it is important to have enough (30) "ground truth" points (Gao, 2006). The time between the *in situ* measurements and collection of satellite data should be as short as possible (Edirisinghe *et al.*, 2004a) and, although it is ubiquitously used (Table 2.8), the coefficient of determination (R^2) is not adequate to estimate the accuracy of a model (Gao, 2006). Scattered trees can also reduce the accuracy of predictions (Donald *et al.*, 2004a). Pastures from Space (PfS^{TM}) is the most comprehensive and utilitarian system used to estimate pasture biomass and pasture growth in Australia (Smith *et al.*, 2011). A summary of studies where satellite data have been used to predict pasture biomass is presented in Table 2.8.

Table 2.8: Summary of studies that have used remotely sensed data to estimate pasture biomass.

Author	Data Used	Comment
Justice & Hiernaux (1986)	NOAA AHVRR	Used NDVI to monitor vegetation in the Sahel semi-arid grasslands. Predictions from a simulation model compared to NDVI biomass.
Hill*, et al.* (1998b)*	Landsat TM	Feed on offer (FOO) estimated and a strong relationship between FOO and NDVI was established (0.76 < R^2 < 0.95) but these strong relationships were achieved when FOO was aggregated into 250 kg/ha intervals. Areas not suitable for grazing were masked. No root mean square error (RMSE) quoted.
Hill*, et al.* (1998a)*	NOAA AHVRR	Demonstrated that NDVI metrics provide a quantification of seasonal characteristics that could affect animal production. The mix of cropping and grazing areas was a problem because crops contributed to NDVI.
Todd *, et al.* (1998)	Landsat TM	NDVI and other indices were used to estimate pasture biomass in a semi-arid environment where vegetation cover is typically around 50% in Eastern Colorado (R^2 0.67, RMSE 2814 kg/ha).
Edrisinghhe*, et al.* (2000)*	Landsat TM and SPOT	Estimated FOO from NDVI (0.80 < R^2 < 0.96, RMSE not stated)
Schino*, et al.* (2003)	Landsat TM	NDVI was the best of 3 indices evaluated to estimate pasture biomass in Italy (R^2 0.57, RMSE not stated).
Edirisinghe *, et al.* (2004a)*	Landsat TM	Estimates of FOO compared on 5 properties in WA (0.40 < R^2 < 0.85, RMSE not stated).
Di Bella*, et al.* (2004b)	SPOT	Used a similar method to predict pasture growth as PfS^{TM}. They concluded remote sensing has the potential to obtain spatially continuous information at near real-time at a relatively low cost.
Hill*, et al.* (2004)*	NOAA AHVRR	Concluded seasonal pasture systems are better suited to make predictions of productivity. Perennial systems are more difficult because the canopy structure is more dynamic. They found that small amounts of standing dead material in the sward had large effects on reflectance of the canopy.
Mata *et al.* (2006)*	IKONOS (4 m) and SPOT (10 m)	Estimated biomass in intensively grazed diary paddocks in WA, Victoria and NSW (0.59 < R^2 < 0.87, RMSE 273-448 kg/ha).
Kawamura *, et al.* (2005)	MODIS	With a limited number of pasture cuts (60) established a relationship between NDVI and pasture biomass (R^2 0.45, RMSE not stated).
Alhamad*, et al.* (2007)	NOAA AHVRR	Used auto correlation techniques to predict pasture biomass for a period of 6 months. The system was used as a possible early warning system for drought conditions.
Numata*, et al.* (2007)	Landsat TM	Normalised difference infrared index produced better results than NDVI (R^2 0.38 and R^2 0.05, respectively, RMSE not stated). Poor results for NDVI were attributed to water content of the pasture.
Xu*, et al.* (2008)	MODIS	Used NDVI to estimate hay production (0.25 < R^2 < 0.65, RMSE not stated).
Zhang & Guo (2008)	SPOT	Large amounts (up to 50%) of dead material and moisture in the sward hampered accurate estimates of green biomass (R^2>0.45, RMSE not stated).
Donald*, et al.* (2010)*	MODIS	Used NDVI in combination with climate, soil and light-use efficiency data to estimate pasture growth rate in WA (0.39 < R^2 < 0.75, RMSE 6.6-13.4 kg DM/ha/day).
Yu*, et al.* (2010)	MODIS	Used NDVI to estimate aboveground pasture biomass (R^2 0.85, RMSE not stated) and then model optimum grazing density in alpine regions of China.
Edirisinghe (2011)*	Landsat TM and SPOT	Landsat TM and SPOT images were used to compare NDVI with pasture data from 8 properties in WA. R^2 varied between 0.13 and 0.91. They developed a generalised model that improved reliability (R^2 0.85, RMSE 315 kg/ha).
Smith *et al.* (2011)*	MODIS	Used NDVI to predict FOO. Predictions below 2000 kg/ha were reasonably accurate (0.71 < R^2 < 0.75, RMSE 265-600 kg/ha). Predictions when FOO was greater than 2000 kg/ha and when pasture began to senesce were not accurate.

* Pastures from Space studies

2.5.2 Pastures from Space (PfS^{TM})

Pastures from Space has developed from an experimental means of predicting FOO and pasture growth (PGR – DM kg/ha/week) to a web based system that provides a service to subscribed producers over the internet (Hill *et al.*, 2004; Fairport, n.d.). PfS^{TM} was a consortium of CSIRO, Department of Agriculture WA and Land Information WA (Mata *et al.*, 2004) and data are provided to farmers via Fairport Technologies "Pasture Watch" (Smith *et al.*, 2004; Smith *et al.*, 2011). A pilot study was established with 77 properties to explore the potential of the FOO predictions at paddock scale. The system proved to be reliable ($0.65 < R^2 < 0.74$) (Edrisinghhe *et al.*, 2000). PfS^{TM} aims to *"deliver near real-time information tools at a whole-farm and within-paddock level, that will underpin tactical and strategic decision making for Australian agricultural businesses"* (Edrisinghhe *et al.*, 2000). It is possible to make reliable predictions of FOO using Landsat TM and SPOT MSS data (Edirisinghe *et al.*, 2011) and MODIS (Smith *et al.*, 2011) but on-site calibration is required (Smith *et al.*, 2011).

PfS^{TM} methodology

The PfS^{TM} methodology begins with satellite-derived NDVI. In the early days the NDVI images were from NOAA AVHRR data (Hill *et al.*, 2004) but since 2002 the daytime overpass Terra and Aqua satellites have provided data at a finer spatial resolution (250 m x 250 m) (Smith *et al.*, 2011). A problem with NDVI images is that many images are contaminated by cloud (Holben, 1986). To overcome cloud in the image, a maximum value composite (MVC) image is used. The maximum value over a 1 or 2 week period is used to represent each image pixel (Smith *et al.*, 2011). When cloud is persistent the most recent (up to 4 weeks) cloud-free NDVI value is used to avoid any null values (Smith *et al.*, 2011).

The NDVI at each pixel is used to estimate the amount of light that can be used for active photosynthesis. The NDVI provides a measure of how much green material was present in the pasture and able to photosynthesise. Pasture growth is then estimated from a light use efficiency (LUE) factor. LUE was based on soil fertility, weather conditions and incident radiation (Hill *et al.*, 2004). Temperature and rainfall play the most significant roles in estimating growth (Coops, 1999). Different plant species have different LUE (Hill *et al.*, 2004). Combining climate variables such as soil moisture, temperature and radiation levels with NDVI enable predictions of PGR (Edrisinghhe *et al.*, 2000). The system has been used to predict PGR throughout Australia (Fairport, n.d.) and was reasonably reliable (studies denoted with * in Table 2.8).

PfS^{TM} offers two estimates (FOO and PGR) useful in precision management of pasture resources. To estimate FOO the date of the autumn break and local estimates of high and low FOO are required. There is a strong relationship between slope of NDVI vs. FOO and the number of days since the break (Edrisinghhe *et al.*, 2000). NDVI can remain constant or decline while FOO continues to increase due to stem elongation and flowering (Edrisinghhe *et al.*, 2000). For a producer to make use of FOO they must make measurements on their property for calibration.

PfS^{TM} has the potential to provide information about pasture biomass at close to real-time. The system allows producers to monitor their pasture resources closely and ensure that available pasture is used efficiently (Anderton *et al.*, 2004; Edirisinghe *et al.*, 2004a; Mata *et al.*, 2004; Gherardi *et al.*, 2006). The systematic approach used by PfS^{TM}, using MODIS data with a resolution of approximately 6 ha, can be used to identify paddocks with below average pasture growth (Anderton *et al.*, 2004).

2.6 Hypothesis 3

A vegetation index derived from satellite data could be used to monitor seasonal changes in wool fibre diameter.

Wool growth is dependent on the nutritional status (i.e. the supply of energy and protein) of the sheep (Adams *et al.*, 2006; Freer *et al.*, 2006). Defining the characteristics of a relationship between satellite-derived pasture biomass and a production characteristic such as wool fibre diameter would help establish the application of remote sensing in the sheep industry. The fibre diameter profile (FDP) offers a mechanism of recording the nutritional status of the animal over the period that the wool was grown (Hansford, 1994; Doyle *et al.*, 1999; Schlink *et al.*, 1999; Australian Sheep Industry CRC, 2004).

2.6.1 Wool fibre diameter profiles

FDPs create a picture of wool fibre diameter changes throughout the year. Jackson and Downes (1979) found that it was possible to generate a FDP by cutting the staple into 10 small segments of equal length and measuring the diameter of each segment. On average each segment represented one tenth of the growing season. However, Reis (1992) reported that the length of the staple is stimulated by feed intake to a greater extent than the fibre diameter. This means that a fibre cut into 10 equal portions will not, in fact, represent 10 equal parts of the growing season. When nutrition is good the wool fibre grows rapidly and tends to have a larger diameter (Brown and Williams, 1970; Brown and Crook, 2005). In other words, the wool fibre grows 'thick and fast' when nutrition is good and 'thin and slow' when nutrition is poor. Cottle (1987) found that the ratio between fibre length and fibre diameter^2 (area) was more constant than with fibre diameter.

To simplify and quantify parameters from FDPs, Brown *et al.* (2002) established three points on the FDP. The first point was the minimum fibre diameter in the profile. The second point was the maximum between the minimum and the outer tip of the profile. The third point was the maximum between the minimum and the base of the profile. Brown *et al.* (2002) used these three points to derive two parameters that they used to quantify attributes of the FDP. These parameters were rate of change1 (Roc1) and Roc2. Roc1 is the slope between the minimum and the maximum closest to the outer tip of the fibre. Roc2 is the slope between the minimum and the maximum closest to the base of the fibre. The slope was derived from a regression of points on the FDP between the minimum and the maximum (Brown *et al.*, 2002) (Figure 2.3).

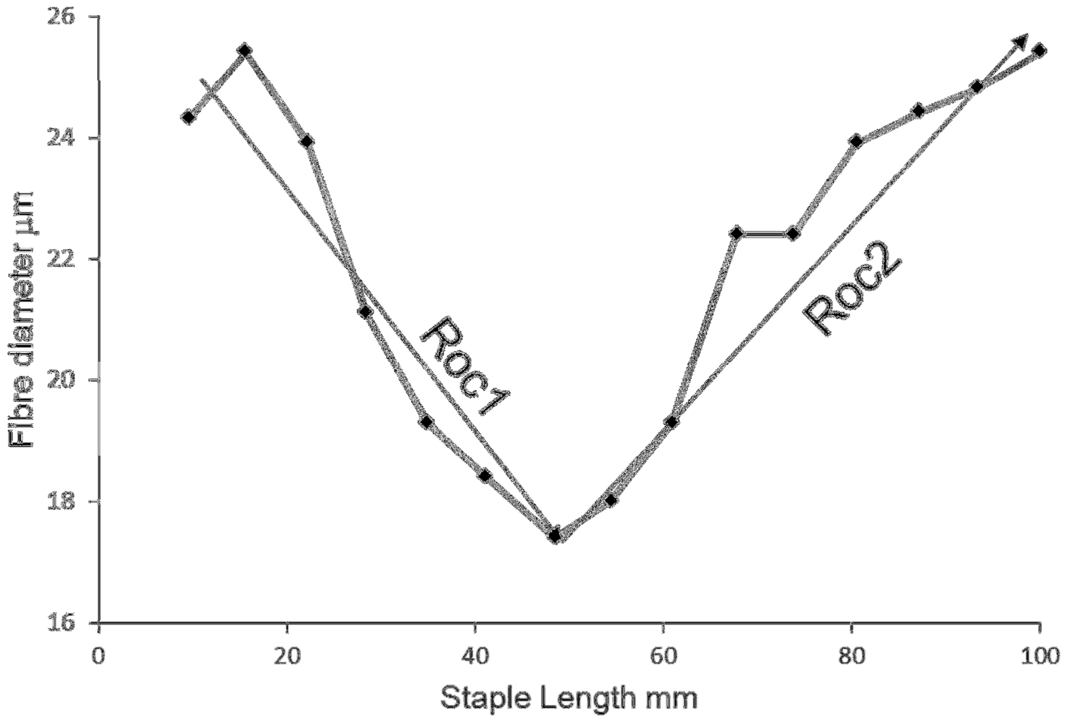


Figure 2.3: Calculation of rate of change (Roc 1) and Roc 2 on a wool fibre diameter profile.

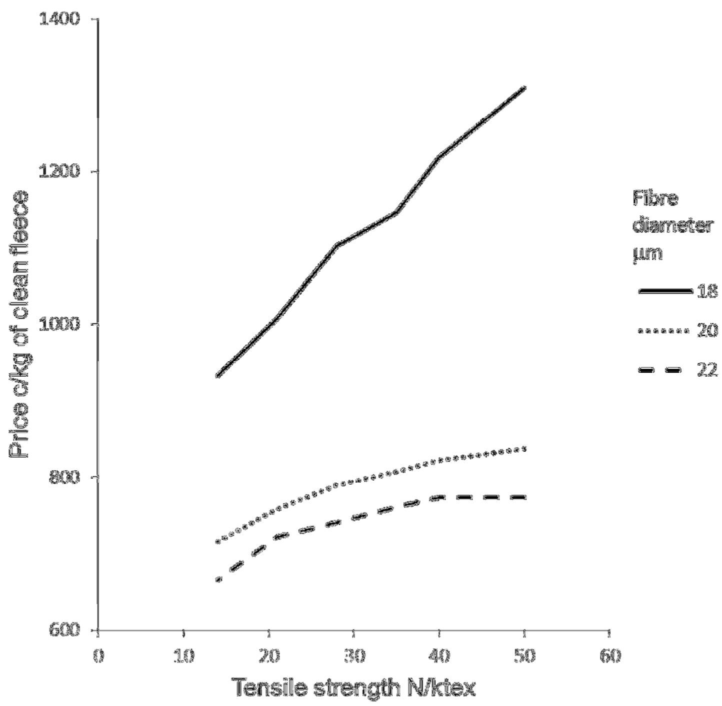
Many researchers have linked changes in the fibre diameter profile with the nutritional environment the animal has experienced (Table 2.9). Changes in fibre diameter along the profile are associated with staple strength (Hansford *et al.*, 1985).

Table 2.9: Examples of studies that have reported that nutrition impacts wool fibre diameter or fibre diameter profiles (FDP).

Study	Finding
Reis (1992)	Supplementary feeding led to an increase in the strength of the staple.
Piper and Dolling (1969)	Feeds with low protein content caused a reduction in wool growth.
Brown and Williams (1970)	The rate of wool growth and fibre diameter had a strong relationship with available green pasture. They also found that high producing sheep were more sensitive to changes in available green pasture than low producing sheep.
Jackson & Downes (1979)	The nutritional environment of individual sheep impacted upon the fibre diameter.
Hansford *et al.* (1985)	Position of break was at the minimum diameter in FDP.
Hansford and Kennedy (1988)	Found relationship between rate of change in fibre diameter and staple strength.
Denney (1990)	Found that the fibre diameter was at a minimum when pasture availability was at a minimum.
Hansford (1994)	Examined the relationship between nutritional environment, genotype and FDP.
Hynd (1994)	Animals on low nutrition had reduced fibre length, fibre diameter, fibre volume and fibre density. Low nutrition animals had reduced bulb diameter, bulb area, papilla length, papilla density and papilla area.
Masters *et al.* (1998)	Found that the FDPs changed as a response to supplementary feeding.
Thompson and Hynd (1998)	Fibre diameter decreased when nutrition was reduced so that animals lost weight. The decrease in fibre diameter was less dramatic if sheep were placed on a maintenance diet rather than a diet that resulted in weight loss.
Doyle *et al.* (1999)	A close relationship between the FDP and pasture biomass.
Brown and Crook (2005)	Changes in FDPs were associated with seasonal changes in body weight, fat depth and skin thickness.

Staple strength

Staple strength (tensile strength of wool fibres) is an important characteristic of raw wool. Weak fibres contribute to reducing fibre length, carding losses and combing noilage (Reis, 1992). Staple strength is the peak force (Newtons) required to break a staple of wool (grams of clean wool per meter – ktex) and the units of measure are N/ktex. In the Australian wool industry 35 N/ktex is used as a benchmark. Wool with strength greater than 35 N/ktex may attract a premium and discounts may start with wool below the benchmark. Wool that has a low tensile strength (<30N/ktex) is considered to be tender wool and very tender wool has a tensile strength lower than 21 N/ktex (AWI, 2009). Tender wool breaks readily during processing. As a consequence, the price paid for tender wool is reduced (AWI, 2009) (Figure 2.4).



(Source: Woolcheque AWI, 2009)

Figure 2.4: Estimate of price paid for wool of different fibre diameters and varying tensile strength in the 08-09 seasons.

To measure staple strength the staple is clamped at each end. A force is applied to stretch the fibres in the staple until they break. There are many factors that contribute to the force required to break the staple and the position of the break (POB). In addition to those factors that follow is the interaction of some, and possibly all, of these factors.

Mean fibre diameter

In general there is a positive relationship between the mean fibre diameter of the staple and the strength of the wool (Denney, 1990; Brown *et al.*, 1999; Brown *et al.*, 2002). However, some studies have indicated that mean fibre diameter is a poor predictor of staple strength (Hansford and Kennedy, 1988; Peterson *et al.*, 1998; Doyle *et al.*, 1999). Hansford (1994) presented results for 2 fleeces where the average fibre diameter was the same (15.7 µm) but the staple strength was different (44 N/ktex and 24 N/ktex).

Minimum diameter of the fibre

The thinnest part of the fibre is the logical place for the break to occur if the intrinsic strength of the fibre (see below) is uniform along the fibre. The minimum diameter in the profile explains a large proportion of the variation in staple strength (Hansford and Kennedy, 1988; Adams and Briegel, 1998; Thompson and Hynd, 1998; Brown *et al.*, 1999; Schlink *et al.*, 1999; Brown *et al.*, 2002), assuming that break usually occurs at the minimum diameter. Huson and Turner (2001) determined that the tender regions of the fibre were thinner than the sounds parts of the fibre.

Intrinsic strength of the fibres

One component of staple strength is the strength of the individual fibres in the staple (Scobie *et al.*, 1996). Intrinsic strength of the fibre is calculated by dividing the force required to break the fibre by the area of the cross section of the fibre at the break. Staple strength is measured in terms of the weight of the fibres per meter (ktex) but there is evidence that the fibres themselves have different strengths per unit area at the break and that the intrinsic strength has a positive relationship with staple strength (Gourdie *et al.*, 1992). Although others (Scobie *et al.*, 1996; Masters *et al.*), found no relationship between intrinsic strength of the fibres and staple strength.

Diameter variation along the fibre

The coefficient of variation along the fibre profile gives an indication of how the diameter varies. Peterson *et al.* (1998) and Schlink *et al.* (1999) found a negative correlation between the coefficient of variation of fibre diameter along the fibre and staple strength and low staple strength has been attributed to variation in fibre diameter along the profile (Dunlop and McMahon, 1974; Hansford, 1994; Doyle *et al.*, 1999). Others have found that variation along the fibre explained more of the variation in staple strength than mean fibre diameter (Denney, 1990; Brown *et al.*, 1999; Brown *et al.*, 2002; Brown and Crook, 2005).

Diameter variation between fibres

Variation in the diameter of individual fibres in the staple is also associated with low staple strength (Thompson and Hynd, 1998; Schlink *et al.*, 1999; Brown *et al.*, 2002).

The rate of change in the fibre diameter

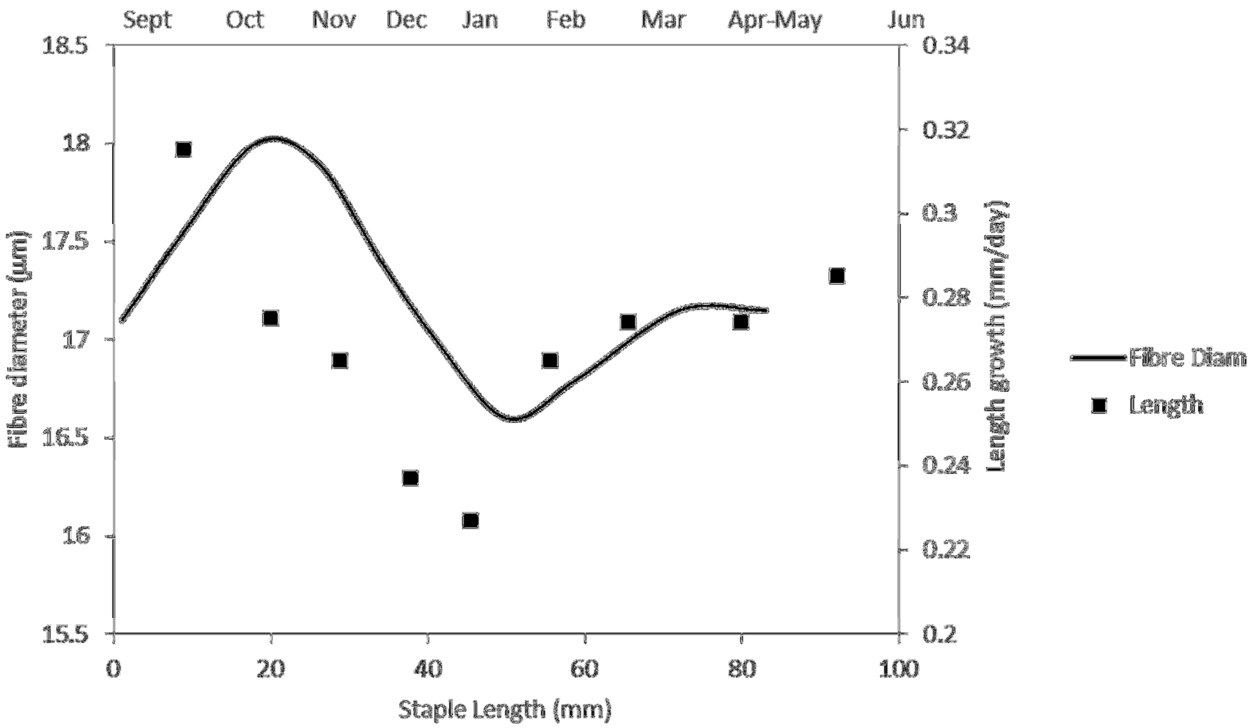
Rapid changes in the profile cause weaknesses in the wool (Hansford *et al.*, 1985; Reis, 1992; Thompson and Hynd, 1998; Brown *et al.*, 2002). Hansford and Kennedy (1988) quantified a (negative) relationship between staple strength and the slope of a line drawn between the minimum and maximum fibre diameter.

Many of the factors above are driven by changes in nutrition that have an effect on the physiology of the skin cells (Hynd, 1994). Adams and Briegel (1998) described staple strength as a complex characteristic influenced by fibre diameter. Thompson and Hynd (1998) found that 80% of the variation in staple strength could be accounted for by variation in fibre diameter illustrated in the FDP. Brown *et al.* (2002) also used parameters derived from an FDP to explain differences in staple strength.

The pattern of growth of the fibre and timing of shearing impacts on staple strength, for example, in a Mediterranean environment shearing in autumn when the fibre diameter is at a minimum increases staple strength (Hansford, 1994; Peterson *et al.*, 1998). POB also has a bearing on the price paid for wool. If the POB is in the middle of the staple two short fibres are more likely to be produced (Hansford, 1994). As a consequence, processors prefer wool with a POB close to the end of the fibre. A penalty of up to 150 c/kg may apply for wool with a high mid POB percentage (AWI, 2009). Monitoring pasture biomass so that rapid changes in the fibre diameter profile do not occur may improve staple strength and, therefore, increase revenue.

2.6.2 Wool fibre diameter profiles and the nutritional environment

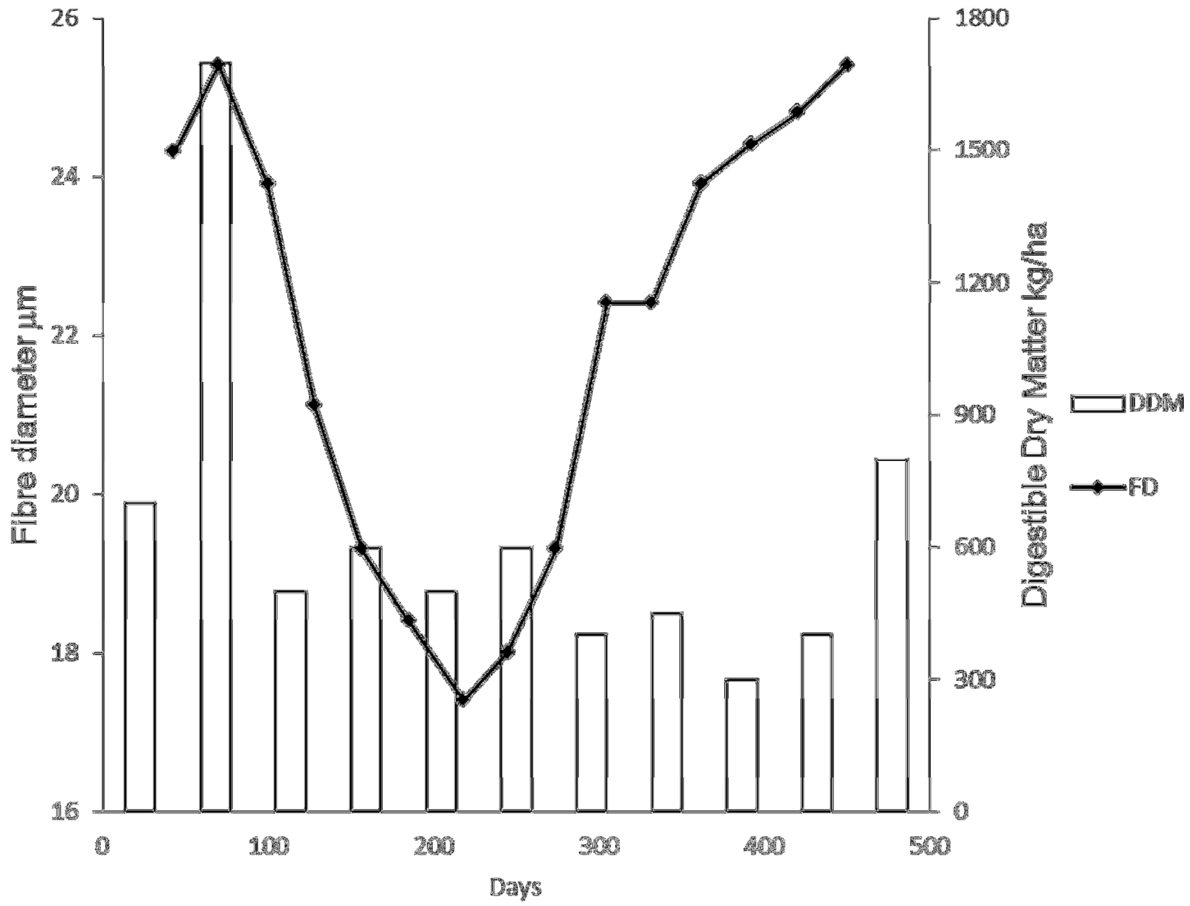
The seasonal change in the nutrients available to the animal is the main cause of variation in wool growth (Stewart *et al.*, 1961). The FDP provides a retrospective view of the grazing environment in the previous season (Hansford, 1994; Doyle *et al.*, 1999; Schlink *et al.*, 1999; Australian Sheep Industry CRC, 2004) (e.g. Figure 2.5) because fibre diameter has a positive association with the level of nutrition (Hynd, 1994). By managing intake it is possible to reduce variation in fibre diameter and maintain staple strength (Mata *et al.*, 2002). Mata *et al.* (2002) found that it was possible to alter fibre diameter by manipulating the amount of feed available by adjusting stocking rate. Although they managed to reduce the average diameter of the fibre there was little impact on staple strength. It was suggested that manipulating nutrition would enable wool producers to increase the value of the clip by reducing the diameter of wool (Mata *et al.*, 2002). However, Doyle *et al.* (1999) were able to produce finer and stronger wool by limiting feed intake via strip grazing. Introducing supplementary feed when feed availability declines and restricting feed intake at the break of season can limit fluctuations in fibre diameter (Masters *et al.*, 1998; Peterson *et al.*, 1998). Rowe *et al.* (1989) concluded that supplementary feeding increased wool strength but needed to start early to avoid tender wool. Smith *et al.* (2011) have suggested a trigger point to start feeding is FOO of 500 kg/ha.



Source: Unpublished data (Australian Sheep Industry CRC, 2004)

Figure 2.5: Relationship between time of year, wool fibre diameter and fibre length growth.

Schlink *et al.* (1999) also found that there was a relationship between FDP and availability of pasture (Figure 2.6). Nagorcka (1977) determined that there was a 3.5 week lag between intake and wool emerging from the skin. Schlink *et al.* (1999) also estimated that there was a lag between wool growth and a change in nutrition and a lag is incorporated in GrassGro (Freer *et al.*, 2006).



(Source: Schlink *et al.*, 1999).

Figure 2.6: Relationship between wool fibre diameter and pasture digestible dry matter.

Matching feed availability and the FDP may enable a producer to examine, retrospectively, their management and determine where rapid changes in FDP occurred. By monitoring the feed availability in the current year they may be able to intervene if a pattern appears that caused tender wool in previous years. For example, a wool producer may supplementary feed early in a dry spell to avoid a rapid change in fibre diameter. Development of detailed analysis of FDPs could lead to "precision farming" in the sheep industry (Australian Sheep Industry CRC, 2004).

In a study that evaluated 40 FDPs of ewe hoggets in a Mediterranean environment (WA) and a perennial environment (Armidale NSW), Brown *et al.* (1999) found that there was evidence that the FDPs were different in different environments and that there was evidence that responsiveness to the grazing environment may account for some genetic differences in staple strength. Characterising a relationship between FDPs and pasture biomass would make it possible to quantify differences in responsiveness to nutrition between genotypes.

The seasonal pattern of pasture biomass and quality is linked to wool production (Stewart *et al.*, 1961; Williams, 1991; Adams and Briegel, 1998; Doyle *et al.*, 1999; House *et al.*, 2002; Hyder *et al.*, 2002), wool quality (Table 2.9) and liveweight change (Mulholland *et al.*, 1976; McMeniman *et al.*, 1986; McMeniman *et al.*, 1989; Atiq-ur-Rehman *et al.*, 1999; Dominik *et al.*, 1999; Freudenberger *et al.*, 1999; Adams *et al.*, 2002; Hyder *et al.*, 2002; Robertson, 2006). Matching animal nutritional requirements with this seasonal pattern in pasture resources on a property has the potential to improve production and profitability on a property (Whelan *et al.*, 1986; Alcock *et al.*, 1998; Clark *et al.*, 2000; Freer *et al.*, 2006). Classifying the grazing environment of sheep on the basis of the pattern seasonal pasture biomass and quality has the potential to match genotypes to a particular environment and, thus, improve production and profitability at a national scale.

2.7 Hypothesis 4

Remotely sensed data and temperature could be combined to produce a meaningful and robust classification of the sheep grazing environments of Australia.

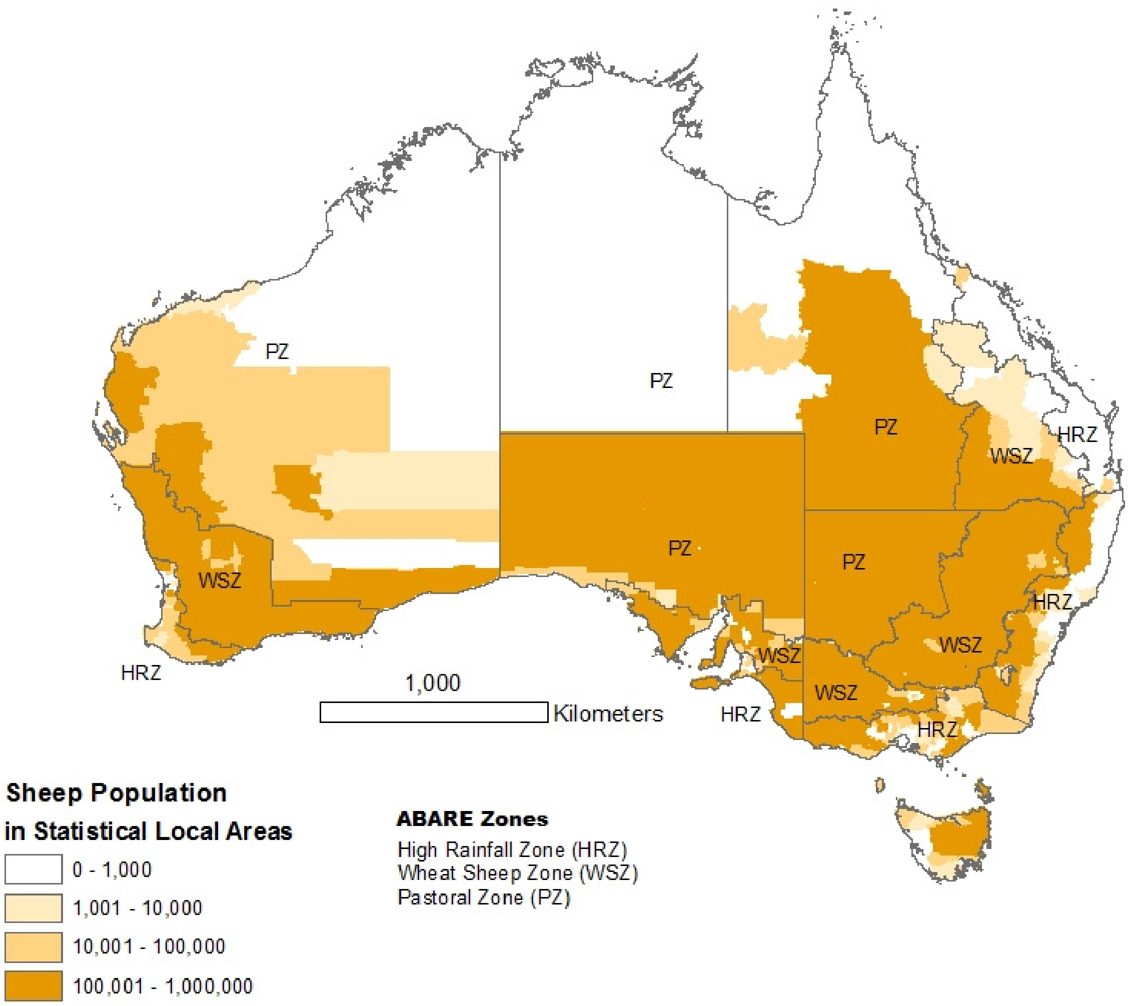
A classification allocates undefined individuals into classes so that all the desired entities in a given class are similar (Cormack, 1971). In the present study the undefined individuals to be classified are sheep properties and the aim is to put them into classes indicating similar grazing environments. It is well accepted that geographic location of the property has a bearing on the grazing environment and, as a consequence, animal performance (Cottle, 1991a; Cottle, 2010). In a review of the distribution of the productivity of the sheep industry, Brown and Williams (1970) found that lambing per cent increased from north to south. Brown and Williams (1970) attributed the differences in wool production and lambing per cent to climate, pasture and nutrition.

The sheep grazing areas in Australia are presently classified into three zones (High Rainfall Zone, Wheat-sheep Zone and Pastoral Zone) (Figure 2.3). These very broad zones are based on climate (Cottle, 1991a) (Table 2.10). Overlaying the sheep grazing population on the ABARE zones reveals that the majority of sheep are in the Pastoral Zone and there are few sheep in the High Rainfall Zone (HRZ) (Figure 2.7) but stocking rates are higher in the HRZ.

Table 2.10: Description of Australian Bureau of Agricultural and Resource Economics (ABARE) zones grazing zones.

Zone	Description
High Rainfall Zone	The amount of rainfall used to differentiate HRZ from the Wheat-sheep Zone varies from state to state. In Qld and NSW annual rainfall of 600 mm is used while 500 mm is used in the other states. Sheep properties in this zone are small in comparison to the other zones but stocking rates are higher.
Wheat-sheep Zone	The rainfall varies from 600-700 mm in Qld, 400-650 mm in NSW and 250-500 mm in the rest of the country. This area is characterised by farms that are able to support cropping enterprises. Around 50% of the Australia's sheep population are in this zone.
Pastoral Zone	Includes arid and semi-arid regions of Australia. The rainfall is very low, 250-650 mm in Qld, 200-400 mm in NSW and 150-250 mm in SA and WA. This zone is characterised by large properties with very low stocking rates.

(Source: Cottle, 1991a)



(Source: Australian Bureau of Statistics, 2001)

Figure 2.7: Australian Bureau of Agricultural and Resource Economics (ABARE) zones overlayed on the distribution of sheep population.

A meaningful classification of sheep grazing environments must be based on factors important to wool and lamb production. Pasture accounts for about 96% of the nutritional requirements of the sheep industry (Cottle, 1991b) and so the amount of pasture biomass would be a useful basis for differentiating environmental classes. In cooler climates pasture growth is limited by low temperatures. In summer, pasture growth may be limited by lack of moisture and pasture quality will be reduced by high temperatures (Pratley and Gordyn, 1991). Thus, temperature is another useful basis on which to differentiate grazing environment.

2.7.1 Pasture biomass

Satellite remote sensed data will provide a measure of the amount of green vegetation over a large area (Justice and Hiernaux, 1986; Henry *et al.*, 2002; Hill *et al.*, 2004; Di Bella *et al.*, 2005; Alhamad *et al.*, 2007; Zhang and Guo, 2008). NDVI represents a crude measure of the pasture biomass (Hill *et al.*, 1998a) and has been used in a number of commercial satellite-derived products to estimate GDM, including PfS™ (Henry *et al.*, 2002; Smith *et al.*, 2004; Fairport, n.d.).

A meaningful classification of sheep grazing environments will need to take into consideration the temporal variability of pasture biomass. Cridland *et al.* (1994) were able to define patterns of pasture growth in Western Australia using NDVI images from NOAA AVHRR data. They were able to differentiate areas with different rainfall patterns and identify seasonal differences. Smith (1994) investigated the relationship between NDVI and wool production in WA. He found strong positive relationships between wool production per hectare and stocking rate, and NDVI and wool clip per hectare. In a later study Hill *et al.* (1998b) found that if the environments of the Pastoral Zone were stratified on the basis of latitude the results were improved. The relationship between NDVI and wool cut per sheep was stronger at lower latitudes. Hill (1998b) postulated that pasture quality limited production at higher latitude. While at lower latitude it was the pasture biomass that limited production. Hill and Donald (2003) used a time integrated NDVI to classify agricultural land in WA. The pasture biomass is only one aspect of defining the nutritional environment of grazing animals. Pasture quality is also important (Paterson *et al.*, 1994; Adams *et al.*, 2006; Freer *et al.*, 2006; Schut *et al.*, 2010). Temperature may be an important factor in determining the pasture quality and may predetermine the relationship between NDVI and wool production.

2.7.2 Pasture quality

"Productivity is the ultimate measure of forage quality" (Buxton and Fales, 1994). Pasture quality is a broad term that is often defined by a function of digestibility and forage intake (Paterson *et al.*, 1994). In the present study the definition of forage quality relates to the digestibility of the feed on offer, as per Reid (1994). When the digestibility of the pasture is high the pasture biomass limits production and when the digestibility is low pasture quality limits production (Han *et al.*, 2003). A feed of low digestibility has a dual impact on animal production. First, less energy is absorbed from the feed and, secondly, intake is reduced (Freer *et al.*, 2006). Thus, pasture quality will be an important feature in defining grazing environment.

Pasture quality is a result of the species present and the composition and texture of each species. Climate impacts on both these characteristics (Schut *et al.*, 2006). Maximum temperature has a negative correlation with pasture quality (Wilson and Ford, 1972; Henry *et al.*, 2000; Han *et al.*, 2003) and impacts on pasture quality in two ways (Buxton and Fales, 1994), as follows.

1. Maximum temperature dictates the species composition of the pasture. C_4 plants fix carbon as a compound with 4 carbon atoms and can photosynthesise when the leaf stomata are closed. Unlike C_3 plants that fix carbon as a compound with 3 carbon atoms and cannot photosynthesise with the stomata closed. C_4 plants are better adapted to hotter drier climates (Campbell *et al.*, 2005). However, C_4 plants are less digestible than C_3 plants because C_4 plants have more cell wall content and a higher proportion of less digestible tissue (Wilson and Hattersley, 1989).

2. High maximum temperatures cause a decrease in digestibility of plants because plants growing at higher temperatures have higher lignin content as they partition more energy into structural tissue with reduced digestibility.

Minson and McLeod (1994) found that every 1ºC increase in temperature was associated with a 1% fall in digestibility. The effect of temperature on digestibility appears to have a greater effect on temperate grasses than tropical grasses. Wilson and Ford (1972) found a decrease in digestibility of 5% between temperate grasses grown at 21/13°C and 32/24°C but temperature had little effect on tropical grasses. In addition, the reduction of moisture in the plants causes a lower concentration of reducing sugars and an increase in lignin and cellulose, which results in decreased digestibility (Purser, 1981). In a study of digestibility, Han *et al.* (2003) sampled pasture over five years. The dominant factor in being able to model pasture digestibility was temperature. Strong relationships ($0.60 < R^2 < 0.87$) were reported between accumulated daily temperature and the digestibility of annual pastures.

Schut *et al.* (2010) indicated that there was a threshold of 4.5°C when temperature started to decrease dry matter digestibility (DMD) and the sum of daily mean temperatures over that threshold had a negative relationship with DMD. Graux *et al.* (2011) when modelling the impact of climate change on livestock production used a threshold of a maximum temperature of 15°C before digestibility was reduced by 0.6% per 1°C increase in daily maximum temperature. In mechanistic models of grazing systems the negative impact temperature has on digestibility can be incorporated by summing daily temperature over the period the biomass has been available for grazing (Jouven *et al.*, 2006). However, Moore *et al.* (1997) use pasture age to predict pasture digestibility and incorporates temperature when predicting phenological stages of pasture. Although other factors, for example solar radiation, soil nutrients and plant pests and disease, *"temperature seems to exert greater effects on digestibility than do other environmental variables"* (Buxton and Fales, 1994).

2.7.3 Remote sensing methods of estimating pasture quality

Dymond, *et al.* (2006) postulated that NDVI should be associated with pasture quality (metabolic energy content) because chlorophyll is correlated with NDVI. Chlorophyll is associated with pasture that is photosynthesising and storing energy. On the other hand, dead grass has low chlorophyll and low energy content of pasture from NDVI. Although they used large pixels (1 km^2) Dymond, *et al.* (2006) were able to predict the metabolisable energy content. Lamb, *et al.* (2002) used spectral data from a hand-held radiometer and a two-layer model of the canopy to predict chlorophyll content and, subsequently, N content of ryegrass (*Lolium* spp.). However, the reliability of the predictions was quite low ($0.60 < R^2 < 0.65$) (Lamb *et al.*, 2002). Starks, *et al.* (2008) were able to predict N concentration and *in vitro* dry matter digestibility of pasture biomass using spectral data with reasonable accuracy (R^2 0.82 and 0.74, respectively).

Some researchers have had limited success predicting pasture quality (e.g. N concentration) using hyperspectral data from hand-held and airborne scanners (Lamb *et al.*, 2002; Edirisinghe *et al.*, 2004b; Starks *et al.*, 2006a; Starks *et al.*, 2006b; Starks *et al.*, 2008). Strong correlations have been found between infrared reflectance and crude protein, neutral detergent fibre, lignin and digestibility (Norris *et al.*, 1976). NIR in forage analysis is based on the absorption at a molecular level by X-H bonds (i.e. O-H, C-H and N-H). The concentration of these bonds is dependent on water, carbohydrate and protein content of the forage (Shenk and Westerhaus, 1994). Some commercial feed testing laboratories use NIR to measure digestibility (Feedtest, n.d.).

NIR has also been used in the field to measure pasture quality (Starks *et al.*, 2004). However, a direct measurement of pasture quality over a large area is not possible with the satellite data available today because the spectral resolution of the sensors does not support the analytical approach applied to hyperspectral sensors (Mutanga *et al.*, 2004). Predicting digestibility using a commercially available hyperspectral imaging device (ASD FieldSpec®) has been quite accurate (R^2 0.83) (Pullanagari *et al.*, 2012b) and (R^2 0.80) (Pullanagari *et al.*, 2012a) but the cost (approximately $50000) of the instruments used would make use of such techniques very expensive for most commercial sheep farmers.

On the other hand, it is possible to estimate temperature over a large area (Jones, 1999). Therefore, using temperature as a surrogate for pasture quality has potential when classifying grazing environments. Brown and Williams (1970) also noted that wool production per head had a negative relationship with temperature. They concluded that management (e.g. stocking rate) played an important role in the variation of wool clip per animal.

2.7.4 Classifying grazing environment

Based on the connection between NDVI and pasture biomass, and maximum temperature and pasture quality, dividing NDVI by maximum temperature has the potential to characterise the grazing environment of sheep. For example, when pasture biomass is high and maximum temperature is low (spring in temperate climates) the value would be higher than in an environment where pasture biomass is high but temperatures are also high (summer in subtropical climates). Using NDVI and maximum temperature as the basis of classifying environments within broadacre zones, therefore, has the potential to produce a meaningful classification of sheep grazing environments.

Temperature and NDVI have been used to classify vegetation type in South America (Sobrinoa *et al.*, 2006). They used average NDVI, the standard deviation of NDVI and monthly mean temperature over a 20 year period to generate 20 vegetation classes. Classes were defined by assigning a maxima and minima for each layer (average NDVI, standard deviation of NDVI and average temperature). A cell was assigned to a particular class if the value for each layer was within the minima and maxima defined (Sobrinoa *et al.*, 2006).

Differentiation of the grazing environments may not be associated with differences in liveweight gain or wool growth on a per animal basis because stocking rate is one means that producers use to compensate for differences in the grazing environment (Brown and Williams, 1970). Denney *et al.* (1990), for example, found that wool production per animal was relatively constant across Weddin Shire. The Weddin Shire is within the NSW Wheat-sheep Zone, approximately 370 km west of Sydney. Stocking rate declined from the eastern part of Weddin Shire (3.3 adults/ha) to western parts of the shire (2.1 adults/ha) while wool production per animal was relatively constant (Denney *et al.*, 1990). Stocking rate was higher on properties that received more rain and had improved pastures and better management (Denney *et al.*, 1990). This change in stocking rate occurred over a distance of less than 100 km. This study demonstrated that matching genotype with grazing environments led to improved productivity. The Sustainable Grazing Systems (SGS) experiment also used stocking rate to accommodate for differences in nutritional environment (Andrew and Lodge, 2003). Producers in the Pastoral Zone have very low stocking rates to compensate for low pasture biomass (Pratley and Gordyn, 1991; Cottle, 2010).

Carrick (2005), when investigating genotype by environment interaction (GxE), classified the environment in terms of performance averages because he had no direct measure of environment. He recommended that the geographic location be incorporated into data collection because it could then be used to associate a property with climatic data. Climatic factors could then be used to classify environments. The results showed that GxE would be a significant issue for a national evaluation of sires (Carrick, 2005). Clustering herds on the basis of region and factors including location, rainfall and temperature have been used to help quantify GxE in beef cattle (Bertrand *et al.*, 1985) and dairy cattle (Weigel and Rekaya, 2000).

By defining the environment based on factors that are important for sheep production (e.g. pasture biomass and pasture quality) it may be possible to derive a classification of sheep grazing regions in Australia that would highlight potential GxE and be used by Sheep Genetics to improve the accuracy of breeding values for sire selection. In the past "environment" has been defined by management groups, as in Brown (2009) who created a flock by year term, but no attempt has been made to quantify the difference between groups. Defining environment in a meaningful way requires an exploration of how the environment impacts on sire selection. If the classification of grazing environment is robust then it would be able to detect GxE.

2.8 Hypothesis 5

The classification of sheep grazing environments could be used to detect genotype by environment interactions between linked flocks.

The outcome of selection must be predicted with confidence. Accurate prediction of genetic merit for livestock is seen as a way of improving productivity (MLA, 2007). Young *et al.* (2010) used bio-economic modelling to show that matching genotype with environment and production systems and optimising pasture utilisation was critical to profitability of prime lamb enterprises. GxE is one factor that makes prediction of outcomes from a particular sire inaccurate. Woolaston (1987) proposed that the effects of GxE can be prevented when the differences between genotypes is large if the most suitable genotype is chosen for a specific environment. Carrick (2005) discovered that it was rare that the same sire was used between distant environmental classes. However, within a climatic or regional environment factors such as management, year of production and the paddock used can impose environmental effects that cause genotypes to shift in their relative performance (Woolaston, 1987).

Selection of the best genotype for a particular environment is a priority of graziers (Reeve *et al.*, 2000). A survey of 2016 beef and sheep graziers (Table 2.3) revealed that selection using breeding and culling was rated 11th out of 16 factors that were considered very important to the success of a grazing enterprise (Reeve *et al.*, 2000). In a survey of 436 Victorian wool producers, 78% believed that the ranking of a sire would change in a different environment (Kaine *et al.*, 2002). Breeders may overestimate the impact of GxE and select sires from the local area in preference to superior sires from other regions. Accommodating GxE when selecting sires requires better estimates of the impact of GxE in different environments.

The focus of the AWI (AWI, 2005) and MLA (MLA, 2006) is for graziers to use their pasture resources more efficiently. To use pasture resources efficiently graziers need to select sheep that are best suited to the quality and pasture biomass throughout the year on their property. There is potential for sheep breeders and commercial producers to increase production by exploiting across-flock genetic variation (Atkins *et al.*, 1998).

2.8.1 Breeding values

Sheep producers can select sires from all over Australia and use Australian Sheep Breeding Values (ASBVs) supplied by Sheep Genetics to choose their breeding stock (Brown *et al.*, 2009). Breeding values of individuals are based on performance in a number of traits important for production e.g. clean fleece weight (CFW). However, phenotypic performance is made up of two components. The first component, genotype, is the combination of gene alleles in the individual. Some combinations of alleles will manifest as performance that is above average for the flock. The second component is the effect of the environment. When determining the breeding value of an animal the environmental component cannot be inherited by the progeny. The genetic component is inherited but not all the genetic material from the sire is passed onto the progeny because 50% of the genetic material comes from the dam and recombination occurs in meiosis during sperm and egg formation.

The heritability (genetic variance divided by phenotypic variance) of a trait can be estimated by regression of the phenotype of the parents on the offspring. The heritability of traits forms the basis for measuring breeding value (Safari *et al.*, 2005). Therefore, breeding values of individuals can be calculated by multiplying the performance of an individual (e.g. 5 kg CFW) compared to that of the flock average (e.g. 4 kg CFW) by the heritability of the trait (0.36 (Safari *et al.*, 2005)). In this example, the breeding value is 0.36 kg but because half the genetic material comes from the other parent the estimated progeny value of the animal is 0.18 kg. Heritability affects the influence that environment can have on a trait. High heritability will reduce the contribution makes to phenotypic variation (del-Bosque-Gonzalez and Kingston, 1987).

The core Sheep Genetics product is ASBVs determined from a database of over one million sheep. ASBVs are available for wool, growth, carcase, reproduction, internal parasite resistance and temperament (Sheep Genetics, 2008). Sheep Genetics provide a service to breeders and producers via MERINOSELECT for wool producers and LAMBPLAN for prime lamb producers.

Specialist wool producers focus their breeding on wool traits. For wool producers seeking to redress loss of wool income with lamb production, the breeding priorities have moved to those beneficial to meat characteristics (Clarke *et al.*, 2002). Producers are trying to increase profits from meat and wool (Fogarty, 2006). Selection is now focused on a number of parameters, listed below (Safari *et al.*, 2005).

Meat - fat and muscle, carcass weight and dress yield.

Wool - greasy fleece weight (GFW), clean fleece weight (CFW), fibre diameter (FD) and staple length.

Reproduction - number of lambs born, number of lambs weaned, weight of lambs weaned and lambs per ewe.

Feed Intake - digestible organic matter intake, efficiency of wool growth and insulin growth factor-1 (IGF1).

The following points highlight the complexity of selection.

- A high CFW in ewes is associated with lower weaning rate (Safari *et al.*, 2005).
- Selecting merino ewes on the basis of their CFW alone could lead to as much as a 20% decrease in weaning rate (Adams *et al.*, 2006).
- Ewes with high CFW had lower fat score and a lower IGF1 concentration in their blood indicating that they had less energy to sustain a pregnancy and produce milk (Adams *et al.*, 2006).
- Adams *et al.* (2002) found that there was a difference in liveweight losses by animals of different strains on low quality feeds.
- Animals selected on the basis of fleece weight alone may perform poorly when placed in a poor nutritional environment, especially in the area of energy intensive requirements such as pregnancy and lactation (Adams *et al.*, 2006; Refshauge *et al.*, 2006).

However, in a review of meat sheep breeding, Fogarty (2009) indicated that there were no major genetic antagonisms between meat and wool traits and that there was no reason to develop a dual-purpose breed (van der Werf, 2006). On the other hand, a meat Merino line of sheep (Fibre Meat Plus, FM+) has been developed experimentally by Ingham and Ponzoni (2001). Attributes such as reproduction rate, growth rate, carcass attributes and meat quality, were improved whilst maintaining fleece weight and a fibre diameter of 19 µm.

The ASBVs calculated using Sheep Genetics data enables wool traits to be combined with traits important for meat production (Fogarty, 2006). However, GxE may reduce the accuracy of ASBVs (Brown *et al.*, 2009) and when breeders have the opportunity to select sires on nationwide ASBVs the impact of GxE may be significant (Dominik and Kinghorn, 2001). An easily accessible method of defining the grazing environment of a region may lead to the better selection of sires by accounting for GxE.

2.8.2 Genotype and environment interaction

Dickenson (1962) summarised GxE as

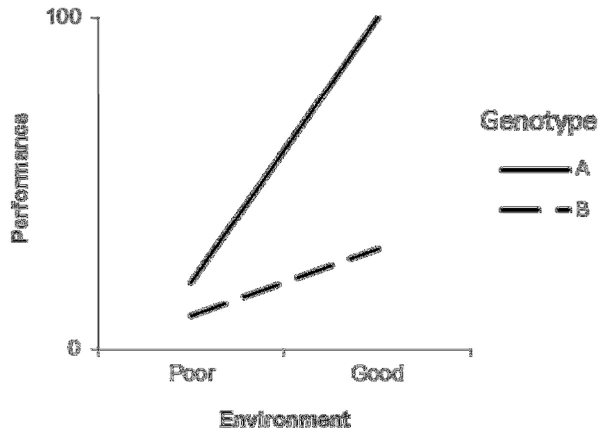
> *"Interaction of genotype and environment hampers selection to the extent that it reduces accuracy in predicting from phenotypic ranking of a series of genotypes in one environment what their ranking would be in other environments."*

Hammond (1947) put forward the argument that environmental conditions had to be optimised before it was possible to select genotypes on the basis of performance. Once selections were made at higher planes of nutrition these gains could be capitalised in less favourable conditions. If this were true the ranking of sires would be the same regardless of the nutritional environment.

Falconer (1952) suggested that the existence of GxE made it preferable to select breeding stock in the environment in which they are to live. Morley (1956) also suggested that sires should be selected in the environment in which their progeny will grow because of the impact of GxE. Dickenson (1955) used the term genotype by environment interaction to define the different effects of environment on phenotype. Haldane (1946) put forward theories of the interaction of 'nature and nurture' drawing examples from a number of species. Haldane argued that too great an emphasis was placed on high levels of production in ideal conditions. Haldane postulated that GxE may have an important role to play if environments changed over time (e.g. climate change).

Genes that do not differ between genotypes cannot contribute to GxE. The performance may be different in the two environments but there is no interaction (Mather, 1975). GxE can manifest in two ways (1) the ranking of genotypes from one environment to the next is different; and (2) the difference between genotypes (e.g. wool yield and fineness) varies in magnitude (scale) between environments (Lin and Togashi, 2002). Both rank and scale manifestations would have an impact on a sheep enterprise. Ranking changes may result in selection of an animal that is not the best suited to the environment. Scale changes may lead to the selection of animals that cannot, for example, produce wool fine enough to attract a premium price.

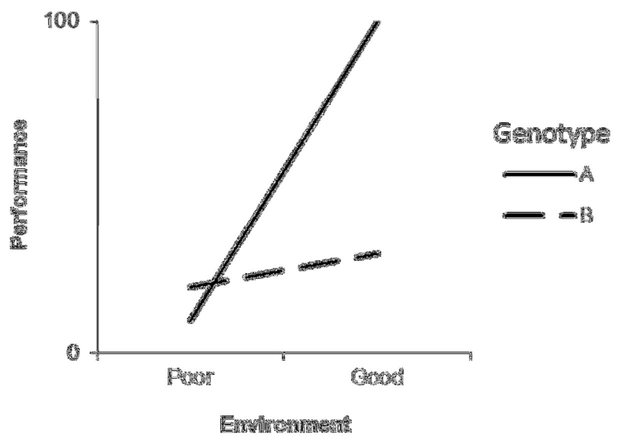
Manifestations of scale GxE will cause a change in the gradient of the line where performance is the dependent variable and grazing environment is the independent variable, as shown in Figure 2.8. In this case selecting genotype A rather than genotype B results in an improvement in performance in the Poor environment but the magnitude of the improvement is greater in the Good environment (Muir *et al.*, 1992). If a premium was paid for Sire A, and his progeny did not perform significantly better than average in the Poor environment, then money has been wasted.



(Source: Muir *et al.*, 1992)

Figure 2.8: Hypothesised example of a genotype by environment interaction (GxE) scale effect of a trait of two genotypes (A & B) in a poor and a good environment.

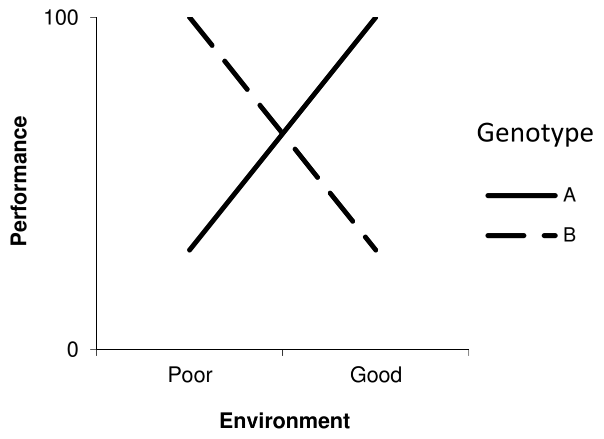
When there is a change in the ranking of genotypes (Figure 2.9) the wrong genotype is selected for the poor environment (Muir *et al.*, 1992).



(Source: Muir *et al.*, 1992)

Figure 2.9: Hypothesised example of a genotype by environment interaction (GxE) ranking effect of a trait of two genotypes (A & B) in a poor and a good environment.

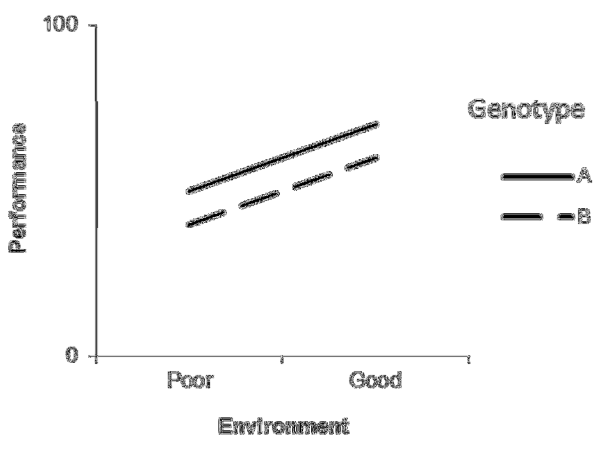
In addition, there is the situation where the two effects combine (Figure 2.10). In this case the wrong genotype would be selected but the magnitude of the loss of benefit is small because the scale has changed (Muir *et al.*, 1992). However, paying a premium for Sire A would constitute a poor investment if his progeny were to run in a poor environment.



(Source: Muir *et al.*, 1992)

Figure 2.10: Hypothesised example of a genotype by environment interaction (GxE) combined scale and ranking effect of a trait of two genotypes (A & B) in a poor and a good environment.

When no interaction occurs environment has no impact on genotype selection (Figure 2.11) (Muir *et al.*, 1992). In this scenario paying a premium for Sire A is a good investment regardless of the environment his progeny run.



(Source: Muir *et al.*, 1992)

Figure 2.11: Hypothesised example of no genotype by environment interaction (GxE).

Selecting a sire from an environment that is favourable and expecting his progeny to thrive in a harsh environment increases the impact of GxE because the genes that dictate performance in a favourable environment are not necessarily the same genes that influence performance in a poor environment (Woolaston, 1985). Selection based on a combination of attributes such as lambing rates, growth rates and wool yield and quality increases the impact GxE has on the accuracy of breeding values. Assessing the consequences of GxE should be part of a sheep producer's selection process. In a survey of Victorian wool producers only 14% of respondents had confidence in selecting rams purely on estimated breeding values (Kaine *et al.*, 2002). If producers select bloodlines with a disproportionate emphasis on the negative impacts of GxE they may not be selecting the best rams for their properties. A classification of grazing environment based on pasture biomass and quality may enable breeders to better accommodate for GxE.

2.8.3 Estimation of genotype by environment effects

Falconer (1952) used the genetic correlation of a single trait in two environments to detect GxE. Genetic correlation is usually used to quantify the genetic link between two traits by plotting the performance of one trait against the performance of the second. A correlation of 1 between a single trait in two environments indicates there is no GxE. A correlation less than 1 indicates some GxE effect. A classification of grazing environments would make it possible to create a correlation matrix and identify where GxE would be significant.

Perkins (1968) put forward a regression approach to GxE (Equation 2.6). The formula is represented pictorially in Figure 2.12. Because the environment is defined by the phenotypic mean of the environment it is not independent of genotype, environment or their interaction. Having an independent measure of environment will enable a more accurate estimate of β (Equation 2.6) and, therefore a more accurate estimate of GxE.

$$y_{ijk}=\mu+G_i + \beta_i\varepsilon_j + \delta_{ij} + e_{ijk}$$

Where:

y_{ijk}: is the performance of an individual
μ: is the overall mean of observations
G_i: is the additive genetic contribution of the ith genotype
β_i: is the linear regression coefficient of the ith genotype across environments
ε_j : is the additive environment contribution of the jth environment
δ_{ij} : is deviation from the regression line of the ith genotype in the jth environment
e_{ijk}: is the residual error

Equation 2.6: Simple model of phenotypic performance (Perkins, 1968).

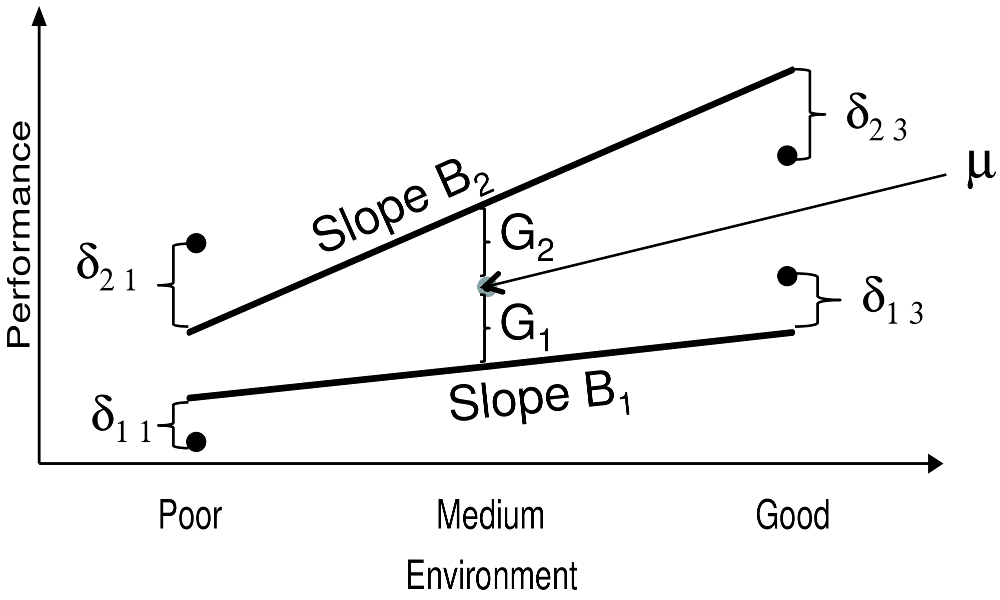


Figure 2.12: Illustration of genotype by environment interaction (GxE) of two genotypes at three environments as per Perkins (1968). Performance is on the y axis and poor, medium and good environments (E1, E2 and E3, respectively).

GxE can be estimated from the interaction effect in a trial where similar genotypes are grazing in different environments (Dunlop, 1962; Lin and Togashi, 2002). In the model that is used to explain phenotypic variation there are four sources of variation. Dominik (2001) summarised them as per Equation 2.7.

$$y_{ijk}=\mu+G_i + E_j + I_{ij} + e_{ijk}$$

Where:

- y_{ijk}: is the performance of an individual
- μ: is the overall mean of observations
- G_i: is the additive genetic contribution of the ith genotype
- E_j: is additive environmental contribution of the jth environment
- I_{ij} : is GxE interaction of the ith genotype in the jth environment
- e_{ijk}: is the residual error

Equation 2.7: Simple model of phenotypic performance (Dominik and Kinghorn, 2001).

2.8.4 Best linear unbiased prediction of breeding values

The accurate prediction of breeding value constitutes an important component of any breeding programme, since genetic improvement through selection depends on correctly identifying individuals with the highest true breeding value. (Mrode, 1996)

True breeding can be estimated by best linear unbiased prediction (BLUP). The general equation for BLUP is provided in Equation 2.8.

$$y = Xb + Za + e$$

Where:

y: is a vector (n x 1) of observations e.g. fleece weight (n: number of observations)
b: is a vector (p x 1) of fixed effects e.g. sex, property, flock (p: number of fixed effects)
a: is a vector (q x 1) of random effects e.g. sire, year (q: number of random effects)
X: is the design matrix[1] (n x p) that relates fixed effect to individual animals
Z : is the design matrix (n x q) that relates random animal effects to individual animals
e: is a vector (n x 1) of residual effects

Equation 2.8: General equation for best linear unbiased prediction (BLUP) (Mrode, 1996).

The aim of using BLUP is to predict the fixed effects (b) and predict breeding values (a) simultaneously (Equation 2.8). The latter are adjusted for the fixed effects using least squares analysis. One drawback of this method is that to make the estimates of breeding values it is necessary to know the variance of the fixed effects (Mrode, 1996).

Maximum likelihood methods were developed to make estimates of the variance of the fixed effects so that the error term was reduced and the residual error between estimates of y and observations of y were minimised (Thompson, 2008). The methodology was called REML and a software package ASReml was developed to perform the analysis for large data sets (Gilmour, 2009; Thompson, 2009). ASReml is used extensively in animal breeding genetics and is used to determine the amount of variation in breeding value that can be accounted for by effects such as flock x year (Brown *et al.*, 2009) and GxE (Carrick, 2005; Haile-Marium and Goddard, 2009; Khaw *et al.*, 2009).

2.8.5 Significance of genotype by environment interaction

Woolaston (1985) suggested that sire by environment interaction had the potential to undermine Merino breeding in Australia and breeding values would be less accurate if GxE existed (Woolaston, 1987). In a study of Australian Merino sheep Dunlop (1962) found that

[1] See glossary for explanation

there was only minor interaction between factors such as fibre diameter and wool production. Dunlop hypothesized that differences in annual climatic factors affected variation more than any GxE. In addition, GxE was not consistent across all traits (Dunlop, 1962). However, Dunlop's (1962) analysis of more than 3000 fleeces did not take into consideration correlation between traits. Analysis using more modern statistical techniques may reveal a stronger interaction. If Dunlop had used a mixed model such as REML as recommended by Safari*, et al.* (2005) the results may have yielded a better estimation of GxE.

Dunlop (1962) concluded by stating that animals should be selected on the basis of all traits and not just a single trait in a particular environment. Other studies have found significant GxE in sheep trials (Table 2.11).

Table 2.11: Examples of genotype by environment interaction (GxE) in sheep trials.

Study	Finding
Morley (1956)	Found significant GxE in weight gain but not fleece characteristics.
Dunlop (1962)	Found a significant GxE in merinos in Australia.
del-Bosque-Gonzalez and Kingston (1987)	Predicted that GxE would impact on selection when the heritability of a trait in different environments was low.
MacLeod *et al.* (1990)	Found a significant GxE for fibre diameter, greasy fleece weight and clean fleece weight.
Atkins *et al.* (1992)	Found interaction between bloodline and region of NSW but did not consider the interaction to be of significance.
Atkins *et al.* (1998)	Found GxE for wool characteristics. They were able to reduce the GxE by incorporating a factor that accounted for the source (stud) of the sires. However, this may simply be a means of identifying the source of the variation associated with GxE.
Osoro *et al.* (1999)	A significant GxE between environments, diet selection and voluntary intake of sheep in Spain.
Brown *et al.* (1999)	Found that there was a significant effect of GxE on staple strength.
Amores *et al.* (1999)	Found significant GxE for birth weight, weaning weight and growth weight but none altered the ranking of Merino sires. The focus of the study was on lamb traits of merinos.
Steinheim *et al.* (2004)	Found significant GxE for lamb weight.
Carrick (2005)	Found significant GxE for weight, greasy fleece weight, clean fleece weight and faecal egg count.
Brown *et al.* (2009)	Found GxE with flock-year as fixed effect in ASReml analysis of Poll Dorset sheep.
Dominik *et al.* (2001)	Found different genetic correlations estimates in high and low nutrition groups.

The results of some GxE experiments are not conclusive and difficult to interpret. Using a limited data set MacLeod *et al.* (1990) found a significant GxE for fibre diameter, greasy fleece weight and clean fleece weight that would alter the ranking of sires. However, when all seven years of data were analysed the GxE was not considered to be of practical importance

(Dominik *et al.*, 1999). Further analysis of the results using the correlation between different traits found that GxE varied between traits (Dominik *et al.*, 2001). Finally, in a simulation of the effects of GxE on different planes of nutrition it was predicted that the GxE would have a significant negative impact on dollar revenue (Dominik and Kinghorn, 2001).

In a review of GxE in the wool industry McGuirk (2009) reviewed work by Morley (1956) and concluded that the GxE reported was over stated and, although there was a scale effect of GxE (Figure 2.8) change in the ranking of sires was not substantiated. He challenged the suggestion that sires would change ranking between environments but supported reporting of the importance of sire by flock/year interactions.

Sheep Genetics accommodates a large number of traits and using many traits in a breeding objective increases the impact of GxE. Therefore, classifying environments for a national breeding system will improve the accuracy of breeding values because environment can be included as a fixed effect in the model. Providing a mechanism that enables breeders and commercial growers to quantify GxE will enable them to be more objective in selecting sires.

2.8.6 Importance of differentiating environment in GxE

Woolaston (1987) begins his review of GxE with the following statement.

> *In the presence of genotype x environment interactions, genetic differences cannot be accurately described without reference to the environment to which they apply.*

The inference of this statement is that the environment must be defined before we can make any judgement about GxE. The “environment” part of the GxE generally refers to how well the animal’s nutritional requirements are met (Falconer, 1952; Dunlop, 1962; Lin and Togashi, 2002; Carrick, 2005) but other factors, such as management, play a significant role (Carrick, 2005). A large environmental difference is defined as “*effects such as location, management system or nutritional regimes”* (Woolaston, 1987). Dominik (2001) differentiated flocks of sheep to quantify GxE on the basis of nutrition. Carrick (2005) classified the environment in terms of performance averages for body weight, fleece weight and wool impurities of the phenotypes under investigation. Carrick (2005) found that correlation of a single trait in different environments decreased as the difference between the environments increased.

Therefore, there appears to be a positive correlation between the magnitude of the difference between environments and the impact of GxE.

The three very broad ABARE zones are of little use to define environment that may impact on GxE. If a GxE is increasingly expressed as environments diverge (Carrick, 2005) then a finer classification of environments may help breeders when selecting stud rams. Carrick (2005) classified environment into five classes. Carrick (2005) indicated that it would be beneficial to be able to define environment better (location and climatic factors) so that it could be used to replace contemporary groups in a multivariate analysis stating *"It was not possible to test climatic environments, localities or even latitude in the present data set."*. However, levels of production are known to change significantly over small distance (e.g. Weddin Shire (Denney *et al.*, 1990)).

Studies of GxE are restricted to where the differences can be characterised (Woolaston, 1987). An Australia-wide classification of sheep grazing environments would provide that characterisation. Woolaston (1987) suggested that environments would need to be categorised and sires ranked in each of the categories. A classification based on the grazing environment would be able to provide the differentiation of environment.

2.9 Conclusion

The application of remotely sensed data to the sheep industry at different scales has potential. It is well established from the literature that measuring pasture resources will become increasingly relevant in grazing animal management, especially with need to adapt to climate change (AWI, 2009). Producers will no longer be able to rely on seasonal patterns imprinted in their memories. They will need real-time estimates of pasture biomass and pasture quality at a scale that will be able to map variation within a paddock. Quantifying a relationship between remotely sensed data and liveweight change and fibre diameter profiles will establish that there are links between remotely sensed data and animal production. Establishing these links is crucial to demonstrating that remote sensing has applications in the sheep industry at a property scale. There is evidence that a robust and meaningful classification of grazing environments at a continental scale is possible. Being able to detect a genotype by environments interaction using the categories generated by the classification will provide the evidence that the classes derived from remotely sensed data have meaning to the sheep industry.

The literature reported demonstrates that the hypotheses developed as part of this thesis have validity. The methodology to test the hypothesis can be developed and the outcomes of the testing of these hypotheses will have significance to the sheep industry.