POTENTIAL FOR REMOTE MONITORING OF CATTLE MOVEMENT TO INDICATE AVAILABLE BIOMASS

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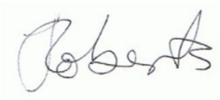
Abstract

There is a call for sustainable intensification of agricultural industries to cope with impending challenges to future food demand and production. Beef and sheep meat production in Australia is dominated by grazing production systems, and equates to the largest land use of the country. Pasture utilisation by livestock can be a major limiting factor in grazing production systems, through under- or over-grazing. This thesis aims to identify if spatio-temporal information from livestock tracking devices can be used to understand livestock-biomass interactions in a rotational grazing system. The specific goal was to determine if this spatio-temporal data might be related to pasture characteristics (particularly biomass quantity) and potentially used as an indicator of the state of the pastures being grazed. Cattle were tracked with GPS for detection and monitoring of specific behaviours including, distance moved, time spent grazing, stationary or travelling, spatial dispersion and social dispersion. Behaviours were compared with declining pasture availability, monitored with an active optical sensor. This thesis explores the behaviour of cattle in three grazing situations. In all experiments distance moved and grazing time results were considered normal, although behavioural changes observed in relation to pasture biomass did not always follow the same pattern. Large daily variation was observed in most results, potentially problematic for detecting a response to biomass. Considering only how the monitored behaviours relate to biomass, the most appropriate behaviour metrics investigated in this research were time spent grazing or moving and the proportion of the paddock utilised. In most cases these metrics exhibited simple, quadratic relationships with biomass. In combination with real-time monitoring systems these metrics might easily be monitored and key thresholds could be determined, resulting in management trigger points from the steepness of an incline or decline, or occurrence of a maxima or minima. There is potential to continue this research in a commercial context to determine if these behavioural metrics can be related to the pasture biomass characteristics that are important to producers. If successful, these behaviour metrics could be used to develop an autonomous spatial livestock monitoring (ASLM) systems to assist graziers make decisions that will substantially contribute to the sustainable intensification of red-meat industries across the globe.

DECLARATION

I certify that the substance of this thesis has not already been submitted for any degree and is not currently being submitted for any other degree or qualification.

I certify that any help received in preparing this thesis and all sources used have been acknowledged in this thesis.



Signature

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List of Acronyms

AOS	Active optical sensor
ASLM	Autonomous spatial livestock monitoring
ATV	All-terrain vehicle
COV	Coefficient of variation
DGLB	Dry green leaf biomass
DSE	Dry stock equivalent
FOV	Field of view
GDM	Green dry matter
GEV	Generalised extreme value
GPS	Geographical position system
HDOP	Horizontal dilution of precision
IHD	Intra herd dispersion
LRI	Livestock residence index
MCP	Minimum convex polygons
MNLI	Modified non-linear index
MSR	Modified simple ratio
NDVI	Normalised difference vegetation index
NIR	Near infrared
NLI	Non-linear index
RBT	Radio beacon triangulation
RMSE	Root mean square error
SAVI	Soil adjusted vegetation index
SR	Simple ratio

CHAPTER 1 – INTRODUCTION AND LITERATURE REVIEW

1.1 INTRODUCTION

Food production and security are very important issues in today's global society especially with the impending challenges facing the agricultural industry of climate change, greenhouse gas production, growing global population, urban encroachment, land sustainability, consumer demand, public perception and animal welfare (Godfray *et al.* 2010; McDermott *et al.* 2010; Godfray and Garnett 2014). These societal and environmental pressures require our agricultural industry to increase food production with reduced resources, whilst encompassing the increased risks and maintaining the sustainability of production systems. There is additional pressure on worldwide food producers to increase production, to align with population growth, including increasing demand for animal feed and biofuels (Nonhebel 2012).

Australian agriculture is not immune to these challenges and recent droughts have highlighted the vulnerability of dryland agriculture in Australia (Qureshi *et al.* 2013). The major food production systems in Australia are predominantly low input, with low rainfall, nutrient poor soils and high climatic variability (Henry *et al.* 2013). Simply put, Australia's climatic variability is the highest of all inhabited continents and Australia's food producing areas are predicted to be among the worst affected by climate change (Henry *et al.* 2013). Australia produces more than 90% of its domestically consumed food and exports sufficient to feed approximately 40 million non-domestic people (DAFF 2013). Australia contributes to approximately 2% of global food trade. Despite this, Australia is a significant contributor to world meat production as the second largest global exporter of beef and sheep meat (FAO 2013; Henry *et al.* 2013). Specifically, in 2011 Australia was the 5th highest ranking country for indigenous beef production and 2nd for sheep production (pooling two China categories). In 2010 Australia was ranked 9th in the world for export quantity of cattle meat and 2nd for sheep meat (FAO 2013).

Beef and sheep meat production in Australia is dominated by grazing production systems (McFadyen and Eldershaw 2012), and equates to the largest land use of the country. Figure 1.1 depicts the land-use areas of Australia in 2005-06. Livestock grazing dominates with 46% of the total land area applied for grazing natural vegetation and 10% for grazing modified pastures, a total of 56% (ABARE 2010).

Considering the current global pressures for food security, appropriate management of Australia's grazing agroecosystems is crucial for future sustainability. While Australia is not expected to suffer domestic food shortages, if the country is to meet the social obligation and challenge of addressing required global food production and security, it must look at ways to increase production while maintaining long-term sustainability (Henry *et al.* 2013).

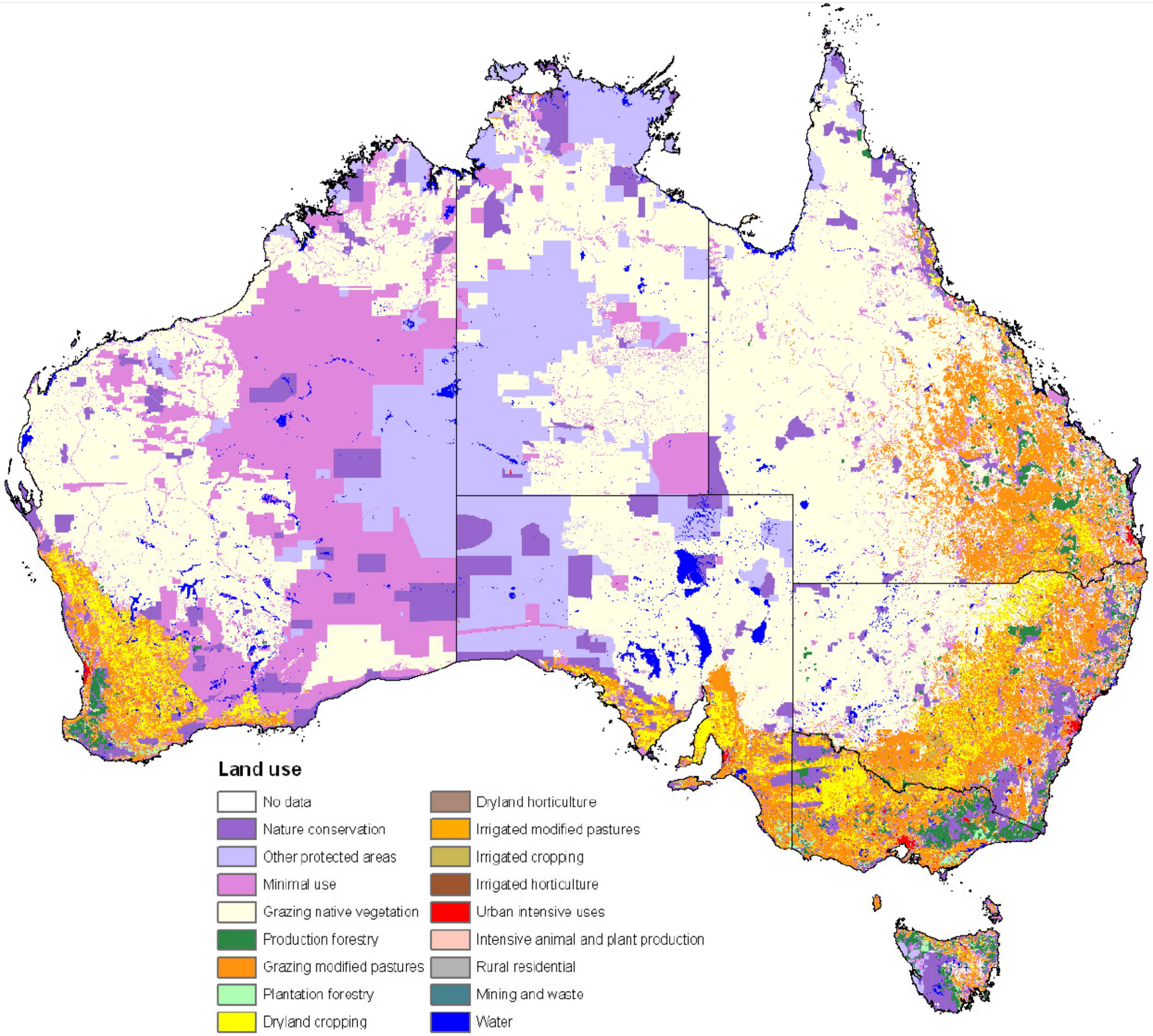


Figure 1.1 Land use of Australia 2005-06 (ABARE 2010).

There is a demand for all agricultural production systems to undergo “sustainable intensification”. This refers to the production of more food from the same area of land whilst reducing environmental impacts (Godfray *et al.* 2010). The Commission of Sustainable Agriculture and Climate Change identified sustainable intensification as one of the seven priority actions to help achieve a food-secure world (Beddington *et al.* 2012). Intensification of management may allow the grazing industry to enhance system sustainability, while maintaining current levels of production.

In order to achieve long-term environment and production sustainability, graziers need to take a systems approach to management and decision making. Grazing agroecosystems are complex and difficult to manage (Scott *et al.* 2013), especially with Australia’s highly variable climate conditions (Behrendt *et al.* 2013; Sutherland *et al.* 2013). This calls for the development of tools which can assist graziers with decision making to achieve sustainable intensification. This thesis will investigate the potential of autonomous spatial livestock monitoring (ASLM) systems as one of these tools.

1.2 Grazing Livestock Production Systems

Appreciating the opportunities for technologies and innovations to impact on the grazing industry requires an understanding of how the current productions systems operate in Australia. There are many management systems available for grazing beef cattle production. Three broad categories for Australia include set stocking, rotational grazing and cell grazing (Mitlöhner *et al.* 2001). The management category applied on a given property often reflects pasture type, climate, water availability, paddock size, stocking density (number of animals per area), and intensity of inputs (e.g. fertiliser and labour), with management decisions closely related to resource availability and patterns (e.g. rainfall). The major difference between management systems is often simply varying timing of pasture grazing and rest periods.

Set stocking, or continuous grazing is the grazing of a paddock over an extended period of time without rotation onto fresh pasture (Hodgson 1979; Mitlöhner *et al.* 2001). This system often takes place on very large paddocks and farms where livestock and pasture monitoring is difficult. Stocking density and inputs are usually very low, often due to climate constraints on water availability. At the other end of the spectrum, cell grazing, or time-controlled grazing, involves regular and systematic moving of livestock to fresh areas with a focus on pasture growth (Mitlöhner *et al.* 2001). Stocking density is often very high and paddocks small with high grazing pressure leading to short rotation times (McCosker 2000). The high stocking density of such systems aims to prevent selective grazing from occurring by forcing the cattle to consume biomass from across the entire grazing area (McCosker 2000). Between these two approaches is rotational grazing, a management system where livestock are grazed on a pasture until a particular time has elapsed or approximate residual biomass quantity has been reached, at which time livestock are moved (rotated) to a fresh pasture (McCosker

2000). This system is usually considered moderate in terms of inputs, timing of rotation and paddock size.

Rotational grazing management systems are the focus of this thesis for several reasons. This management system is common in Australian livestock production. For example, a major Australian research project titled “Cicerone”, conducted to explore outcomes of different management systems, considered rotational grazing to be the control group as it was considered a “typical” management system (Mpiti-Shakhane 2008). Rotational grazing systems are considered more flexible; timing is adaptable and often requires rapid decision making because of the inclusion of multiple paddocks and rapidly changing pasture states (Mpiti-Shakhane 2008). Set stocking, on the other hand, is often used in locations where season dictates access to livestock and decisions for rotations in cell grazing are often pre-determined and short in duration. Whilst the focus is on rotational grazing systems, this present research will also have relevance to the more intensive (cell grazing) and more extensive (set stocking) grazing livestock management systems.

A major benefit of pasture-based livestock production is the ability of the animals to utilise plant biomass which cannot be digested by humans. There are large areas of agricultural land which are not suitable for crop or horticulture production, but will, and do, sustain large numbers of grazing animals (For example, the grazed native pastures identified in Figure 1.1). As a case in point, the northern Australian grazing region significantly contributed to the production of 450,000 tonnes of exported beef and veal in the first half of 2011 (McRae *et al.* 2011). As a consequence of the significant livestock production, particularly beef cattle from large areas of land with limited suitability for other management types, there is a necessity to improve the sustainability and introduce, where possible, sustainable intensification (Godfray *et al.* 2010; Godfray and Garnett 2014) to the industry.

The way in which cattle utilise a pasture has a major impact on the environmental and production sustainability of an agroecosystem. When cattle begin a ‘rotation’ they graze selectively and may only utilise other areas of the available paddock once preferred areas are unavailable (Irving *et al.* 1995). The uneven use of paddocks by cattle is well documented (Low *et al.* 1980; Senft *et al.* 1985). Intensive rotational grazing by increasing the stocking density attempts to evenly distribute grazing pressure across paddocks (Hart *et al.* 1993; Irving *et al.* 1995).

The density of stock on a pasture is considered to be one of the most important factors in managing grazing systems (Ralphs *et al.* 1990; Hart *et al.* 1993; Hickman *et al.* 2004). Under-stocking results in wasted forage and lower animal gain per unit area (Ralphs *et al.* 1990). Over-stocking results in overgrazing which leads to agroecosystem degradation, particularly pasture and soils, and ultimately lost animal production (Ralphs *et al.* 1990). Overgrazing of pasture species also allows for increased survival of less desirable species, reducing the carrying capacity of the agroecosystem (Ellison 1960).

Increased stocking density is a technique applied in an attempt to achieve even utilisation of pasture. It is thought that with high stocking density the vegetation experiences high grazing pressure for short periods, thus substantially reducing species selectivity by grazing livestock (Norton 1998). The higher density determines that in order to gain enough food cattle cannot be selective in what they eat as the feeding competition is too high.

Despite intensifying grazing systems through stocking rates or paddock size, certain areas will still be grazed more heavily than others (Bailey and Brown 2011). Norton (1998) and Taylor *et al.* (1985) believe that uneven distribution of grazing may never be eliminated. Over time cattle disperse further, but will continue to utilise initial areas throughout a grazing period, possibly leading to degradation of preferred grazing areas. This highlights the challenge and importance of grazing management (Taylor *et al.* 1985). Based on this challenge, Hart *et al.* (1993) suggested that issues such as degradation from the overuse of certain areas within a paddock should be monitored and the whole paddock should be managed considering these patches.

Within rotational grazing systems, management strategies which focus on pasture utilisation and yield are among the most appropriate and successful means of improving grazing system production and profitability (Westwood 2008). While improving utilisation increases efficiency for one aspect of the agroecosystem – the plant system, it is important to avoid compromising the animal system. The performance of a grazing animal (production) is dependent on receiving enough nutrients from pasture to achieve its nutritional requirements (Mpiti-Shakhane 2008). The major challenge of a grazing system is matching the pasture with the need of the animal, while ensuring neither is jeopardised. It is important, not to focus on one over the other, but consider them both, their relationship and how the plant system and the animal system respond to management. The core of a grazing system is the interaction between pasture and animal.

1.3 The Plant System

1.3.1 Managing Pasture

The primary goal of a grazing enterprise is to increase profit through effective use of available biomass. This requires matching animal production requirements with pasture availability (Cros *et al.* 2001). As such, rotational grazing systems are generally operated on supply and demand of pasture to animal needs (Westwood 2008).

Poor pasture utilisation is one of the largest limitations to the conversion of pasture dry matter to live-weight gain (Westwood 2008). Increasing pasture biomass utilisation is one of the primary means of increasing the productivity of extensive livestock systems. The precise control of grazing across a paddock can achieve pasture utilisation of up to 70% (Westwood 2008; Monk 2010) which is much higher than the current industry average of 30-40% (House 2003; MLA 2004). Additional to increasing economic efficiency, high pasture utilisation results in decreased production of methane per kilogram of animal product and is identified as the primary means of reducing overall greenhouse gas emissions from grazing systems (DeRamus *et al.* 2003). In order to achieve a sustainable grazing system pasture supply must be matched with animal requirements (Mpiti-Shakhane 2008).

When attempting to increase pasture utilisation it is important to ensure overgrazing is avoided. Overgrazing results in pasture degradation and soil erosion (FAO 1999). It is influenced by four factors: stocking density, season, livestock distribution and grazing frequency (Hormay 1956). In rotational grazing systems, stocking density alone will not dictate grazing pressure across a landscape, with preferred areas receiving heavier impact while non-preferred areas receive light or no utilisation regardless of stocking intensity (Teague *et al.* 2008) during a rotation. With the potential for underutilisation, loss of animal production and overgrazing in grazing systems, monitoring of pasture is essential to achieve optimal utilisation without compromising production or environment.

Optimal pasture utilisation is commonly thought to be achieved through the targeted grazing management of pastures where the sward is maintained between a minimum and maximum biomass. Grazing guidelines commonly provide recommended biomass levels. For example, general guidelines from the industry body Meat Livestock Australia (MLA) are to maintain pasture biomass between 1,500 and 2,500 kg of green dry matter (GDM) per ha and avoid grazing below 1,000 or allowing pasture to exceed 3,000 kg/GDM/ha (MLA 2004). Specific pasture species may require varying management. For example, perennial ryegrass in spring time should be maintained between 1,600 and 2,500kg/GDM/ha (FitzGerald and Lodge 1997). A recent study of vegetation biomass measurement tools in an extensive rotational grazing system in northern New South Wales, involved a commercial operator who aimed to maintain green herbage mass of tall fescue pastures between 1,000 and 3,000 kg/GDM/ha (Trotter *et al.* 2010a).

The aim of managing pastures within a biomass range is to provide pasture to animals at an appropriate height for eating whilst maintaining high growth rate, digestibility and nutrition (when plants are in a vegetative stage and in leafy condition), thus maximising performance of cattle and utilisation (MLA 2004; Teague *et al.* 2008). This optimal grazing management strategy is commonly achieved by monitoring pastures across a farm and rotation of livestock from paddock to paddock based on current and forecast fresh pastures (FitzGerald and Lodge 1997; MLA 2004).

1.3.2 Measuring Pasture

Given the importance of biomass to overall production, it is worth reviewing the various techniques and technologies available to producers to objectively measure biomass. Producers are known to alternate between heuristic visual observation and quantitative approaches of pasture monitoring for grazing management decision making (Gray 2001). Often farmers rely on visual observations alone (Gadberry *et al.* 2014). Quantitative tools are often only used until the farmer felt they were 'calibrated' (Eastwood and Kenny 2009) after which they relied on visual estimates alone. While visual estimation is an accepted and historical practice (Campbell and Arnold 1973), it is subjective and, for some production systems, regular observation of pastures and livestock is not possible, practical or economic despite the understanding that pastures can vary significantly over space and time and between species (Westwood 2008; Gadberry *et al.* 2014).

In addition to monitoring the variability within a pasture, the animal-plant interaction must be considered. When monitoring pastures the focus should be on the green leaf component rather than the total dry matter (Stobbs 1975; Gregorini 2012), as this is the major constituent in the diet of grazing animals (Stobbs 1975). The variability and importance of green leaf component is incorporated in some of the quantitative methods for on-farm pasture monitoring tools.

Traditional quantitative methods for directly measuring pasture biomass, which include harvesting, sorting between green and senescent material and weighing samples (Haydock and Shaw 1975; Omer *et al.* 2006), are destructive, time consuming, expensive and difficult on a large scale (Trotter *et al.* 2010a). Sensors have been developed with the goal of time-efficient, non-destructive, labour-saving methods of estimating plant biomass (Ehlert *et al.* 2003). These include a pendulum meter (Ehlert *et al.* 2003), height sensors (Dalley *et al.* 2009), rising plate meters (Earle and McGowan 1979; Gourley and McGowan 1991; Harmoney *et al.* 1997; Ganguli *et al.* 2000); leaf canopy analysers (Harmoney *et al.* 1997; Ganguli *et al.* 2000); and reflectance sensors (Starks *et al.* 2006; Zhao *et al.* 2007; Trotter *et al.* 2010a). The reported accuracies vary for method of determination, sensor type and for each situation including plant species, sward type and operator. Therefore, a comparison of biomass estimation accuracy for some cases is difficult. For example, Earle and McGowan (1979) presented 13-18% COV using a rising plate meter for biomass estimation of perennial ryegrass, while Ganguli *et al.* (2000) determined the accuracy of estimating Bermuda Grass biomass with a weighted plate meter by calculating the root mean square error (RMSE) (445 kg/DM/ha). Comparisons of sensors for accuracy should be based on similar methods and situation, such as methodology of data collection and plant species. The accuracy of sensors which measure different plant attributes will likely vary for plant species. Harmoney *et al.* (1997) found that the accuracy of four different methods (leaf canopy analyser, rising plate meter, Robel pole and height sensor) to determine biomass was dependent on the forage type and species, with non-jointing grass species more predictably estimated than jointing grass, and swards with legumes leading to underestimation of biomass. While all of these measures can provide non-destructive, reasonable estimates of biomass there are disadvantages, including limited accuracy; limited objectivity; the need for skilled operators; and difficulty in sampling often, rapidly and over large areas (Trotter *et al.* 2010a).

Optical reflectance sensing of plants is an expanding field and widely incorporated in arable crop production (Erdle *et al.* 2011). These sensors provide non-destructive, objective data which can be linked to location and utilised over large areas, recording many points. There are many optical instruments to measure plant biomass (Yule and Pullanagari 2009). Some optical tools measure reflectance at particular wavelengths. Passive reflectance sensors utilise ambient light while an active optical sensor (AOS) emits light onto the target, allowing the tool to be used independently of ambient light (Yule and Pullanagari 2009; Erdle *et al.* 2011). The use of AOSs in agriculture is likely to increase (Holland *et al.* 2012).

An example of an AOS is the Crop Circle™ (Holland Scientific, Lincoln, NE, USA). The Crop Circle™ works by irradiating the plant canopy with radiation in red and near infrared (NIR) wave bands, then measuring the radiation reflected by the canopy with an integrated photo detector (Holland *et al.* 2012). Once measured, the red, NIR and Normalised Difference Vegetation Index (NDVI) (Rouse Jr *et al.* 1974) is recorded.

Using the Crop Circle™ for biomass monitoring requires calibration of the sensor to the pasture species in question (Trotter *et al.* 2010a). This calibration algorithm depends on plant morphology and canopy architecture which means pasture composition (live and dead fraction) and phenology need to be considered. This process requires static scan data coupled with harvested plant samples within the sensor field of view (FOV). While the calibration process is necessarily destructive, subsequent deployment does not require extensive plant sampling.

Mathematical combinations of red and NIR reflectance, spectral indices have the potential to estimate the quantity of green vegetation (Holland *et al.* 2012). An evaluation of several of these vegetation indices was conducted by Trotter *et al.* (2010a), using a Crop Circle™ sensor. Results of this study found pasture biomass estimates to have a RMSE as low as of 288 kg/ha in estimating GDM. This result, using the Crop Circle™ with Soil Adjusted Vegetation Index (SAVI) was reported to compare favourably with other studies involving different instruments and analysis processes (Trotter *et al.* 2010a). Other research investigating the RMSE of AOS in pasture systems found a range of 8-24% error in estimating GDM. Using a “leave one out” cross-validation relative to the mean, Schut *et al.* (2006) recorded a range of errors from 8-22%, while Künnemeyer *et al.* (2001) found RMSE of cross validation to be 24% relative to the mean ryegrass GDM.

1.4 The Animal System

1.4.1 Cattle Behaviour

The concept of animals as a surrogate indicator of the state of a pasture is not new. Shepherds have observed and herded livestock for thousands of years, keenly observing both the feed available to their livestock and the characteristics of animal behaviour as an indicator of pasture or forage (Meuret 1993, as cited in Meuret 1996; Allsopp *et al.* 2007; Salomon *et al.* 2013). In some parts of the world traditional herding still occurs and is, in fact, encouraged (Salomon *et al.* 2013). Squires (1982) argued that because forage use is determined by the interaction of social and maintenance behaviours of cattle, herd behaviours such as dispersion could be used to identify nutritional stress.

Nutritional and behavioural sciences are linked by ruminant nutrition at the pasture level (Gregorini *et al.* 2008). The way an animal behaves can reflect its health and well-being (Robert *et al.* 2009). Therefore, the study of how and when cattle change their behaviour in response to a changing pasture (Eibl-Eibesfeldt and Klinghammer 1970; Lehner 1987; Martin and Bateson 1993; Fox 1998) has the potential to be useful in agricultural ecosystem management.

To better understand the potential for animals to act as indicators for pasture biomass we must first examine how animals interact with the plant system. “The primary concern of all animals is the gathering of food" (Albright 1969) and therefore they are strongly affected by available feed. Grazing livestock spend most of their day either grazing, ruminating or idling (Vallentine 2001). Consideration of these activities, among others, and deviation from what is considered a normal pattern of behaviour may indicate stress (Vallentine 2001) and there is the possibility of predicting forage conditions from the grazing behaviour of cattle (Arnold and Dudzinski, 1978; Low *et al.* 1981; Squires 1982).

When investigating cattle behaviour it is important to remember that cattle class and genetics have a strong influence on an animal’s activity and response. Cattle of different ages have been noted to walk varying distances (Bailey *et al.* 2006). Hormonal state is linked with walking behaviour of cows, for example, cows often increase travelling behaviour during oestrous (Arney *et al.* 1994) and prior to parturition (Phillips 2002b). Additionally, cows have been found to increase travelling after calf weaning (Anderson *et al.* 2012). Bulls are known to be more active, especially at night (Phillips 2002b). Bull travelling behaviour is possibly influenced by the lower risk of predation and also for locating mating partners. Genetics also has an influence on cattle activity and foraging behaviour. Different breeds have been reported to differ in the time spent engaged in active and inactive behaviour states (Funston *et al.* 1991; Hessle *et al.* 2008). Cattle within breeds have also been found to varying walking differences and respond differently within an environment. For example, Bailey *et al.* (2006) observed two classes of cattle exhibit different preferences for grazing in different terrains.

“Bottom dwellers” spent more time grazing areas in lower riparian zones (less challenging terrain), while “hill climbers” were willing to climb steep hills to access grazing areas (Bailey *et al.* 2006). This variation has implications for land management, through selecting cattle with behavioural traits suited to landscape (Bailey *et al.* 2006).

Pasture Influence

There are many livestock behaviours related to pasture biomass, with overall pasture intake a key driver. Intake is often the first limiting factor on animal performance (Westwood 2008), and is defined as the product of the amount of herbage eaten per bite, the rate of biting and the grazing time in a given time interval (Allden and Whittaker 1970).

Ingestive grazing behaviour is affected by grass canopy architecture (Smart *et al.* 1998). Pasture less than about 20 cm in height may restrict bite size due to the mechanism with which cattle eat (Mpiti-Shakhane 2008; Westwood 2008). Pasture plant and leaf density will also influence bite size and rate (Westwood 2008), affecting the movement speed of the livestock. A decline of grazing time in relation to decreased biomass availability can also be attributed to fatigue from limiting the energy of feed (Chacon and Stobbs 1976).

Pasture heterogeneity, including species, plant parts and time of day, leads to variation in herbage chemical composition and, therefore, nutrients supplied to grazing animals (Gregorini *et al.* 2006; Mpiti-Shakhane 2008). Cattle have been found to eat mixed diets with preferences for certain species and plant parts. Cattle select leaf over stem material (Chacon and Stobbs 1976; Hendrickson and Minson 1980). This may be due to ease of prehension of leafy plant parts (Hendrikson and Minson 1980) or because of accessibility (Cosgrove and Edwards 2007). Rutter (2006) reviewed an extensive range of studies investigating the diet preference of grazing livestock and found sheep, dairy sheep, dairy cattle and beef cattle all preferred legumes over grass, with diets ranging from 60 to 78% legume for cattle. Cattle and sheep eat higher proportions of legumes during morning grazing events and grass during evening grazing events (Rutter *et al.* 2004a; Rutter *et al.* 2004b; Rutter 2006). This may be linked with decreased clover availability as the day goes on (Rutter 2006), or due to the changes in plant nutrients over the day (Mayland *et al.* 2005) which could influence nutrient intake and satiation over periods of less grazing activity (i.e. night time) (Rutter 2006). Paddock utilisation is affected differently in homogenous than heterogeneous pasture. In a study by Bailey *et al.* (1990), cattle in homogenous pastures did not utilise the same area for more than two consecutive days.

Cattle, whilst grazing areas of high biomass quantity and/or quality, move slowly as they spend more time biting the available feed than moving through it. Conversely, in areas of low feed abundance they increase their forward movement (Laca *et al.* 1994). This behavioural activity indicates that cattle movement could be an indicator of biomass quantity and quality.

Motivation for moving extends from walking between grazing patches to include locating grazing sites, water, supplements, companionship, shelter and locating mating partners (Zeeb 1983). A summary of 16 studies, undertaken by Arnold and Dudzinski (1978), found beef cattle travelled between 1.2 and 12.6 km in a day, although, it has been noted that the average daily travel distance is around 4 km (Broom and Fraser 2007).

The daily proportion of time spent grazing is expected to be within 20-58% (Arnold and Dudzinski 1978 29-50%; Vallentine 2001, 20-50%; Fraser *et al.* 2009, 34-40%). Cattle are crepuscular and undertake several grazing events during a day. Usually these events follow a diurnal pattern, with the two peak grazing events occurring in the morning, around dawn, and in mid-to-late afternoon. This is largely thought to be influenced by daylight (illumination and cloud cover) (Albright and Arave 1997) and is supported by a comprehensive investigation of the literature and collation of data from 131 studies undertaken by Arnold and Dudzinski (1978). However, there may also be some effect of grazing behaviour linked to the diurnal cycle of nutrients within plants, as previously identified. Herbage quality varies over 24 hours, due to net photosynthesis, respiration and translocation (Mayland *et al.* 2005). Soluble sugars in plant leaves increase during the day (Mayland *et al.* 2005; Gadberry *et al.* 2014) and decrease at night during dark respiration. Cattle have shown a preference for afternoon harvested forage over morning harvested forage and can even distinguish between forages that differ by 0.5% soluble sugars (Mayland *et al.* 1998; Mayland *et al.* 2005). Paddock utilisation was found to be more dispersed for afternoon grazing than morning grazing events in a study by Trotter *et al.* (2010b) investigating spatial pasture utilisation. During periods of limited forage availability, cattle reduce activity as a result of fatigue (Chacon and Stobbs 1976; Cosgrove and Edwards 2007). Grazing livestock alter grazing time to cope with both low and high feed intake rate (Allden and Whitiker 1970). Specifically, cattle reduce grazing time in the morning and increase in the afternoon, in line with increased plant carbohydrates (Gadberry *et al.* 2014). It is possible that the initial daylight grazing activity is to support “gut-fill”; the animals are less selective and are foraging to achieve satiation. During the major afternoon grazing event, cattle may be more selective and graze based on their nutritional requirements and plant available nutrients.

Cattle move at different speeds depending upon activity. Thus, cattle speed could be used to infer behaviour. Putfarken *et al.* (2008) and Anderson *et al.* (2012) (in separate research) developed speed models to determine when cattle are undertaking particular behaviours. The study by Putfarken *et al.* (2008) investigated the grazing behaviour of cattle, using speed to determine when cattle were grazing. Located in North West Germany with an area of 180 ha at low stocking density, the speed model was used to investigate the location of grazing sites. Global Positioning System (GPS) receivers on each animal were used to record their position every five minutes. Grazing behaviour was determined to be at or above 6 m per 5 minutes, up to and including 100 m per 5 minutes, with 45%

of the records considered grazing. Research conducted by Anderson *et al.* (2012), undertaken in the Chihuahuan desert on a 433 ha paddock, used 1 Hz GPS records, calibrated with one minute visual observations, to determine the average speed per minute. Results of this study concluded that in the first of two study periods grazing speeds of cows was found to be between 0.061 and 0.549 m/s and in the second study period, grazing speeds were between 0.059 and 0.49 m/s (Anderson *et al.* 2012).

The spatial distribution patterns of grazing cattle are strongly influenced by vegetation patchiness (Senft *et al.* 1987; Walker *et al.* 1989; Brock and Owensby 2000; Adler *et al.* 2001). Rangeland use by cattle is significantly correlated to standing crop and crude protein (Pinchak *et al.* 1991). Ganskopp and Bohnert (2009) found grazing cattle spatially responded to forage quantity and quality attributes, however, forage (quantity and quality) characteristics alone were extremely poor predictors of where cattle grazed. Drivers of grazing locations were surmised to be strongly related to biomass attributes as well as geophysical characteristics of the paddock (Ganskopp and Bohnert, 2009).

Gregarious herd animals, such as cattle, are conflicted between individual and group activities (Vallentine 2001). Research has found that social cohesion is influenced by herd size (Hacker *et al.* 1988), paddock size (Laca 2009) and pasture availability (Dudziński *et al.* 1982; Squires 1982). Hacker *et al.* (1988) reported that individuals in small herds remained in tight proximity, while cattle in larger herds exhibited greater individual independence. Cattle are also known to split from a single herd into smaller herds in response to declining pasture availability where paddock size allows (Dudziński *et al.* 1982). Intra-herd dispersion of livestock increases when pasture biomass or quality is limiting in order to take advantage of the heterogeneity of the pasture (Squires 1982). Cattle have also been found to prefer spending time in close proximity to other herds (Trotter and Lamb 2008).

Clearly cattle behaviour is strongly affected by the pasture itself. The behaviours are varied and range from direct eating behaviour, for example grazing time, to the way in which they interact with each other, that is, herd and individual dispersion.

Abiotic Influence

While certain behaviours are known to be strongly linked with available food, cattle behaviour in general is influenced by many factors, both biotic and abiotic. Some of these variables include climate, biomass attributes, distance to important landscape features, such as water, shelter and topography, and social structure of the herd (Coughenour 1991). Behavioural variation can include timing of activities and spatial utilisation of the landscape.

To highlight the complexity of cattle behaviour, Teague *et al.* (2008) defines a herbivore as an "animal with a point-sampling defoliation apparatus, that moves in forward motion and normally walks long distances, that responds to visual and tactile cues and reacts to its surroundings in various ways, that engages in activities other than defoliation, that is, a social creature influenced by history, necessity and chance, that has biological limits to bite size and energy expenditure, and that develops patterns of behaviour in response to its environment and companions." While it is obviously important to understand how animal behaviour relates directly to feed availability, it is equally important to know how cattle respond to other external, physiological and social factors.

Weather affects the timing and duration of grazing behaviour. Both low and high temperatures, humidity and wind have an effect on grazing behaviour. Prescott *et al.* (1994) found daily temperatures positively correlated with grazing time, although, both hot and cold thermal stress leads to a decline (Hafez 1968; Vallentine 2001). The principal heat dissipation mechanism in cattle is evaporative cooling and is influenced by external factors of temperature, humidity and wind (Hafez 1968; Blackshaw and Blackshaw 1994). It is thought that cattle reduce feed intake when suffering from hyperthermia as digesting and processing food generates heat (Blackshaw and Blackshaw 1994; Baumgard and Rhoads 2012). Roath and Krueger (1982) found cattle avoided grazing during the hottest part of the day. Grazing time was found to be significantly lower in dark coloured cattle than light coloured cattle during periods of heat-stress (Finch *et al.* 1984), indicating that when an animal is under increased heat-load grazing time is reduced. Cold weather also leads to decreased grazing, and as wind speed increases distance moved decreases (Malechek and Smith 1976). Additionally, research by Baumgard and Rhoads (2012) found that cattle suffering from hyperthermia underwent post absorptive metabolic changes, largely independent of reduced feed intake, concluding that there are multiple effects of heat on cattle metabolism. Put simply, cattle alter grazing behaviour patterns to reduce energy expenditure during periods of weather stress (Malechek and Smith 1976).

Paddock size and the location of landscape features influence utilisation and distances moved by cattle. Features include feed or nutritional supplements, water, biomass availability and degree of ground slope. Where cattle have access to larger areas, daily distance moved increases because of a natural urge to feed on better-quality pasture and to locate in areas with a comfortable environment, such as, finding shade to camp under on a hot day. Ganskopp (2001) observed cattle walked between 5.53 and 5.99 km per day on three paddocks ranging from 825-859 ha. In a 20 ha paddock, cattle were noted to travel 5.2 km/day (Anderson and Kothmann 1980) and 4.2 km/day in a 34 ha paddock (Hart *et al.* 1993). In a range of paddocks from 0.01 to 2000 ha cattle walked between 0.9 and 12.6 km/day (Albright and Arave 1997). Additional to changes in travelling distances, increasing paddock size resulted in lower herd cohesion (Laca 2009). George *et al.* (2008) found paddock utilisation changed when supplement separation was extended out to approximately 600 m. Senft *et al.* (1985) and Hart (1993) noted a difference in distance moved related to water proximity.

Key Behaviours Responsive to Pasture Availability

Animal behaviours reflect available food, encompassing palatability, nutrition and forageable biomass, therefore, the best method of determining livestock-available food is by monitoring the animals that are eating it. Biomass clearly affects cattle distribution, intake rate, grazing time, and social dispersion, as summarised in Table 1.1. However, the challenge of how these behaviours might be used to assist with biomass-based management remains. It must be remembered that feed availability and quality are not the only factors affecting cattle behaviour.

Table 1.1 Some key cattle behaviours which are affected by declining biomass.

Key Behaviour	Response to Declining Pasture	References
Grazing time	Increase, then decrease	(Coleman 1992; Vallentine 2001)
Intake rate	Slows	(Chacon and Stobbs 1976; Bailey *et al.* 1996)
Paddock utilisation	Disperse	(Ganskopp and Bohnert 2006; Laca 2009)
Social dispersion	Disperse	(Laca 2009; Squires, 1982)

If we intend to improve monitoring and decision making in rotational grazing systems utilising spatio-temporal cattle behaviour, we must explore efficient methods of observation. There is a substantial body of literature relating to direct visual observation of livestock in a research context, and this should be reviewed as it forms the basic principles of ethology. That said, for a rotational grazing system a time and cost effective alternative for direct visual observation must be found if an operational grazing monitoring system is to be developed.

1.4.2 Observing Livestock Behaviour in Fields

Visual Observation

Ethology is complex, as natural behaviours can be influenced by the presence of a human (Robert *et al.* 2009). Direct observation of animals is the necessary link between laboratory and “real world” behaviour, imperative to achieving a more accurate and objective understanding of behaviour (Altmann 1974). Traditionally, human observation is the main method of ethology. There are several levels of methodology in behavioural observation; the more common methods are displayed in Figure 1.2. The first level is ‘sampling rules’, which include *ad libitum*, focal, scan and behavioural sampling (Martin and Bateson 1993). The second level is ‘recording rules’, which is either continuous recording or time sampling (Martin and Bateson 1993). The selection of methodology for monitoring animal behaviour is very important as particular sampling methods can only answer certain research questions and can minimise the alternative hypothesis consistent with the data (Altmann 1974).

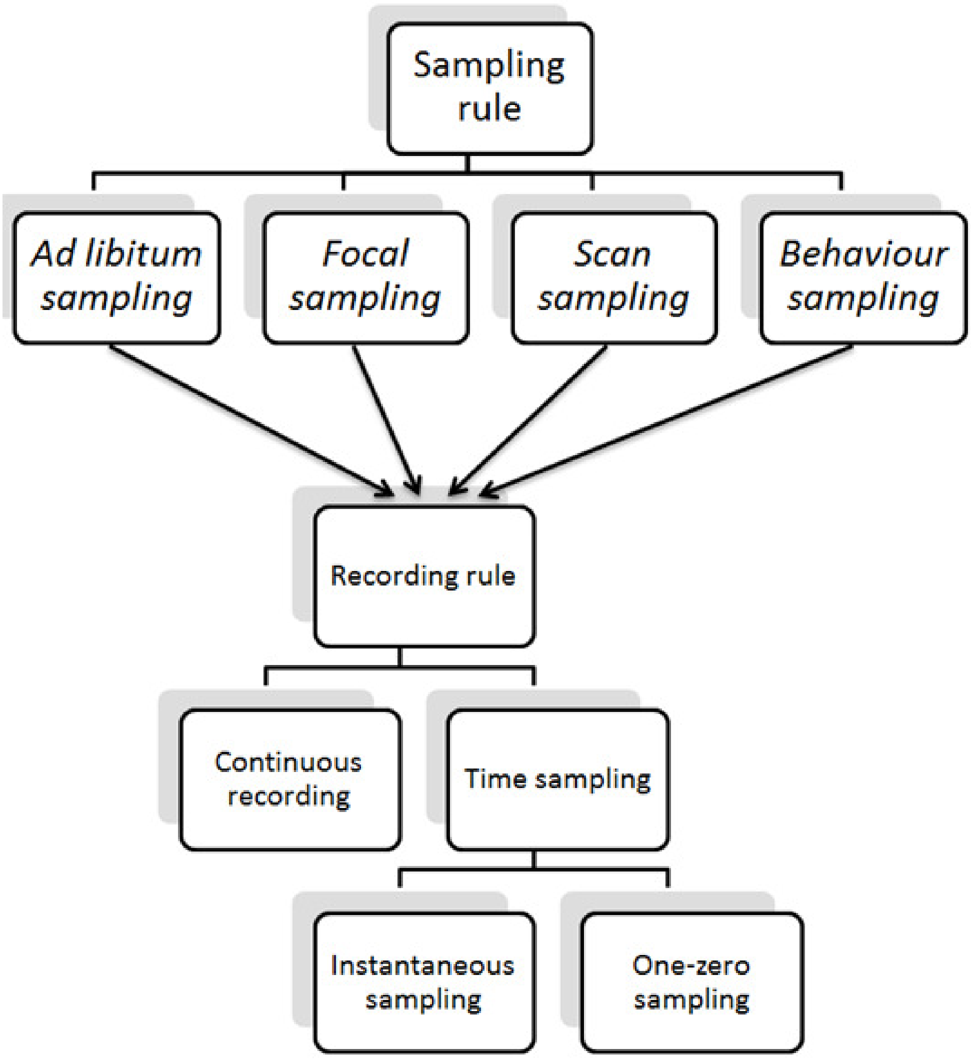


Figure 1.2 The hierarchy of sampling rules (determining who is watched and when) and recording rules (determining how their behaviour is recorded) for determining methods of observing animal behaviour. Adapted from Martin and Bateson (1993).

Ad libitum sampling has no constraints (Martin and Bateson 1993; Lehner 1996). This method relies on opportunistic observations, with the observer noting whatever is visible and seems relevant at the time. This method is very common in field studies (Altmann 1974), consequently the behaviours recorded are often the most obvious and from those animals which are most conspicuous (Lehner 1996), potentially introducing bias (Martin and Bateson 1993).

Focal animal sampling is the continuous observing of one or a few animals for a specified amount of time (Mitlöhner *et al.* 2001). Focal sampling is considered one of the best ways of monitoring group behaviour. Nevertheless, this can be a difficult technique in the field if the focal animal is able to leave the observer's FOV (Martin and Bateson 1993). This sampling technique was used by Mitlohner *et al.* (2001), who found as few as one animal successfully represented a feedlot pen of ten cattle depending on the duration of the activities to be recorded.

Scan sampling is an observation method where behaviours of multiple animals are recorded at a fixed time interval (Altmann 1974) and is a common method for behavioural observation of cattle

(Ray and Roubicek 1971; Gonyou and Stricklin 1984; Kondo *et al.* 1984; Mitlöhner *et al.* 2001). Focal sampling and scan sampling can be integrated in the same observation session (Martin and Bateson 1993). A comparison of several behavioural observation techniques with continuous observation (see below) concluded that scan sampling is an effective technique for monitoring feedlot cattle behaviour (Mitlöhner *et al.* 2001). The trial by Mitlöhner *et al.* (2001) highlighted that the interval of scan sampling can change the effectiveness of the observations. The success was dependent upon scan intervals, with longer intervals (30 or 60 minutes) less accurate and precise than short intervals (1, 5, 10 and 15 minutes) (Mitlöhner *et al.* 2001). There is some concern that scan sampling may be biased by obvious animals or activities. However, this can be overcome by increasing the number of animals monitored and selecting a time interval appropriate to match the duration of the behaviours studied (Martin and Bateson 1993; Mitlöhner *et al.* 2001).

Behaviour sampling involves the recording of any incidence of particular behaviour and is often used for recording rare or significant behaviours (Martin and Bateson 1993). This method is compatible with scan and focal sampling; however rare behaviours, or those with short duration may be missed (Martin and Bateson 1993; Lehner 1996).

Continuous observation involves the uninterrupted recording of an animal's behaviour at any given time (Mitlöhner *et al.* 2001). While continuous observation can be accurate, this method is often not feasible because of the extensive labour requirements and the potential to miss observations if a large number of behaviours or animals are being monitored (Martin and Bateson 1993).

Time sampling can be divided into two categories: instantaneous and one-zero sampling. Instantaneous time sampling is where the behavioural state of an animal at a point in time is recorded (Altmann 1974; Lehner 1996). Instantaneous sampling often has short time intervals as this provides a more accurate estimate of behaviour (Martin and Bateson 1993). One-zero time sampling records whether or not a behavioural state or event occurred during a sample interval (Lehner 1996). Consequently, this method is heavily dependent upon sample interval to gain an accurate insight into the actual frequency and duration of behaviour (Lehner 1996).

Remote Observations

Whilst the aforementioned human observer field methods have been proven to be “successful”, lighting and weather conditions limit monitoring capability and the skill of the observer is critical for ensuring objectivity and avoiding potential observer bias. The use of a remote monitoring system that avoids any human influence on cattle behaviour and in the recording of that behaviour is an obvious next step in developing tools to monitor changes in cattle behaviour (Robert *et al.* 2009).

Constant video surveillance achieves the former and is frequently used for animal behaviour monitoring (Laca *et al.* 1992; Stewart *et al.* 1997; Hergenhan *et al.* 2009; Robert *et al.* 2009). Video surveillance has the major advantage of removing observer bias or fatigue effects and allows the observer to re-observe or confirm behaviour retrospectively (Stewart *et al.* 1997). Unfortunately, over long periods of time, video surveillance can become cost prohibitive and labour intensive (Robert *et al.* 2009). Moreover, data may be missed in video surveillance due to the animal moving out of the view of the camera either because of inanimate obstructions, the presence of other animals, or simply a limited FOV (Stewart *et al.* 1997). Additionally, weather conditions, lighting and the capacity for data storage may also be an issue.

Ideally, the monitoring of grazing livestock behaviour would consist of observing each animal in the herd at all times and noting all behaviours and durations. Unfortunately, this is generally not feasible. While grazing related behaviour is usually obvious and easy to observe, cattle do not graze at all times. Thus, one practical observation method to gain an understanding of a whole herd of cattle at pasture is to scan sample grazing related behaviours (grazing, walking, resting) of focal animals, if herds are small enough, all animals' behaviours, or a combination of the two.

Replication and Experimental Units

Irrespective of the observation method, replication is very important. The level of replication required is dependent on factors such as the experimental unit (Mitlöhner *et al.* 2001). For example, individual animal or the herd, with a higher replication required when investigating at the individual animal level as there will inherently be greater variation between individuals than between herds (Mitlöhner *et al.* 2001).

The suitability of using individuals or groups of animals as the experimental unit is a contentious issue among some livestock scientists due to perceived pseudoreplication. Pseudoreplication can be defined as "the use of inferential statistics to test for treatment effects with data from experiments where either treatments are not replicated (though samples may be) or replicates are not statistically independent (Hurlbert 1984). Between 1998 and 2005 several papers and letters to the editor of the Journal of Applied Animal Behaviour Science on this topic were published (Rook and Huckle 1995; Phillips 1998; Weary and Fraser 1998; Rook 1999; Iason and Elston 2002; Phillips 2002a; Archer *et al.* 2003; Shutler *et al.* 2005; Archer and Friend 2005). Pseudoreplication as it relates to replicate independence and treatment have been topical in this discussion.

Cattle are social animals, and are known to influence the behaviour of others (Rook and Huckle 1995). As such, the question of an animals' independence for statistical analysis arose, because some statistical methods require observations to be independent (Iason and Elston 2002). Observational studies may contribute to our understanding of livestock; however care must be taken to not use inappropriate statistical analysis (Rook 1999). Phillips (1998) summarised some influences on synchronised animal behaviours, i.e. weather, photoperiod, feed form (i.e. grazing pasture). We know that behaviours are differently influenced by synchrony. As such, as selective approach to determining if the experimental unit should be an individual or a herd should be undertaken (Phillips 2002a) depending on the social dependence of the observed behaviour. In some cases statistics such as an ANOVA may be justifiable (Phillips 1998). However, Phillips (1998) also suggested a subset of animals which have been "observed not to interact" could be used for behavioural analysis. This technique is unlikely to exclude social effects on behaviour. Just because two cattle are not observed to interact with each other, does not mean there is no social influence. This concept is supported by Weary and Fraser (1998) who identified that members of a herd may share similar traits, therefore cannot be treated as independent. Rook (1999) highlighted that competition is also a factor which must be taken into account when considering statistical analysis, for example, food one animal has eaten is no longer available to another animal. Thus, feed available to an individual is influenced by others. Phillips (1998), Rook (1999) and Iason and Elston (2002) all agree for behaviours influenced by synchrony the safest way to avoid invalid statistical analysis is to "analyse results on the basis of group means" (Iason and Elston 2002). Iason and Elston (2002) identified time spent grazing as the behaviour most influenced by synchrony. Thus, for research relating to grazing behaviours and where direct competition for food occurs the behaviour of cattle cannot be thought of as independent of other herd members. In these cases it is more appropriate to treat the herd as the experimental unit, rather than the individual animal.

Experimental treatment is also an important factor to consider when monitoring livestock. Individual cattle within a herd may be replicates if experimental treatments can be applied to individuals. However, using individuals as replicates when a treatment is applied to the whole herd is pseudoreplication (Weary and Fraser 1998).

There are strong arguments for using the herd as the experimental unit when dealing with grazing livestock. Nevertheless, if the influence of synchrony on behaviour is thought to be limited then it may be appropriate to observe the individual as a replicate. Furthermore, using herd replicates of grazing animals may be difficult as the conditions in which the animals are kept must be identical or the results may be influenced (Phillips 2002a). Due to the nature of livestock behaviour research it may be impractical to only monitor behaviour at the group level. Finally, limitations on statistical analysis should not lead to ignoring biologically important results (Archer and Friend 2005).

1.4.3 The Use of Spatial Livestock Behavioural Monitoring Tools

Geographical Positioning System

The global positioning system (GPS) is "a system of orbiting satellites used for navigational purposes and capable of giving highly accurate geographic coordinates using hand-held receivers" (Heywood *et al.* 2006). Originally GPS receivers were designed to provide real-time navigation information, although many are capable of storing locational data and other attributes which can be downloaded (Heywood *et al.* 2006).

A GPS receiver determines location from time signals from orbiting satellites. Using the time taken to receive a time signal the receiver-satellite distance can be calculated (Swain *et al.* 2011). Triangulation, based on the distance of the GPS device from several satellites, allows the location to be determined (Swain *et al.* 2011). Ordinary 'uncorrected' GPS can provide an accuracy of position on the horizontal plane to within 5 to 10 m (Swain *et al.* 2011).

Position accuracy is a function of the geometry of selected satellites (Spilker Jr 1996). There are several measures of positioning accuracy or dilutions of precision (DOP): geometrical (GDOP), positional (PDOP), horizontal (HDOP), vertical (VDOP) and time (TDOP) (Note: $PDOP^2 = HDOP^2 + VDOP^2$ and $GDOP^2 = PDOP^2 + TDOP^2$ (Langley 1999)). Generally, the more satellites used to determine position the lower the DOP values and therefore the higher the accuracy (Langley 1999).

Errors, including missed logs and location errors, are inherent to GPS and can lead to bias (Lewis *et al.* 2007). There are three main causes of error: clock error, atmospheric distortion and multipath (bounced) error (Swain *et al.* 2011). Missed location fixes have been attributed to environmental factors including tree cover, cover type, terrain and time of year (Di Orio *et al.* 2003; Lewis *et al.* 2007).

Using GPS for Cattle Observation

In the last 15 years, GPS receivers have been used to acquire cattle observation data by many researchers (Turner *et al.* 2000; Ganskopp 2001; Schlecht *et al.* 2004; Ungar *et al.* 2005; Ganskopp and Bohnert 2006; Ganskopp and Johnson 2007; Reed and Soliem 2007; Schwager *et al.* 2007; Hessle *et al.* 2008; Johnson and Ganskopp 2008; Putfarken *et al.* 2008; Swain *et al.* 2008b; Trotter and Lamb 2008; Clark and Johnson 2009; Ganskopp and Bohnert 2009; Guo *et al.* 2009; Handcock *et al.* 2009; Tomkins *et al.* 2009; Bailey *et al.* 2010; Trotter *et al.* 2010b; Ungar *et al.* 2011; Anderson *et al.* 2012; Henkin *et al.* 2012; Orr *et al.* 2012; González *et al.* 2015). Anderson *et al.* (2013) identified 99 studies which employed GNSS technology to monitor free-ranging cattle and stated it is the "most common system to date for monitoring ungulate movement". GPS monitoring can potentially provide accurate and efficient grazing behaviour information and is not limited by weather or darkness (Turner *et al.* 2000). The recording of animal positions can contribute to the understanding of pasture utilisation, animal performance and behaviour, along with the understanding of variables which may affect cattle such as, pastures and landscape features (Turner *et al.* 2000). Using GPS spatial information, distance moved, speed, location within the paddock and proximity to other spatially identified objects can be obtained, all of which are known to be related to pasture availability and/or utilisation by cattle.

It has been established that moving and stationary behaviours of livestock can reflect changes in available biomass (Section 1.4.1). Grazing and travelling behaviour can be influenced by many things (including pasture availability (Coleman 1992), time of day (Trotter *et al.* 2010b), weather (Prescott *et al.* 1994)), but the speed of stationary activity will show little fluctuation over time. This provides potential for GPS monitoring to provide robust estimates of cattle activity. Any movement captured while an animal is in a stationary behaviour state (i.e. standing, lying, ruminating), will relate to the error of the device or small movements of the part of the body the device is attached to (Anderson *et al.* 2012). Speed is very easily derived from GPS data by determining the distance over the time difference of two consecutive points. Stationary and active (travelling and grazing) behaviour are mutually exclusive behavioural states and so GPS has the potential to easily discern when an animal is stationary.

While GPS has great potential as a tool for animal spatial behaviour studies, there are challenges to overcome. Firstly, precise and accurate location data are essential for developing robust animal resource selection functions (Swain *et al.* 2008b), although the level of accuracy and precision required depends on the situation and aim. Accuracy and precision have implications for a range of investigations including resource selection, determining behavioural states, and proximity to landscape features and other animals. Another major challenge is determining an appropriate sampling frequency for a particular investigation (Johnson and Ganskopp 2008). There is a trade-off between high temporal resolution data sampling and sampling duration (Johnson and Ganskopp 2008). High temporal resolution data sampling is attractive because it maximises spatio-temporal behavioural information gathered. Consequently, this leads to large data sets and potential difficulty of data analysis and interpretation (Schwager *et al.* 2007). Moreover, this can limit sampling duration due to finite battery life. For an investigation which requires a high level of accuracy and precision in small areas (less than 100 m^2), Swain *et al.* (2008b) concluded that the GPS fix rate should be no more than 10 seconds. The determination of fix rate should be considered carefully with the desired outcomes of research. Cattle move in a spatially tortuous manner and so if there is a requirement to investigate the movement patterns of cattle, a shorter fix rate may be necessary as a more tortuous path will incur a higher loss of information with a longer fix interval (Schwager *et al.* 2007), as shown in Figure 1.3.

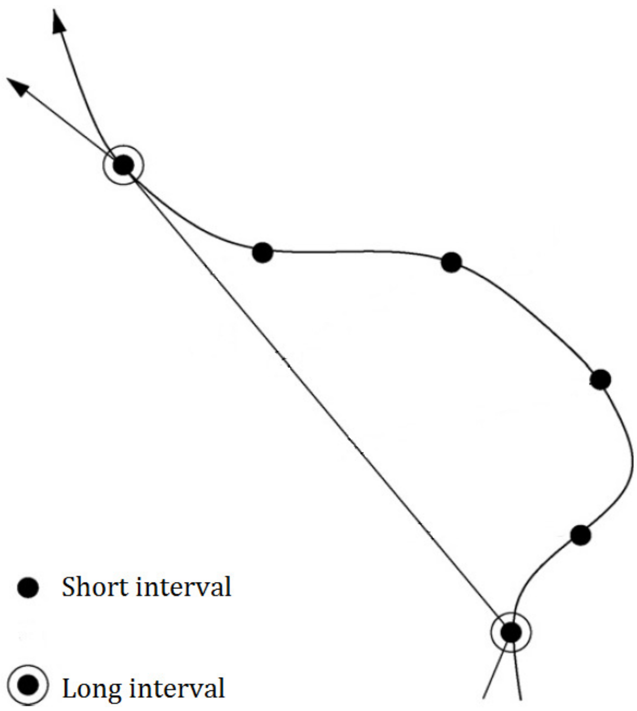


Figure 1.3 Assumed paths based on interval length. A short interval shows a more complex path, resulting in longer distances over the total time being recorded. A long interval shows a simple path, resulting in less distance moved over the total time. Adapted from Schwager *et al.* (2007).

Using GPS to monitor livestock behaviour in research is not novel and has assisted scientists to achieve research goals that require livestock monitoring or to investigate the potential utility of ASLM systems. Thomas *et al.* (2008) investigated the relationship between sheep behaviour and forage abundance. The research investigated the predictability of changes in sheep behaviour as available, edible dry matter was depleted. Results demonstrated that GPS measured behavioural indices "provide useful information about the animal's environment" and the authors claim that "production, welfare and environmental outcomes could be improved by using animal behaviour as a real-time biological monitor" (Thomas *et al.* 2008). These monitoring systems could achieve this through focusing on specific behaviours which are known to relate to biomass availability, and are not limited to sheep.

Aims of numerous previous studies include: determining seasonal, breed and paddock variation on forage use (Hessle, 2008), modelling behavioural states (Guo, 2009; Schwager *et al.* 2007), detecting predator-avoidance behaviour (Clark and Johnson, 2009), determining the effect of weaning on behaviour of cows and calves (Anderson *et al.* 2012), investigating spatial and temporal foraging behaviour of cattle in particular environments (Tomkins *et al.* 2009, Henkin *et al.* 2012, Bailey *et al.* 2010), determining the efficacy of salt and water to manipulate cattle distribution (Ganskopp, 2001), locating preferred grazing locations (Ganskopp and Bohnert, 2006; Ganskopp and Bohnert, 2009; Putfarken *et al.* 2008; Trotter and Lamb, 2008), identifying potential nutrient redistribution zones (Trotter *et al.* 2010b), investigating how stocking rate influences pasture utilisation (Tomkins *et al.* 2009), ascertaining the contribution of factors to GPS error (Ganskopp and Johnson 2007; Johnson and Ganskopp 2008; Swain *et al.* 2008a) and methods to reduce error (Ganskopp and Johnson 2007; Swain *et al.* 2008a). The addition of GPS was found to improve understanding of cattle behaviour. Anderson *et al.* (2012) noted that speed thresholds for determining cattle behaviour improved observation modelling. As well as investigating locations of livestock, researchers have successfully used GPS data to determine proportions of time cattle spend in particular areas and diurnal activities (Ganskopp 2001; Tomkins *et al.* 2009; Trotter and Lamb, 2008; Trotter *et al.* 2010b).

A summary of some of the research incorporating GPS tracking of cattle is presented in Table 1.2. This includes the duration of tracking, cattle class, log rate and success rate of data capture. All the listed research achieved above 90% success in varying environments, with a range of log rates and on different classes of cattle (predominantly cows), and less than 10 animals were tracked at a time for short periods (<3 weeks).

In some cases accuracy was determined and reported. This was achieved by comparing recorded locations of devices from a fixed, known location. Accuracy varied and some of the examples used differential corrections reporting mean errors of 1.7, 2.1 and 5.8 m (Ungar *et al.* 2005) and 1.7 +/- 0.7 m (Ganskopp and Johnson 2007). However, even experiments with uncorrected GPS devices, such as the UNETracker, found a considerably small mean error of 4.14 m +/- 3.04 m (Trotter and Lamb 2008). Examples of uncorrected Lotek (Lotek Engineering Inc., Newmarket, Ontario, Canada) devices resulted in a mean errors of 4.5 +/- 0.4 m (Ganskopp and Bohnert 2006), 3.9 m +/- 0.8 m (Ganskopp and Johnson 2007) and 8 m, 95% of the time (Turner *et al.* 2000). Turner *et al.* (2000) noted interval had an effect on mean error; with the shortest interval tested (5 minutes) the least error-prone.

The log interval for cattle research (summarised in Table 1.2), was most commonly 5 minutes, ranging from 1 second to 60 minutes. The balance between required interval for observing particular behaviours and battery life appears to be the main consideration. For example, in research where the interval between position recordings was 1 second (Anderson *et al.* 2012), data was downloaded and batteries replaced every second day. This required handling the cattle each time. Consequently, it is possible that such frequent human interference could have a significant influence on livestock behaviour.

Table 1.2 Summary of some research using GPS to monitor behaviour of grazing cattle, including the number of cattle tracked, study length, type of animal tracked, position log rate of the GPS and the percentage of potential logs received. Incidence of "/" indicates separate deployments within the same study in order of occurrence.

Study	No. devices	Study time	Animal	Log rate	% of fixes achieved	Research objective
Ganskopp (2001)	6	21 days	Cows	20 mins	99.4 (4 cows) / 81 (1 cow)/ 21 (1 cow)	Evaluate efficacy of salt and water manipulations for affecting cattle distribution
Turner *et al.* (2000)	5	4/7/7	Cows	5 mins	Not stated	In relation to GPS tracking: review, explain, describe application and discuss grazing livestock behaviour and implications of that for research and management
Ungar *et al.* (2005)	6	38 days	Cows	20 mins	Not stated	Evaluate potential of Lotek GPS to predict cattle activity in contrasting rangeland environments
Ganskopp and Bohnert (2006)	12	9 days	Cows	10 mins	100	Determine proportions of time cattle graze within senescent and conditioned pasture
Ganskopp and Johnson (2007)	12	15 days	Cows	5 min	94.5	Assess effects of individual GPS accuracy and evaluate methods for filtering GPS records of inactive animals
Schwager *et al.* (2007)	3	39/43 hours	Cows	43/53 sec	Not stated	Applying K-means classification algorithm to categorise animal tracking data into behaviour classes
Hessle *et al.* (2008)	24	3 days	Heifers	15 mins	Not stated	Determine effects of breed, season and plant moisture on the extent and location of grazing and ruminating behaviour of cattle
Johnson and Ganskopp (2008)	12	15 days	Cows	5 mins	90.9	Evaluate effects of GPS sampling intervals on proportion of pasture used and daily distance moved by cattle
Putfarken *et al.* (2008)	3	10 months (1 collar rotated every 7 days)	Cows	5 mins	Not stated	Elucidate preferred vegetation of sheep and cattle and if preference changes throughout a year
Swain *et al.* (2008b)	6	3.65 days	Cows	25 sec	96.3	Test hypothesis: As time interval between GPS fixes increased, so too would the prediction errors
Trotter and Lamb (2008)	4	14 days	Steers	10 mins	99	Develop a GPS tracking device and investigate the impact of cattle on grazing/cropping rotations
Clark and Johnson (2009)	20/80	~5 years	Cows	30/5mins	Not stated	Evaluate effects of wolf presence on cattle behaviour, location selection and productivity
Ganskopp and Bohnert (2009)	12	15 days	Cows	5 mins	90.9	Test hypothesis: grazing cattle seek nutritionally superior pasture
Guo *et al.* (2009)	6	4 days	Cows	10 sec	Not stated	Explore a model of cattle movement to estimate behavioural parameters
Tomkins *et al.* (2009)	6	~6 weeks, 4 times	Steers	60/60/30/30 mins	Not stated	Determine landscape use patterns of steers and identify drivers for selection including edaphic and environmental factors and the influence of stocking rate

Bailey *et al.* (2010)	3	8-10 days 3 times	Cows	30/10/10 mins	Not stated	Compare grazing behaviour of different cattle cohorts (naïve and familiar) in the Chihuahuan Dessert and a subtropical environment
Trotter *et al.* (2010b)	6	10 days	Steers	5 mins	Not stated	Testing new GPS tracking collar and deriving information from cattle monitoring for livestock manager use
Anderson *et al.* (2012)	5/12	12/12 days	Cows	1 sec (averaged to 60 sec)	≥90 (for 2 cows each study)	Determine if GPS could be used to classify foraging, walking and stationary behaviour of cattle from speed
Henkin *et al.* (2012)	37/214	24 hours	Cows	5 mins	95/94	Determine the effect of terrain on cattle grazing behaviour

While high temporal resolution data is appealing for the increased potential to understand livestock, over estimation of movement may occur when cattle are, in reality, stationary or very slow moving. In such situations, the inherent error can be larger than the movement (Heezen and Tester 1967; Ganskopp and Johnson 2007). This is especially important when high frequency position logging is used as the cattle path may appear more tortuous than it actually is (Figure 1.3) or when GPS devices are set to "sleep" between logging positions as this can result in higher error (Jurdack *et al.* 2010). The opposite can happen with low temporal resolution where the estimation of actual distance moved may be underestimated (Turner *et al.* 2000) (Figure 1.3). For example, change in cattle speeds occurred when position-fix frequency was increased from 30 to 5 minutes in research conducted by Clark and Johnson (2009). This change may be due to the increased frequency of sampling, although, there were several situational differences between the studies and so Clark and Johnson (2009) could not be definitive about the cause, surmising it could have been due to collar technology, GPS position fix rate, or environmental or ecological factors. In an investigation of the effect of sampling interval on position accuracy, Swain *et al.* (2008a) found the shorter the interval the more positionally accurate the consecutive points were. Fix rates were found to be increasingly accurate as interval decreased under 60 seconds and the recommended interval to achieve the best accuracy in this situation was 10 seconds or less.

The design of GPS receiver devices is important to the success of GPS for animal tracking. Anderson *et al.* (2012) found that exposed wires often lead to failure of position recordings due to physical damage and failure of data storage onto a mini SD card. The original UNETracker designed by Trotter and Lamb (2008) also had external cables for the antenna. This was deemed a design flaw leading to the UNETracker II design encompassing both GPS receiver and antenna inside a polycarbonate box (Trotter *et al.* 2010b).

Combination of GPS with Other Sensors

The inclusion of other sensors and/or biostatistics in addition to GPS has contributed to our understanding of cattle behaviour. The integration of motion sensors and accurate position data provides the best indication of behavioural state (Ungar *et al.* 2005). González *et al.* (2015) developed and evaluated a behaviour classification algorithm for cattle using GPS and 3-axis accelerometers set to record at 4 and 10 Hz, respectively. Guo *et al.* (2009) used a combination of high-fix rate GPS, accelerometer and magnetometer data, and a Hidden-Markov Model to more accurately determine the behavioural state of cattle. Magnetometers and accelerometers enable determination of angular and directional speed. When combined, these sensors provide the ability to monitor behaviour such as foraging, ruminating, bedding, and relocating, which may not be associated with large scale movements. Magnetometers and a K-means algorithm were incorporated with GPS by Schwager *et al.* (2007) to determine active and inactive behaviour. Despite increased information, this study limited activity classification to only two states. An advantage of integrating an unsupervised learning-algorithm, (i.e. K-means), is the potential to introduce variation in sample rate during a single deployment, based on activity state (Schwager *et al.* 2007). For example, this could potentially increase the sampling interval when cattle are stationary and shorten it during active states, such as, grazing. As yet, to the author's knowledge, this has not been investigated for cattle behaviour. Another example determined distinctive eating behaviour with IGER behaviour recorders which monitor jaw movements in association with locational information from GPS (Hessle *et al.* 2008). This improved accuracy of grazing time estimates as biting and chewing when eating can be distinguished from chewing in rumination and also distinguished rumination from resting behaviour by combining movement with chewing activity. Many researchers (Turner *et al.* 2000; Ganskopp 2001; Ganskopp and Bohnert 2006; Henkin *et al.* 2012) used a combination of GPS and motions sensors to determine behavioural state. The combination of several devices provides significant information on livestock at the individual level. However, the system for behaviour determination becomes increasingly complex with additional concurrent data to be analysed. Despite the success of sensor integration, many examples of GPS for cattle monitoring provide evidence that grazing behaviour can be successfully determined without additional sensors present (Putfarken *et al.* 2008; Trotter and Lamb 2008; Tomkins *et al.* 2009; Trotter *et al.* 2010b) and may be more suited for commercial application. Single-sensor animal monitoring is attractive as it limits data storage, power and data analysis requirements. Moreover, several commercial devices are currently being designed for ear tags. Consequently, weight becomes very important and motion sensors potentially become unsuitable because of independent ear movements of livestock (Trotter *et al.* 2010b).

Trotter and Lamb (2008) successfully monitored cattle activity over two weeks by comparing GPS data and remotely sensed biomass information. Tracked cattle spent most of their active time in areas of high pasture NDVI (high biomass), than those of low NDVI. The activity measure was distance moved per hour and was comparable to findings of other researchers (Ungar *et al.* 2005).

GPS has been successfully utilised in research on grazing livestock and is noted to be a significant improvement on other livestock monitoring methods (Turner *et al.* 2000). Unfortunately, there are some disadvantages which limit GPS suitability for operational deployment in industry, predominantly because of cost and energy requirements of the devices. As well as the trade-off of battery-life and sampling interval, there are other complications of applying GPS to livestock tracking. Firstly, GPS devices, particularly commercial equipment for livestock industry, is expensive, upwards of >AUD$1,500 each (Trotter *et al.* 2010b). To ensure accuracy of assumed behaviour many researchers calibrate actual behaviour with GPS data (Turner *et al.* 2000; Ganskopp 2001; Ungar *et al.* 2005; Ganskopp and Johnson 2007; Putfarken *et al.* 2008; Ganskopp and Bohnert 2009; Bailey *et* *al.* 2010; Anderson *et al.* 2012; Henkin *et al.* 2012). This requires visual observations which are difficult to obtain, especially in extensive pasture situations (Ungar *et al.* 2005). There are other ASLM options for remote tracking of livestock which may be more suited to commercial deployment. One example is Radio Beacon Triangulation (RBT).

Radio Beacon Triangulation Technology

Taggle® is a commercial example of a RBT system comprising of on-animal devices (ear tags) which emit a radio signal that is recorded by several stationary receivers (Andrews 2010; Trotter 2012). The location of a device is determined by triangulation based on flight time of the signal from the device to each of the receivers (Trotter 2012). These devices can transmit between 7 and 20+ km depending on terrain and have an accuracy of approximately +/-15 m (Andrews 2010).

Despite having a lower accuracy than GPS devices, Taggle® provides real-time position data of livestock, is less expensive than other commercial ASLM technologies (Trotter 2012) and individual tags have a life expectancy upwards of 3 years (Andrews 2010). A Taggle® system is established for monitoring sheep and cattle at the University of New England's "SMART Farm", which covers approximately 1,100 ha (Trotter 2012).

There are some limitations of Taggle®. The system's current power requirements for the receiving base stations restrict where they can be located (Trotter 2012) and interference in certain terrain, (i.e. hills and trees), can limit the tracking footprint. The Taggle® system requires further development for widespread commercial deployment. At the time of writing the author had not located any published research relating to the use of Taggle® for livestock monitoring or direct comparison with other spatial monitoring technology, such as, GPS. However, recent personal communication confirms the continuing development of this technology (Foyster 2013; Trotter 2013).

Autonomous Spatial Livestock Monitoring Systems for Behavioural Monitoring

When planning livestock observation several considerations should be made for choosing an autonomous spatial livestock monitoring system. These include the inherent error, required position log interval to capture behaviour of interest, establishment cost, requirement for real time data versus retrospective data, lifespan of a unit, potential deployment time, animal of interest, permanency of the device on an individual animal and the likelihood of successful data capture.

While traditional methods of behavioural monitoring have improved our understanding of cattle behaviour, they are not suited to providing immediate knowledge of livestock interaction within an agroecosystem. There is potential to learn about spatio-temporal livestock behaviour through automated behavioural observations (Umstätter *et al.* 2008) coupled with ASLM systems including RBT and GPS. Furthermore, technology-assisted management could improve pasture health, agroecosystem conservation, livestock welfare and production, and allow decisions to be made immediately in response to behaviour detection (Umstätter *et al.* 2008).

The utilisation of spatial tracking data for behavioural research reduces error associated with direct observations by humans (Brock and Owensby 2000). Tracking devices also remove the influence of human presence on cattle, and are thought to have little to no adverse effect on large herbivores (Rutter *et al.* 1997).

There are several real-time spatial monitoring (tracking) systems currently in development that are aimed at livestock industries. The ability to monitor pasture in relation to grazing animal behaviour from automated behaviour observations has the potential to allow for immediate managerial actions in response to changing animal behaviour (Umstätter *et al.* 2008). Now is the time to identify the needs of growers and the types of decision support tools that will be available to generate and handle the data that will follow. Improving our understanding of dynamic grazing behaviour will allow us to advance management of our grazing systems for improved production and sustainability.

1.5 Summary and Scope of Thesis

Pasture utilisation is a key driver of grazing production systems, and these agroecosystems must be carefully monitored to ensure both environmental and production sustainability. Accurate pasture monitoring in grazing systems is difficult and can be expensive and/or time consuming. Cattle behaviour is closely related to pasture characteristics, such as biomass quantity, therefore cattle movement and behaviour over time through remote spatio-temporal tracking devices has the potential to indicate pasture parameters. This information could support a farmer's decision making process by including the animals response to changing pastures.

While AOS provide accurate biomass estimates, they are unsuitable for some enterprises. For example, farms where accessing the paddock for monitoring is difficult, i.e. very large properties and paddocks, irregular in timing for example where season dictates access, or where long sampling intervals necessitate sensor re-calibration. These tools, as with visual monitoring, require time, effort and regular sampling to be reliable. Moreover, there is little to no suitable method for regular on farm assessment of pasture quality. This is an important missing link in pasture monitoring and can have a major impact on pasture and animal health with production and economic flow-on effects. As the purpose of pasture monitoring is to optimise pasture availability for, and utilisation by, livestock, an alternative approach to direct pasture monitoring may be to monitor grazing animals themselves.

Given the opportunities and challenges previously identified, this thesis aims to identify if spatio-temporal position information from livestock tracking devices can be used to understand livestock-biomass interactions in a rotational grazing system. Furthermore, this research sets out to specifically determine if spatio-temporal animal behaviour can predict when sufficient pasture biomass to support grazing becomes unavailable.

Within this thesis, cattle behaviour derived from GPS technology will be investigated in response to decreasing pasture biomass to determine the potential of these behavioural attributes as a pasture biomass indicator. The steps in undertaking this research include determining if:

1. GPS tracking of cattle could be used to determine specific behaviours;
2. these behaviours (identified in 1) could relate to pasture availability;
3. a simple movement metric of cattle behaviour could be related to pasture availability.

This thesis investigates a novel approach to applying a relatively new technology (GPS livestock tracking) to monitoring available feed. Due to the nature of spatio-temporal data collected for this research and the fact that the scientific field of precision livestock is, and thus the techniques used are, relatively new, a large focus of this thesis is on methodology including: data collection, analysis techniques, and interpretation.

This thesis contains six chapters as depicted in the schematic of Figure 1.4. Chapter 2 outlines a methodological study which develops and applies some basic spatio-temporal techniques to cattle tracking data and Chapter 3 describes an introductory experiment to ascertain if there are comparable cattle behavioural patterns as biomass declines in similar environments. Chapters 4 and 5 are concurrent in the flow of the research, both based on the same experiment, and the results from Chapter 4 inform Chapter 5. Specifically, Chapter 4 presents the development of an experiment-specific, speed-based behaviour model for cattle and Chapter 5 demonstrates a comprehensive experiment involving multiple herds and paddock rotations to investigate the potential of speed and other behavioural attributes as tools for determining declining feed availability. Finally, Chapter 6 presents a summary and the conclusions of this research.

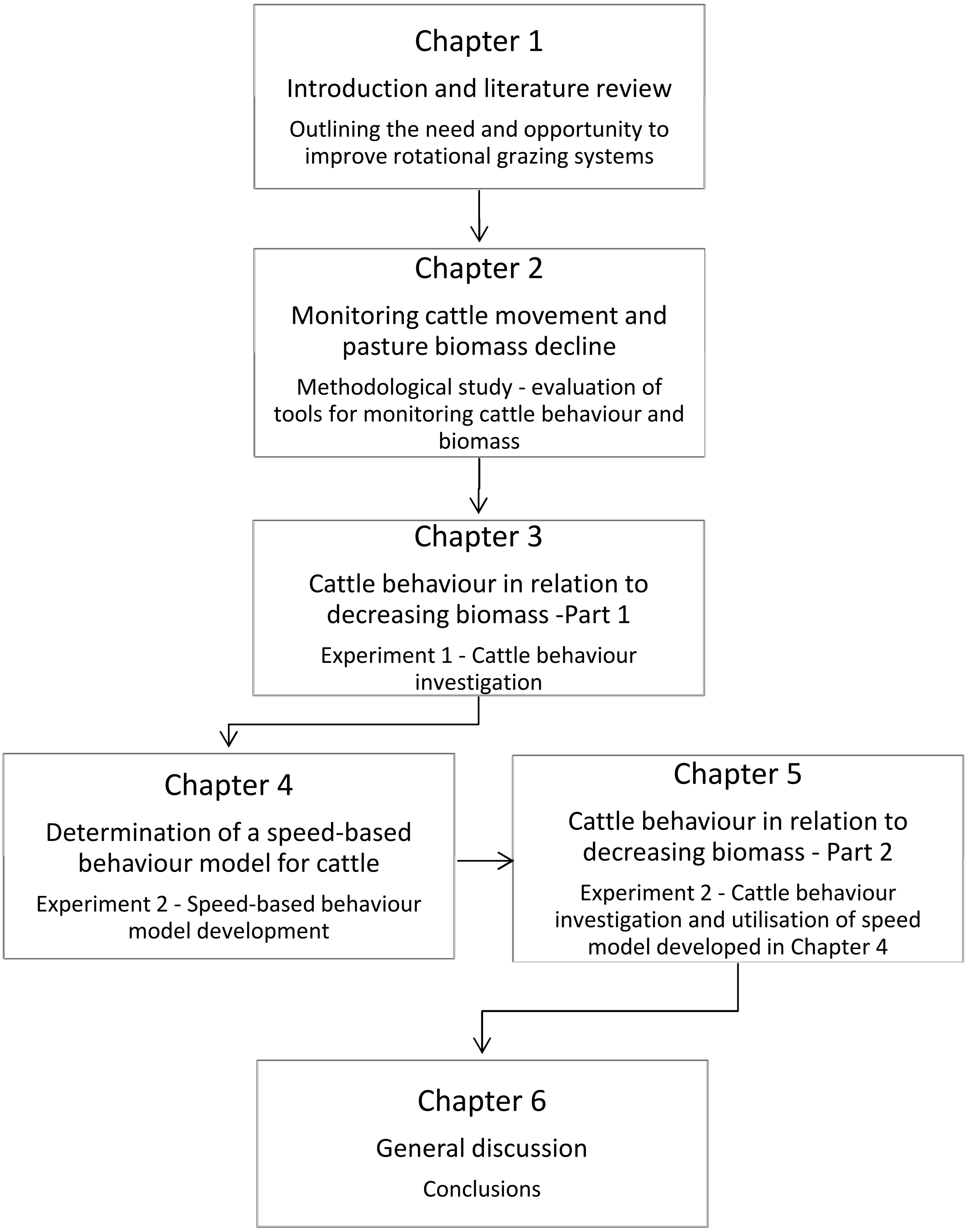


Figure 1.4 Flow of chapters, including the number, title and focus of each chapter. Note: Chapters 4 and 5 are both based on the same experiment.

CHAPTER 2 – MONITORING CATTLE MOVEMENT AND PASTURE BIOMASS DECLINE: PRELIMINARY STUDY

2.1 INTRODUCTION

Pasture utilisation is a limiting factor in Australian rotational grazing production systems. Adequate monitoring of pasture biomass for decision making purposes is crucial for improving utilisation. The objective of this preliminary study was to explore and understand the basic data produced by GPS tracking devices. This research examines specific movement metrics that might be derived from the positional data recorded by GPS receivers and how these relate to the key behaviours identified in Table 1.1. Furthermore, and building on the earlier work of Trotter *et al.* (2010a), the value of AOSs as a tool for measuring and mapping available biomass for future experimental deployments was also explored.

The specific objectives of this trial were to:

1. gain an understanding of the basic data processing requirements and opportunities for quantifying pasture biomass with an AOS as an experimental tool;
2. gain an understanding of the basic data processing requirements and opportunities for quantifying grazing metrics gained from GPS tracking of livestock;
3. explore methods of converting positional logs of cattle into metrics of potential value including:
    a. speed,
    b. distance moved,
    c. time spent grazing, and
    d. paddock spatial utilisation; and
4. explore means of combining grazing metrics and quantified biomass in terms of assessing grazing behaviour in light of available biomass for grazing.

2.2 Materials and Methods

2.2.1 Field Site and Events

The study site was a 51 ha paddock located at the Douglas McMaster Research Station; a 1500 ha mixed cattle and cropping enterprise located in the Northwest Slopes region of New South Wales, Australia (150^{o}36’0” E, 29^{o}17’6” S WGS84). The study began on the 8th of August 2008 and finished on the 24th of September 2008; a duration of 48 days.

The herd was managed as part of a ‘normal commercial system’ during the study period, not as a controlled experiment. Consequently, the study period was interrupted by management operations (31 August to 5 September 2008) in which the herd was removed and returned to the paddock. This period, hereafter referred to as the ‘Exclusion Period’, coincided with a major rainfall event. Prior to the Exclusion Period cattle had access to one water trough located in the south eastern corner of the paddock and following the Exclusion Period an additional water trough was available in the north eastern corner. Because of the break in the natural grazing cycle (the rainfall events and variation in cattle and water management) the total grazing duration was divided into four periods; Periods 1 and 2 before, and Periods 3 and 4 after the exclusion Period. Period 1 spanned from the 12th to the 21st of August inclusive, Period 2 from the 22nd to the 30th of August inclusive, Period 3 from the 6th to the 14th of September inclusive and Period 4 from the 15th to the 23rd of September inclusive. For the purposes of this study, the changes in livestock behaviour were compared between Periods 1 and 2 and then Periods 3 and 4. This enabled a simple comparison of how behaviour might have changed in relation to reducing biomass whilst the cattle had access to relatively similar resources. Due to the change in management and landscape access, it was not deemed feasible to make a comprehensive comparison between periods that occurred before (Period 1 and 2) and after (Periods 3 and 4) the Exclusion Period although some notable trends will be discussed.

2.2.2 Weather

Weather data including rainfall and maximum daily temperature were obtained from the closest Australian Bureau of Meteorology (Australian Government Bureau of Meteorology 2008) weather recording site located at 'Coolatai', approximately 40 km east of the study site (150°61’ E, 29°20’ S).

2.2.3 The Plant System

Paddocks were sown to forage oats (*sp. Avena Sativa var. Warrego*) on the 9th of May 2008. The forage oat crop was monitored for biomass quantity using an AOS; Crop Circle™ ACS-210 (Holland Scientific, Lincoln, NE, USA) which has a FOV of 32° by 6°. The AOS recorded red and NIR reflectance values. In this work, owing to the pre-configuration of the particular instrument used, the reflectance values were converted into NDVI values (Rouse Jr *et al.* 1974) and recorded.

AOS Calibration

To compare sensor NDVI values with actual biomass, the AOS was calibrated from 25 static biomass samples in quadrats of 0.7 m X 1.0 m, at the commencement of the trial on the 30^{th} of July 2008. These samples were then harvested at 4 cm above the ground, sorted into green and dead material, dried for 48 hours at 90°C and weighed. The dried weights and corresponding NDVI values from the AOS scan were used to create a calibration curve by plotting NDVI against measured GDM and fitting a logarithmic curve in Microsoft Excel®. The RMSE of the difference between actual and estimated values was calculated. This was calculated in excel by taking the square root of the squared average difference between the measured and actual values.

Determining Whole Paddock Biomass

Two AOS biomass surveys were undertaken; at the beginning of the study in Period 1 (13 August 2008; Figure 2.1), and at its conclusion following Period 4 (24 September 2008) with the Crop Circle™ linked to a Trimble differential GPS mounted on an all-terrain vehicle (ATV) and following the protocol of Trotter *et al.* (2010a). Active optical sensor records were collected along transects spaced at 25 m intervals.

Figure 2.1 The study paddock showing the forage oats at the commencement of the trial.

To ensure complete along-transect coverage, the sensor was started prior to entry into the paddock. As the sensor continuously records data at six records per second regardless of the ATV speed, when the ATV slows or stops a large number of records are logged for the same location. In both of the situations, excess points were removed from the dataset to reduce bias of repeated measures or measures not applicable to the site. This was achieved in ArcGIS® version 9.3.1 (ESRI 2008). All positional data was projected to datum WGS84 56S.

For each of the two surveys, the Crop Circle™ NDVI data were interpolated with block kriging in Vesper® (Whelan *et al.* 2001). Whelan *et al.* (2001) describe block kriging as a method to "predict the weighted average of a variable over some block of length (dx) and width (dy) centred about some prediction point (x)), y0)". This method results in a smooth map. A block size of 50 m and a grid size of 5 m were used. Following this, GDM values were calculated for each grid point from the sensor calibration equation. The inferred GDM was averaged for each scan day. The derived green dry biomass data for a given day was mapped in ArcGIS® for visual analysis.

2.2.4 The Animal System

This research was conducted under the University of New England's animal ethics authority number AEC08/017 (Appendix A.1).

The paddock was stocked with a herd of 151 cattle consisting of three different cohorts; small steers, large steers and in-calf cows. Cattle were weighed prior to entry into the study and the dry stock equivalent (DSE) calculated where 1 DSE is considered equivalent to a two year old, 45 kg merino sheep (wether) (McLaren 1997). Details of these cohorts are displayed in Table 2.1. The number of head per hectare is not reported here for two reasons. Firstly there are several classes of cattle and secondly, post Exclusion Period, an additional area was provided to the cattle with the access to a second water point.

Table 2.1 Livestock cohorts including weight before entry to the study and standard deviation, and the dry stock equivalent (DSE) in the paddock. Note: the total DSE in the paddock during the study is 1,770.

Cohort	Number of Animals	Initial Average Weight (kg)	Weight Standard Deviation (kg)	DSE/Animal	Total DSE
Small Steers	99	243	28	10	990
Cows	30	569	71	15	450
Large Steers	22	450	74	15	330
Total	151				1770

GPS System

Six UNETracker GPS collars (Trotter and Lamb 2008) were deployed on animals in the herd from 9 August to 23 September 2008, as shown in Figure 2.2. The details of the collared cattle are presented in Table 2.2. As the cattle were newly introduced to the paddock, the first three days (9-11th August) of the data collection were excluded from analysis as this was considered an exploration phase where the cattle were adjusting to the new paddock (Vallentine 2001). Collars were programmed to log a positional record every 10 minutes. In this study, six of the 151 animals were tracked. The collars were also programmed to undertake "over determination", meaning that the positional fix was recorded based on the location of all of the available satellites (more than the minimum of four), which results in improved position data quality (Hulbert and French 2001; Trotter & Lamb 2008; Buerkert and Schlect 2009). This meant that the GPS devices had to receive signals from at least 5 satellites before determining a positon, and would not record otherwise. Additionally, the maximum fix acquisition time was set to 60 seconds. Therefore, if a position was not determined in 60 seconds the device would return to sleep mode, which conserves the battery life.

Figure 2.2 Four of the livestock in the study on the 28/08/2008. Note: the small steer on the left is fitted with a UNETracker collar around the neck.

Table 2.2 Details of tracked animals including the cohort and initial weight.

Collar	Cohort	Initial Weight (kg)
1	Large steer	403
2	Cow	648
3	Small steer	297
4	Small steer	251
5	Small steer	221
6	Small steer	222

Upon completion of the experiment, the collars were removed from the cattle and the raw GPS data downloaded. The data was then processed through a spread sheet in Excel® which converted the raw data strings into time, date, latitude, longitude, number of satellites used for position determination, and HDOP.

Data was cleaned in Excel® and ArcGIS® to remove any points outside the experiment period and incomplete or erroneous data. Incomplete data refers to data strings missing information. Erroneous data is positional information that exceeds the following distance thresholds; (i) more than 10 m outside the paddock boundary or (ii) a recorded location a large distance from both previous and succeeding logs. The threshold for this filtering was based on calculating a speed from the distance between consecutive positions divided by the time interval between consecutive records. Unfortunately, the author was not able to locate literature which included maximum cattle speeds. Significant livestock monitoring is necessary to determine the true upper limit of cattle speed, especially as this value is highly dependent on the log rate of the GPS device (Figure 1.3). Consequently, the author examined the data for values associated with incomplete data and erroneous data and the upper limit for cattle speed of 3 m/s was concluded. Descriptive statistics of the individual tracking devices was produced, including the number of logs recorded of the expected, satellites used to record fixes and average HDOP.

Distance Moved

The cleaned dataset was imported to ArcGIS®, and the eastings and northings of the position logs was determine with the ArcMap® extension 'Hawth's Tools' (Beyer 2004). The diurnal activity was determined by averaging the distance moved for each daylight hour over the experimental period. Movement metrics were also derived, including step-length (the distance between consecutive position fixes). From step-length, herd average distances travelled per day were calculated by summing all the distances between position logs for each animal on each day, then averaging these values for all tracked animals.

Speed-based Behaviour

Average speed was determined by dividing the step-length over the time interval between consecutive points. Based upon a speed-behaviour model developed by Putfarken *et al.* (2008), the animal's activity was determined. Each point was subsequently classified by speed as either stationary (<0.02 m/s), grazing (≥0.02≤0.33 m/s) or travelling (>0.33 m/s). The mean proportion of time spent grazing by all six animals monitored was then calculated for each day of the deployment period by dividing the number of intervals between points classified in each behavioural category over the total number of intervals per day.

Spatial Distribution

A livestock residence index (LRI) was calculated and mapped to determine how the livestock were utilising the paddocks. Here we define utilisation as grazing behaviour and LRIs were calculated from grazing data determined from speed. The LRI unit for any given location is the proportion of time a tracked animal was located in that area of the paddock compared to the time spent in the paddock as a whole (Trotter *et al.* 2010b). In order to calculate the LRI, a 50 m X 50 m grid was first created for the paddock and the GPS location points accumulating in each cell (defined by the grid) were counted. The counts for each grid cell were divided by the total point count over the entire paddock and multiplied by 100 to obtain a percent occupancy for each cell. The LRI is given by:

$$LRI_x = \frac{\sum_x raw\ point\ count}{\sum_n raw\ point\ count} \times 100$$

Note: a cell was considered utilised if LRI>0.25. At the time of the analysis, to the author's knowledge, a threshold for LRI, or area utilisation, had not been investigated. As such, the value of LRI was chosen to reflect little or no positions recorded, in this case 0.25 equates to 14 positions.

2.3 RESULTS

2.3.1 *THE PLANT SYSTEM*

AOS CALIBRATION

The biomass calibration from the AOS Crop Circle™ and biomass sampling is presented in Figure 2.3. Fitting an exponential curve ($y = 23.2e^{5.3x}$) for the correlation between GDM and NDVI resulted in an r-square of 0.80 and a RMSE of 165 kg/ha GDM. This RMSE equated to 18% of the mean biomass (896 kg/ha GDM).

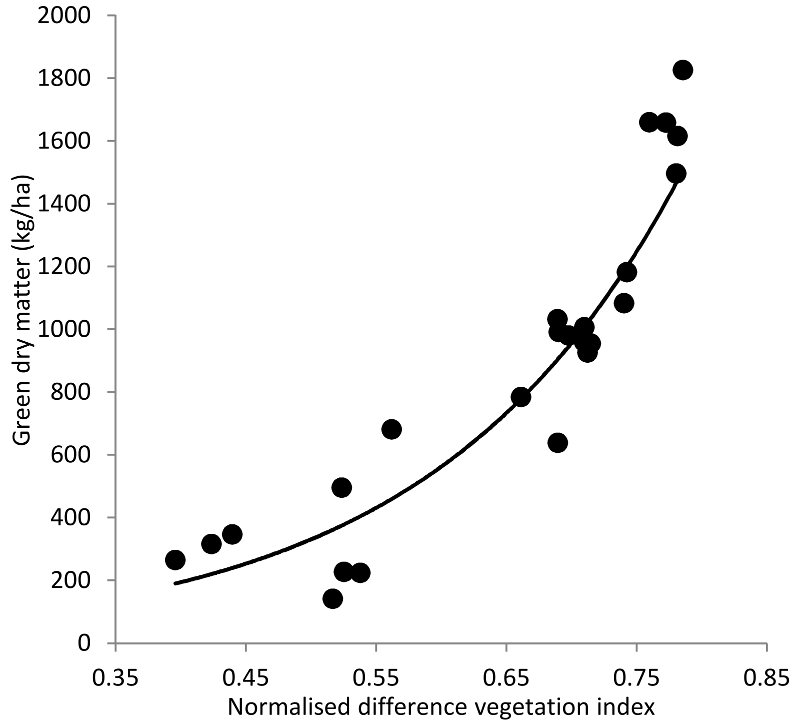
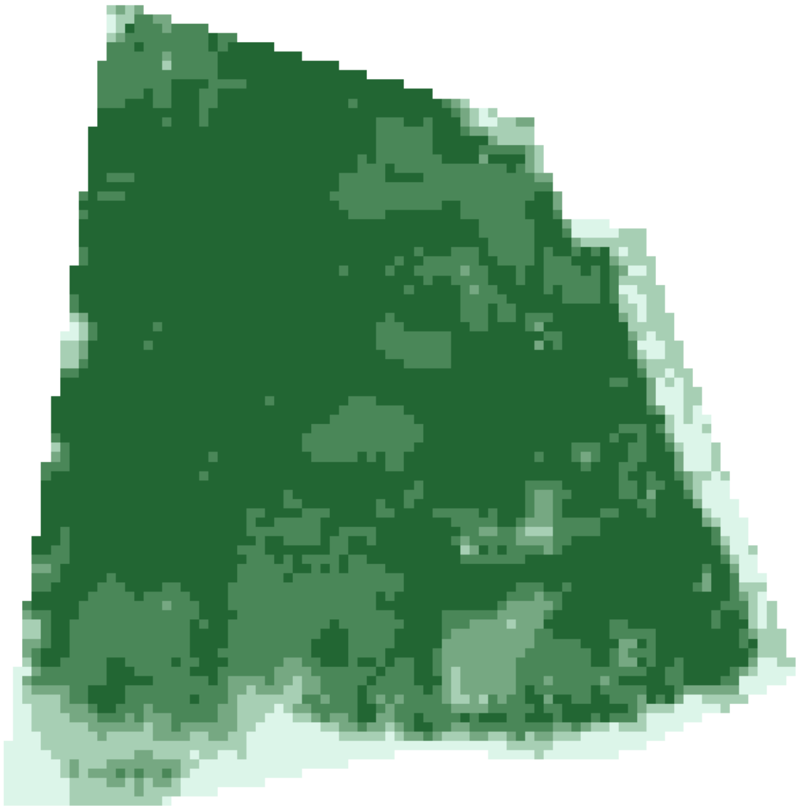


Figure 2.3 The calibration of green dry matter and normalised difference vegetation index for the Crop Circle™ as a forage oats biomass estimating tool at Douglas McMaster Research Station. The formula for the log transformation was used to estimate biomass values based on normalised difference vegetation index recorded in the field.

WHOLE PADDOCK BIOMASS

Based on the calibration model developed, GDM maps of the paddock produced for the 13 August 2008 and the 28th of September 2008 are given in Figure 2.4, A and B respectively. On the 13th of August the mean paddock GDM was 928 kg/ha (standard deviation = 296 kg/ha) and on the 24 September 2008 it was 279 kg/ha (standard deviation = 109 kg/ha).

A)



B)

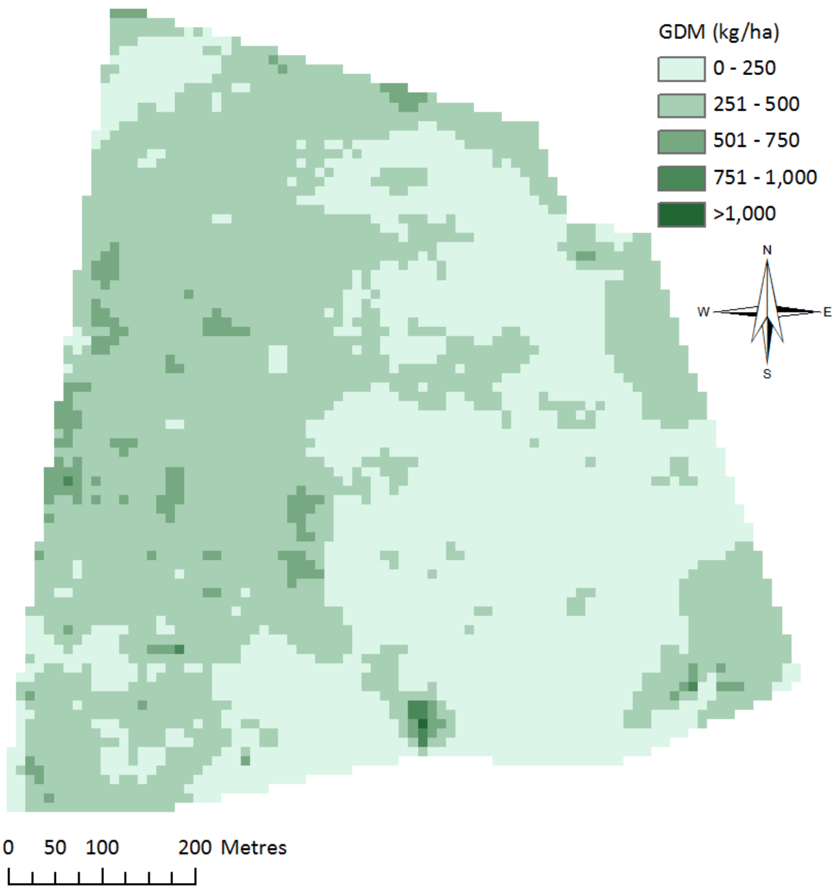


Figure 2.4 Green dry matter (GDM) (kg/ha) maps for A) the beginning of the study, 13th August 2008 (928 kg/ha average biomass) and B) the end of the study, 24th September 2008 (279 kg/ha average biomass).

The biomass difference between the AOS scans is shown in Figure 2.5, as the GDM values from the 13th of August, minus the GDM on the 24th of September. In most areas there was an overall decrease in biomass (purple), however, some areas showed growth (i.e. negative value of decline) (green) and others little or no change (grey).

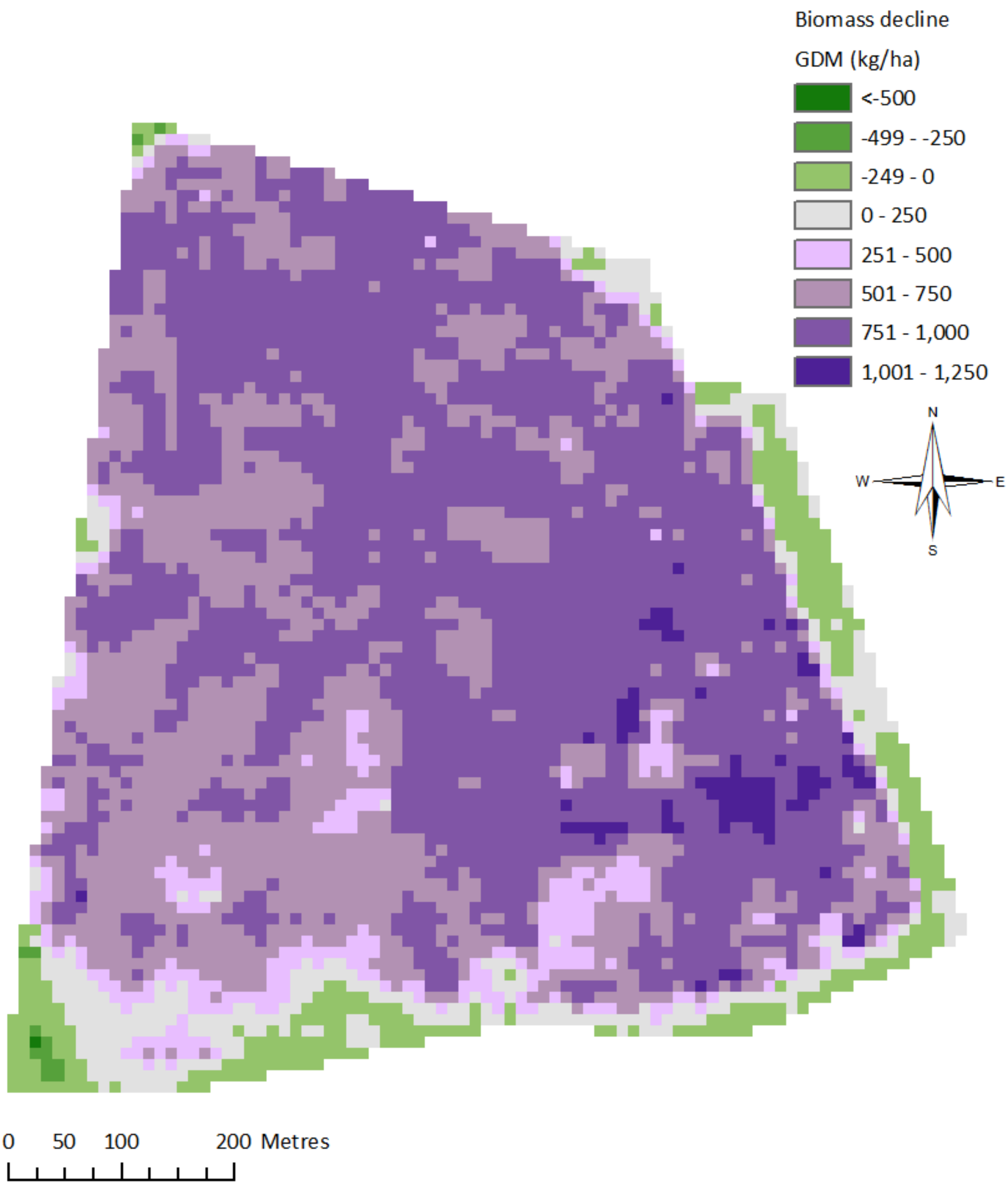


Figure 2.5 The biomass decline between the initial and final biomass monitoring events in green dry matter (GDM) per hectare. The scale shows the areas that declined (purple shades from light to dark increasing in decline) and those that increased (green from light to dark increasing in growth). Note: that a negative decline (shown in green) equates to net growth.

2.3.2 The Animal System

GPS System Performance

The results of the GPS position logging, post cleaning, are presented in Table 2.3. While not all of the expected logs were recorded, the result of 99% is high. The high average satellite and HDOP for the logs are high.

Table 2.3 Summary of GPS position data for the six deployed collars, including the expected number of recorded positions, the average number of recorded positions, the percent of expected positions actually recorded, the average number of satellites used to record a position and the average horizontal dilution of precision (HDOP) of recorded positions.

Expected Position Logs	Average Position Logs Recorded	Percent of Expected Logs	Average Satellites	Average HDOP
37,152	36,850	99	7.0	2.0

Distance Moved

The diurnal activity, displayed as average distance moved of each day hour, is displayed in Figure 2.6. Two major peak activity periods are notable, the first in the morning between hours 5 and 7; and the second in the afternoon between hours 15 and 17. There are also two smaller increases in activity in the middle of the day and the middle of the night.

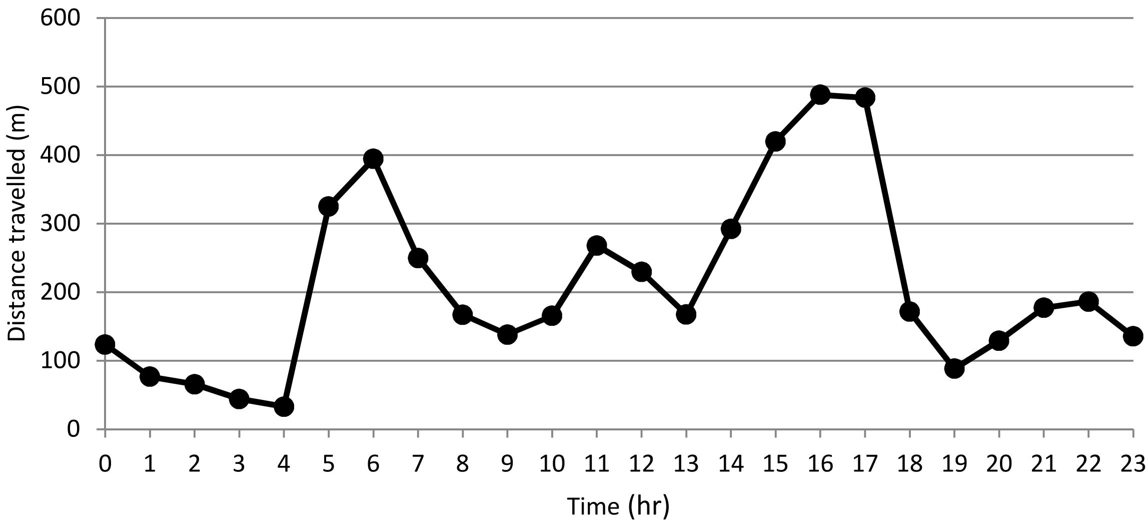


Figure 2.6 Diurnal activity of cattle, defined by the average distance moved per day hour. Each data point is the average of 6 animals.

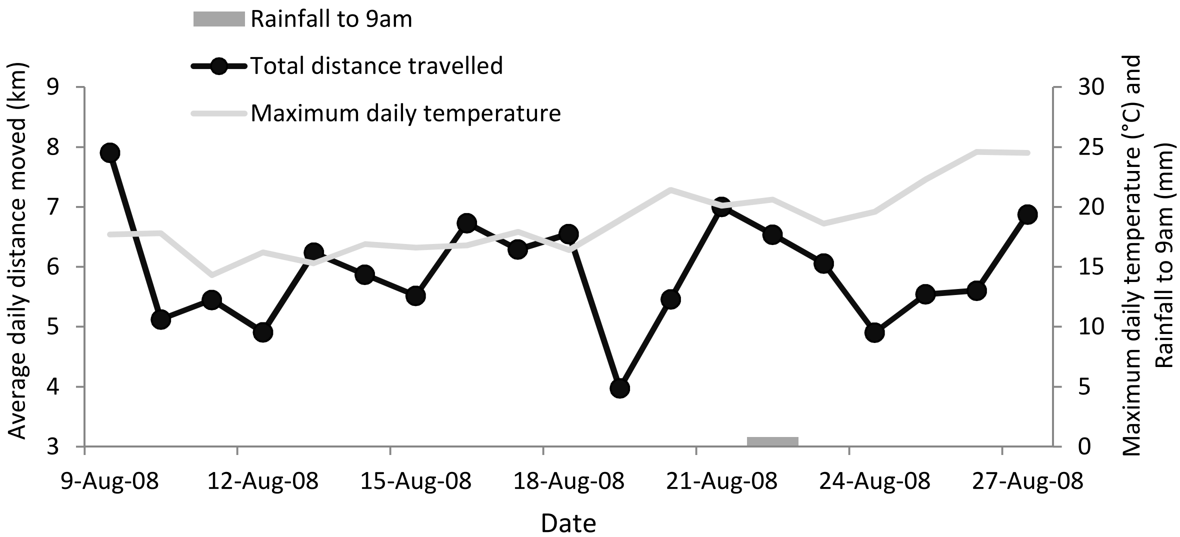
The average daily distance moved in this study is displayed in Table 2.4. The period average daily distance moved appeared to decline as the study went on.

Table 2.4 Average daily distance moved for each of the four periods of the study.

Period	Mean Distance Moved (km)
1	5.9
2	5.7
3	5.2
4	4.4

Average daily distance moved is compared to daily temperature and rainfall for pre- and post-Exclusion Period in Figure 2.7 A and B respectively. Response of cattle (distance moved and time spent grazing) did not appear to respond in line with temperature changes. However, there was a peak in activity on the same day as a rainfall event on the 14th of September. Average daily distance moved was at its highest on the first day of Period 1. The range of results was larger in Periods 1 and 2 (4.0 to 7.9), than 3 and 4 (3.9 to 5.9) and showed more day-to-day variation.

A)



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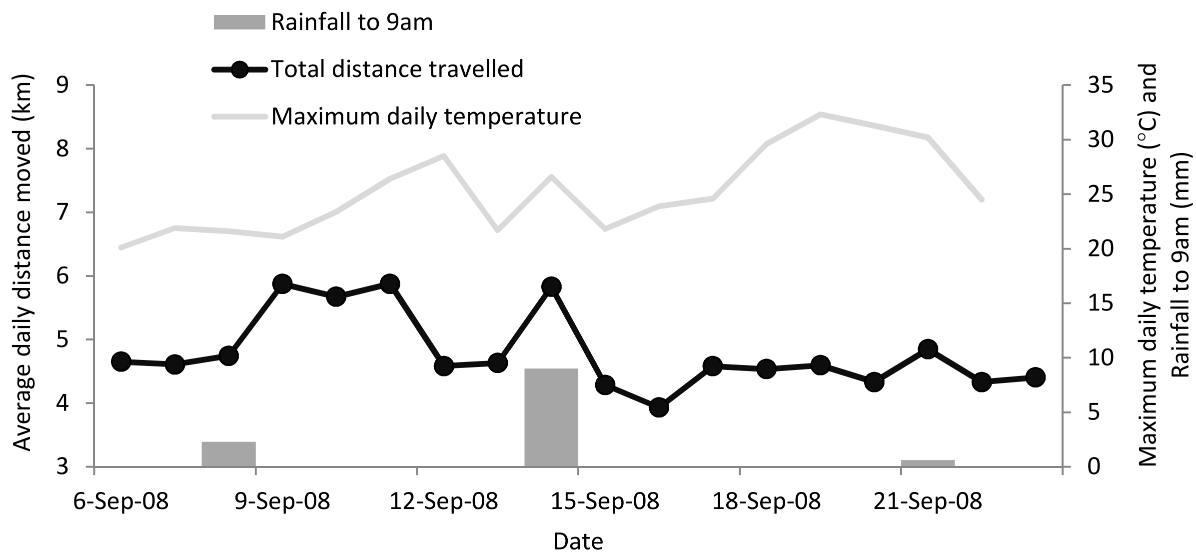
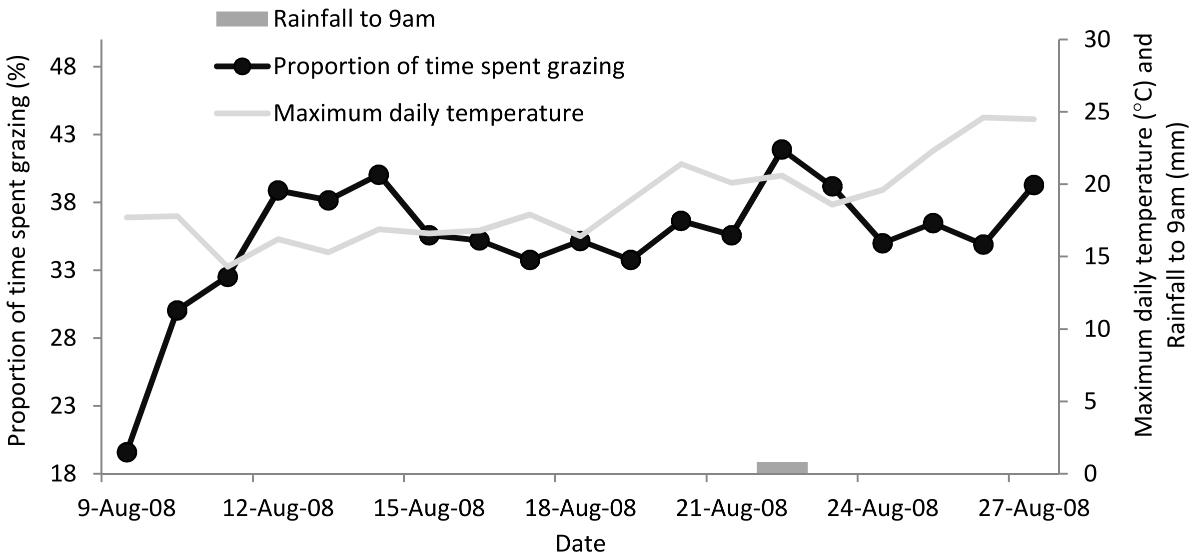


Figure 2.7 Mean total distance moved by the cattle (each data point is the average of 6 animals), rainfall and maximum daily temperature for A) exploration phase, Period 1 and Period 2 and B) Period 3 and Period 4.

SPEED-BASED BEHAVIOUR

Daily average time spent grazing (estimated from cattle speed using the Putfarken *et al.* (2008) model), is presented along with daily temperature and rainfall in Figure 2.8 for before (A) and after (B) the Exclusion Period. Minimum grazing time was seen on the first day. Except for this day where the average time spent grazing was 19.6, the range for pre- (30.0 to 41.9) and post- (33.0 to 43.4) Exclusion Period was similar.

A)



B)

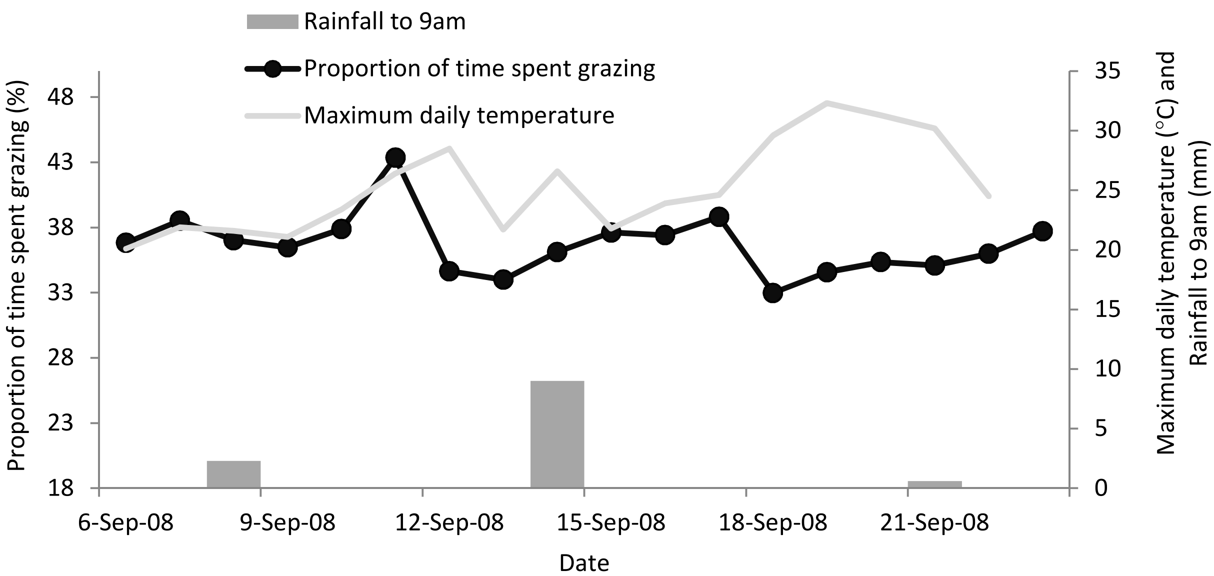


Figure 2.8 Percent time spent grazing (each data point is the average of 6 animals), rainfall and maximum daily temperature for A) exploration phase, Period 1 and Period 2 and B) Period 3 and Period 4

The average daily proportion of time spent grazing was similar across all periods as displayed in Table 2.5.

Table 2.5 Average daily proportion of time spent grazing for each of the four periods of the study.

Period	Average Daily Proportion Grazing Time (%)
1	36.3
2	36.7
3	37.2
4	36.2

Spatial Distribution

Livestock residence index maps created to display the livestock utilisations of the paddock are presented by period (Figure 2.9). Periods 1 and 2 show more usage on the south and east boundaries of the paddock and little usage elsewhere. Post exclusion periods, periods 3 and 4, show more uniform utilisation across the whole paddock.

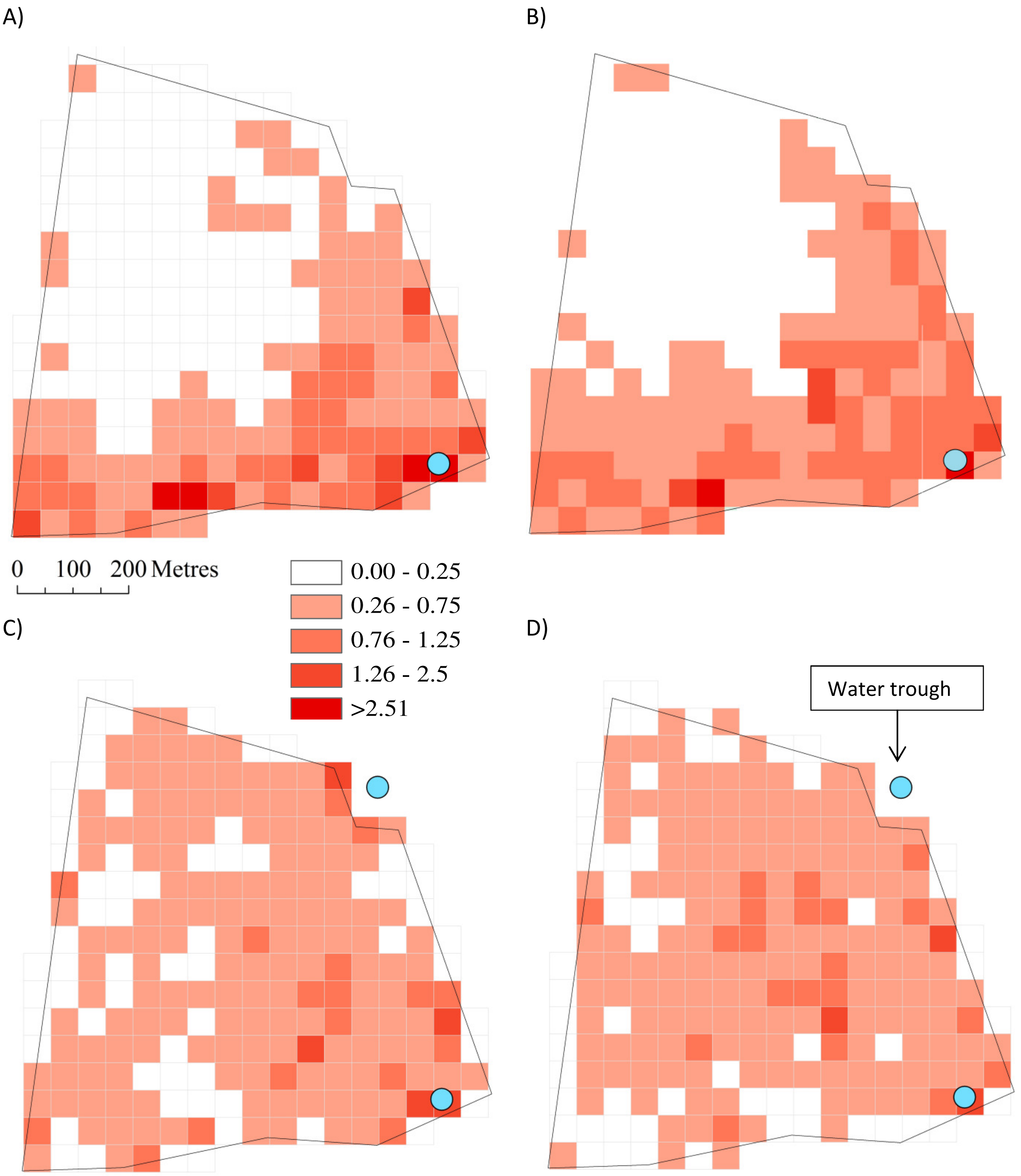


Figure 2.9 Livestock residence indexes highlighting the areas (cells) utilised by cattle in Periods A) 1, B) 2, C) 3 and D) 4. Note: the inclusion of the second water trough in C and D.

The count for the number of cells utilised when grazing in each paddock is presented in Table 2.6. The number of cells considered utilised is much higher after the Exclusion Period.

Table 2.6 Number of cells with a livestock residence index of more than 0.25.

Period 1	Period 2	Period 3	Period 4
114	128	164	170

2.4 DISCUSSION

2.4.1 *THE PLANT SYSTEM*

AOS CALIBRATION

Biomass was monitored with AOS, the calibration yielding an r-square of 0.8. The author was unable to find comparable results on estimating quantity of forage oats with AOS. However, Trotter *et al.* (2008) reported the relationships of dry biomass with NDVI for two forage sorghum crops to have R^2 values of 0.26 and 0.68, lower than the results of this study. The correlations from Trotter *et al.* (2008) were considered poor and it was recommended to consider multiple vegetation indices and select that with the best relationship to biomass.

As well as a high r-square, the RMSE is considered low at 18% of the mean biomass. Other studies reported RMSE values of up to 24% from cross validation of green dry matter of a ryegrass pasture (Künnemeyer *et al.* 2001).

WHOLE PADDOCK BIOMASS

In connection with GPS, the AOS estimated spatial variation across the paddock. The spatial variation in the distribution of GDM is apparent in Figure 2.4 A), with higher GDM (>1,000 kg/ha) evident in the central and northern parts of the paddock at the start of the study. At the conclusion of the monitoring period (Figure 2.4 B), there was a net reduction in GDM with the western areas of the paddock retaining higher levels (~>250 kg/ha) compared with the eastern boundary (~<250 kg/ha). Overall, these results showed there was a decrease in available biomass over the study period. Without regular intermediate biomass monitoring, a pattern and rate of pasture decline cannot be confirmed. Because of livestock removal and rainfall in the exclusion period, it is possible that pasture grew, resulting in a slowed overall rate of pasture decline during the study. The difference in biomass (Figure 2.5), supports this, with the varying levels of pasture decline (losses up to 1,250 kg/ha GDM) and in some areas, growth (gains up to 500 kg/ha GDM).

Despite the overall biomass quantity decrease during the study, this data has limited value in investigating the relationship with livestock behaviour because of the lack of biomass monitoring throughout. To gain a better insight into forage availability, and thus potential effects on livestock behaviour, it is recommended that an experiment includes biomass monitoring throughout a rotation. Furthermore, in this trial the calibration data was only collected at the commencement of the trial and there could have been morphological changes in plants over the study time. As such, the sensor calibration may be less accurate for the grazed pasture sward over time.

2.4.2 The Animal System

GPS System Performance

The six collars successfully deployed represented 4% of the total herd tracked. With the combination of cattle cohorts present this study, and the low proportion of livestock tracked, the results may not reflect the entire herd (Mitlöhner *et al.* 2001). Despite this potential limitation, the data collected offered valuable insights into the challenges faced in using GPS tracking to monitor animal behaviour.

The GPS tracking collars demonstrated a data capture rate of 99%; marginally higher than reported for other studies (Table 1.2) with the exception of the study by Ganskopp and Bohert (2006) which reported 100 %. Similarly, the relatively high average number of satellites (7) for position recordings was a function of programming the GPS unit in "over determination mode" (Trotter & Lamb 2008), so that there must be more than four satellites for a position recording to occur. The average HDOP of 2 for position logs is considered very good (French 1996). Together, the high satellites and HDOP suggests accuracy and precision of recorded positions. Additionally, it is possible that the over determination mode may lead to a low number of positions recorded as those calculated with few satellites would not be kept. However, the high data capture rate and high average number of satellites used to determine location show this was not an issue. The use of a maximum awake time limited power consumption during times of poor satellite acquisition. The GPS settings resulted in high quality data without significant loss of battery life.

The biomass maps (Figures 2.4 and 2.5) highlight there are areas of high biomass at the end of the trial. The feed available in these areas could have resulted in the paddock biomass never decreasing to a limiting level, thereby, not inducing a change in the grazing behaviour of the livestock.

Abiotic Influences

The daily temperatures during the study did not correspond with either distance moved (Figure 2.7) or grazing time (Figure 2.8). Conversely, the largest rainfall events did coincide with an increase in both distance moved and grazing time, although none of the rainfall events were large (<10 mm) and additional peaks in activity on dry days renders these observations inconclusive. The lack of weather effect may be due to the large distance between the experimental site and the weather station.

An inverse relationship between mean daily temperature and grazing time of cattle (Vallentine 2001), and sheep (Thomas *et al.* 2008) has been demonstrated. Comparatively, in this study the temperature recorded was only the daily maximum and minimum. It was difficult to isolate the effects of temperature from other variables which highlights the challenge of attempting to ascribe behavioural changes to specific factors. GPS-derived parameters, such as grazing time, cannot be specifically attributed to particular variables, without increased control and monitoring of variables including human interference, paddock changes (introduction of second water trough) and pasture re-growth.

Distance Moved

The diurnal activity (Figure 2.6), a measure of movement, followed the expected trend with the highest peaks around sunrise and sunset, and minor peaks in the middle of the day and night (Arnold and Dudzinski 1978; Roath and Krueger 1982; Trotter and Lamb 2008; Trotter *et al.* 2010b). As this traditional trend in daily activity was evident through GPS locational data of the cattle it supports the use of this remote monitoring for spatio-temporal behavioural investigation.

Daily distance moved (Table 2.4) was within the expected range; minimum herd average daily travel was 3900 m and maximum herd average daily travel was 7900 m with an average of 5300 m/day). Examples of similar studies have found daily distances to be 5200 m/day in a 20 ha paddock (Anderson and Kothmann 1980) and 4200 m/day in a 34 ha paddock (Hart *et al.* 1993).

Literature suggests that with decreasing pasture availability, distance moved would increase (Vallentine 2001) and although we did see an overall reduction in pasture biomass in our trial field it may be that the animals were never ‘nutritionally limited’. Daily distances travelled are known to change depending on climate factors such as temperature, wind and rain (Anderson and Kothmann 1980). Contrarily, no discernible relationship was observed (Figure 2.7). Perhaps the most significant change might be explained between the first two periods, and the second two periods where an extra water point was made available in the northern end of the paddock. This most likely contributed to a reduced average daily distance moved between the two trial periods (Table 2.4), as the cattle would have been closer to water when in the northern parts of the paddock, and therefore travelled shorter distances for drinking.

Speed-based Behaviour

As for distance moved, daily grazing time was expected to increase over the study in line with diminishing pasture availability until biomass becomes so limiting that grazing time then begins to decline (Chacon *et al.* 1978; Gibb *et al.* 1999). In contrast, there was little difference between the time spent grazing for Periods 1-4 (Table 2.5; range of 1%, minimum 36.2 and maximum 37.2%), although there was some variation between days (Figure 2.8).

Although there was no opportunity to collect validation data for behaviour in this preliminary study, the use of a speed-based model to infer grazing provided realistic results in terms of calculating the average time spent grazing. Excluding the exploratory phase, the animals were found to spend on average a minimum of 33 % and a maximum of 43 % of their time grazing. Although the proportion of time spent grazing was well below the 48 % reported by Putfarken *et al.* (2008), from which the speed-based grazing behaviour model was derived, it was within the range reported in several other studies, such as Stricklin *et al.* (1976) (35-38%) and Vallentine (2001) (29-50%). While the results appear realistic, the use of the Putfarken *et al.* (2008) speed model to determine behaviour is a genuine limitation of this study. The agroecosystem in which this speed-based behavioural model was developed is quite different to that used in this study and cattle speeds may vary situationally.

SPATIAL DISTRIBUTION

As suggested in Chapter 1, an alternative to simply monitoring animal movement and grazing time is examining the change in spatial landscape utilisation of livestock. During Period 1 (Figure 2.9 A) the south-east of the paddock experienced higher LRI values. The northern and western areas were the least utilised. In the LRI map for Period 2 (Figure 2.9 B), the south-east of the paddock again exhibited the highest LRI, and the north-west, the lowest. The differences in paddock utilisation between Periods 1 and 2 show a small increase LRI. There is an increase in the number of paddock cells with an LRI larger than 0.25 by 14 grid cells, equating to 0.07 ha. This may represent an increase in the time spent in areas which provide a level of plant biomass that warrants visitation and are subsequently utilised by the animals in order to achieve adequate biomass intake.

The LRI map for Period 3 (Figure 2.9 C) highlights approximately even visitation across the paddock. Most areas of lower LRI seen are along fence lines with some in the centre of the paddock. Differences between Periods 3 and 4 (Figure 2.9 D) are quite subtle; there does not appear to be an increase in the total paddock utilisation and in fact the cells with an LRI >0.25 increase marginally by only 6 cells, equating to 0.03 ha.

The LRI maps for Periods 3 and 4 demonstrate a significant increase in the spatial extent of and movement over the paddock as a whole, compared with Periods 1 and 2. However, as this followed the Exclusion Period and rainfall it is difficult to determine the dominant influences affecting alterations in behaviour. Certainly, the decline in available forage would have contributed, as would the introduction of the second watering point (Bailey *et al.* 2006). It is possible that, while overall GDM available was low, the stocking density may have allowed for regrowth. The visitation across the whole paddock in Periods 3 and 4, compared to 1 and 2, may be attributed to cattle searching for new growth. Cattle are known to select fresh growth, because of increased palatability and nutrition (Allred *et al.* 2011).

Cattle increase grazing pressure in preferred areas (Hart *et al.* 1993), until these areas become unavailable, when they then disperse into other areas (Irving *et al.* 1995). This was observed with the compared livestock utilisation and pasture variation maps, however, as previously highlighted, a direct comparison before and after the Exclusion Period is not valid. The LRI map for Period 1 demonstrates the initial utilisation of the paddock which avoided considerable areas the higher GDM apparent in the north western quarter. The greatest change of biomass was in the eastern and southern parts of the paddock where areas of >1,000 kg/ha were reduced to 0-250 kg/ha of GDM. This corresponds to a possible utilisation of >750 kg/ha GDM. This dramatic change matches the higher level of livestock residence seen in Periods 1 and 2. An increase in spatial utilisation as the study progressed was expected, in line with an overall paddock decrease in available pasture GDM (Bailey *et al.* 1996). The LRI map for Period 2, revealed some dispersal of grazing pattern as livestock foraged for new feed, however, cattle continued to underutilise the high GDM in the northern and western areas of the paddock reflected in Figure 2.4.

While the final average paddock biomass amount appears to be at levels limiting to cattle (well below 1,500 kg/ha DM), there were large differences in biomass decline from the initial values across the paddock. This is a consequence of preferential grazing as supported by the livestock utilisation maps. In Periods 1 and 2 the cattle rarely utilise the north west of the paddock, in Periods 3 and 4, the south east areas remain popular (Figure 2.9).

Towards Indicator Metrics

Due to the nature of the data collected, the specific relationship between monitored behaviours and biomass is inconclusive. Herd management and the limited biomass observations prevented comparisons between behaviour monitored in the first half of the study with the second half, when biomass was known to be different. While a relationship between biomass quantity and cattle behaviour could not be elucidated, it is encouraging to note that spatial behaviour and biomass appeared to concur overall.

2.5 Conclusions

The GPS tracking devices deployed in this trial proved suitable for spatio-temporal behavioural observations insofar as behavioural attributes including daily distance moved and grazing time were successfully extracted from GPS records over the study period. Spatial behaviour across a paddock was also observed using LRIs. The results of this preliminary study suggests that there is opportunity to utilise spatial monitoring tools in conjunction with an objective pasture monitoring tool such as the Crop Circle™ to investigate livestock and pasture interactions.

While this study was successful in testing the basic tools for livestock tracking and biomass monitoring, the simple behavioural components investigated suggest that biomass did not become limiting. Increased monitoring of pasture throughout grazing rotations would have contributed to understanding the changes in biomass. In order to achieve the objective of investigating behaviour in relation to declining biomass, a response to limited feed must be elicited. The following chapter, Chapter 3, aims to investigate this further.

CHAPTER 3 – CATTLE BEHAVIOUR IN RELATION TO DECREASING BIOMASS: PART 1

3.1 INTRODUCTION

The previous chapter found that simple measures of spatial and temporal behaviours of cattle grazing pasture can be extracted from GPS data. Specifically, it was found that distance moved, grazing time and livestock residence could be quantified. The study also highlighted the potential to combine behaviour and biomass parameters. Additionally, regular biomass monitoring, an increase in the proportion of the animals tracked, minimising intervention to the livestock and paddock area, and the design of an experiment such that a decline of available biomass to a limiting amount is achieved, are recommendations to improve on the preliminary investigation of Chapter 2.

The objective of this chapter is to investigate the relationship between specific, simple spatio-temporal behaviour metrics of cattle and the declining biomass availability in a paddock utilising the lessons learned above. The specific behaviours are:

1. distance moved by cattle per day;
2. grazing time of cattle per day;
3. area of the paddock utilised by cattle based on the LRI; and
4. within-herd social distribution of cattle.

3.2 METHODOLOGY

3.2.1 FIELD SITE AND EXPERIMENTAL EVENTS

This experiment was undertaken at University of New England's Douglas McMaster Research Station (150^{o}36'0" E, 29^{o}17'6" S WGS84) as described in Section 2.2.1. Two level, diagonally adjacent paddocks were used in this experiment: Paddock 1 (2.21 ha) and Paddock 2 (1.76 ha). Paddocks were chosen based on availability of forage, the number of cattle available (and GPS devices) to ensure biomass decreased over a suitable duration and because they were initially thought to be equal in area. Unfortunately, after the fences were built and a GPS survey was undertaken it became apparent that paddock areas differed. Both paddocks comprised of vertisol soils of similar characteristics. The key events during the experiment are outlined in Table 3.1, including rainfall and biomass monitoring events.

Table 3.1 Experimental calendar of events, displaying the day number, plant sampling (plant cuts), paddock transects with all-terrain vehicle (ATV), rainfall events and the removal of livestock.

Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
	Day 0 Plant cuts ATV biomass survey 30/8/10	Day 1 Steers introduced	Day 2	Day 3	Day 4	Day 5
Day 6 Rainfall event	Day 7	Day 8	Day 9 ATV biomass survey	Day 10 Plant cuts	Day 11 Rainfall event	Day 12 Rainfall event
Day 13	Day 14	Day 15	Day 16 Plant cuts ATV biomass survey	Day 17	Day 18	Day 19
Day 20	Day 21 Rainfall event	Day 22 Rainfall event	Day 23	Day 24	Day 25 Steers removed paddock 2	Day 26
Day 27	Day 28 ATV biomass survey attempted	Day 29 Rainfall event	Day 30 ATV biomass survey Steers removed paddock 1	Day 31 Plant cuts		

3.2.2 Weather

Weather data was obtained retrospectively from the Bureau of Meteorology (http://www.bom.gov.au/climate/data/). Rainfall was gathered from Coolatai (Willunga) weather recording station (150°61' E, 29°20' S, elevation 425 m). This recording station was the closest to our experiment site (40 km away). However, as temperature data was not provided from this site, it was collected from the next closest weather recording station located 89 km away (Pindari Dam 151°24' E, 29°39' S, elevation 462 m). Daily incidence of rainfall and temperature were compared with daily distance moved and grazing time behaviour to determine if an effect was evident.

3.2.3 The Plant System

Paddocks were sown to forage oats (*sp. Avena Sativa var. Warrego*) (Figure 3.1). The timing of the experiment was so that grazing commenced when the plants were at the "booting" stage. Booting is part of the sheath elongation growth stage, between vegetative and reproductive growth, when the inflorescence is enclosed in the uppermost leaf sheath (Moore *et al.* 1991).

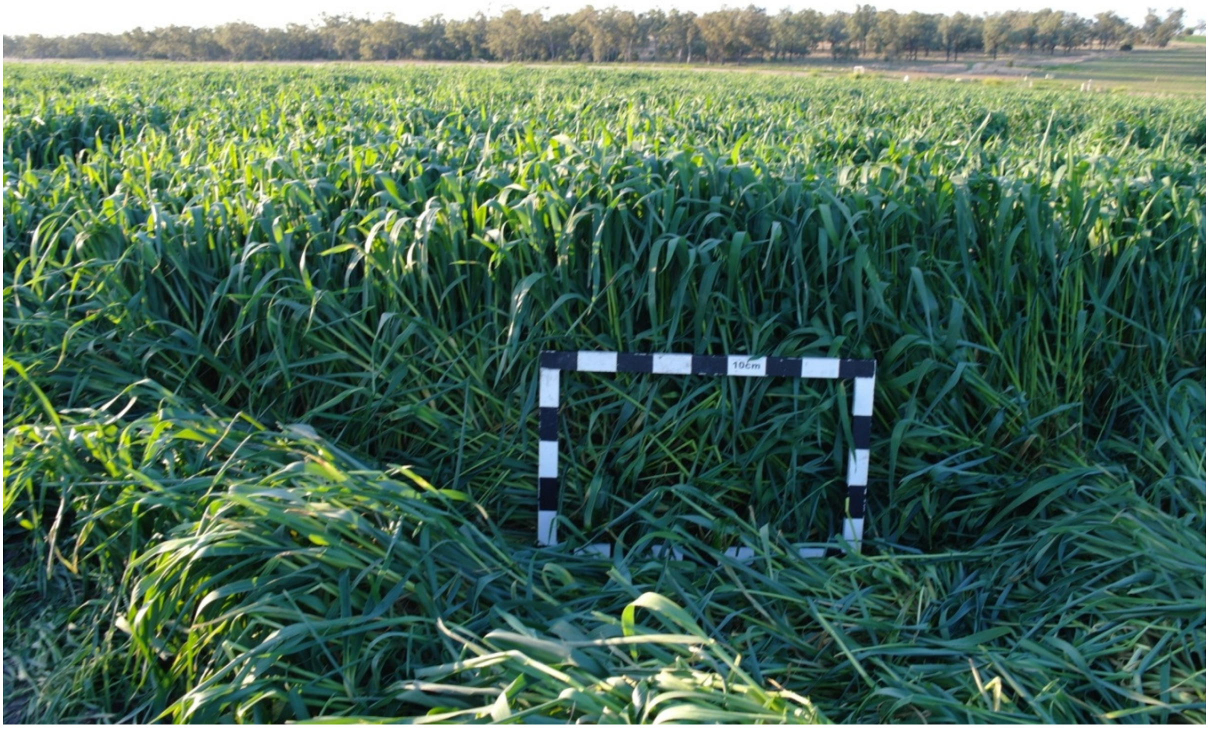


Figure 3.1 Paddock 1 on experiment day 1, containing forage oats variety "Warrego" approximately 9,393 dry green leaf biomass (kg/ha). Each check (black and white) on the quadrat is 10 cm in length and 5 cm wide, giving a total external height of 60 cm and a width of 90 cm.

Forage biomass quantity was monitored using the AOS as described in Section 2.2.3. This involved two processes; firstly, calibration of the reflectance data (collected by the AOS) to actual biomass determined by destructive sampling of several small Crop Circle™ sensed areas. This process was drawn from Zhao *et al.* (2007) and Trotter *et al.* (2010a). Secondly, whole field ATV surveys were conducted with the AOS to map biomass.

AOS Calibration

An improved method to correlate reflectance values and actual biomass using the Crop Circle™ was devised. Here the AOS was mounted to a stationary rig at a height of 140 cm, with a footprint at ground level of 15 by 84 cm. The setup of the AOS and rig is presented in Figure 3.2. This included a data logger with screen, an on/off switch and the Crop Circle™ sensor, which was pushed from one end of the rig to the other and back to record the reflectance of the sample site which was also 84 cm in length. Figure 3.3 displays the equipment for biomass sampling.

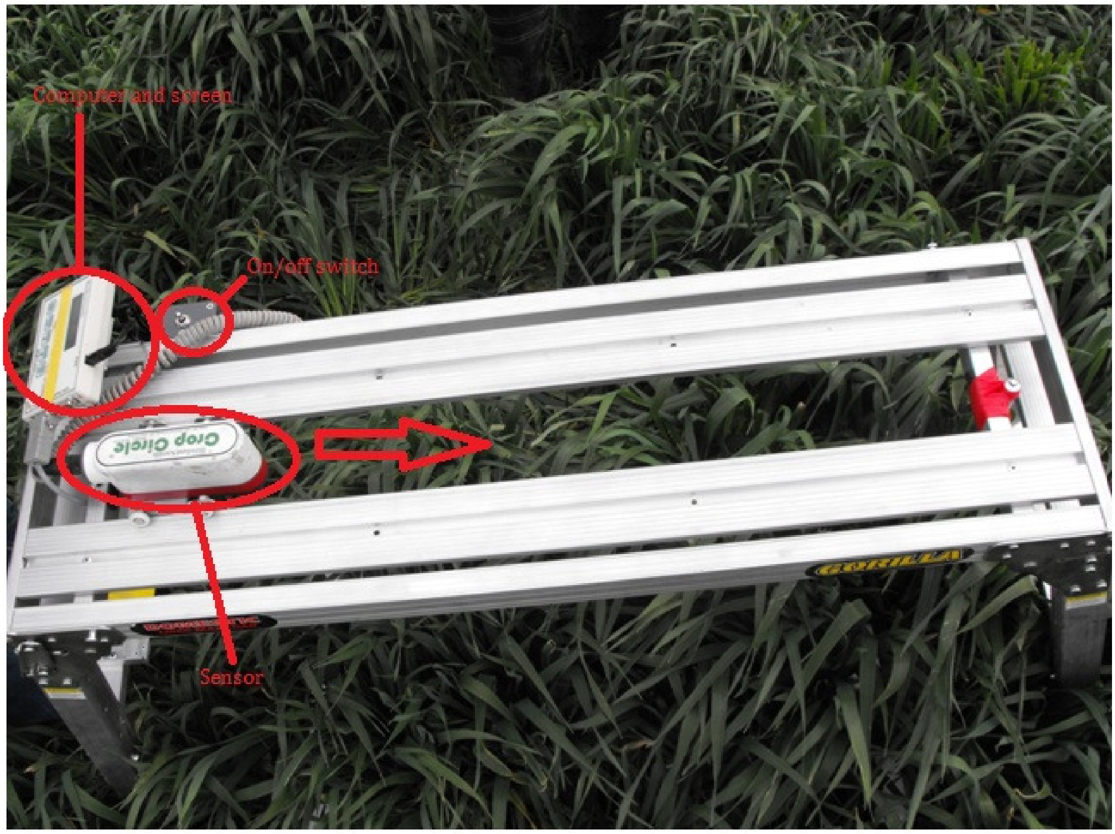


Figure 3.2 The Crop Circle™ mounted to the stationary rig. This includes a data logger and screen (top left), an on/off switch (right of data logger) and the Crop Circle™. This rig enabled recording of biomass reflectance to compare with biomass amount for calibration.

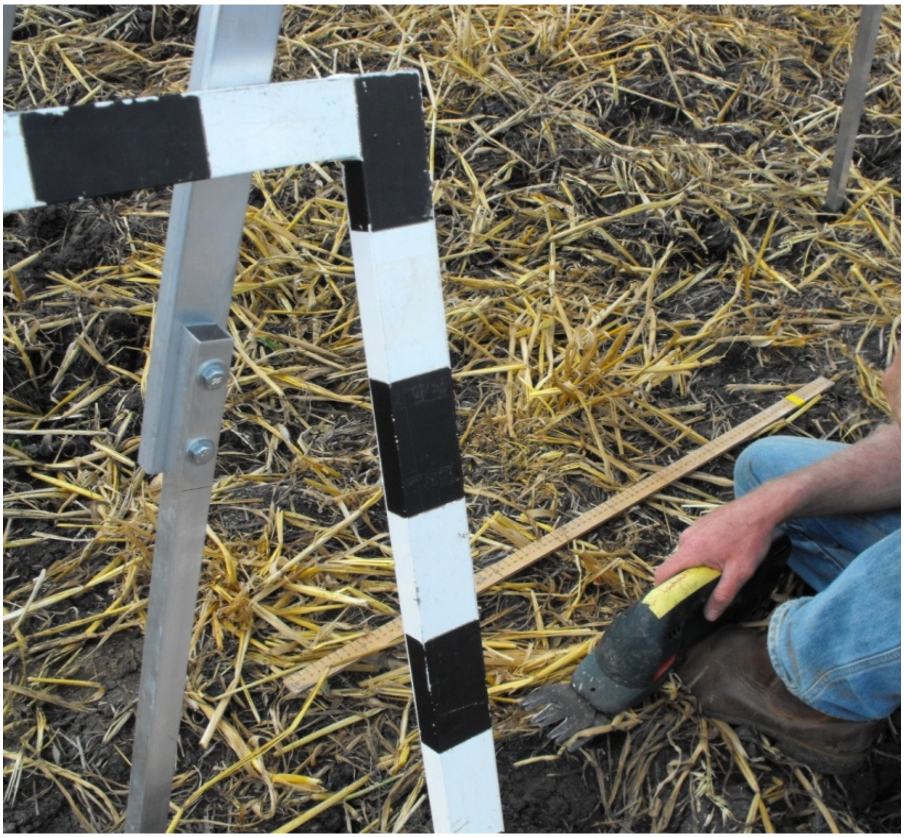


Figure 3.3 Taking biomass cuts corresponding to Crop Circle™ stationary biomass reflectance scans. The ruler is placed to align directly with the Crop Circle™ field of view so that the biomass cut matches the scan.

Seven sites per paddock were recorded four times during the experiment (Table 3.1). At each site approximately 50 reflectance values were recorded by the AOS. Reflectance recorded included red, NIR and NDVI. From the red and NIR, further vegetation indices were calculated including Simple Ratio (SR), Modified Simple Ratio (MSR), Soil Adjusted Vegetation Index (SAVI) with constants of 0.25, 0.5 and 0.75, Non Linear Index (NLI) and the Modified Non Linear Index (MNLI). Formula abbreviations and references for each index investigated are displayed in Table 3.2, adapted from Trotter *et al.* (2010a). These vegetation indices were compared with the corresponding physical biomass samples.

Table 3.2 Summary of biomass indices investigated (Adapted from Trotter *et al.* (2010a)).

Index/Band	Abbreviation	Formula (Band)	Reference
Near Infrared (Band)	NIR	(880 nm)	Holland *et al.* (2004)
Red (Band)	red	(650 nm)	Holland *et al.* (2004)
Simple Ratio	SR	$SR = \frac{NIR}{Red}$	Jordan (1969)
Modified Simple Ratio	MSR	$MSR = \frac{(NIR/Red) - 1}{(NIR/Red)^{1/2} + 1}$	Chen (1996)
Normalised Difference Vegetation Index	NDVI	$NDVI = \frac{NIR - Red}{NIR + Red}$	Rouse Jr *et al.* (1974)
Soil Adjusted Vegetation Index	SAVI	$SAVI = \left(\frac{NIR - Red}{NIR + Red + L}\right)(1 + L)$	Huete (1988)
Soil Adjusted Vegetation Index (L=0.25)	SAVI(0.25)	$SAVI = \left(\frac{NIR - Red}{NIR + Red + 0.25}\right)(1 + 0.25)$	Huete (1988)
Soil Adjusted Vegetation Index (L=0.50)	SAVI(0.50)	$SAVI = \left(\frac{NIR - Red}{NIR + Red + 0.50}\right)(1 + 0.50)$	Huete (1988)
Soil Adjusted Vegetation Index (L=0.75)	SAVI(0.75)	$SAVI = \left(\frac{NIR - Red}{NIR + Red + 0.75}\right)(1 + 0.75)$	Huete (1988)
Non-Linear Vegetation Index	NLI	$NLI = \frac{NIR^2 - Red}{NIR^2 + Red}$	Goel and Qin (1994)
Modified Non-Linear Vegetation Index	MNLI	$MNLI = \frac{(NIR^2 - Red) * 1.5}{NIR^2 + Red + 0.5}$	Gong *et al.* (2003)

After AOS scanning, forage at each site was harvested at 4 cm above the ground. The area harvested for each site was 15 cm by 84 cm, corresponding to the AOS FOV. The scans were aligned to the plant rows, which were sown at 30 cm apart. Information about each site was recorded including: date; site; and wet weight.

Calibration samples were sorted into green leaf, green stem and dead fractions before being dried in an oven at 90°C for 48 hours. These fractions were then weighed and converted to provide estimates of total dry weight biomass (kg/ha); dry green leaf biomass (DGLB) (kg/ha); dry green leaf (%); dry stem biomass (kg/ha); dry stem (%); total dry green biomass (kg/ha); total dry green (%); and ratio of stem to leaf. These attributes were then compared to the various indices that could be calculated from the AOS following the protocols of Zhao *et al.* (2007) and Trotter *et al.* (2010a). Log transformations of selected attributes were undertaken as the relationship between AOS indices and vegetation is frequently reported as being non-linear (Trotter *et al.* 2010a). The correlations between the calibration sample vegetation attributes and the various indices were evaluated using R^2.

Removal of some points from the calibration dataset was required. These are highlighted in Figure 3.4, the graph presenting vegetation index (SAVI(0.75)) and biomass (DGLB). The initial dataset before the removal of those points presented an R^2 of 0.86. The equation of linear regression was: $y = 0.0001x + 0.20810$. The records collected on the 15/9/10 with a biomass of zero were removed from the calibration as they represented sites where there may have been some green biomass present, although, in a form that was not available to the livestock. This green matter was crushed to the ground and covered in mud, as shown in Figure 3.5. The protocol for taking biomass samples as outlined above was to sample at 4 cm above the ground. If the green matter was below this it was not sampled. Consequently, the AOS captured the reflection of this biomass; however, it was not harvested and considered too dirty and close to the ground to be eaten by cattle. These values appeared to be outliers, so consequently removed. On the 27/9/10 the records collected with a biomass of zero values were considered valid and therefore included. Unlike the zero values excluded from the 15/9/10, there appeared to actually be very little to no green matter present in the scans as shown in Figure 3.6.

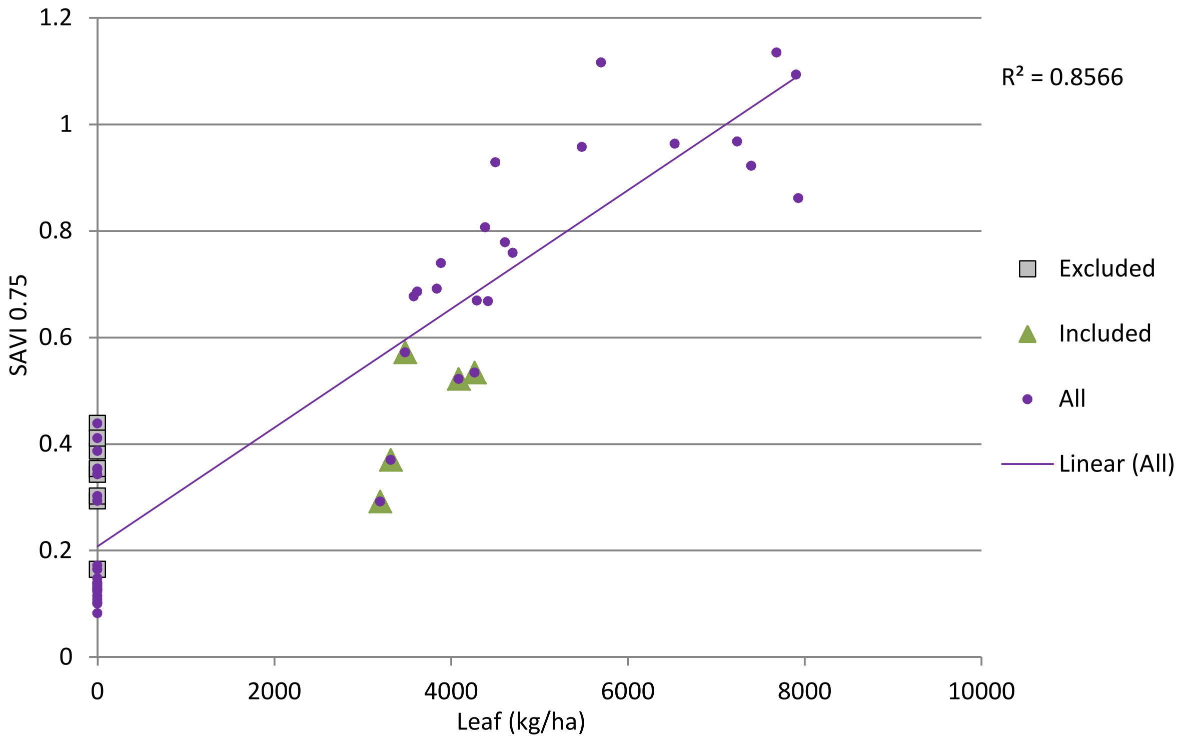


Figure 3.4 Vegetation index soil adjusted vegetation index (SAVI) with constant L = 0.75 and corresponding dry green leaf biomass (DGLB) (kg/ha) values where the initial dataset including all points is displayed in purple (All), the values from the 15/09/2011 which were included in the data analysis in green (Included) and the values from the 15/09/2011 which were excluded from the data analysis in grey (Excluded). The linear trend line shown in purple is based on the initial dataset (All) and had an R^2 of 0.86.

Figure 3.5 Photo of 0 kg/ha available biomass site for the 15/09/10 Note: there is green material; however, it is unavailable for sampling or for cattle to eat, due to trampling and height.

Figure 3.6 Photo of 0 kg/ha available biomass site for the 27/09/10. Note: there is no green material present and dead material is trampled into the soil, thus unavailable for animals and biomass sampling.

DETERMINING WHOLE PADDOCK BIOMASS

During the experiment, four paddock biomass surveys were undertaken with the Crop Circle™ (Trotter *et al.* 2010a). Unlike the surveys conducted in Chapter 2, the AOS was mounted to a two wheeled motorbike. The unit was mounted at 140 cm above the ground, linked to a GPS (Garmin Ltd, Kansas, United States of America) and configured to log 6 times per second. Four, 10 m apart, transects of the paddocks were scanned each survey. The equipment for biomass surveys is displayed in Figure 3.7.

Figure 3.7 Crop Circle™ mounted on the bike for undertaking paddock transect scans. The sensor is mounted from the bike forks on the left side in front of the handle bars. The data logger and screen is located in the centre of the handle bar. The GPS is taped to the seat of the bike and is out of this picture.

Using ArcGIS® version 9.3.1 (ESRI 2008) transect data were cleaned as per Section 2.2.3. For each scan day and paddock, AOS scans were interpolated for the selected index, SAVI(0.75) by block kriging in Vesper® (Whelan *et al.* 2001). A block size of 10 m and a grid size of 5 m were used. Dry green leaf biomass (kg/ha) values were then calculated for each grid point based on the calibration developed. The biomass values were then averaged for each paddock on each scan day. The DGLB was plotted by day and a curve fitted to the data. This curve allowed the estimation of DGLB (kg/ha) for each day of the experiment.

To determine the error of prediction, the RMSE was calculated in "R" (2012, Vienna, Austria) using the Data Analysis and Graphing package (Maindonald and Braun 2011). A residual sum of squares of 764,125 was calculated from a k-fold cross validation with a fold number of 10. A residual sum is a corrected measure of prediction error averaged across all folds (Starkweather 2011). To determine the RMSE, the square root of the overall mean squared error was taken. The RMSE was calculated to be 874 DGLB (kg/ha). This RMSE is 12 % of the mean biomass which was 7,074 DGLB (kg/ha).

3.2.4 The Animal System

This research was conducted under the University of New England's animal ethics authority number: AEC10/055 (Appendix A.2).

Paddocks were stocked with 50, Hereford, Angus and Hereford/Angus crossbred steers with a mean weight of 277 kg (SD=21 kg). The herd was randomly split into two mobs of 25. These mobs were placed into the two experiment paddocks. Because of paddock size variation, Paddock 1 had a stocking density of 11.3 hd/ha and Paddock 2, 14.2 hd/ha.

Forty-four UNETrackerII collars (Trotter *et al.* 2010b) were deployed randomly across the 50 steers; 22 animals in each mob were collared, which equates to 88%. The GPS devices were set to log in a multiple-interval tracking duty cycle, in which the GPS collects four, 15 second apart logs every 15 minutes. The devices were also set to have a maximum awake time of 120 seconds. This was undertaken to address the trade-off between energy consumption and localisation performance of the devices. Allowing the device to shut down between position recording decreases the overall power consumption, however, the uncertainty of position increases with the length of time a device is shut down (Jurdak *et al.* 2010). It was reported by Swain *et al.* (2008b) that GPS accuracy improved as log interval decreases below one minute and Turner *et al.* (2000) found shorter intervals to be least error prone. In this scenario, the GPS devices shut down during the long interval, but not the short interval. As such, the battery-life was extended while minimising a reduction in device accuracy.

The UNETrackerII collars were designed with the antenna facing skywards when on an animal. In order to keep the GPS at this position on the neck, a weight (heavier than the GPS device), was placed on the bottom of the collar. This was to improve the accuracy, precision and fix rate of the positions logged by reducing interference from objects between the antenna and satellites, such as, the ground, trees and other animals (Di Orio *et al.* 2003).

Upon completion of the experiment, the collars were removed from the steers, and the raw GPS data downloaded. Using Excel® and ArcGIS®, this data was then cleaned as described in Section 2.2.4. The average distance moved per day and speed-based behaviours (grazing, travelling, and stationary) were calculated as per the methods presented in Section 2.2.4.

To investigate the general trends in behaviour and for improved herd comparisons, quadratic trend lines of the data were applied to results of time spent grazing, travelling and stationary per day, daily time spent grazing as biomass declined, proportion of the paddock used per day and as biomass declined. This allowed for a simple review of the general behaviour changes.

There were some changes to the LRI methods presented in Section 2.2.4 in this experiment. Firstly, the grid cell size for the LRIs was 25 m^2. The LRIs for all the cells in each paddock were mapped and displayed as one of two levels, not utilised or utilised. The levels are defined as: not utilised if the LRI for a cell was 0.01 or less; utilised if the LRI was more than 0.01. The proportion of paddock utilised is calculated by dividing the number of cells considered utilised by the total number of cells, which varies depending on paddock size and cell size. Additionally, the LRI threshold for utilisation is determined by the number of points within a cell, in this experiment the count of points which relate to the threshold for LRI is one. Thus, if a cell has one point within it, it is considered utilised. Therefore, the threshold value for utilisation in this experiment is different to that presented in Section 2.2.4, because of smaller paddock and cell sizes.

To investigate the potential for social interaction to change in line with reducing feed a "social metric" was developed. This was based on single interval tracking data and involved creating a new data set of only the first point from each multiple-interval tracking cycle, creating a 15 minute log interval. The social metric was derived by identifying the distances between animals during a grazing event each day. The daily peak grazing hour was determined by counting the number of grazing behaviour instances in each. The hour of the day which most often had the largest number of grazing incidences was 6:00-6:59am. To ensure only one location from each steer was included, a fixed 15 minute window within the peak hour was chosen, as each animal would only be represented once in this time frame. The fixed window was from 6:25:00am until 6:39:59am, chosen in particular as this period represented all cattle with no missing or excluded data points. Two different metrics were then calculated to express the dispersion of animals on a daily basis. The first was minimum convex polygons (MCP) and the second was distance between points providing intra-herd dispersion (IHD) values.

To create MCPs, a polygon is created from a series of lines which encapsulates all of the data points, using the outer most points as vertices. The resulting polygon is the smallest possible convex polygon which includes all points. Minimum convex polygons were created in ArcGIS® using add-in Hawth's Tools, following which the area of each polygon was calculated and exported in Excel® for further analysis. Commonly, MCPs are calculated to assign a home range to one or more animals based on the extent of all locations of that animal for a given time period (Ganskopp 2001, Ganskopp and Vavra 1986, Kamler *et al.* 2003, Perotto-Baldivieso *et al.* 2012). In this experiment, MCP is used to determine the spatial distribution (area) of the herd at a moment in time for each day of monitoring. A different application of this technique was used because daily herd home range (derived from MCP) was unlikely to provide meaningful results due to the small area available per animal.

Intra-herd dispersion is calculated by determining the distance from each data point to all others and then finding the average distance. This provides a value for the proximity of the cattle to one another. The IHD was determined by creating a matrix (not reported) of the distance (in metres) of each point in the dataset to each other point. This was undertaken in ArcGIS® using a distance calculator from add-in Hawth's Tools. The result was a matrix of the exact distance of each steer's position to every other steer. This dataset was then imported into Excel® where average distance between animals was calculated to determine the IHD.

The proportion of paddock utilised, MCP areas and IHD results were graphed against day and biomass. Polynomial trend curves were fitted to grazing, travelling and stationary time, proportion of paddock utilised, and values at inflection points were calculated. The inflection point values provided a single measure which could be compared between the two replicates.

3.3 RESULTS

3.3.1 THE PLANT SYSTEM

The relationship between each of the physical attributes and reflectance indices of biomass is presented as R^2 values in Table 3.3. The best relationship was found to be between DGLB and SAVI with an L factor of 0.75. In addition to having the best R^2, DGLB (kg/ha) was also deemed to be the most relevant vegetation measure in terms of the relationship to animal intake, performance and ultimately behaviour, as leaf matter is the major constituent of the grazing animals diet (Stobbs 1975). As a consequence, the paddock scale biomass estimates used to compare with animal behaviour were derived using the DGLB and SAVI calibration.

Table 3.3 The relationship between biomass and vegetation indices investigated with R^2. Dry green leaf biomass (DGLB) (kg/ha) and soil adjusted vegetation index with constant L=0.75 (SAVI(0.75)) were chosen, the R^2 is presented in bold.

Biomass	NDVI	SR	SAVI(0.5)	SAVI(0.25)	SAVI(0.75)	NLI	MNLI	MSR
Total biomass	0.14	0.06	0.19	0.17	0.21	0.21	0.24	0.08
Dry green leaf (kg/ha)	0.82	0.69	0.90	0.87	**0.91**	0.90	0.92	0.75
Dry green leaf (%)	0.81	0.87	0.85	0.85	0.85	0.80	0.79	0.87
Dry stem (kg/ha)	0.38	0.23	0.50	0.46	0.53	0.53	0.61	0.29
Dry stem (%)	0.79	0.55	0.80	0.81	0.78	0.86	0.79	0.65
Dry total green (kg/ha)	0.50	0.38	0.64	0.59	0.68	0.65	0.76	0.43
Dry total green (%)	0.91	0.77	0.94	0.94	0.92	0.95	0.91	0.85
Dry leaf:stem	0.76	0.81	0.71	0.74	0.69	0.69	0.60	0.81
ln(Total Biomass)	0.21	0.12	0.26	0.24	0.27	0.28	0.29	0.15
ln(dry green leaf kg/ha)	0.90	0.65	0.83	0.87	0.80	0.91	0.74	0.76

The linear relationship between the chosen biomass measure and vegetation index is displayed in Figure 3.8. There is a strong linear relationship evident (R^2 = 0.91) and the equation was: $y = 0.0001 + 0.1348$. It is noteworthy that at the lower end of both DGLB and SAVI(0.75), while there were several zero results for biomass, there are still positive vegetation index results. This is partly because soil also reflects in the red and NIR bands (to a lesser extent than green biomass) which are included in this index. The chosen index, SAVI(0.75), takes into account soil reflectance and this effect is minimised. The presence of other plant material (not leaf) which remains (i.e. stem and dead material) may also contribute to red and NIR reflectance; however these are not included in this biomass measure.

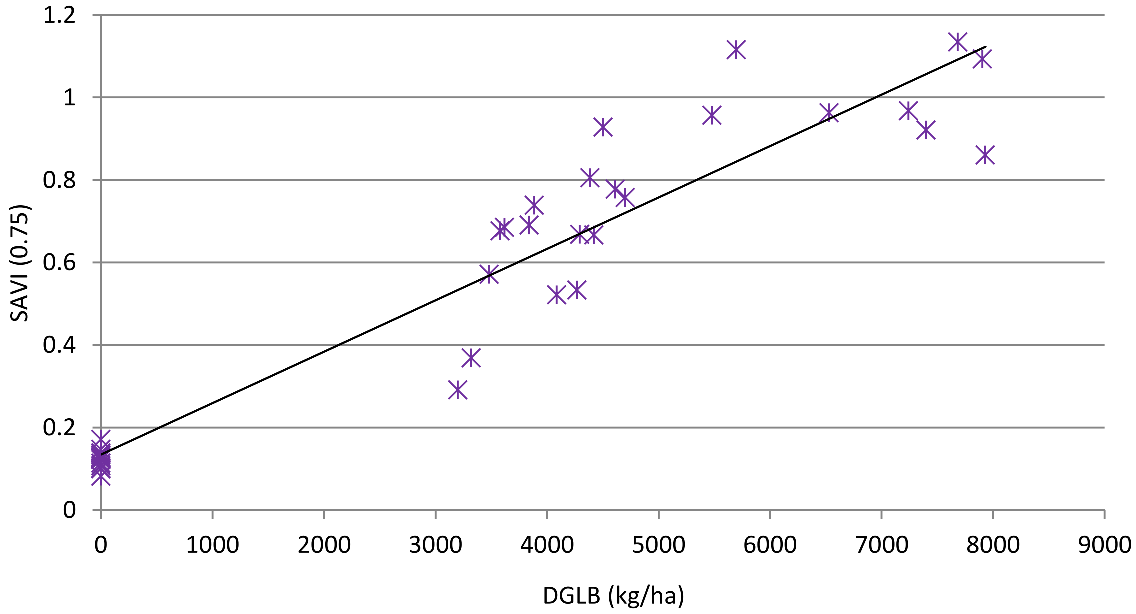


Figure 3.8 The linear relationship between dry green leaf biomass (DGLB) (kg/ha) and soil adjusted vegetation index with constant of 0.75 (SAVI(0.75)). The R^2 is 0.91.

The measured biomass values (points) and the trend curves created from the relationship between DGLB and SAVI(0.75) reflectance values, are shown in Figure 3.9. The equation of the trendline for Paddock 1 and 2 were: $y = 5.65x^2 - 469.58x + 9393.4$ $(r^2 = 0.99)$ and $y = 8.95x^2 - 594.47x + 9645.5$ $(r^2 = 0.98)$, respectively. Dry green leaf biomass progressively decreased over the experiment period, from 9,393 to 237 kg/ha (day 30) in Paddock 1, and from 9,646 to 378 kg/ha in Paddock 2 (day 25). This decline was expected based on both stocking density and paddock observations, as visually presented in Figure 3.10 and Figure 3.11. In Paddock 1 on day one the biomass amount was so high that cattle were difficult to see; by day 30 there was essentially no edible biomass remaining.

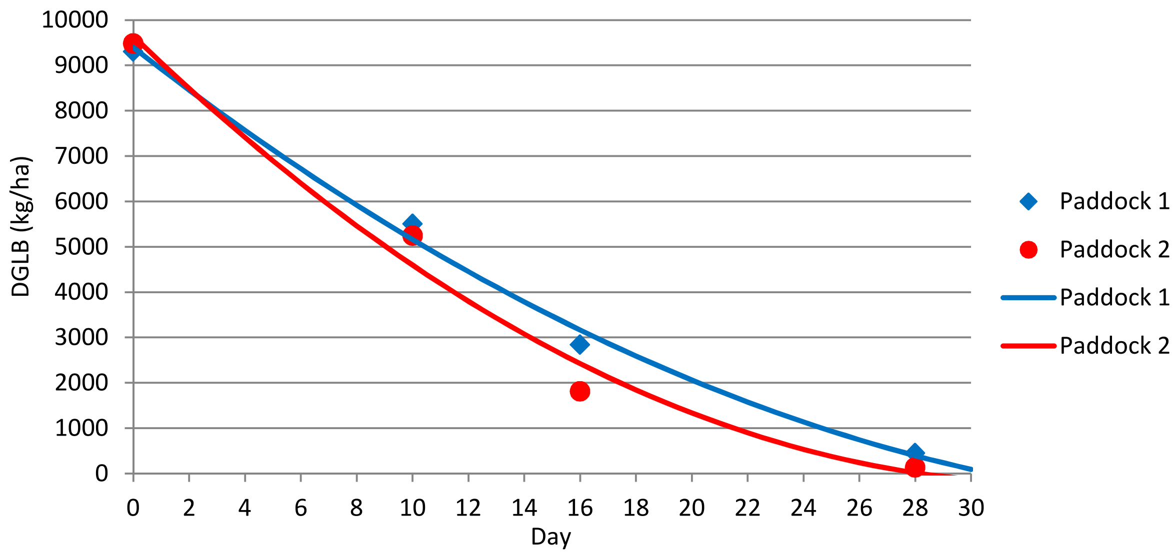


Figure 3.9 Measured (markers) and estimated (curves) dry green leaf biomass (DGLB) (kg/ha) over the experiment period.

Figure 3.10 Cattle in paddock 1 on experiment day 1, containing forage oats. The estimated dry green leaf biomass is 9,393 kg/ha.

Figure 3.11 Paddock 1 on experiment day 30, containing forage oats. The estimated dry green leaf biomass is 237kg/ha.

Initially, due to the slightly higher R^2 of 0.92, vegetation index MNLI was explored for estimating paddock biomass. However, the results did not appear to accurately describe what was happening in reality. As shown in Figure 3.12 negative vegetation index values occurred and the equation of the linear regression was: $y = 0.0002x - 0.2237$. Additionally, and more importantly, the curve of decline did not reflect actual paddock biomass (Figure 3.13), as demonstrated by site photographs (Figures 3.10 and 3.11) there was very little to no available biomass in the paddocks by the end of the experiment. The SAVI curve (Figure 3.9) presents this, but the MNLI graph indicated a reasonable amount of remaining biomass. Part of this may be attributed to SAVI accounting for soil reflectance.

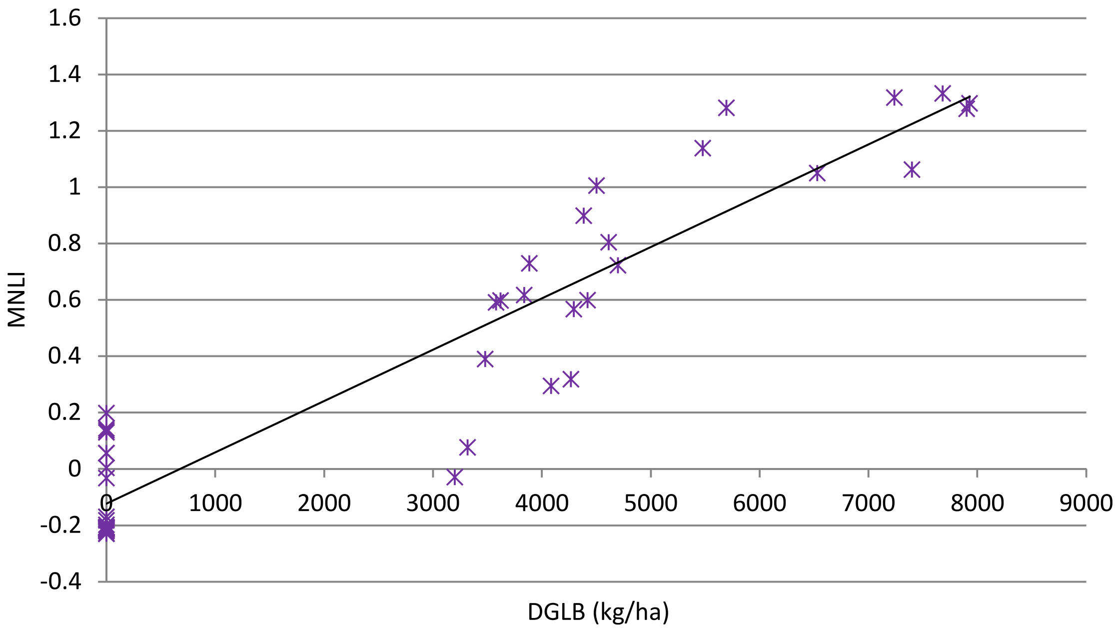


Figure 3.12 The linear relationship between dry green leaf biomass (DGLB) (kg/ha) and modified non-linear index (MNLI). The R^2 is 0.92.

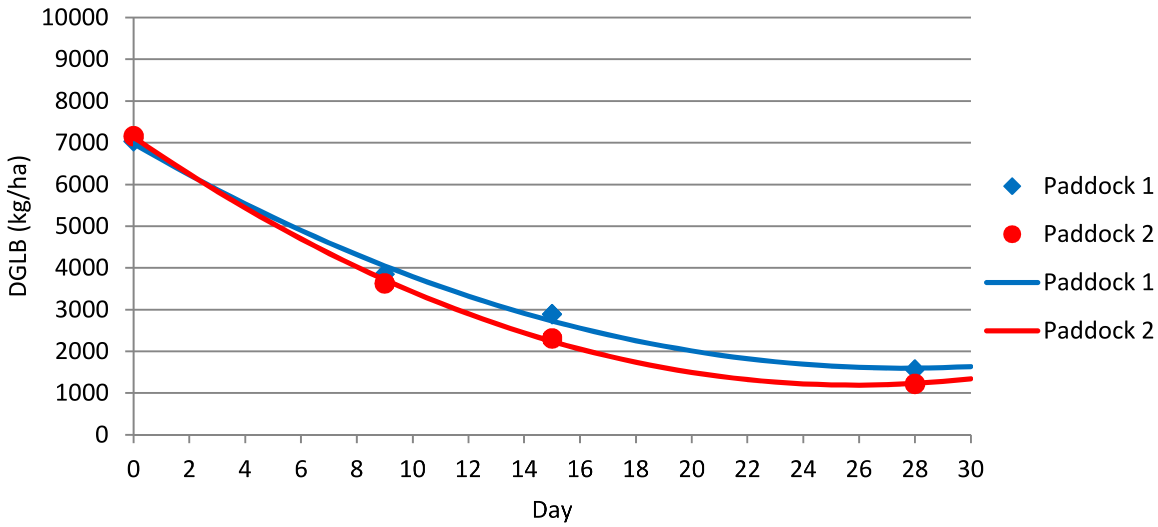


Figure 3.13 Measured (markers) and estimated (curves) dry green leaf biomass (DGLB) (kg/ha) over the experiment period when using modified non-linear index for estimating biomass.

3.3.2 The Animal System

GPS System Performance

Successful data capture was achieved for 78% of the cattle. Based on erroneous and missing data the final number of cattle tracked in Paddock 1 was 18 and in Paddock 2, 21. This was because of collar loss in the paddock resulting in incomplete datasets, GPS chipsets which had corrupt data (therefore not meaningful once downloaded), or large amounts of missing data due to device malfunction.

A summary of the descriptive statistics of the GPS collars deployed is presented in Table 3.4. This includes the average per cent of location fixes received, satellites and HDOP of all of the location fixes. Values were the same for average satellites and HDOP for both herds. The percentage of expected fixes actually received was 1% higher for Paddock 2.

Table 3.4 Summary of descriptive statistics for average herd GPS performance, including the average number of recorded positions, the percent of expected positions actually recorded, the average number of satellites used to record a position and the average horizontal dilution of precision (HDOP) of recorded positions.

Paddock	Count of All Position Fixes	% Expected Fixes*	Average of Satellites	Average of HDOP
1	192653	96%	8.8	1.3
2	187169	97%	8.8	1.3
Total	379822	96%	8.8	1.3

* The expected number of fixes for Paddock 1 was 200,448 and for Paddock 2 was 193,536.

Distance Moved

The daily average distance moved in Paddock 1 (Figure 3.14), ranged from 2,500 m to 6,646 m with a mean of 4,311 m. In Paddock 2 distance moved ranged from 2,764 m to 6,103 m with a mean of 4,051 m. On day one, 10 and 16 maximum daily distances were observed for both herds. Additionally, after day 25 cattle in Paddock 1 displayed high distances moved per day.

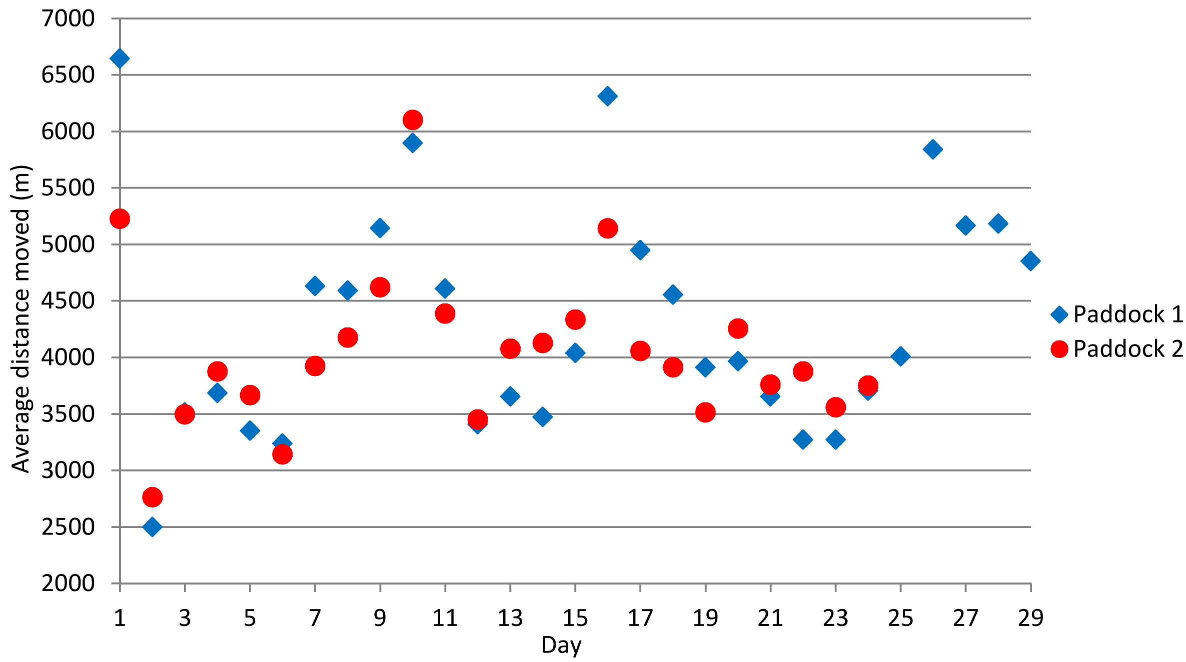


Figure 3.14 Average distance moved per day over the experiment period. Each data point is the average of all animals within a herd.

Daily distance moved and weather data, including maximum temperature and rainfall are compared in Figure 3.15. There was no relationship of average distance moved and weather data observed. Note the missing temperature data for some days is because this data was not available for that site from the Bureau of Meteorology (http://www.bom.gov.au/climate/data/).

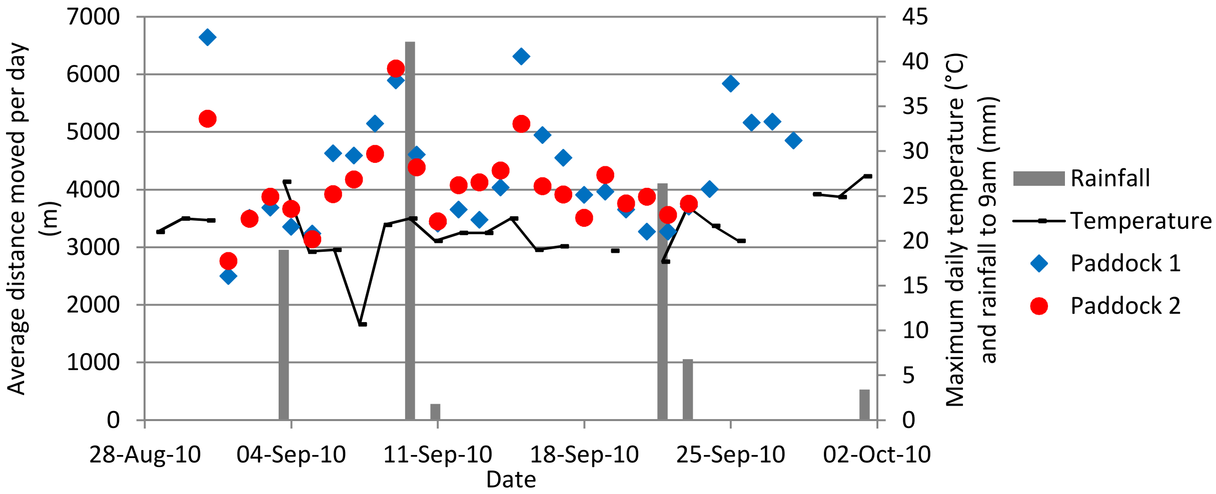


Figure 3.15 Daily average distance moved (m), rainfall (mm) and maximum temperature (°C) for Paddock 1 and Paddock 2. Each data point for average distance moved is the average of all animals within a herd.

Speed-based Behaviour

The herd percentage of the daily time that cattle spent grazing is presented in Figure 3.16. Note initially data appears to follow a linear trend before following a quadratic pattern. As such, quadratic curves were fitted to the data from day 6. Data from day 6 onward appears to follow a quadratic trend quite well with an R^2 of 0.62 for Paddock 1 and 0.77 for Paddock 2. The equations for the quadratic curves were $y = -0.0749x^2 + 2.6035x + 18.144$ and $y = -0.1264x^2 + 3.6998x + 15.353$ for Paddock 1 and 2 respectively. Peak grazing (as determined by local maxima on the quadratic curves) was day 17 for Paddock 1 and day 15 for Paddock 2. On day 10 there is an increase compared to the previous and consecutive days in time spent grazing for both herds.

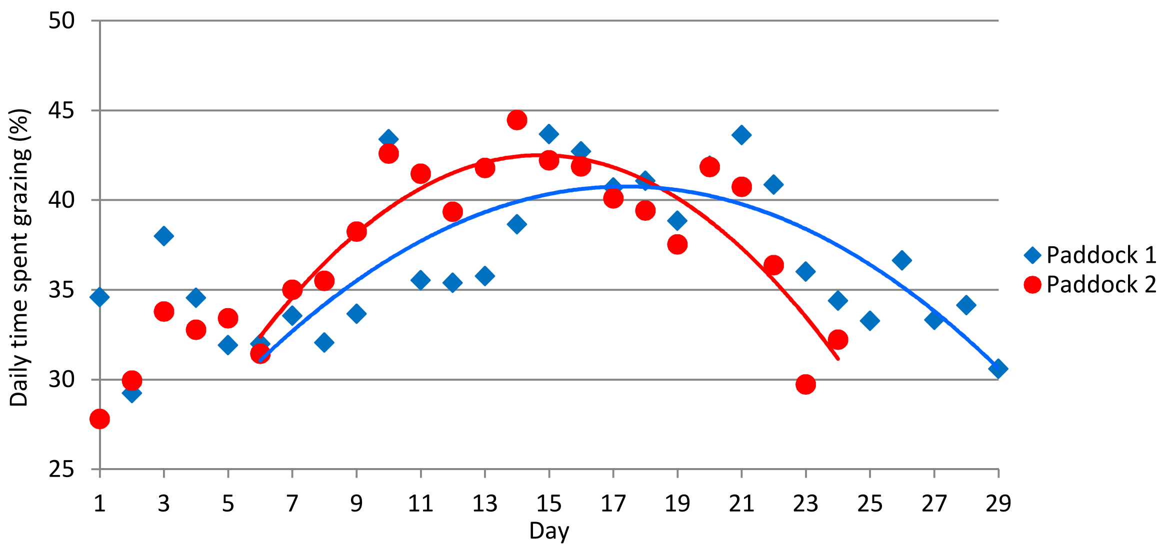


Figure 3.16 Average percentage of day spent grazing by the cattle. Quadratic curves are fitted to the data from day 6 with an R^2 of 0.62 for Paddock 1 and 0.77 for Paddock 2. The maximum grazing time in Paddock 1 (41%) occurred at day 17 and in Paddock 2 (43%) at day 15, derived from the quadratic trend lines. Each data point is the average of all animals within a herd.

Daily time spent grazing and weather data, including maximum temperature and rainfall are compared in Figure 3.17. There does not appear to be a strong relationship between average grazing time per day and the weather data recorded.

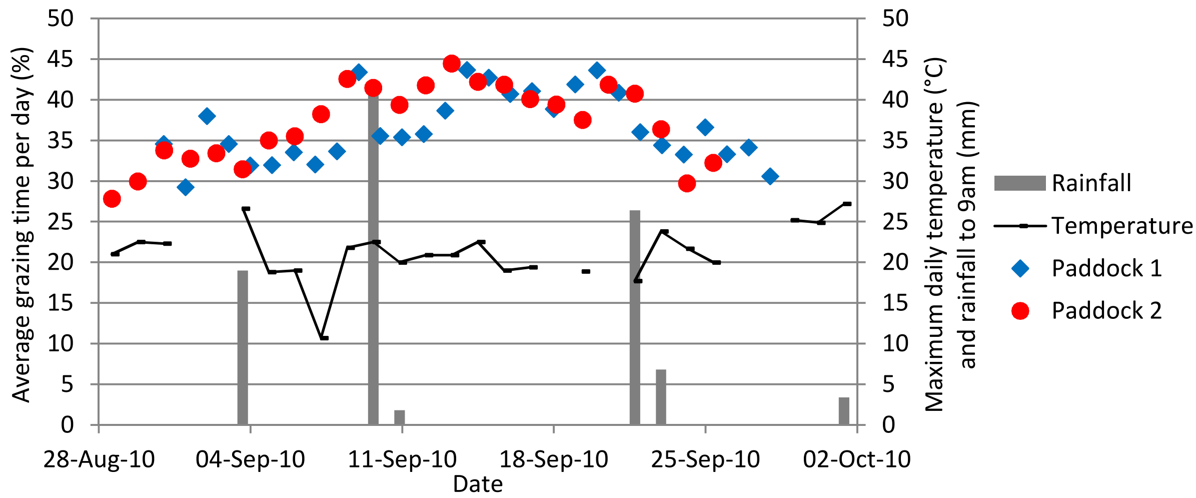


Figure 3.17 Daily time spent grazing (%), rainfall and maximum temperature for Paddock 1 and Paddock 2. Each data point for grazing time per day is the average of all animals within a herd.

The herd percentage of the day that cattle spent travelling is presented in Figure 3.18. Quadratic curves were fitted to the data from day 6 for comparability to other speed-based behaviour results. The R^2 Paddock 1 was 0.23 and 0.05 for Paddock 2. Travelling time does not follow a quadratic trend; unlike the other speed-based behaviour's investigated (Figures 3.16, 3.19 and 3.20). This is obvious through both the very poor relationship of the data to the quadratic trend line (represented by the r-squared values) and the visual analysis of the results suggests a linear trend. Consequently, there was no value in investigating the maxima (and minima) of time spent grazing per day. There were increases in travelling behaviour on the initial day, days 10, 16 and following day 25, relative to other days.

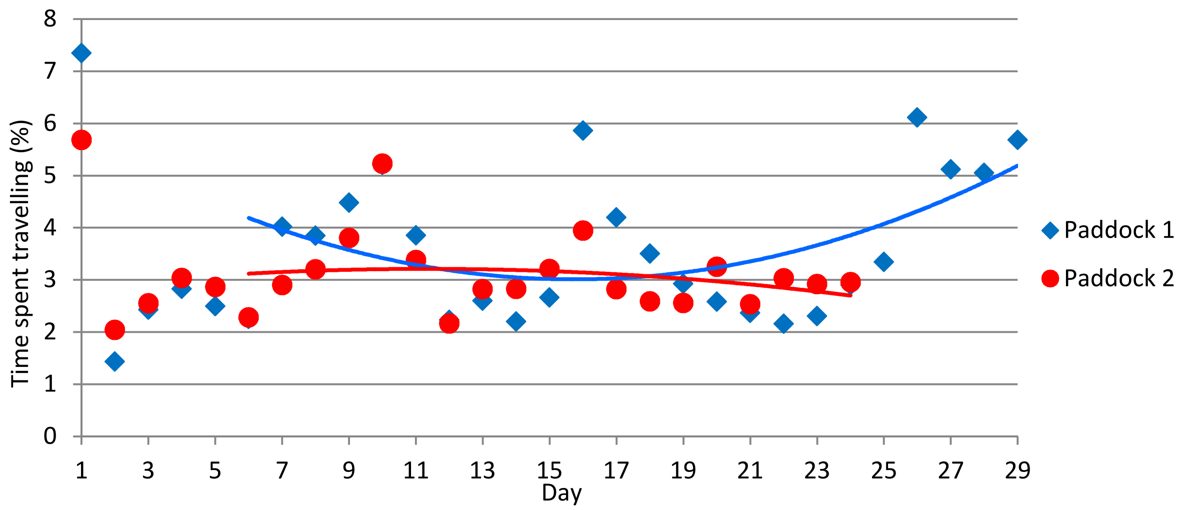


Figure 3.18 Average percentage of day spent travelling by the cattle. Quadratic curves are fitted to the data from day 6 with an R^2 of 0.23 for Paddock 1 and 0.05 for Paddock 2. The minimum moving time in Paddock 1 occurred at day 16 and the maximum moving time in Paddock 2 was at day 11. Each data point is the average of all animals within a herd.

The herd percentage of the day cattle spent stationary is presented in Figure 3.19. There appears to be a different behavioural trend pre- and post- day 6. As such, quadratic trend curves were fitted from day 6, with an R^2 of 0.44 for Paddock 1 and 0.72 for Paddock 2. The equations for the quadratic curves were $y = 0.0642x^2 - 2.2641x + 76.096$ and $y = 0.1355x^2 - 3.9721x +$

83.436 for Paddock 1 and 2 respectively. This data followed the inverse trend of grazing time per day with local minima's occurring rather than maxima's. Base stationary behaviour (as determined by local minima point of quadratic curves) was day 18 for Paddock 1 and day 15 for Paddock 2. On day 10 stationary times were quite low compared to the previous and consecutive days.

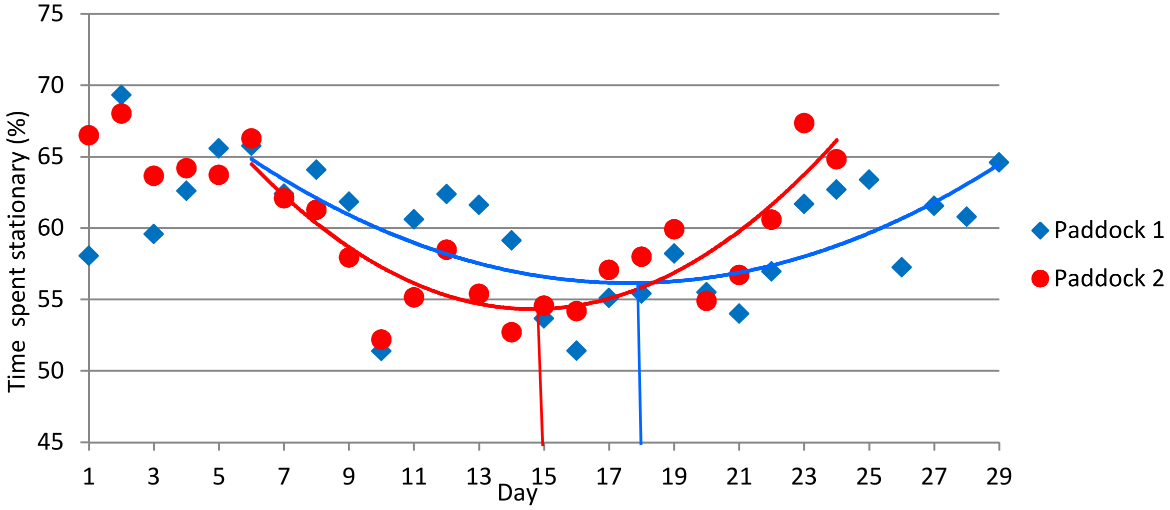


Figure 3.19 Average percentage of day spent stationary by the cattle. Quadratic curves are fitted to the data from day 6 with an R^2 of 0.44 for Paddock 1 and 0.72 for Paddock 2. The minimum stationary time in Paddock 1 occurred at day 18 and in Paddock 2 at day 15, derived from the quadratic trend lines. Each data point is the average of all animals within a herd.

The proportion of time spent grazing as daily estimated biomass declined in each paddock is displayed in Figure 3.20. Days 1 to 5 (as noted in Figure 3.16 and 3.19) appear to follow a different behavioural pattern. Consequently, a quadratic trend line was applied from day 6. Data from day 6 onward appears to follow a quadratic trend quite well with an R^2 of 0.57 for Paddock 1 and 0.75 for Paddock 2. The equations for the quadratic curves were $y = -0.00000009x^2 + 0.0059x + 31.183$ and $y = -0.0000001x^2 + 0.0081x + 29.223$ for Paddock 1 and 2 respectively. The maximum grazing time (derived from the quadratic trend) in Paddock 1 was 41% and corresponds to 3,248 kg/ha DGLB. For paddock 2 the maximum was 43% which corresponds to 3,304 kg/ha DGLB. The peak grazing time for both paddocks occurred within 56 kg/ha DGLB.

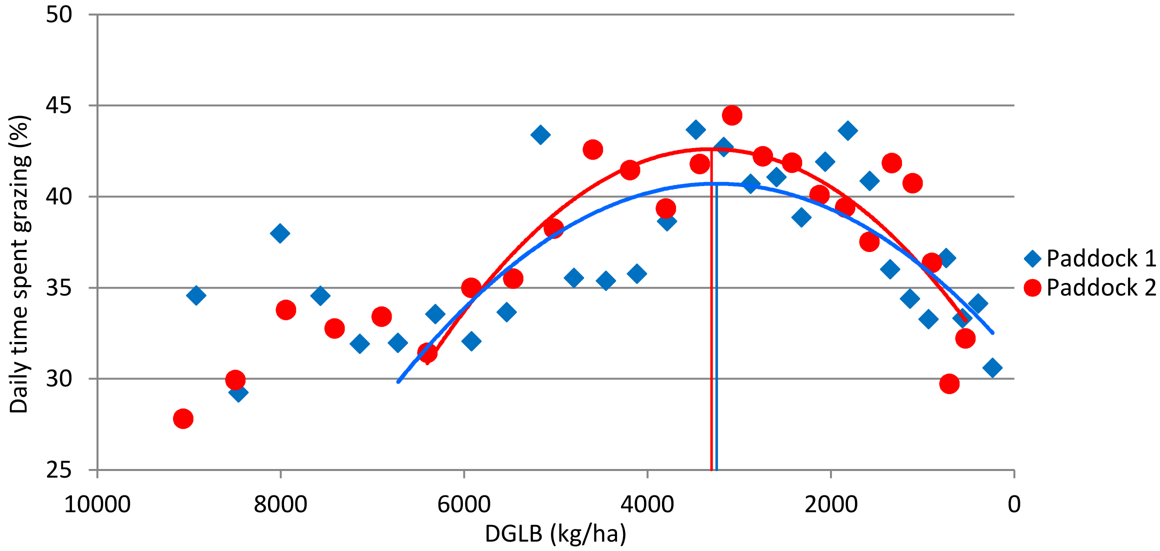


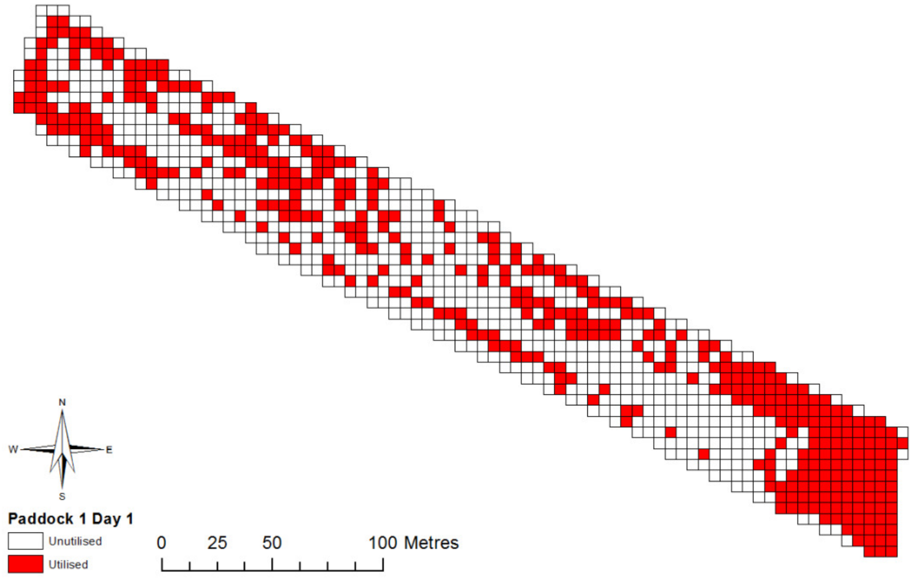
Figure 3.20 Average time spent grazing (% of day) as estimated dry green leaf biomass (DGLB) declines. Quadratic curves are fitted to the data with an R^2 of 0.56 for Paddock 1 and 0.75 for Paddock 2. The maximum grazing time in Paddock 1 (41%) occurred at 3,248 DGLB (kg/ha) and in Paddock 2 (43%) at 3,305 DGLB (kg/ha), derived from the quadratic trend lines. Each data point is the average of all animals within a herd.

Spatial Distribution

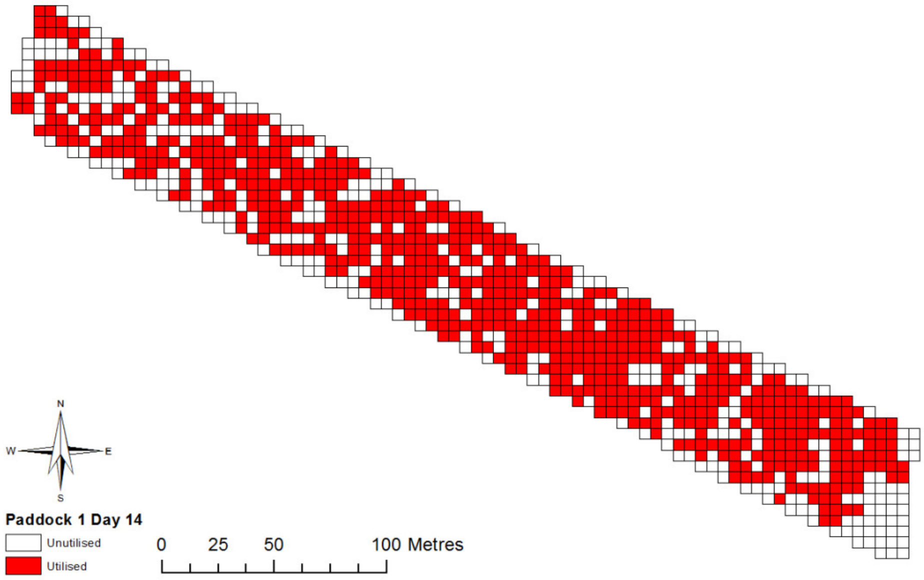
Maps of LRI were created for each day of the trial for each herd. As an example, Figure 3.21 presents the areas of Paddock 1 utilised by the tracked cattle on day 1, day 14 and day 29. The LRI maps for Paddock 2, present paddock utilisation on day 1, 12 and 24 and shown in Figure 3.22.

In both paddocks it is visually evident that on the first day cattle spent time at the northwest and southeast ends of the paddocks with some utilisation on the northern and southern boundaries. On the middle days cattle in both paddocks are more evenly spread across the whole paddock with some lack of use of the southeast corner for Paddock 1 and northwest corner for Paddock 2. On the final days for each herd there is utilisation across the paddocks, however it is much less uniform, appearing patchy.

A)



B)



C)

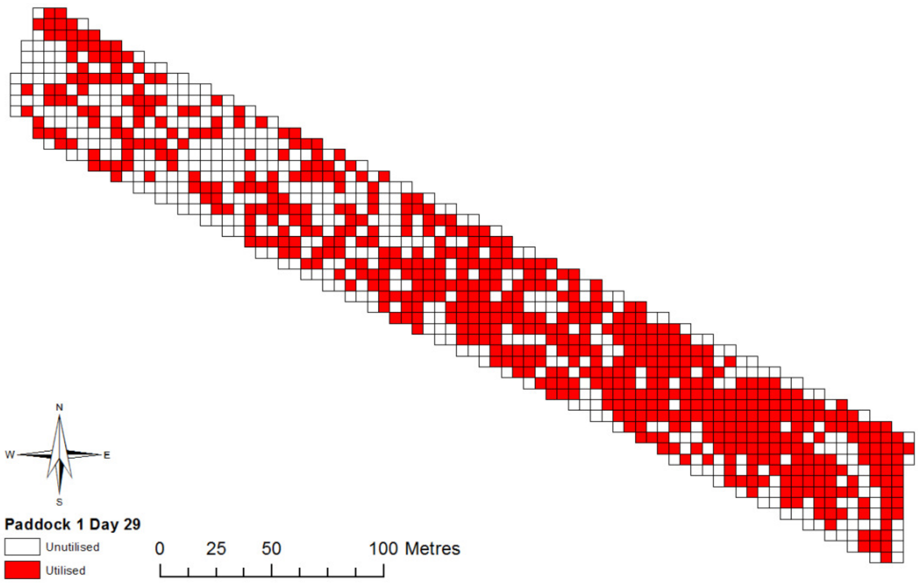


Figure 3.21 Paddock 1 livestock residence index maps on A) day 1; B) day 14; and C) day 29, where red cells are utilised and white are unutilised. Utilised is defined by having one or more positions logged within a cell.

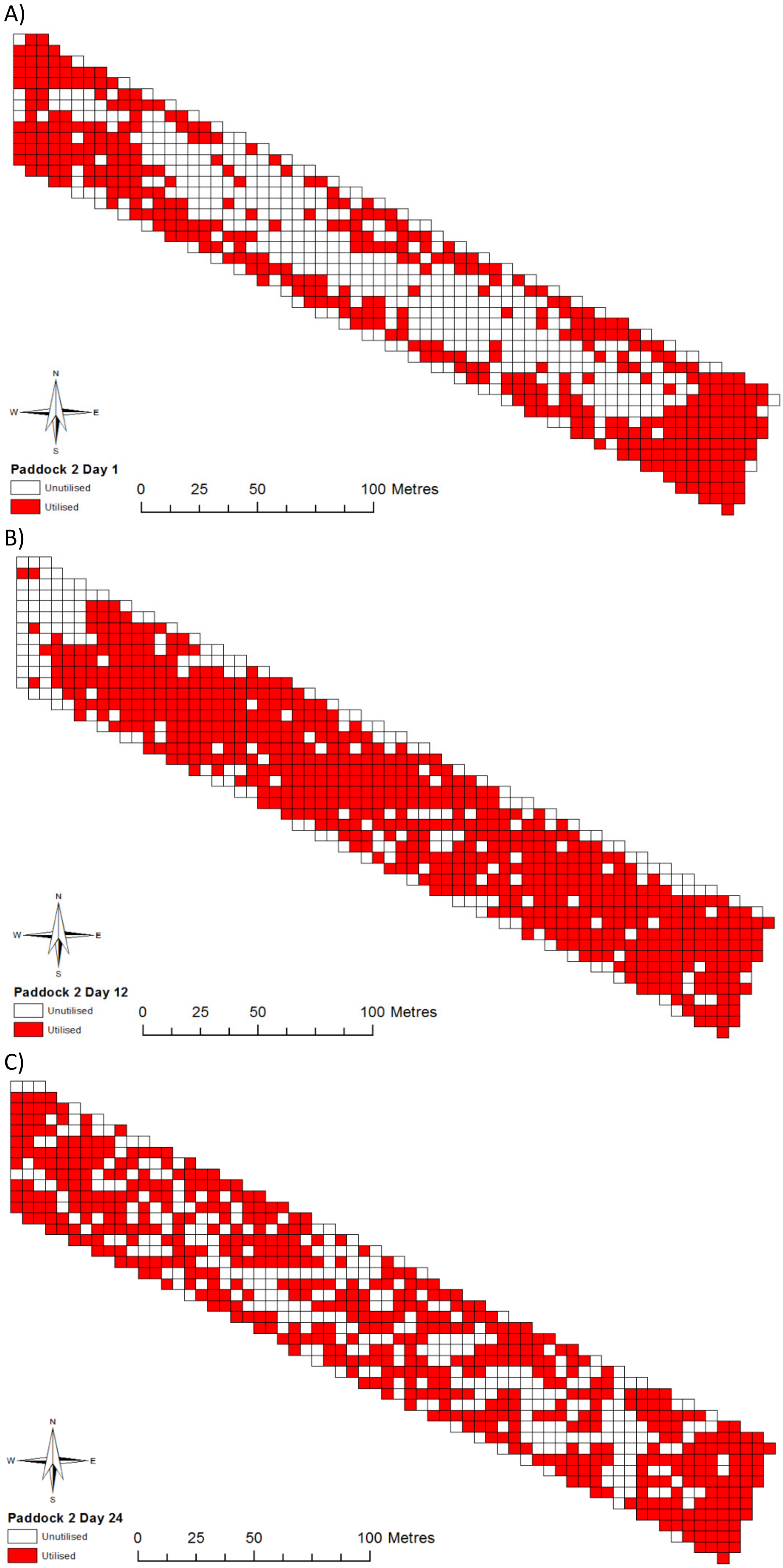


Figure 3.22 Paddock 2 livestock residence index maps on A) day 1; B) day 12; and C) day 24, where red cells are utilised and white are unutilised. Utilised is defined by having one or more positions logged within a cell

The daily cattle LRIs determined the proportion of each paddock utilised by the livestock. This was compared by day (Figure 3.23) and against estimated DGLB for each herd (Figure 3.24). A quadratic curve was fitted to the data. The equations for the quadratic curves presented in Figure 3.23 were $y = -0.1177x^2 + 4.2452x + 28.859$ (r^2 =0.86) and $y = -0.172x^2 + 5.1641x + 40.84$ (r^2 =0.86) for Paddock 1 and 2 respectively. The equations for the quadratic curves presented in Figure 3.24 were $y = -0.0000001x^2 + 0.0059x + 56.42$ (r^2 =0.80) and $y = -0.0000001x^2 + 0.0065x + 66.688$ (r^2 =0.78) for Paddock 1 and 2 respectively. The maximum proportion, as determined by the quadratic, of Paddock 1 was on day 18 (Figure 3.23) and at 3,001 DGLB (kg/ha) (Figure 3.24) and for Paddock 2, on day 15 (Figure 3.23) and at 3,250 DGLB (kg/ha) (Figure 3.24). The biomass difference between the two paddocks at the trend line maxima is 249 DGLB (kg/ha). In both Figures 3.23 and 3.24, it is obvious that cattle in Paddock 2 used a higher proportion of area than Paddock 1 cattle.

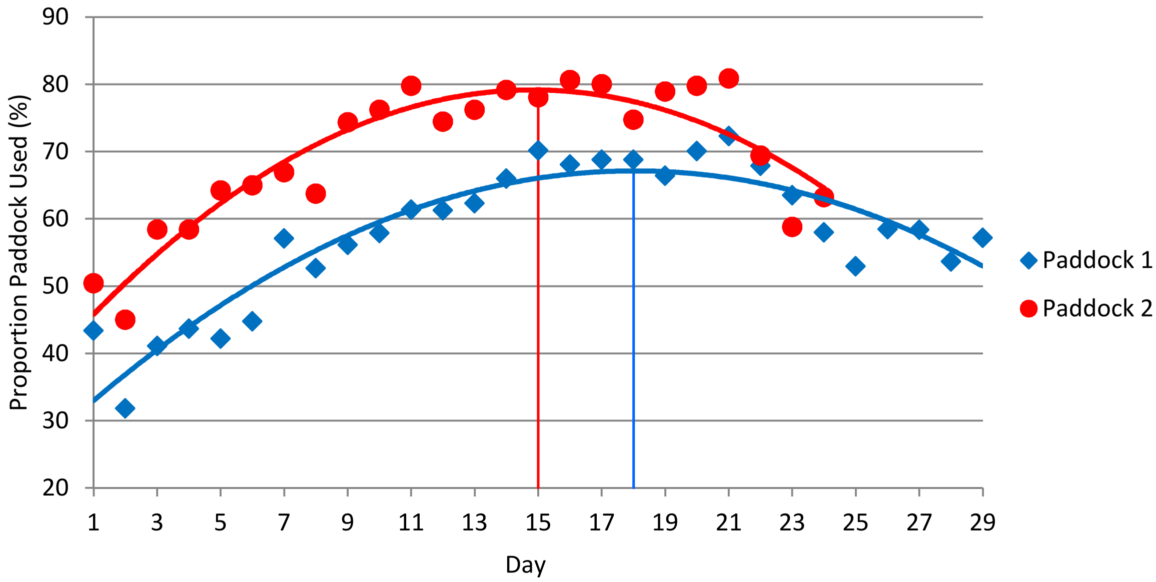


Figure 3.23 Daily proportion of Paddock 1 and Paddock 2 used by the cattle as calculated by livestock residence indexes. (R^2 for Paddock 1 = 0.86 and R^2 for Paddock 2 = 0.86). The maximum proportion of paddock utilised in Paddock 1 occurred on day 18 and in Paddock 2 on day 15, derived from the quadratic trend lines.

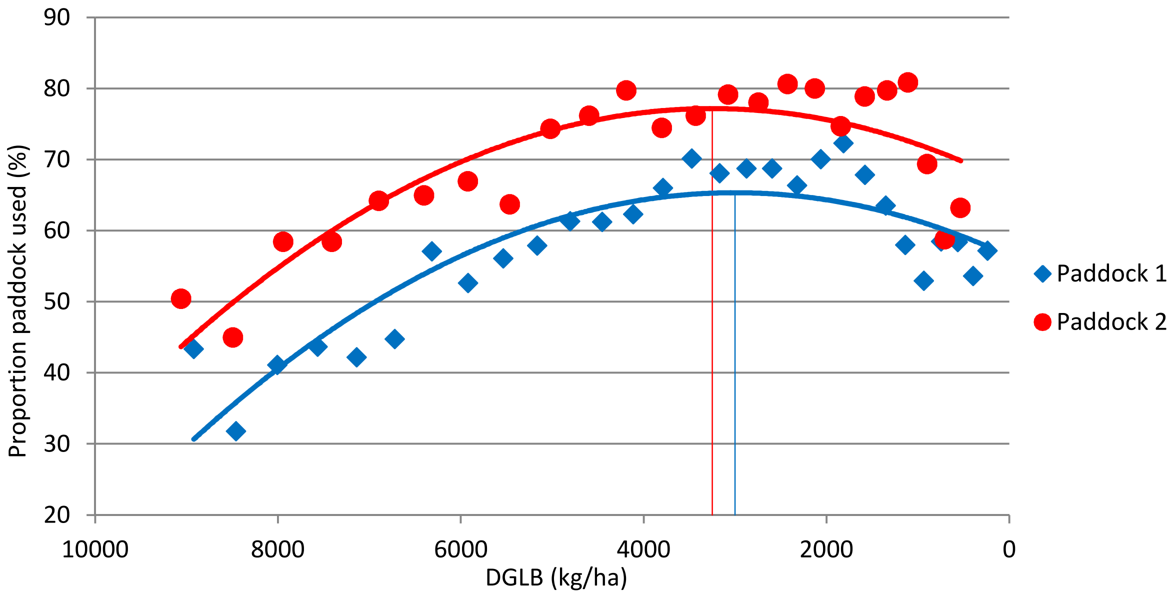


Figure 3.24 Proportion of Paddock 1 and Paddock 2 used by the cattle as calculated by livestock residence indexes correlated against daily estimated dry green leaf biomass (DGLB) (kg/ha). (R^2 for Paddock 1 = 0.80 and R^2 for Paddock 2 = 0.78). The maximum proportion of paddock utilised in Paddock 1 occurred at 3,001 DGLB (kg/ha) and in Paddock 2 at 3,250 DGLB (kg/ha), derived from the quadratic trend lines.

Social Dispersion

Based on the peak grazing window dataset, MCPs for each herd were created for every day of the experiment. Due to the large number of MCP maps generated, a selection was chosen for presentation, including day 1, the middle day for each herd, and the last day. The MCPs for Paddock 1 on the first, middle and end day of the experiment are displayed in Figure 3.25. The MCPs for Paddock 2 include the first, middle and last day (Figure 3.26). It appears from this selection of maps that the MCPs increased as the experiment progressed.

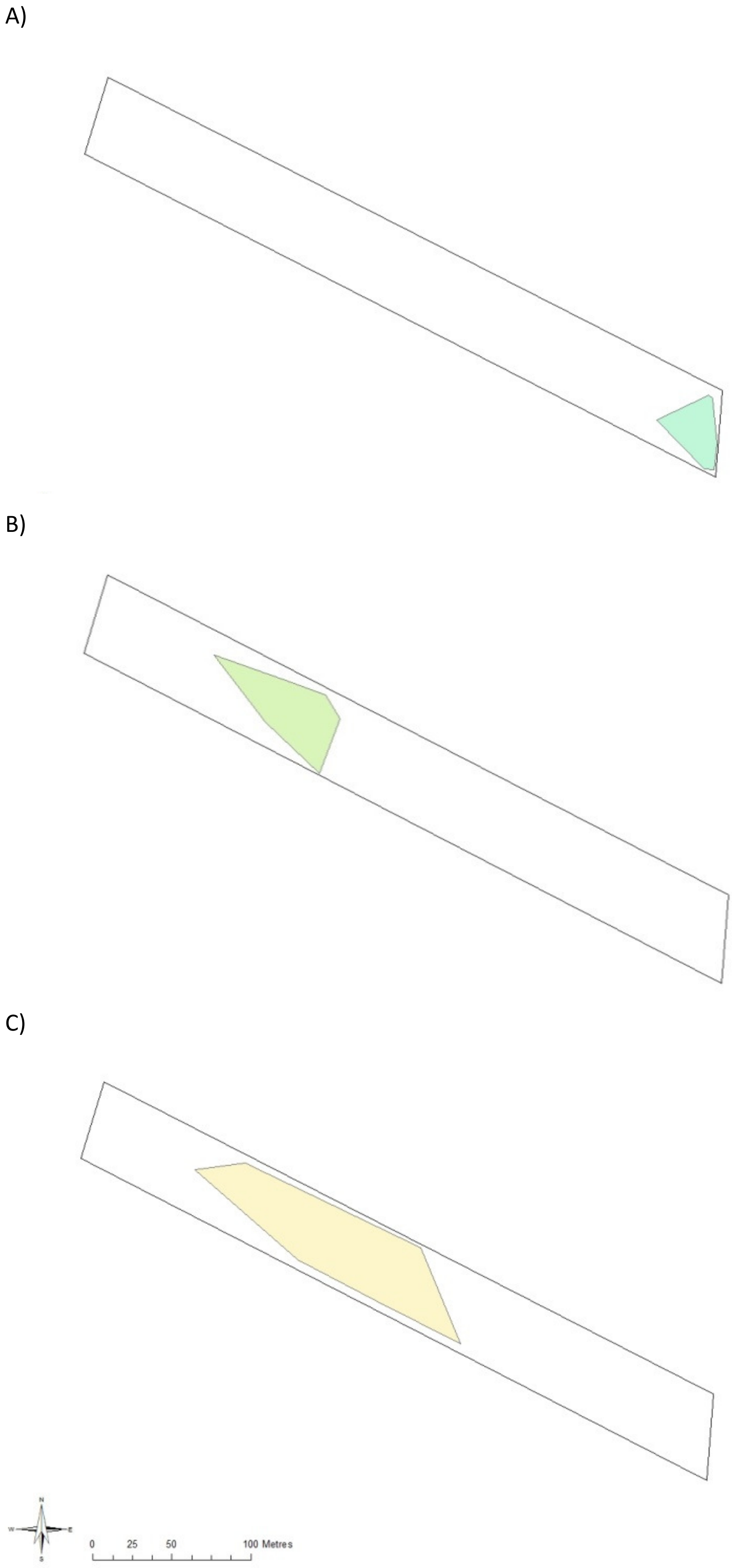


Figure 3.25 Paddock 1 minimum convex polygon maps on A) day 1 (Area = 989 m^2); B) day 14 (Area = 2,180 m^2); and C) day 29 (Area = 6,079 m^2).

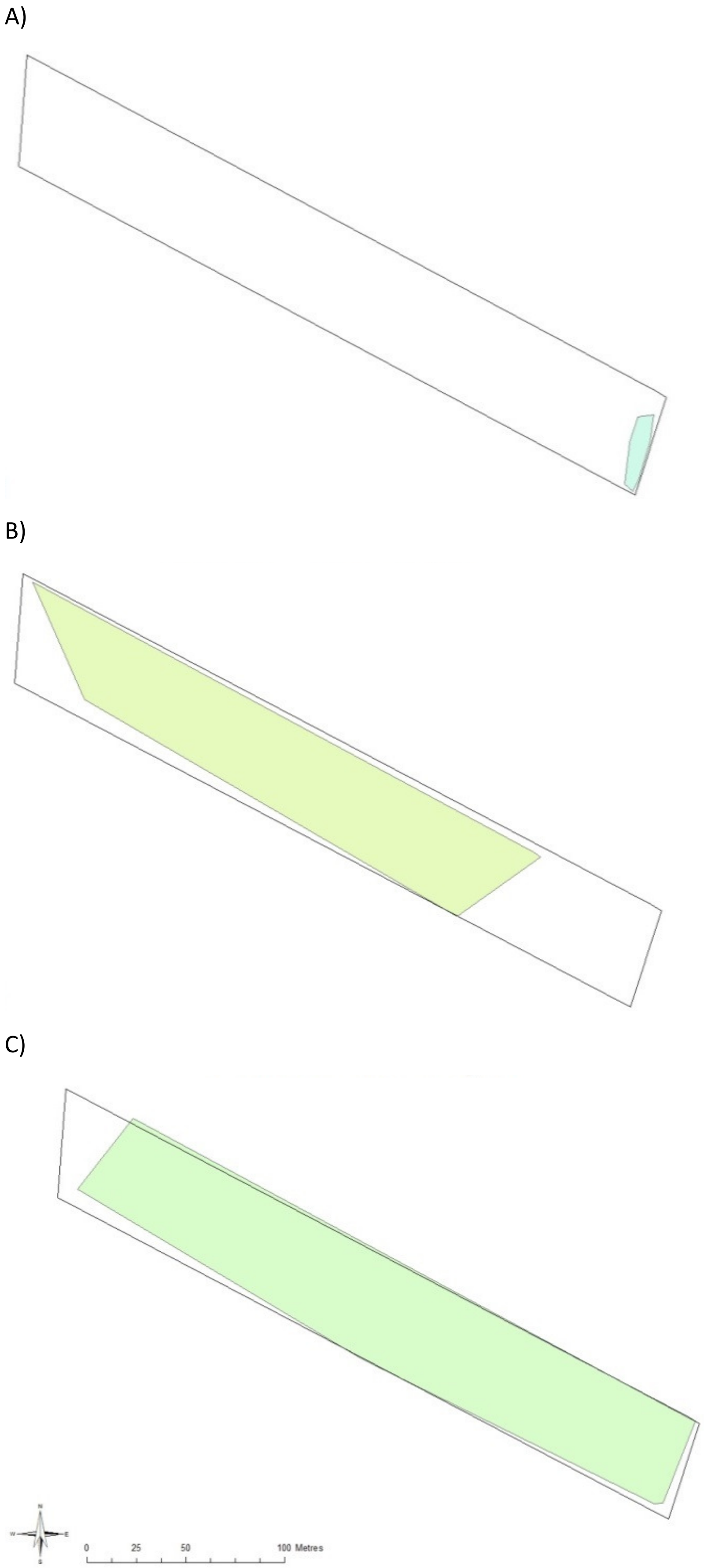


Figure 3.26 Paddock 2 minimum convex polygon maps on A) day 1 (Area = 295 m^2); B) day 12 (Area = 10,675 m^2); and C) day 24 (Area = 15,761 m^2).

The MCP areas for each herd are shown against both day (Figure 3.27) and DGLB (Figure 3.28). Although there were no clear trends suggesting that fitting a curve was valid, there were some apparent shifts in this behaviour which were categorised into different phases. Phase 1 was exemplified by very low MCP in both herds. Phase 2 was defined by an MCP of >2000 m^2 achieved and maintained. Phase 3 was defined as the MCP exceeding 11,000 m^2; however, this threshold was not maintained once breached. The change from Phase 1 to Phase 2 occurred at a similar biomass (between 6,400 and 6,700 DGLB kg/ha); however the change from Phase 2 to 3 for biomass was much larger and overlaps occurred (between 2,061 and 1,813 DGLB kg/ha for Paddock 1 and between 1,108 and 1,336 DGLB kg/ha for Paddock 2).

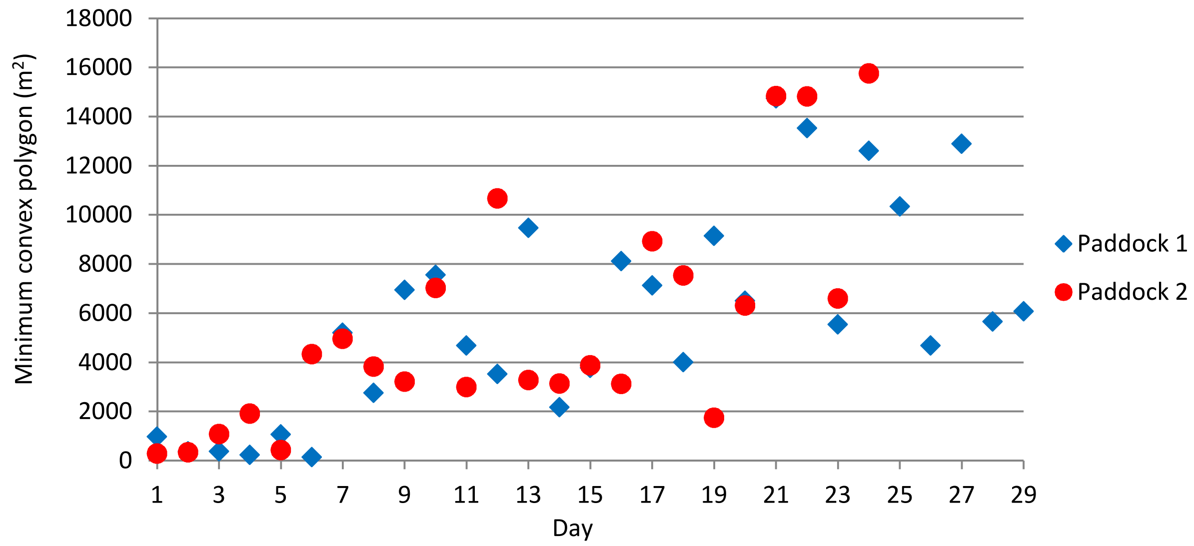


Figure 3.27 Daily minimum convex polygon areas for each herd.

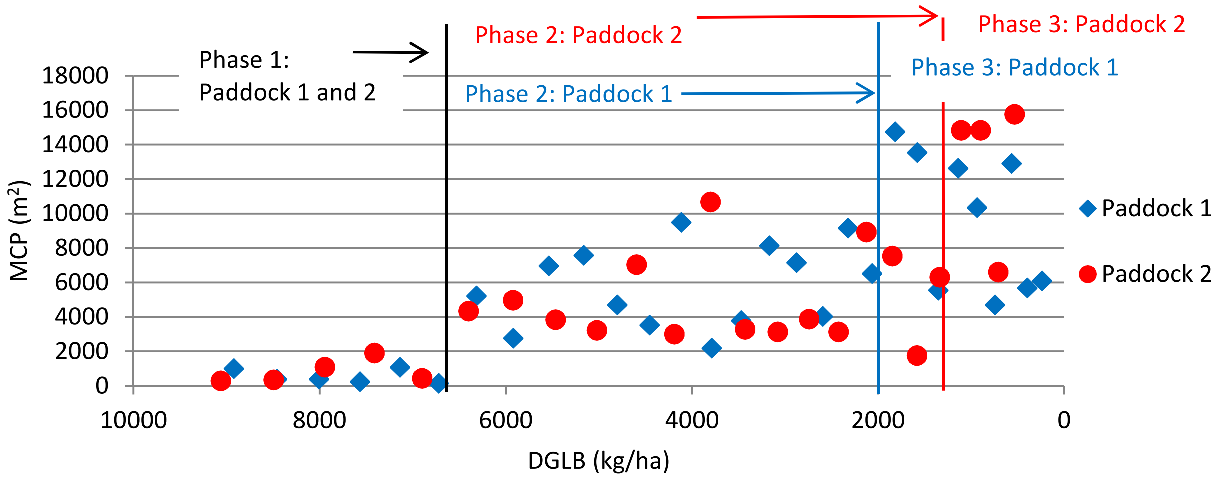


Figure 3.28 Daily minimum convex polygon (MCP) areas and estimated dry green leaf biomass (DGLB) for Paddock 1 and Paddock 2. Three distinct phases for each herd have been identified with vertical lines. The point of interest is between Phase 1 and Phase 2 when MCPs suddenly increase after stability at 6,313 kg of DGLB for Paddock 1 and at 6,401 kg of DGLB for Paddock 2.

The IHD daily averages are presented with day, Figure 3.29, and DGLB, Figure 3.30. Similarly to the results of the herd MCPs, there were no clear trends suggesting validity in fitting a curve, there were apparent shifts in behaviour. As such, IHD was also categorised into different phases. Phase 1 was exemplified by very low IHD in both herds. Phase 2 was defined by an IHD of >27 m achieved and maintained (with one outlier from Paddock 2 at 25 m towards the end of the experiment). Phase 3 was defined as the IHD exceeding 125 m for Paddock 1 and 100 m for Paddock 2; however, this threshold was not maintained once breached. The change from Phase 1 to Phase 2 occurred at a similar biomass (between 6,400 and 6,700 DGLB kg/ha); however the change from Phase 2 to 3 for biomass was much larger and overlaps occurred (between 2,061 and 1,813 DGLB kg/ha for Paddock 1 and between 1,108 and 1,336 DGLB kg/ha for Paddock 2).

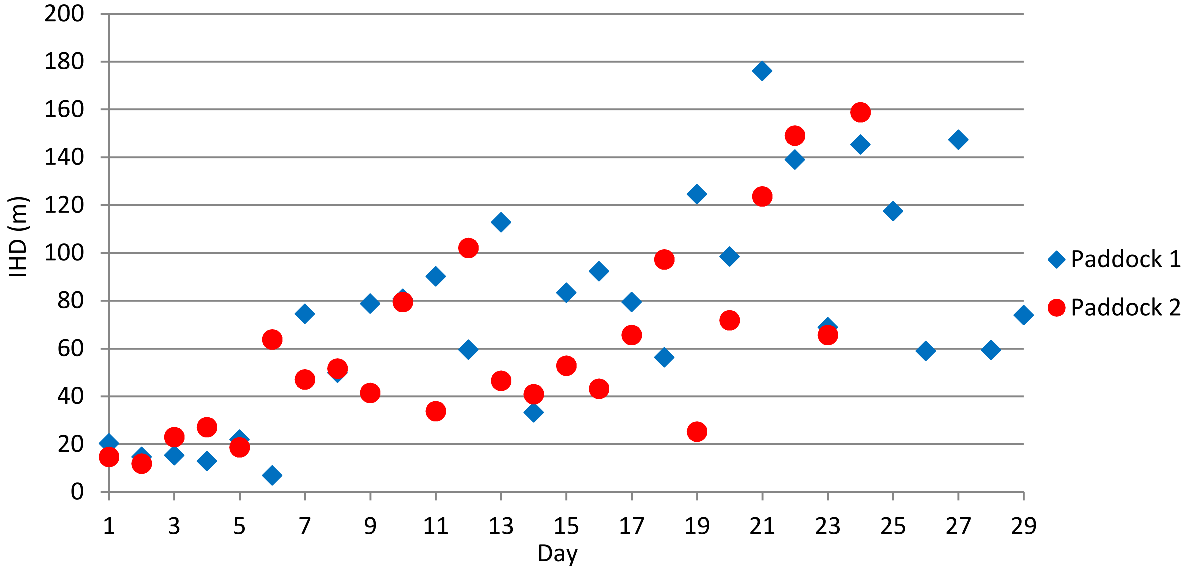


Figure 3.29 Daily average intra herd dispersion (IHD) for each herd.

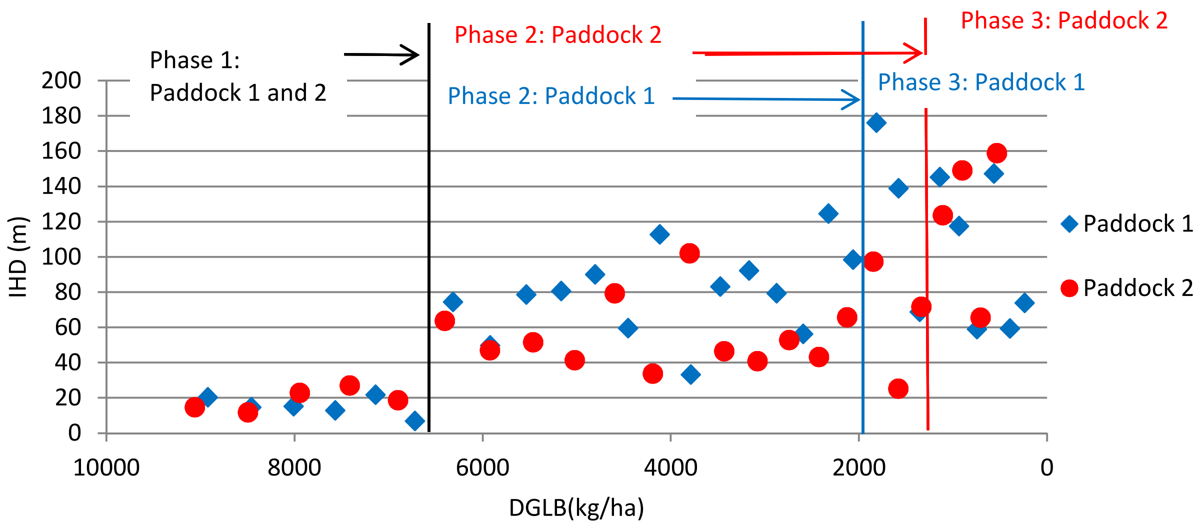


Figure 3.30 Daily intra herd dispersion (IHD) and estimated dry green leaf biomass (DGLB) for Paddock 1 and Paddock 2. Three distinct phases for each herd have been identified with vertical lines. The point of interest is between Phase 1 and Phase 2 when IHDs suddenly increase after stability at 6,313 kg of DGLB for Paddock 1 and at 6,401 kg of DGLB for Paddock 2.

Based on the results of the MCP areas and the IHD as biomass declined, 3 distinct phases for each paddock were observed. The key points of these phases are summarised and presented in Table

3.5. Both MCPs and IHDs increased for each phase. Note that the differences in MCPs are not directly comparable across herds due to different stocking densities.

Table 3.5 Phase change values for Paddock 1 and Paddock 2 of minimum convex polygons (MCP) and intra herd dispersion (IHD) and the difference between paddocks for IHD.

	MCP (m^2)		IHD (m)		
Phase	Paddock 1	Paddock 2	Paddock 1	Paddock 2	Difference
1	538	817	15	19	4
2	5794	5004	80	58	22
3	9570	13008	110	124	14

3.4 DISCUSSION

3.4.1 THE PLANT SYSTEM

AOS CALIBRATION

The relationship of DGLB with vegetation index SAVI(0.75) had a high R^2 (0.91). The strong relationship with the vegetation is not surprising as the leaf component is the greenest part of the plant due to a higher chlorophyll component, and chlorophyll is known to absorb high amounts of red and reflect high amounts of NIR radiation (Filella and Penuelas 1994). There is some suggestion of a flattening out of the relationship between SAVI and DGLB (Figure 3.8) when the biomass was above approximately 5,000kg/ha of DGLB and the corresponding SAVI(0.75) higher than approximately 0.9.

The RMSE for biomass prediction was 874 DGLB (kg/ha). This equated to 12% of the mean biomass. Other studies reported RMSE values of up to 24% from cross validation of green dry matter of a ryegrass pasture (Künnemeyer *et al.* 2001). Additionally, the RMSE of Chapter 2 resulted in an RSME of 18% of the mean biomass, thus, this is considered a good result.

WHOLE PADDOCK BIOMASS MONITORING

The biomass decreased as the experiment progressed (Figure 3.9). This was an expected outcome based on the stocking densities. Whole paddock biomass was monitored four times over the experiment. Initially it was intended that additional biomass surveys be undertaken but weather prevented this on several occasions. Despite this, the biomass monitoring undertaken provided adequate information on the decline of pasture availability.

By the end of the experiment (Paddock 1 = Day 29; Paddock 2 = day 25) each paddock had less than 400 DGLB (kg/ha). The recommended minimum biomass for cattle is 1,500 kg/ha GDM (MLA 2004). As such, we can conclude that biomass was limiting to the cattle by the end of the experiment. This was crucial to investigating how behaviour changes as feed becomes unavailable.

3.4.2 The Animal System

GPS System Performance

The focus of this research is the relationship between pasture availability and cattle behaviour at the herd level. Thus, the herd is our experimental unit. To ensure the pasture reached a limiting amount a high stocking density was required. Unfortunately, due to resource limitations, there were not enough collars to be deployed on all cattle. As such, 88% of cattle had tracking collars. Further to this, GPS loss and malfunction resulted in successful data capture from 39 cattle (78%). When working with GPS, unfortunately missing data is not unusual (Frair *et al.* 2004). Despite not being able to monitor all animals, we were able to capture a large proportion of the herd. The behaviours analysed are assumed to reflect the whole herd's. The results of the monitored behaviours of the two herds were similar.

Over both herds the proportion of expected position logs recorded was 96% (Table 3.4). This appears to be successful and falls within the range reported by other studies (90-100%) (Table 1.2). The average number of satellites (8.8) meet the requirement of at least four satellites and a HDOP result of 1.3 is considered to be very good (French 1996). The consistently high number of satellites and successful position solutions indicate the over determination setting and maximum awake period did not have a large effect on the devices.

One challenge for data analysis was the lack of collar synchronisation. Synchronised tracking data would provide more accurate and reliable information on the distribution of animals. Currently synchronising GPS animal tracking devices is unachievable and GPS development should to be undertaken to achieve this. Once synchronisation can be achieved the potential of animal tracking for production systems will become more reliable and useful in a wider range of situations. There is potential to improve data handling if it could be synchronised.

Abiotic Influences

Weather was investigated in relation to distance moved (Figure 3.15) and grazing time (Figure 3.17). Daily maximum temperature and rainfall did not appear to affect the behaviour of the cattle. There was a decline in both of these behaviours after a rainfall event on the 10th of September, however the decline continued, suggesting the rain was not the cause. There did not appear to be a relationship between maximum temperature and behaviour. The weather during the experiment was too mild to influence behaviour. The lack of a weather effect may be due to the large distance between the weather station and the research site.

Human Influence

The presence of humans has been found to induce a behavioural response from cattle (Murphey *et al.* 1981). Both day 10 and day 16 were days where biomass sampling was undertaken and researchers were present in each paddock. Both herds behaved similarly in response to the human interaction and cattle appeared inquisitive of the researchers at the time. Several behaviours varied on day 10, including increased distance moved, increased proportion of day spent grazing and travelling, and decreased time spent stationary. On day 16, distance moved and time spent travelling also peaked.

Distance Moved

The mean distance moved was 4,311 m for Paddock 1 and 4,051 m for Paddock 2. This is considerably lower that the distance recorded in Chapter 2 (5,300 m/day); however it is similar to that reported by Hart *et al.* (1993) which was 4,200 m/day. On day 1 the cattle were very active, both herds having a total distance moved of more than 5,000 m in the day and included the highest value recorded for this experiment of 6,646 m (Figure 3.14). The high distance can be attributed to an exploratory phase of the cattle in a new environment (Vallentine 2001). This highlights the exploratory phase is not representative of 'normal' herd behaviour as a function of available biomass. The peak for Paddock 1 at the end of the experiment may be a socialisation affect due to the removal of the steers in Paddock 2. The relocation possibly unsettled the cattle in Paddock 1 resulting in increased travel time. While the herd from Paddock 2 was held in a paddock out of line of site, the Paddock 1 herd could have still sensed the other animals through sound and smell. These cattle were originally in one herd and during this experiment, although separated, remained in close proximity. As such, social contact may have been maintained throughout, despite the physical separation of a fence. There were no clear trends apparent in the change of total distance moved as biomass declined in this experiment; therefore this metric is unlikely to be a useful indicator of declining biomass.

Speed-based Behaviour

Following the Putfarken *et al.* (2008) model, relevant speed-based behaviours investigated were grazing, travelling and stationary movement. Initially a linear behavioural trend was observed lasting the 5 days before a quadratic pattern of behaviour became apparent for daily grazing and stationary movement. Because of this, for speed-based behaviours quadratic trend lines were applied from day 6 onwards and the analysis focuses on this aspect of the results.

The proportion of time spent grazing was within the expected range of 20-50% (Vallentine 2001) and was similar for both herds (Paddock 1 = 29-44% and Paddock 2 = 28-45%). Considering the progression of the results from the quadratic, daily grazing time increased to a maximum of 41% for Paddock 1 and 43% for Paddock 2 before declining until the finish of the experiment (Figures 3.16 and 3.20). This behaviour pattern was previously described by Chacon and Stobbs (1976). They depict that grazing time increases, then decreases as biomass declines; with reduced intake, grazing time increased ($P < 0.01$) and declined after a peak. Chacon and Stobbs (1976) attributed the decline in grazing time to fatigue because of limiting energy gained from feed consumed and concluded that dry matter intake was limiting at high grazing intensity. In this experiment the grazing time pattern is similar in both herds. However, peak grazing time, derived from the quadratic, presented timing by day (Figure 3.16) does not align (Paddock 1 = Day 17, Paddock 2 = day 15). This is because of the higher stocking density in Paddock 2, which resulted in less area available per animal and consequently a faster reduction in biomass and earlier behaviour response. Peak grazing time of the herds was much closer in relation to declining biomass (Figure 3.20). The local maxima (from the fitted quadratic) of grazing time occurred within 57 kg/ha of estimated DGLB, supporting that grazing time is related to available biomass.

Travelling time per day was similar in both herds as seen in Figure 3.18. In Paddock 2 values were more consistent with all but two points falling between 2 and 4% of each day. Unlike grazing and stationary time, daily travelling time was fairly consistent irrespective of biomass reduction, with increases on day one and days with human interaction. Thus a quadratic trend of behaviour was not observed. The lack of effect on travelling due to biomass depletion observed in this experiment could be because of paddock size. In a very large rangeland paddock, livestock may travel further in search of food (Vallentine 2001). In small paddocks the cattle can easily see or search for food without travelling far. The days with high time spent travelling supports the exploration phase of the cattle, particularly when combined with the high distance moved. As explored for distance moved, it is likely that the removal of the Paddock 2 herd is thought to have affected time spent travelling of the Paddock 1 herd. Without the increase in travelling time at the end, the overall behaviour trend would have been more similar to that of Paddock 2.

Stationary behaviour (Figure 3.19) was similar in both herds; decreasing and then increasing over the experiment, opposite to grazing behaviour. In paddock 2, peak grazing occurred on the same day as minimum stationary behaviour, and for Paddock 1 there was only one day difference. The Paddock 1 herd exhibited more stationary behaviour than Paddock 2, where stationary behaviour is replaced with higher grazing, rather than travelling behaviour. This suggests in small paddocks travelling behaviour is least affected by biomass availability, the animals sacrificing rest and/or rumination time for locating sufficient feed.

As highlighted in the previous chapter, the use of a speed model for cattle behaviour under different conditions may not be accurate across all cattle. While it was intended, unfortunately validation of behaviour speeds was impossible for this experiment because of a limited view of cattle. The starting biomass in the paddocks was so high cattle could not be easily seen, as shown in Figure 3.10, let alone individual animals and their behaviours distinguished. This highlights a potential application for livestock sensors as they do not require a clear line of sight view of cattle. Had this been an experiment which relied on human or video collected observations it would have failed. While the speed model was unable to be validated in this experiment, the speed-based behaviours are within expected ranges. The development of a situation-specific speed-based behaviour model will be presented in the following chapter.

Spatial Distribution

The LRI maps (Figures 3.21-3.22) show the cattle spent most of their time in the eastern and western ends of the paddocks and this utilisation pattern occurred throughout the experiment. Predominantly, the livestock residence in the centre of the paddock changes with decreased biomass. Initially cattle avoided the central part of the paddocks. As biomass declined, cattle increase utilisation in the central area, until a point, at which it declines again.

The proportion of the paddock utilised, derived from LRIs, was calculated. The proportions for each herd (based on the maxima of the fitted quadratic) peaked at a similar biomass with a difference of only 249 kg/ha of DGLB between paddocks (Figure 3.24), which is well within our biomass error. This indicates that the proportion of paddock utilised is influenced by forage amount. These results match cattle grazing time (day 6 onwards), exhibiting an initial increase in the proportion of the paddock utilised and grazing time, before declining. While the two herds exhibited similar paddock utilisation, the difference in proportion (i.e. Paddock 1 has a consistently lower proportion than in Paddock 2) is due to Paddock 2 having a higher stocking density. Unlike the speed-based behaviours there does not appear to be two segments of behavioural trend. Rather the cattle seem to follow a quadratic pattern in paddock utilisation from day 1 and the derived curve fitted very well to the data with an R^2 value of 0.80 in Paddock 1 and 0.78 in Paddock 2. While maximum grazing time of cattle seemed to occur at a closer biomass amount than for proportion of paddock used, the better fit of this data to a quadratic suggests this metric may be more useful for an online monitoring tool than grazing time.

Decreasing nutrient availability of feed is known to result in decreased cattle feeding activity once nutrients are so low that the animals expend more than they can consume (Chacon and Stobbs 1976). The limited activity (grazing time, stationary time and proportion of paddock utilised) towards the end of the experiment suggests a state of negative energy balance (lower energy in available feed than required to eat the food) may have been achieved. It is possible the forage oats was limiting in nutrients. However, this was not investigated as monitoring pasture quality was outside the scope of this research.

Social Dispersion

Spatial dispersion was investigated through whole herd dispersion (with MCPs) and within herd dispersion (with IHD). Similarly to the LRI results, the MCP maps (Figures 3.25 and 3.26) present cattle preference at the ends of the paddocks when biomass is high. The MCPs were alike for both herds. At the beginning of the experiment the animals appeared to be close together with little variation. As time progressed and biomass decreased, the distance between animals increased, and day to day variation was larger (Figure 3.28). The results are supported by behavioural observations that livestock become more dispersed both between and within herds (Dudziński *et al.* 1982; Vallentine 2001). In a 170 km^2 paddock, monitored with 108 aerial surveys and nearest neighbour statistical analysis, cattle were found to increase dispersion with decreasing biomass availability (Dudziński *et al.* 1982). Vallentine (2001) reviewed seven articles which also established social dispersion of cattle increased when biomass declined. It is interesting that the small paddocks used in this experiment did not obscure this behaviour. The use of spatial and social aspects of cattle behaviour for biomass assessment is promising.

There appears to be 3 phases in MCP and IHD behaviour (Figures 3.28 and 3.30, respectively). There were obviously two phases of the speed-based behaviours, the first of which seemed more linear and the second more quadratic in nature. Two possibilities of why an initial period exists with relatively stable behaviour are the high available, uniform, biomass and/or the physical barrier of tall and dense biomass. Initially, high and uniform biomass was easily accessed from camp sites reducing the desire of cattle to graze over large areas at the beginning of the experiment; especially if forage was so dense the cattle also had some difficulty or simply preferred not to move through it to access other areas of the paddock. Additionally, the need for herd cattle to be within sight distance of each other would have prevented high dispersion when biomass was very tall. The second phase occurs from around 6,313 to 2,061 kg/ha DGLB in Paddock 1 and 6,400 to 1,336 kg/ha DGLB in Paddock 2. This phase could be the response of cattle to an environment they are familiar with, which is non-limiting for biomass and allows greater line of sight distance between cattle. Phase 3 occurred after biomass levels of 2,061 kg/ha DGLB in Paddock 1 and 1,336 in Paddock 2. Based on the recommended grazing level of 1,500 kg/ha DGLB, the third phase occurs above this in Paddock 1 and below in Paddock 2. It is possible that the biomass was becoming limiting in both paddocks at this time.

The change in MCP area and IHD is very similar for individual herds and occurs at the same biomass. However, this biomass level is quite different to the biomass at maxima's for grazing time and the proportion of paddock utilised, at more than 6,000 DGLB (kg/ha). At this high amount, the biomass was not limiting, suggesting that another factor is driving this change. Possibly, as previously suggested, the change from Phase 1 to Phase 2 could be linked with visibility of the cattle. The change between Phase 2 and 3 occurred when biomass is thought to be at a limiting level (< 1,500 kg/ha GDM (MLA 2004)). It may be that these social behaviours are affected by biomass, but the response occurs at a lower amount than for speed-based behaviour and paddock utilisation, thus is triggered at a higher stress state of the animal.

The difference in MCPs was not directly comparable between mobs as there are different numbers of animals included in the area (Table 3.5). This presents an advantage of considering the IHD for a commercial monitoring system, as it is an average of the cattle included. Therefore, IHD between herds was compared. There was little difference between IHD in any of the phases. This could be due to small paddock size, especially the narrow width of paddocks limiting the distances cattle could be from each other.

3.4.3 Towards Indicator Metrics

Maximising the yield of animal products requires increasing the risk of vegetation and environmental damage (Reece *et al.* 2008). Additionally, increasing stocking rates (to increase production) escalates the cumulative grazing pressure and eventually individual average animal performance will decline while overall production will continue to increase, albeit at a slowing rate (Reece *et al.* 2008). A balance between individual animal production, overall production and ecological risk must be obtained and monitored. Monitoring livestock behaviour may be an approach to monitor cumulative grazing pressure, both at the individual and herd level, and thus, the ecological risk. Additionally, monitoring the change in behaviour, rather than exact measures, allows for a potentially more easily adapted agroecosystem monitoring system that is not situation-specific. For example, in this experiment cattle were seen to eventually decrease time spent grazing as biomass declined (below 3,000 kg/ha DGLB, Figure 3.20). At 3,000 kg/ha GDLB, social dispersion was not yet at the maximum monitored for this experiment (Phase 2 of 3, Figure 3.29). This indicates there may have been high individual animal competition for limited resources.

A summary of key results of this experiment is presented in Table 3.6. This includes behaviours and related DGLB values. These have been specifically selected as they provide the most consistent relationship with DGLB. All of the DGLB differences occurred well below the RSME of biomass prediction (874 kg/ha).

Table 3.6 highlights cattle behaviours which could be suitable for indicating pasture biomass availability through a real-time autonomous spatial livestock monitoring system. The key point of interest for grazing time and paddock proportion occurs at a similar biomass (3,001 to 3,305 kg/ha of DGLB). This suggests there is a key threshold biomass level inducing grazing behaviour changes, i.e. in this situation around 3,000 kg/ha of DGLB. The potential threshold level may be a reflection of when cattle are beginning to find biomass availability limiting. It is recommended that common, improved pasture species in Australia are grazed to no less than 1,500 kg/ha GDM (MLA 2004). Unfortunately, as this is a forage crop (not a pasture), and with the RSME of 874 kg/ha DGLB, it is unknown if this result is reflective of limiting biomass.

Table 3.6 Summary of key results for Paddock 1 and Paddock 2, showing the corresponding dry green leaf biomass (DGLB) (kg/ha) with: the maximum daily grazing time, maximum proportion of paddock used, the point of interest for the minimum convex polygons (MCP), and the point of interest for intra herd dispersion (IHD).

	Paddock 1 Behaviour	Paddock 2 Behaviour	Paddock 1 DGLB (kg/ha)	Paddock 2 DGLB (kg/ha)	DGLB Difference (kg/ha)
Maximum grazing time (%)	41	43	3248	3305	121
Maximum paddock proportion (%)	65	77	3001	3250	249
MCP (m^2)	5216	4344	6313	6401	88
IHD (m)	74.5	63.7	6313	6401	88

Note. Maximum grazing time and paddock proportion determined from the maxima of the fitted quadratics as displayed in Figures 3.20 and 3.24. The point of interest for MCP and IHP occurs at the change from behavioural phase 1 to phase 2, as displayed in Figures 3.28 and 3.30.

The alignment of key points in behaviour trends to similar biomass values shows there is potential for use in commercial environments irrespective of the pasture species being grazed. Either, a residual biomass approach (biomass driven decision support) could be taken, or, perhaps more simply, the extent of behavioural change (animal driven decision support) may be used to create a threshold which triggers the evaluation of available biomass. To achieve a biomass threshold trigger species specific research may be required, and at very least a behavioural relationship to different plant types (temperate grass, tropical grass, herbs etc.) should be investigated. The development of an animal response threshold may be applicable in most situations. To achieve this, the production response of cattle would need to be investigated with the behavioural trend which occurs when biomass declines.

3.5 Conclusion

In this experiment, aspects of animal behaviour and biomass were successfully measured with technology. This has positive implications for using such technology in both research and commercial production systems. Additionally, the reduction of human variation (Brock and Owensby 2000) and in-field error may be reduced with the development of this technology.

Several specific behaviours were successfully monitored in relation to declining biomass. The results highlight that spatial behaviour of cattle changes as available biomass decreases and livestock tracking can detect these behavioural changes. Specifically, the results have shown cattle change the way they utilise a paddock spatially and temporally as biomass declines. They also change how they interact with each other as feed declines. Most importantly, the results in this study show us that spatio-temporal cattle behaviour can be detected and monitored with GPS technology alone.

The major findings of the experiment, as related to the objectives, are that as biomass declines:

- there is a clear increase in grazing time that then decreases;

- area grazed by stock increases to a point before decreasing; and
- cattle disperse, indicating social relationships become less important.

Similarity between herds gives strength to the argument that a metric could be developed to enable better livestock rotations. It remains to determine if key behaviour patterns observed in this experiment are repeated in other situations and to improve methods of investigating these behaviours, (such as social dispersion), and developing a speed model particular to the specific grazing system.

CHAPTER 4 – DEVELOPMENT OF A SPEED-BASED BEHAVIOURAL MODEL

4.1 INTRODUCTION

The research presented in Chapters 2 and 3 of this thesis utilised the speed model developed by Putfarken *et al.* (2008). The research of Putfarken *et al.* (2008) was undertaken in a similar situation to the experiment presented in this chapter in terms of landscape, climate, sampling frequency and cattle type, however paddock size was considerably smaller. Since this experiment was conducted, Anderson *et al.* (2012) also developed a speed model based only from location data. The research of Anderson *et al.* (2012), used different GPS sampling frequency, cattle class, breed, landscape and climate, and the resulting speed model was dissimilar to that presented by Putfarken *et al.* (2008).

Drivers of differing speed models relate to both the tracking devices and the speeds of the animals wearing them. The sampling frequency of GPS devices will have a large effect on the monitored speeds. The higher the frequency, the longer the path derived from the location data (Figure 1.3) (Schwager *et al.* 2007), which results in the recorded speed (distance over time) increasing. So, behaviour speeds are likely to be faster when models are derived from higher frequency location monitoring. Additionally, inherent GPS error can influence speeds. Device error may lead to varying distances between location points. The relative error could change depending on the GPS clock error, atmospheric distortion and multipath (bounced) error (Swain *et al.* 2011) and the sleep-wake cycle of the GPS.

Although cattle are herd animals, they are individuals and often behaviours reflect this (Howery *et al.* 1996). Explorations of cattle use of particular pasture areas utilised over several decades support this (Roath and Krueger 1982; Senft *et al.* 1985; Senft *et al.* 1987; Howery *et al.* 1996; Bailey *et al.* 2006). There is, unfortunately, limited literature which explores the influence of effectors on individual cattle speed. One example where speeds were noted more than once is the research reported by Anderson *et al.* (2010) found the travel speed of cows differed pre- and post- weaning of calves. The resulting and two models developed separately in the same location in 2009 and 2011 were based on different speeds associated with behaviour (Anderson *et al.* 2012).

The different situations and varying results of the research presented by Putfarken *et al.* (2008) and Anderson *et al.* (2012) highlight that one speed model does not fit all cattle monitoring situations. Therefore, it was hypothesised that speeds associated with behaviour in this experiment will be different to those previously reported in the literature. The aim of this chapter was to create a speed model specific to this livestock monitoring situation.

4.2 METHODOLOGY

4.2.1 FIELD SITE

The field experiment was undertaken at the Precision Agriculture Research Group Demonstration Site, University of New England, Armidale, New South Wales, Australia (30°28'49"S, 151°38'34"E WGS84). There were six adjacent paddocks each of 0.35 ha, fenced with 3 strands of electric tape. The livestock in this field experiment were familiar with electric fences. Paddock maps and areas are displayed in Figure 4.1.

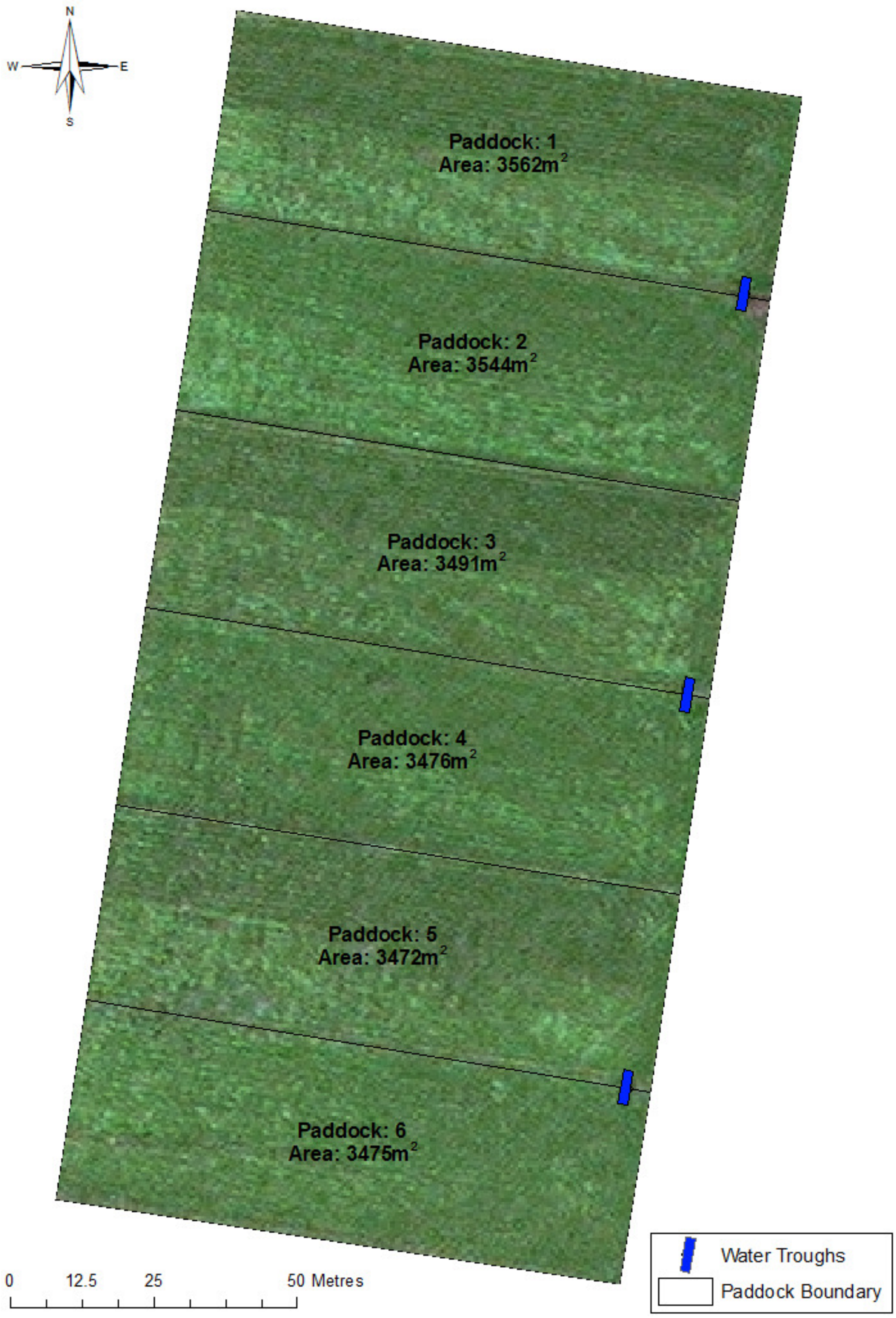


Figure 4.1 Map of the field site at the Precision Agriculture Research Group Demonstration Site, University of New England, Armidale, where GPS tracking collars were deployed on 18 steers. The allocated paddock numbers, areas and locations of water troughs are labelled.

The average aspect and slope for each paddock is presented in Table 4.1 and a digital elevation map of the experiment site is displayed in Figure 4.2. Slope and aspect were similar across the paddocks, with the exception that paddocks 1 and 2 were dominated by a northerly aspect, while the other paddocks had large areas with a north east aspect.

Table 4.1 Average slope and aspect for each of the paddocks and the whole trial site for the GPS tracking experiment at the PARG Demonstration Site, University of New England, Armidale.

Paddock	Slope (degrees)	Aspect (degrees)
1	3.5	17.52
2	4.2	17.21
3	5.1	29.29
4	5.32	28.19
5	5.7	23.86
6	5.46	23.26
All	4.86	23.32

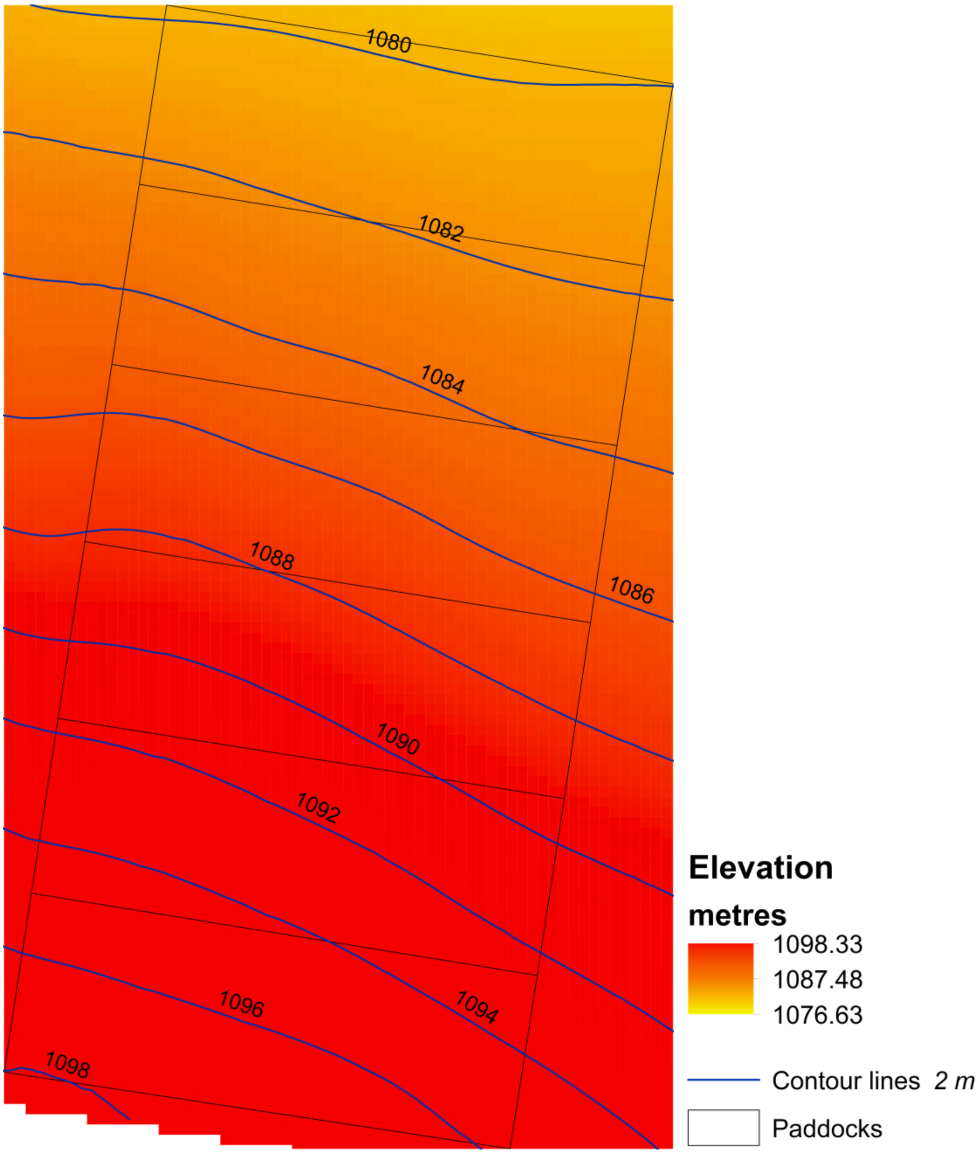


Figure 4.2 Digital elevation map of the paddocks in the GPS tracking experiment at the Precision Agriculture Research Group Demonstration Site, University of New England, Armidale.

4.2.2 The Animal System

In this experiment; the term ‘herd’ is considered to encompass all 18 experimental animals, while ‘mob’ refers to the groups of 6 cattle. The three mobs (six animals each) were randomly allocated to an initial paddock, with an empty paddock between each to reduce inter-mob socialisation. A recent study involving GPS tracking of sheep in 3 mobs found there was bias towards shared fence lines (Barwick 2011).

Mobs were rotated so that the mob at the base of the hill was moved to the top, and the other 2 mobs moved to the adjacent paddock downhill. This was an attempt to remove possible slope and aspect effects between rotations.

Livestock Tracking

This research was conducted under the University of New England's animal ethics authority number AEC11-087 (Appendix A.3).

UNETracker II GPS collars (Trotter *et al.* 2010b) were deployed on the cattle, set to multiple-interval tracking of 5 records, spaced 15 seconds apart, every 15 minutes. The devices were set to have a maximum awake time of 120 seconds. GPS units were started at the same time, on the hour in an attempt to achieve synchronisation of position logs, as the devices could not be programmed to synchronise.

Livestock Observations

Cattle were visually observed every third day of the trial period. A vehicle was located approximately 50 m north east of paddocks providing the observer with a good view of the cattle in all paddocks (Figure 4.3). There was one main observer who undertook all observations from sun-up (approximately 5am) until 9am, 11am to 2pm and from 4pm until sundown (approximately 6pm). From 9-11am and 2-4pm, secondary observers recorded behaviour. These secondary observers were trained by the main observer to reduce human bias on the results.

Figure 4.3 A photo of the experiment taken from the observation point on an observation day (9/10/11), facing south west. This picture shows some of the steers from each of the mobs in rotation 2, where mob 1 is in Paddock 2 (foreground), mob 2 is in Paddock 6 (background) and mob 3 is in Paddock 4 (mid picture) during a camping event. Regrowth of the pasture utilised in rotation 1 (Paddocks 1, 3 and 5) can be seen between the rotation 2 utilised paddocks.

Individual Animal Scan Sampling

The behaviour observation method chosen was individual animal scan sampling in which one animal per mob was monitored throughout the experiment. One steer from each of the mobs (12, 22 and 32), was marked with orange tail paint for identification. The behaviour of each of the focal (marked) animals was recorded every 15 minutes with the Apple iPod application WhatISee© (Heuser 2009) (Figure 4.4). This application had a spread sheet designed to record the time at which the focal cattle were exhibiting a particular behaviour state. Recordable behaviour states chosen were: "Standing", "Lying", "Grazing", "Walking" and "Other". These behaviours are mutually exclusive meaning only one could be observed at a time. Additionally, (for the purpose of GPS derived behaviour data synchronisation with visually observed activity), one minute observations on steer 22 were also undertaken from 7:33am until 6pm on the 18th of September using WhatISee© (Heuser 2009). This one minute data was filtered to remove any observations which were within 30 seconds of each other. This occurred on several occasions due to observer delay.

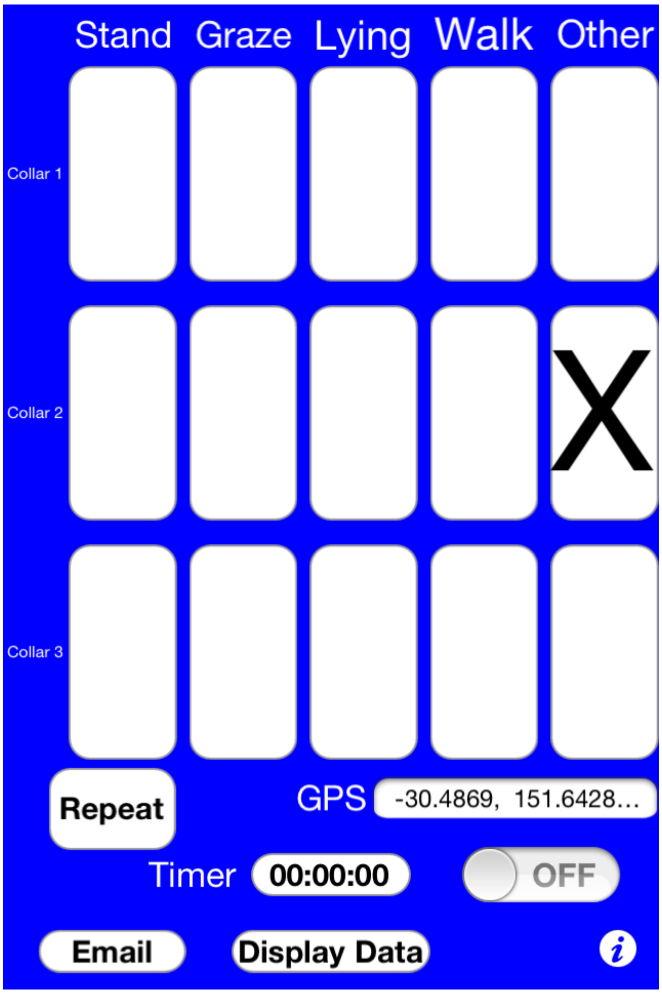


Figure 4.4 Screen shot of WhatISee© (Heuser 2009), used for recording observations of cattle behaviour. Row labels relate to focal animal and column to behavioural state. At the timed alarm the behaviour of each focal animal was recorded by touching the appropriate cell, as shown by the "X", which shows at that time collar 2 was exhibiting "Other" behaviour.

4.2.3 Statistical Methods

All statistical analysis was completed with the statistical software "R" version 2.15.0 (2012, Vienna, Austria). The specific analytical R packages used for upcoming analysis were chron (James and Hornik 2011), evd (Stephenson 2002), lubridate (Grolemund and Wickham 2011), ggplot2 (Wickham 2009) and simpleboot (Peng 2008).

Behaviour States

The visual observation dataset consists of behavioural observations on steers 22 (at one minute intervals), 12 and 32 (at 15 minute intervals) from 5:30am until 6:00pm on the 18/09/2011. From the one minute observations of steer 22, any change in behavioural state from one recording to the next (i.e. from lying to grazing) was noted. The "other" behaviour state records were removed from the analysis because of small sample sizes of less than 5% of observed activity states for each observed animal (n = 0, n = 29, n = 1 for steers 12, 22 and 32 respectively). Unfortunately, limited walking behaviour was observed with a very small sample size of less than 1% for the 15 minute observations (n = 0, n = 1 for steers 12, and 32 respectively) as well as only 3% for the one minute observations of steer 22 (n= 22). Consequently, "walking" behavioural states were pooled with the "grazing" state, to create what is termed the “moving” state. Additionally, “lying” and “standing” states were pooled to form the “stationary” state.

To determine the probability of a state change within a given time period, a mathematical method was developed based on the one minute observation data. The purpose of this was to determine if it was valid to apply a visually observed behavioural state from the 15 minute scan sampling to the 15 minute position data. Essentially to answer the question: was data collection at a 15 minute resolution accurately representing cattle behaviour?

Using the one minute visual observation data, a time referenced state vector was created for steers 12, 22 and 32:

$$\mathbf{S}_{(i)} = [S_1, S_2, \dots, S_t, \dots, S_T],$$

where $\mathbf{S}_{(i)}$ is the state, i is the steer index, t is the observation index time and T is the final observation time.

Each of the state symbols, $\mathbf{S}_{(i)}$, represents one of the observed behaviour states denoted “M” for moving or “S” for stationary; observed at the 15 minute time period containing one GPS log cycle.

The time referenced state vectors, $\mathbf{S}_{(i)}$, for each steer in the herd was combined to give a herd-state, **H**, matrix, which is defined as:

$$\mathbf{H} = \begin{bmatrix} \mathbf{S}_1 \\ \vdots \\ \mathbf{S}_\mathrm{N} \end{bmatrix}.$$

A binary indicator function, $\mathrm{I}(\mathbf{S}_\mathrm{i})$, was used to specify at what times a change of state occurred for the i^{th} animal (n = 3). If the state changed from the previous time, $t-1$, the binary indicator was given the value 1, otherwise it was 0; for each time and each animal:

$$\mathrm{I}(\mathbf{S}_\mathrm{i}) = \begin{cases} 1, & \text{if } S_t \neq S_{[t:(t-1)]} \\ 0, & \text{otherwise} \end{cases}$$

for all the time indices excluding the first i.e. $t > 1$.

The indicator function was applied to all time-referenced state vectors $\boldsymbol{S_i}$ to create a state change matrix within the herd:

$$\mathbf{B} = \begin{bmatrix} \mathrm{I}_{\mathrm{S}_1} \\ \vdots \\ \mathrm{I}_{\mathrm{S}_\mathrm{N}} \end{bmatrix}.$$

Note: the number of columns in **B** will be one less than **H** because it describes the state changes between consecutive time steps.

From the rows of state change matrix **B**, time-lag indicator vectors $\mathbf{L}_k$ for select time-lags, k={P_1, P_5, P_{10}, P_{15}, P_{30}, P_{60}}, of matrix values were created for each animal. Entries within the $\mathbf{L}_k$ matrices were given by:

$$\mathbf{L}_{k(\mathrm{i})} = \sum_{t=1}^{\mathrm{T}} \left| B_{(i)[(t+1)k]} - B_{(i)[t_k]} = 1 \right|$$

In other words the entries in $\mathbf{L}_{k(\mathrm{i})}$ vector are formed for each animal by the sum of all possible combinations of state change indicators which are separated by time lag "*k*" formed by the sum of state indicators whose absolute difference is one for fixed lags. In the case where the fixed lag "*k*" was not available e.g. k = 5 minutes, the $\mathbf{L}_{k(\mathrm{i})}$ values are denoted unavailable as "NA" value.

For each of the animals, the probabilities, ($P_{k,i}$), of a state change occurring for the lag times, k, were calculated from the time lag indicator vectors $L_{k(i)}$. For the i^{th} animal, this probability is calculated as:

$$P_{k,i} = \frac{\sum_{\mathrm{i}=0}^{\mathrm{n}} \mathbf{L}_{\mathrm{k(i)}}}{\mathrm{T}_k}$$

for the time lag indicator vector $L_{k(i)}$ with T_k entries.

The probabilities of each time lag {P_1, P_5, P_{10}, P_{15}, P_{30}, P_{60}} for steer 22 were assessed using a linear regression model to detect any change in probability magnitude with lag. This model had the form:

$$P_k = \beta_0 + \beta_1 \mathrm{k} + \varepsilon,$$

where $\varepsilon \sim N(0, \sigma^2)$ is the error or residual term which is assumed to obey a normal distribution, 'k' denotes the time lag between observations, P_k is the response referring to the probability of state change at time lag k, and β_0, β_1 are the regression coefficients (intercept and slope respectively).

A t-test was used to assess the slope coefficient for statistical significance. The intercept coefficient and its estimated uncertainty were also assessed to determine the base rate probability of state changes for lag times longer than one minute. The data from steer 22 was selected for the development of the regression model because it had the finest resolution of time periods. The probabilities for the other steers were calculated but had only three distinct lag values, {P_{15}, P_{30}, P_{60}}, and therefore were not assessed using the regression model.

Cattle Speed

The distance and time between consecutive GPS logs can be used to calculate the interval speed. Although five logs per GPS burst were taken, only the first four logs were averaged for this calculation. This is because in order to calculate the speed of a point, the position of the next point is required. For the last point in a burst series the next point is the first log of the consecutive burst, nearly 15 minutes later. The fifth log of each burst formed a single interval dataset (15 minutes). The longer a GPS has been "awake", and the smaller the interval between logs, the more accurate the position recorded will be (Swain *et al.* 2008a, Jurdak *et al.* 2010).

Speeds calculated from the GPS tracking were matched in R to visual observations based on time of log recording to within +/- 30 seconds. If speed was calculated to be greater than 0.5 m/s for a stationary observation it was removed as erroneous as these are extreme speeds for inherent stationary GPS error.

Speed Threshold

The location data from focal animals (12, 22 and 32) contributed to the determined threshold value of speed. Initially, a mathematical model was developed to estimate the speed at which an animal is deemed either "stationary" or "moving" from their GPS record.

Bootstrap samples of the speed records were used to estimate the mean speed for each state and to produce the order statistics used to fit the generalised extreme value distribution model (GEV). These bootstrap samples were formed by randomly sampling a single speed record for each steer in each state. The first of the bootstrap samples is denoted $B^{*(1)}$. This was repeated 999 times to form the sequence of bootstrap sample vectors:

$$\mathbf{B}^* = \{B^*_{(1)}, \cdots, B^*_{(j)}, \cdots, B^*_{(999)}\}$$

The median speed was then calculated from the bootstrap samples in each case, $\tilde{v}^* = \{\tilde{v}_1^*, \tilde{v}_2^*, \cdots, \tilde{v}_{999}^*\}$, and the mean value of these bootstrap estimates of $\overline{\tilde{v}^*}_{stationary}$ and $\overline{\tilde{v}^*}_{moving}$ were calculated along with the 95% confidence intervals using the percentile methods (Davison and Hinkley 1997).

For each of the steers and visual observation days the state (stationary or moving) histograms of speed records were examined. Based on the histograms, generalised extreme value (GEV) distributions were estimated (equation 1.9, Chapter 1, Smith (2003)) using the median values from the bootstrap samples:

$$f(\tilde{v}^*) = \exp\{-\left(1 + \zeta \frac{x - \eta}{\psi}\right)_+^{-\frac{1}{\zeta}}\}$$

where $\tilde{v}$ denotes median speed in m/s, η is the location parameter, $\psi > 0$ is the scale parameter, and ζ is the shape parameter. The maximum or zero selection function, ψ_+, is defined as:

$$\left(1 + \zeta \frac{x-\eta}{\psi}\right)_+ = \max\left(1 + \zeta \frac{x-\eta}{\psi}, 0\right),$$

and ensures the exponent in the definition of the distribution is always greater than or equal to zero, thereby constraining the magnitude of the distribution to be between zero and one.

The speed threshold of the moving state change was determined with the GEV to estimate where the probability of a moving state change was greater than 0.5.

The GEV was also employed to estimate the speed thresholds of each individual steer. The thresholds were only approximate in this case because the speed records were sampled from correlated records of each steer on the same day and are unlikely to be statistically independent.

4.3 RESULTS

4.3.1 BEHAVIOUR STATES

The linear regression model for the probability of state change with time observation window was estimated to have the following parameters:

$$\hat{\beta}_0 = 10.2589 \pm 1.6547, t = 6.2, p = 0.0034$$

The results of the investigation of time lag for steer 22 do not support the alternative hypothesis as the estimate

$$\hat{\beta}_1 = 0.0095 \pm 0.0582, t = 0.163, p = 0.8785, df = 4$$

is not statistically significant. The null hypothesis $H_0: \beta_1 = 0$ is therefore assumed to hold.

The probability of a state change for the given time intervals (1, 5, 10, 15, 30 and 60 minutes) are presented in Table 4.2. The state change probability for different time lags was non-significant indicating that the probability of a state change for steer 22 on the 18/9/2013 is constant irrespective of time lag (Table 4.2). The intercept indicates an approximately 10% probability of a change of state for each time lag. Similar fixed probabilities were found for steer 12 and steer 32. The practical implication of this result is that the number of state changes which occur overall in a 15 minute window should be the same as in a one minute window.

Table 4.2 Raw detected and probability of state changes after time elapsed for steer 22.

Timing (minutes)	Number of Changes	Number of Observations	Probability of State Change	Standard Deviation
1	64	519	12.33	0.0020
5	8	94	8.51	1.0
10	5	47	10.64	2.0
15	4	32	12.50	3.0
30	1	16	6.25	6.30
60	1	8	12.50	13.0

4.3.2 *Cattle Speed*

The distribution parameters were estimated for the GEV using the maximum likelihood routines in R package evd, as reported in Table 4.3.

Table 4.3 Generalised extreme value parameter estimates for the distributions of the two states.

State	$\hat{\nu}$	$\hat{\psi}$	$\hat{\zeta}$
Moving	0.0180+/-0.0003	0.0094+/-0.0002	0.1975+/-0.0163
Stationary	0.0185+/-0.0002	0.0064+/-0.0001	-0.1861+/- 0.0141

Analysis of speed and behaviour observations resulted in histograms containing 'long-tails', which were 'right-skewed' (weighted toward smaller values), and had larger magnitudes at low probabilities, for example Figure 4.5.

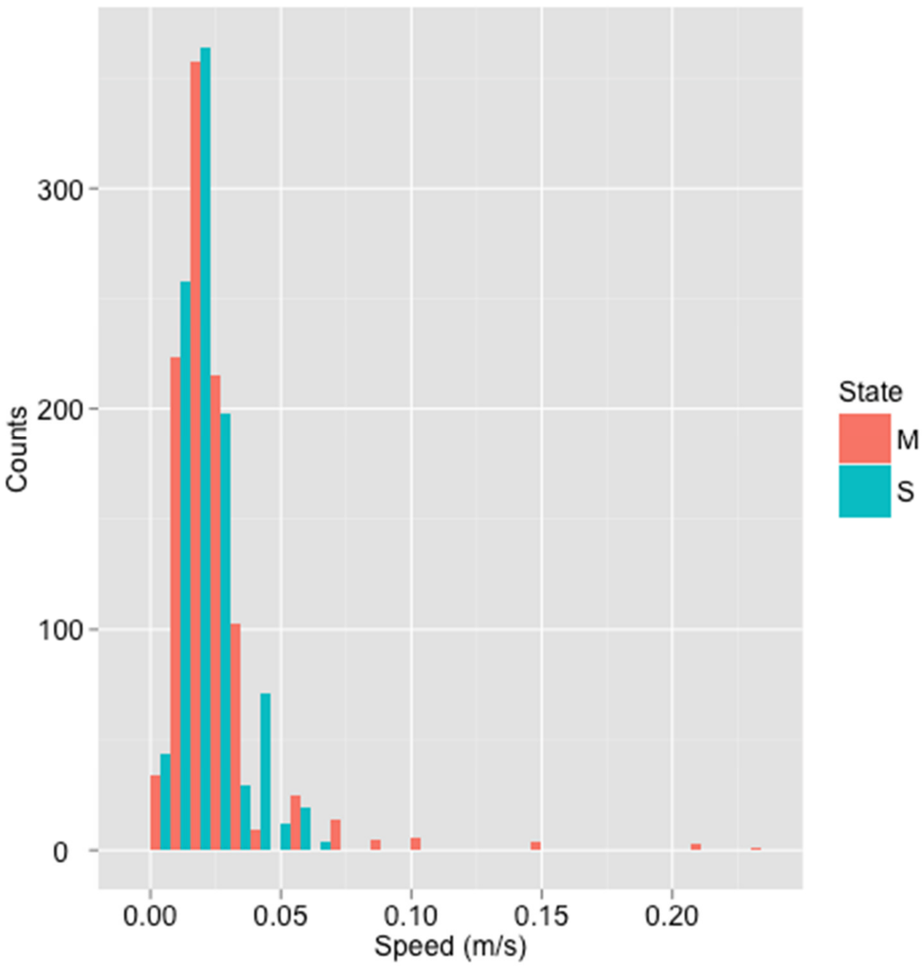


Figure 4.5 Histograms of GPS speeds for 'Stationary' and 'Moving' behaviours of steers 12, 22 and 32 on the 9-10-2011.

There were a total of 87,260,908 possible combinations from which 999 bootstrap samples were obtained which equates to 0.0011% of all possible combinations if each of the bootstrap samples is unique.

4.3.3 *Speed Threshold*

There is a difference in mean speeds of moving and stationary behaviour states as the confidence intervals do not overlap, presented in Table 4.4.

Table 4.4 Key parameter estimates of mean speed (m/s) for the moving and stationary states for the herd.

State	95 % Confidence interval	
	Lower	Upper
Moving	0.0258	0.0301
Stationary	0.0204	0.0212

Since there is a difference between behavioural states, a speed threshold to determine the behavioural class of either moving of stationary was calculated, as displayed in Table 4.5. Behaviours below the threshold are considered stationary and those equal to or above the threshold are considered moving.

Table 4.5 Individual animal grazing thresholds for steers 12 and 32 on each of the behavioural observation days.

Steer	Date	Threshold (m/s)
12	15/09/11	0.0262
12	18/09/11	0.0240
12	21/09/11	0.0248
12	24/09/11	0.0260
12	30/09/11	0.0252
12	03/10/11	0.0253
12	06/10/11	0.0248
12	09/10/11	0.0258
12	12/10/11	0.0259
32	15/09/11	0.0257
32	18/09/11	0.0252
32	21/09/11	0.0260
32	24/09/11	0.0254
32	30/09/11	0.0245
32	03/10/11	0.0258
32	06/10/11	0.0253
32	09/10/11	0.0238
32	12/10/11	0.0238
	Average	**0.0252**
	SD	**0.0008**

There is a strong transition between probabilities, jumping from 0.024 m/s to 0.026 m/s (Figure 4.6). The speed threshold is when the probability of a behaviour occurring is 0.5; this equated to 0.025 m/s (3 dp). Thus, stationary behaviour relates to speeds less than 0.25 m/s and moving behaviour to speeds equal to or larger than 0.25 m/s.

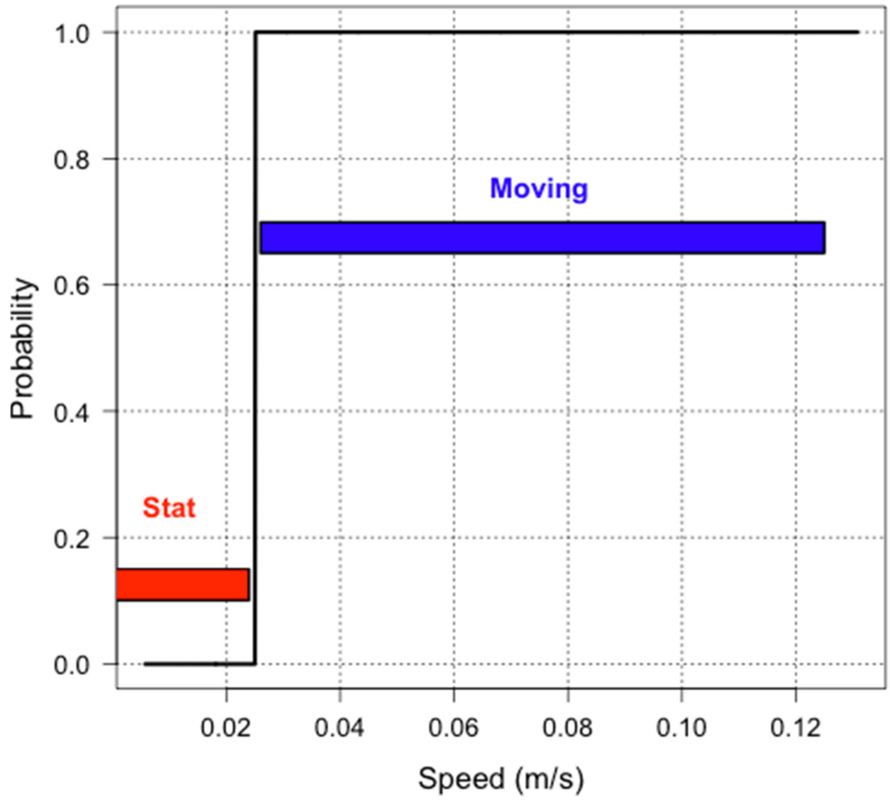


Figure 4.6 Probability of moving behaviour occurring at speeds (m/s) for steers 12, 22 and 32 on the 9-10-2011.

Putfarken *et al.* (2008), Anderson *et al.* (2012) and Guo *et al.* (2009) reported travelling behaviour in their research. Travelling behaviour was not exhibited in this experiment, and therefore speed could not be attributed to it. The grazing associated speeds reported in the literature are presented in Table 4.6, along with the moving result from this experiment.

Table 4.6. Comparison of results from research which developed activity speed models for cattle tracked with GPS devices.

Author	Experiment	Grazing Speed (m/s)
Putfarken *et al.* (2008)		0.220-0.330
Guo *et al.* (2009)		<0.400
Anderson *et al.* (2012)	1	0.060-0.550
	2	0.059-0.500
This experiment		≥0.025*

*moving speed

4.4 Discussion

4.4.1 Behaviour States

The probability of a state change did not vary significantly for the time lags tested (Table 4.2), implying that the same number of changes are expected to occur during 1 minute as for 15 minutes. Across the whole herd, the probability of state change is likely to differ between animals but will remain constant for an individual animal. Therefore, increasing a time resolution through the GPS sampling rate will not improve the number of successful state change detections. The use of a 15 minute GPS sampling interval has a similar proportion of missed behavioural changes to other intervals investigated and was both economical (battery-life) and practical (data processing) for this research. It should be noted that these results do not consider if a particular GPS sampling rate is favoured for particular state change detection, time of day or animal.

While not relevant for this research, there are several situations where the appropriate sampling period is dependent upon more than state changes. The first is if monitored behaviours are infrequent or short duration (Mitlöhner *et al.* 2001). The second is if the total number of observations recorded is important. An increased number of observations reduce uncertainty in the estimates of the apparent rates. For this experiment, we can be confident that the speed threshold developed is not GPS sampling period dependent.

4.4.2 Speed

The skewed, long tailed histograms of speed, Figure 4.5, indicated that the statistical distributions were not like the usually assumed Gaussian distribution. Therefore, a model other than the Gaussian was required to describe the distribution of speed values. Parametric models such as the GEV assume that each sample observation is statistically independent and identically distributed (Smith 2003). The original speed samples of a single steer on one day is unlikely to meet this criterion. However, using bootstrap samples of the median values of speed (at random times within a single day) for three different steers is far more likely to meet the statistical independence criterion.

The large number of possible speed sample combinations of data for the bootstrap analysis, (87,260,908), indicates that it is unlikely that the records for the individual steers will be sampled with the same set of explanatory covariates, such as, time. It is therefore reasonable to assume statistical independence when the speed record bootstrap samples are not conditioned on other variables such as time of day or location relative to other animals.

4.4.3 Speed Threshold

There is an overlap of behaviour speeds between- and within- animals (between days) (Table 4.5). This is not unexpected as each individual animal is likely to move at slightly different speeds when undertaking activities and in response to daily influences, such as, feed availability (Laca *et al.* 1994) and weather as seen in sheep (Powell 1968) and people (Daamen and Hoogendoorn 2003; Hoogendoorn and Daamen 2005). Error of GPS also contributes to individual speed as each device will have different error, potentially apparent in the speed results (Lachica and Aguilera 2005; Putfarken *et al.* 2008).

The variation of speeds between individual animals and by observation day, Figure 4.5, varied little with a standard deviation of 0.008 m/s. Additionally, speeds did not appear to change relative to available biomass. The observation days spanned across two rotations of declining biomass

(Maximum measured biomass = 6,408 GDM kg/ha, minimum measured biomass = 636 GDM kg/ha), with no trend apparent for the speed of the animals on the nine observation days. This result suggests, in this experiment, cattle speed was not influence by available biomass.

The lack of travelling behaviour exhibited by the cattle in this experiment could be due to small paddock area, with little distance required to reach camp areas, water or feed patches. Compared with paddock sizes used in other speed model development research, (Putfarken *et al.* (2008) = 180 ha; Anderson *et al.* (2012) = 433 ha; Guo *et al.* (2009) = 7 ha), at 0.35 ha, these paddocks are very small.

Although the threshold between stationary and moving was different to those previously reported (Table 4.6), it is similar to that of Putfarken *et al.* (2008). The larger difference to the models of Anderson *et al.* (2012) and Guo *et al.* (2009) is likely because of differing position fix rates. The finer resolution of sampling will capture more distance as there is less time from point to point, thus leading to higher "speeds" at fine resolution. Cattle move in a tortuous nature, so the more points of a path captured, the further the distance recorded will be (Figure 1.3).

4.5 CONCLUSION

The development of a speed model based on GPS tracking and visual observations of cattle was investigated. This enhanced the accuracy of the behaviours derived from the GPS, thus improving our understanding of cattle behaviour and the relationship with available pasture.

The aim of developing a speed model specific to this experiment was to test if the speed threshold between behaviour states was situationally different. The speeds associated with activity in this experiment are different to those reported in other research including Putfarken *et al.* (2008), Anderson *et al.* (2012), and Guo *et al.* (2009) and supports the hypothesis. Thus, different situations, cattle class and GPS log rates will result in different speeds associated with behaviour. Speeds may also change daily with environmental influences, including feed availability; low feed has resulted in cattle increasing speed while grazing (Laca *et al.* 1994; Westwood 2008). The extent of the influence of within- and between- animal speed variations on speed-based behavioural analysis must be determined before commercial development. Speed can be very informative for behavioural monitoring, although, as speed appears to be influenced by many factors, regular calibration may be required for use in industry. The need for calibration in varying situations is yet to be determined and research identifying the major drivers which vary behaviour speed and the effect on the reliability of positional data is required. Despite this unknown, calibration of this speed model does not preclude the application of this technology and the technique used can be self-adjusting.

The development of cattle and site specific speed models is feasible in research settings. This speed model will be applied in Chapter 5, to predict the moving and stationary behaviour of the cattle in this experiment. This enabled analysis of the amount of time cattle spend undertaking these activities and other behavioural attributes related to moving and stationary behaviour, for example, where cattle are grazing.

CHAPTER 5 – CATTLE BEHAVIOUR IN RELATION TO DECREASING BIOMASS: PART 2

5.1 INTRODUCTION

Cattle grazing behaviour can be identified using position data collected with on-animal GPS devices (Chapter 4; Putfarken *et al.* 2008; Anderson *et al.* 2012). This information has successfully been applied to monitoring other grazing related behaviours including distance moved, grazing time and livestock residence; and has provided an indication of spatial and social dispersion (Chapter 3).

Biomass availability is known to affect grazing related behaviours, including grazing time (Coleman 1992; Vallentine 2001), grazing location (Ganskopp and Bohnert 2006; Laca 2009) and social dispersion (Laca 2009; Squires, 1982). As biomass becomes unavailable grazing time begins to increase and eventually decreases (Chapter 3; Allden and Whittaker 1970; Chacon and Stobbs 1976; Coleman 1992; Vallentine 2001). Spatial and social dispersion have been found to increase with declining biomass (Squires, 1982; Ganskopp and Bohnert 2006; Laca 2009). Similarly to grazing time, the proportion of a paddock utilised decreases as biomass continues to decline (Chapter 3). A major cause for the eventual reduction in grazing related behaviour is thought to be due to fatigue from limited energy intake (Chachon and Stobbs 1976; Cosgrove and Edwards 2007).

It was confirmed in Chapter 3 that GPS monitoring of livestock could be used to identify the influence of biomass decline on cattle behaviour including grazing time, paddock utilisation and social dispersion. It is essential to investigate the repeatability of these behaviour patterns under different conditions.

Additionally, previous research (Chapter 3) highlighted necessary methodological changes to improve the reliability of using GPS to monitor grazing behaviours of cattle. An important aspect of this included monitoring the spatio-temporal behaviour of cattle on a common pasture species rather than a forage crop to better reflect industry practice. The speed model produced in Chapter 4 was specifically developed to improve analysis of GPS speed-derived behaviour in this experiment. Moreover, it was highlighted that further development of social dispersion monitoring may be advantageous. The previous methods for calculating social dispersion (Chapter 3) were limited by data processing capability and while this method monitored social dispersion successfully, there was large unexplained variability between days. A more robust method of dispersion analysis is required. Therefore, improvements have been made to the methods of cattle behaviour monitoring and analysis for investigating the hypothesis.

The primary objective of this chapter was to further investigate key behaviours associated with grazing cattle as pasture biomass declines in a perennial grass pasture. These key behaviours are:

- time spent moving (previously grazing);
- spatial dispersion; and
- social dispersion.

The two herds investigated in Chapter 3 displayed similar patterns of the key behaviours. It is hypothesised that behaviours in this experiment will respond similarly to the results of Chapter 3 as biomass declines. The expected behaviour patterns are:

- a clear increase in grazing time that then decreases;
- area grazed by cattle increases to a point before decreasing; and
- average distance between cattle will increase.

5.2 METHODOLOGY

5.2.1 EXPERIMENTAL EVENTS

The location of this experiment is outlined in Section 4.2.1.

The experimental events including: timing of rotation, behavioural observation, plant monitoring and rainfall is outlined in Table 5.1. A three day pattern of biomass and livestock monitoring occurred. People were excluded from the site on the first day of the cycle, visual observations were undertaken on the second day and the pasture was sampled on the third day. This rotation was executed to reduce human interaction with cattle while regularly collecting pasture and behaviour data.

Table 5.1 Trial calendar and important dates for GPS cattle tracking experiment at the Precision Agriculture Research Group Demonstration Site, University of New England, Armidale in Spring 2011.

Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
	Day 0 (12/09/11)	Day 1 (13/09/11) Collars deployed Steers introduced to paddocks	Day 2 (14/09/11)	Day 3 (15/09/11) Visual observations	Day 4 (16/09/11) Biomass sampling	Day 5 (17/09/11)
Day 6 (18/09/11) Visual observations	Day 7 (19/09/11) Biomass sampling	Day 8 (20/09/11)	Day 9 (21/09/11) Visual observations	Day 10 (22/09/11) Biomass sampling	Day 11 (23/09/11)	Day 12 (24/09/11) Visual observations
Day 13 (25/09/11) Rainfall event	Day 14 (26/09/11) Last full day of rotation 1 Rainfall event	Day 15 (27/09/11) Cattle rotated Biomass sampling	Day 16 (28/09/11) First full day of rotation 2	Day 17 (29/09/11) Rainfall event	Day 18 (30/09/11) Visual observations Rainfall event	Day 19 (01/10/11) Biomass Sampling
Day 20 (02/10/11) Rainfall event	Day 21 (03/10/11) Visual observations Rainfall event	Day 22 (04/10/11) Biomass sampling	Day 23 (05/10/11)	Day 24 (06/10/11) Visual observations Rainfall event	Day 25 (07/10/11) Rainfall event	Day 26 (08/10/11)
Day 27 (09/10/11) Visual observations Rainfall event	Day 28 (10/10/11) Biomass sampling	Day 29 (11/10/11)	Day 30 (12/10/11) Visual observations	Day 31 (13/10/11) Biomass sampling		

5.2.2 Weather

Weather data was obtained retrospectively from the Bureau of Meteorology (http://www.bom.gov.au/climate/data/). The nearest weather station was located at Armidale Airport (151.62 °E 30.53 °S, elevation 1079 m, 6 km from the site)

5.2.3 The Plant System

Paddocks were sown to tall fescue (*Festuca arundinacea v. Dovey)* in autumn 2011, chosen for its popularity in the region of this experiment. The pasture was dominated by the fescue; however, there were some broad leaf weeds (<5%) in the paddocks. Grazing began during the vegetative stage of the fescue. The paddocks were fertilised with super-phosphate and mown several weeks prior to the start of the experiment to delay the reproductive growth stage of the plants and to promote even biomass quantity across all paddocks.

Biomass monitoring was planned to be undertaken every three days. Whole paddock biomass monitoring was achieved every third day except for one occasion due to rain. Calibration sampling was completed on all days that biomass monitoring occurred except for one.

AOS CALIBRATION

The Crop Circle™ (Section 2.2.3) was mounted at 1 m for both the calibration and the transect scans of the paddock. This equated to a footprint length of 60 cm. A lower height above ground than in Section 2.2.3 was chosen because of the lower plant height. The static scanning rig was set up as in Section 3.2; however, the paddock transects were taken with the AOS mounted to an ATV. The AOS was connected to a dGPS (Trimble Navigation Limited, Sunnyvale California, USA) and a Trimble TSCe Ranger Field computer coupled with a 1 Hz Trimble ProXRS dGPS receiver (Cosby *et al.* 2013). Four, 7 m apart transects of each paddock in a rotation were surveyed. The equipment is shown in Figure 5.1.

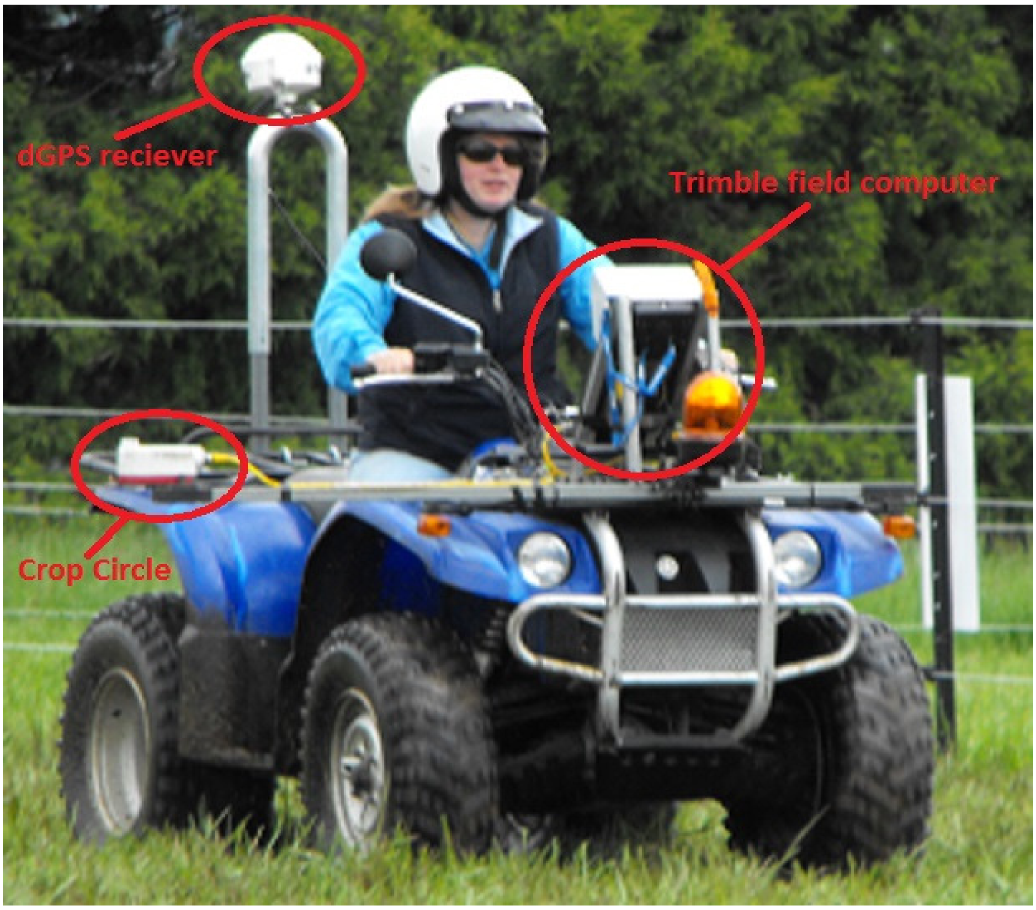


Figure 5.1 The all-terrain vehicle set up with the Crop Circle™ and the Trimble dGPS for taking paddock transects for estimating biomass.

After transects were complete, nine biomass samples were taken, three from each of the in-use paddocks. From each of the three paddocks, a high, medium and low biomass sample was taken. Across all nine samples, a range of biomass was included based on the NDVI value displayed on the Crop Circle™ screen. This was to ensure an even distribution of calibration plant samples to improve the biomass estimation equation.

The most time expensive aspect of the biomass estimation methodology was dividing the biomass samples into dead and green material. This process can be accelerated by taking a representative sample of the calibration cut and sorting it into green and dead. This was completed by tipping out a whole sample, mixing it and dividing it in half until approximately 10-20 g remained. Once sorted, samples were dried for two days at 80°C. Weights were recorded and represented the whole sample by applying the percentage of green and dead from the weight of the subsample to the weight of the whole sample.

DETERMINING WHOLE PADDOCK BIOMASS

Once biomass was separated into dead and green, green dry matter (GDM) (kg/ha) was compared to corresponding static AOS scans. The calibration methodology is the same as that presented in Section 3.2.3, using GDM. Linear, exponential and polynomial lines were fitted to all measured paddock values to determine the most appropriate biomass calibration. The R^2 was similar across all with all results above 0.93. The exponential calibration equation was chosen for each paddock based on the visual observations of the field during the experiment and because the linear equation showed inferior biomass estimation at lower values. Vegetation index NDVI was applied to the calibration equation to estimate biomass. The RMSE of the biomass calibration was calculated as for Section 3.2.3. For each biomass sampling day and in-use paddock, AOS transect scans were interpolated for NDVI as in Section 3.2.3, using a 7 m block size and 1 m paddock grid.

5.2.4 THE ANIMAL SYSTEM

Cattle were monitored with GPS and by visual observation, as outlined in Section 4.2.2 and the GPS data was cleaned following the same methods as described in Section 2.2.4.

As this experiment had three mobs of cattle and two rotations, results were investigated for each mob in each rotation. The key for each dataset is displayed in Table 5.2.

Table 5.2 Mob rotation including mob number, rotation number and paddock number for the whole research herd.

Mob	Rotation	Identification	Paddock
1	1	M1R1	3
2	1	M2R1	1
3	1	M3R1	5
1	2	M1R2	2
2	2	M2R2	6
3	2	M3R2	4

Descriptive statistics of the GPS logging success were calculated as per Section 3.2.4. Unfortunately collar 15 was lost during rotation 2 and so the data was only included for rotation 1.

Distance Moved

As in Chapters 2 and 3, the average distance moved per day was calculated as per the methods presented in Section 2.2.4. Distance moved was also compared to daily estimated GDM for each mob and rotation.

Speed-based Behaviours

The speed model developed in Chapter 4 was the basis for investigating speed-based behaviours. Speed was calculated for each point and the experiment-specific speed model developed was applied. From this, behaviour class (stationary or moving) was attributed to each GPS location. Behaviour derived from the speed model was used to investigate the daily proportion of time spent undertaking moving behaviour and where the cattle were when moving, as for Section 3.2.4. Changes in moving behaviour were compared with changes in estimated daily GDM for each mob and each rotation.

Spatial Dispersion

Livestock residence index maps were calculated for each of the mobs and each rotation, as for Section 3.2.4. Cells were considered utilised if one or more moving position logs were within them and unutilised if they contained no moving position logs. This is equivalent to a moving point LRI of 0.1. A fine grid size allows for higher resolution, however, this also creates longer computing time and larger file size. As such, a paddock grid size of 1 m X 1 m was selected, which also matches the grid for biomass kriging. Proportion of paddock utilised was calculated as per Section 3.2.4

Social Dispersion

Social dispersion of the steers was investigated with a nearest-neighbour analysis in R. This analysis was calculated for each hour of every day of the experiment. The data set for each steer was adapted to suit this by including only the last data point from the initial multiple-interval tracking set and the first and second points of the consecutive multiple-interval tracking set within an hour. The location of these points was averaged to provide an hourly position of each animal. The maximum distance between one steer and all other steers within a mob was calculated. The hour which contained the largest number of the maximum distances per day was counted for all mobs and rotations. The morning and afternoon hour with the most maximum distances recorded were selected as windows for further investigation. For these windows, the maximum and mean distance between steers was calculated and compared with biomass.

Behaviour Stability

When monitoring animals in relatively large fields with heterogeneous biomass (forage oats) that was eaten all the way down to ground level there were clear discernible behavioural patterns for distance moved, time spent grazing, and the proportion of the paddock utilised - which followed a quadratic trend (Chapter 3). Upon reviewing the same metrics in this experiment with smaller paddocks and more realistic pastures (perennial fescue) these behaviours did not result in such consistent patterns before the forage was completely consumed. Further to this, large daily variation was observed and, consequently, it was challenging to find a simple way of comparing the mobs and rotations. As such, further analysis into behavioural stability was undertaken for distance moved, time spent moving, proportion of the paddock utilised and IHD. Because of this, two additional methods were applied to the datasets of this experiment to investigate their potential for contributing to comparing mob behaviours. The first was the rate of change of behaviour metrics. Secondly, stability of the rate of change of behaviours was explored based on the recent energy statistical analysis investigated for accelerometer monitoring of livestock behaviour by Trotter *et al.* (2012a) and Trotter *et al.* (2012b). In the research of Trotter *et al.* (2012a) and Trotter *et al.* (2012b), the energy statistic provided a measure of similarity or variation by denoting the magnitude of the departure of the peak or valley from the mean. This analysis successfully contributed to the detection of standing, walking or grazing cattle behaviour through accelerometer data. In this research the energy statistic will be referred to as 'stability' for clarity.

The rate of change of the behaviour metrics was determined by calculating the difference in consecutive behavioural changes divided by the respective difference in consecutive biomass values. These results were then converted to absolute values. Graphs of the absolute values for behavioural rate of change (slope) against estimated daily GDM were generated. The stability of the rate of change (slope) as biomass declines was calculated using the following formula:

$$Stability_N = Absolute\ value\ of\ \left(\frac{Slope_N}{Average\ Slope_{1:N}}\right)$$

Note: $Slope_1$, the initial slope, is always equal to 1.

5.3 Results

5.3.1 *The Plant System*

AOS Calibration

In order to determine if the subsampling method was representative of the whole sample, five samples, from different paddocks, (one high, two medium and two low biomass samples) were completely divided into dead (senescent) and green and compared to their respective subsamples. The proportion of green and dead material was recorded and compared between the subsample and the remaining biomass.

The proportion of green and dead vegetation in the five test subsamples and the remaining sample are displayed in Table 5.3. The results of the subsampling test show that this method did not exactly reflect the proportion of the remaining sample; nevertheless, in all cases the difference was less than

15%. Because of the inexact nature of pasture sampling, this technique was deemed to be appropriate in estimating pasture biomass and the method was applied to all samples.

Table 5.3 Percent of green and dead biomass from subsamples and corresponding whole samples from the calibration cuts

Date	Paddock	Biomass Level	Subsample Green %	Subsample Dead %	Whole Sample Green %	Whole Sample Dead %	Difference %
13/09/2011	1	High	68	32	55	45	13
19/09/2011	3	Medium	56	44	49	51	7
22/09/2011	5	Low	40	60	48	52	8
27/09/2011	4	High	70	30	64	36	6
4/10/2011	2	Low	55	45	60	40	5

The relationship between GDM (kg/ha) and reflectance indices of biomass is presented as R^2 values in Table 5.4. The linear relationship of measured biomass and vegetation index with the highest R^2 were the three SAVI variants, as presented in Table 5.4. Nevertheless, the actual function fitted to achieve this did not accurately represent the change in biomass observed in the field. The SAVI index actually predicted a slight increase in biomass at the start of the trial which was not observed in the field. The NDVI achieved a marginally lower R^2 (0.74) although the function more accurately represented the change in biomass that occurred in the paddocks.

Table 5.4 Relationship between vegetation indices derived from near infrared and red reflectance measured by the Crop Circle™ and biomass samples. Note: the vegetation index selected for biomass prediction in this experiment is normalised difference vegetation index (NDVI), as highlighted in bold.

	NDVI	SR	SAVI (0.5)	SAVI (0.25)	SAVI (0.75)	NLI	MNLI	MSR
R^2	**0.74**	0.70	0.75	0.75	0.75	0.59	0.61	0.74

Whole Paddock Biomass

The relationship between measured and estimated biomass is displayed in Figure 5.2. Both the measured biomass and the calibration curves clearly show a constant decrease in biomass as the experiment progressed. The RMSE was 632 GDM (kg/ha). This equates to 34% of the mean biomass (1,851 kg/ha GDM).

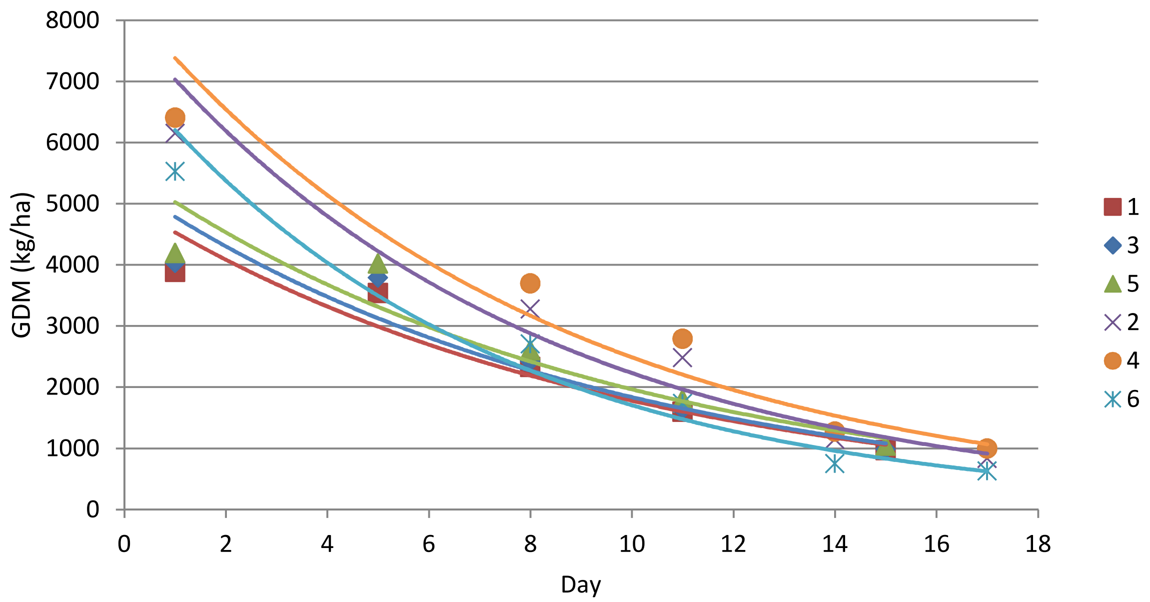


Figure 5.2 Measured (markers) and estimated (curves) green dry matter (GDM) (kg/ha) for all paddocks during the experimental period, identified by paddock where 1, 3 and 5 make up rotation 1 and 2, 4 and 6 are rotation 2. Note: rotation 1 biomass monitoring spanned 15 days and rotation 2, 17.

5.3.2 The Animal System

All cattle gained weight over the duration of the experiment, with an average animal gain of 884 g/day (data not reported).

GPS System Performance

The descriptive statistics of the cleaned raw tracking data is displayed in Table 5.5. This includes the average per cent of location fixes received, satellites and HDOP of all of the location fixes. The results are similar for each collar. The average number of satellites used to determine a position was above 8 for all collars, ranging from 8.1 to 8.7. Average HDOP was between 1.2 and 1.4 for all collars. The percentage of expected fixes actually received ranged from 89 to 96%. Note that the number of expected position fixes achieved was lower for collar 15 because it fell off during one rotation.

Table 5.5 Descriptive statistics of individual GPS collars over both rotations. Note: All collars achieved ≥ 89% of expected fixes.

Collar	Number of points collected	% fixes*	Average of satellites	Average of HDOP
11	12115	90	8.1	1.4
12	12439	93	8.4	1.3
13	12269	91	8.3	1.3
14	12782	95	8.6	1.3
15	5375	93	8.3	1.4
16	12710	95	8.6	1.3
21	12501	93	8.2	1.4
22	12557	93	8.2	1.4
23	12629	94	8.4	1.3
24	12165	91	8.2	1.4
25	12589	94	8.3	1.3
26	12685	94	8.3	1.4
31	12562	93	8.2	1.4
32	12646	94	8.4	1.3
33	11949	89	8.2	1.3
34	12870	96	8.7	1.2
35	12657	94	8.5	1.3
36	12530	93	8.3	1.3
Total	**218030**	**93**	**8.3**	**1.3**

* The number of expected logs for each device was 13,406, except for collar 15 (5,760).

It was noted that a significant number of points were outside of the paddock boundaries during the experiment. With further investigation, it appeared that there was a shift of the UNETracker II logged positions to the south of up to approximately 6 m. Investigation of these points did not reveal a pattern of time or device which may have contributed to this nor human error related to inconsistent datum, coordinate system or projection. Therefore, in order to keep these data, a 7 m buffer was created for each paddock so that investigations of cattle across the paddock could be completed. This meant that there were many cells that the cattle never entered, because they were physically unable to and the GPS directional shift did not align, resulting in low values of proportion of paddock utilised.

Distance Moved

The average daily distance moved for each mob in both rotations is presented by day in Figure 5.3, which reveals that rotation 1 had a shorter overall duration (12 days) than rotation 2 (16 days). Although the range in average daily distance moved varies between different mobs and rotations (up to 679 m on a given day) there appears to be some consistency in the trends with a relatively stable or slightly decreasing section before increasing at, or after, day 9 to a peak between days 10-12. There is an additional decrease in average distance moved before a further increase at the very end (days 11-16) for the second, longer, rotation. These trends are by no means clear and a substantial amount of noise exists within the data.

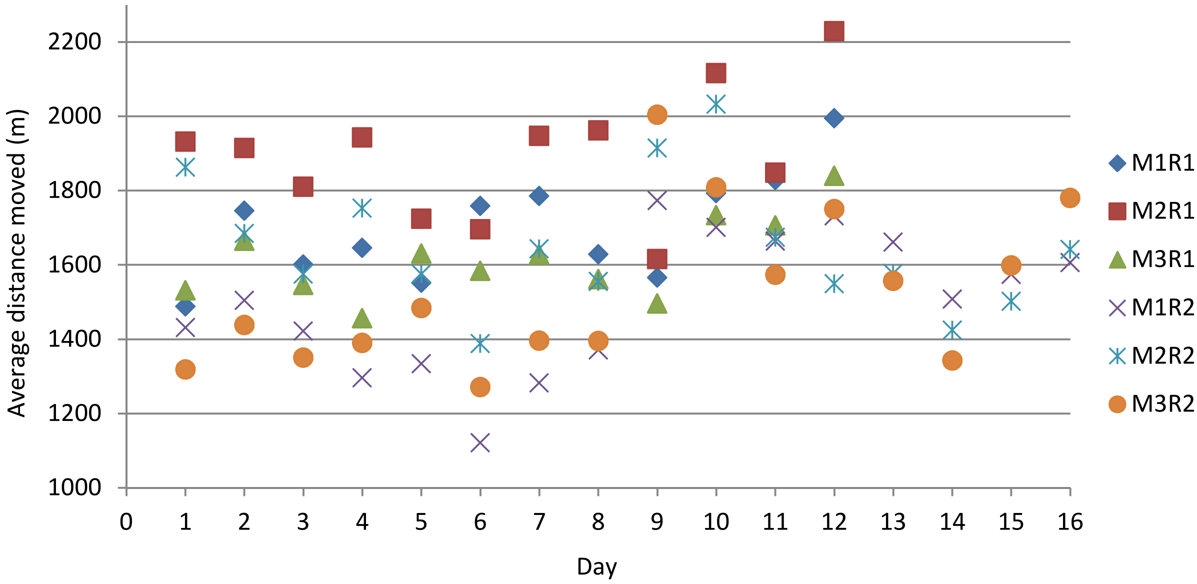


Figure 5.3 Average daily distance moved for each mob. Each data point is the average of all animals within a mob. M = mob number and R = rotation number

The comparison of average daily distance moved against biomass (Figure 5.4) reveals the variation of pasture that existed between the two rotations. Whilst the cattle were grazing the paddocks in rotation 1 the pasture continued to grow in the rotation 2 paddocks. This resulted in considerably higher starting values in rotation 2 (5,375 to 6,542 kg/ha GDM) than rotation 1 (3,318 to 3,676 kg/ha GDM). There appears to be some trends in the relationship between biomass and average distance moved. In rotation 1, mobs 1 and 3 show a fairly stable distance moved followed by an increase as biomass declined whilst mob 2 shows a more erratic decrease, then increase. Again like the previous daily investigation of data these trends are certainly by no means clear. In rotation 2, mobs 1 and 3 again follow a similar pattern. Initially, distance moved is unchanging before an increase.

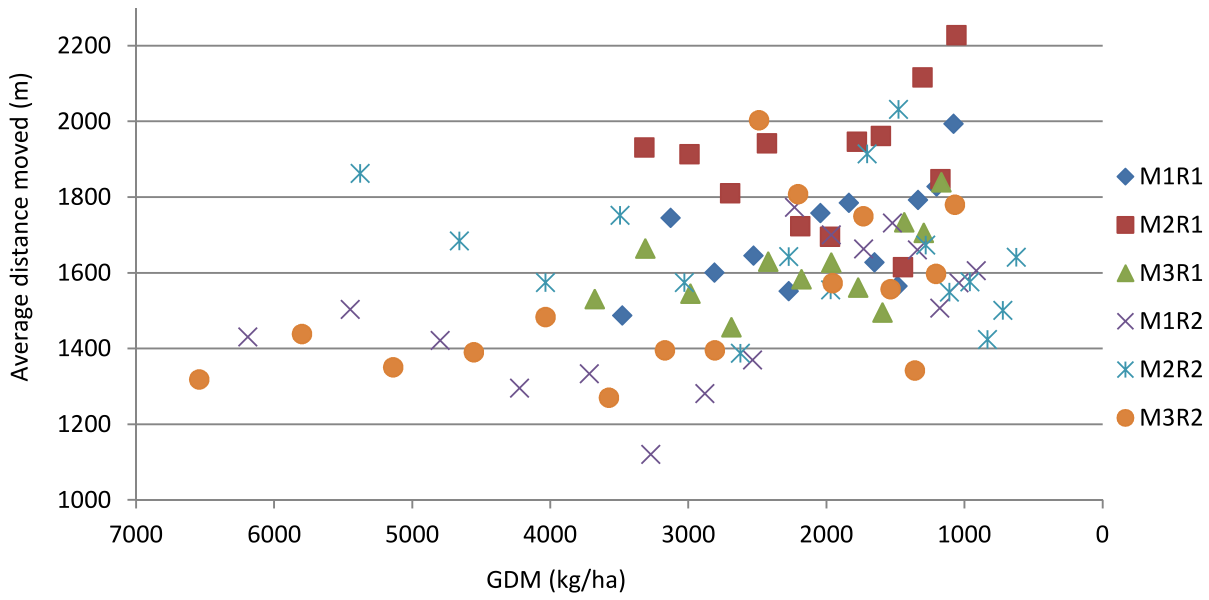


Figure 5.4 Daily average distance moved as green dry matter (GDM) (kg/ha) declined for all mobs and rotations. Each data point is the average of all animals within a mob. M = mob number and R = rotation number

Some weak relationships were observed for average distance moved. However, the results depicted an erratic nature including a lack of repeated patterns across mobs and rotations as biomass declined. Because of the high daily variation in distance moved, the absolute rate of change was calculated from the data (Figure 5.5). The rate of change was initially unchanging for rotation 2 when biomass was above 4,000 kg/ha GDM. The rate of change of M1R2 and M3R1 were predominantly steadfast throughout, with few large shifts in rate of change. All mobs/rotations showed the rate of change became increasingly dramatic as biomass declines, particularly after biomass is less than 2,700 kg/ha GDM.

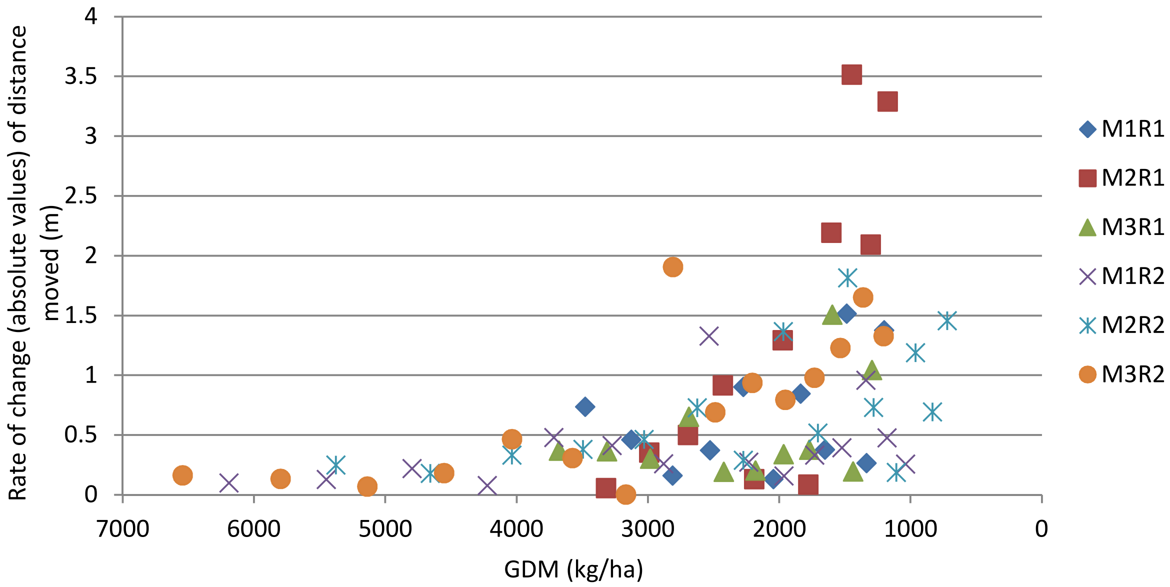


Figure 5.5 Absolute rate of change for distance moved as green dry matter (GDM) (kg/ha) declined for all mobs and rotations. M = mob number and R = rotation number

The stability of the slope of daily distance moved as biomass declined is presented in Figure 5.6. The stability statistic was developed to determine if an increase in erratic behaviour of the specific metric might provide some relationship with biomass. The stability for daily distance moved never exceeded 20 until biomass declined to 3,311 kg/ha GDM (M3R1). All mobs breached stability of 20 by 1,973 kg/ha GDM. While slope appeared less stable at GDM below 3,400 kg/ha for all mobs, no clear association with specific biomass was observed.

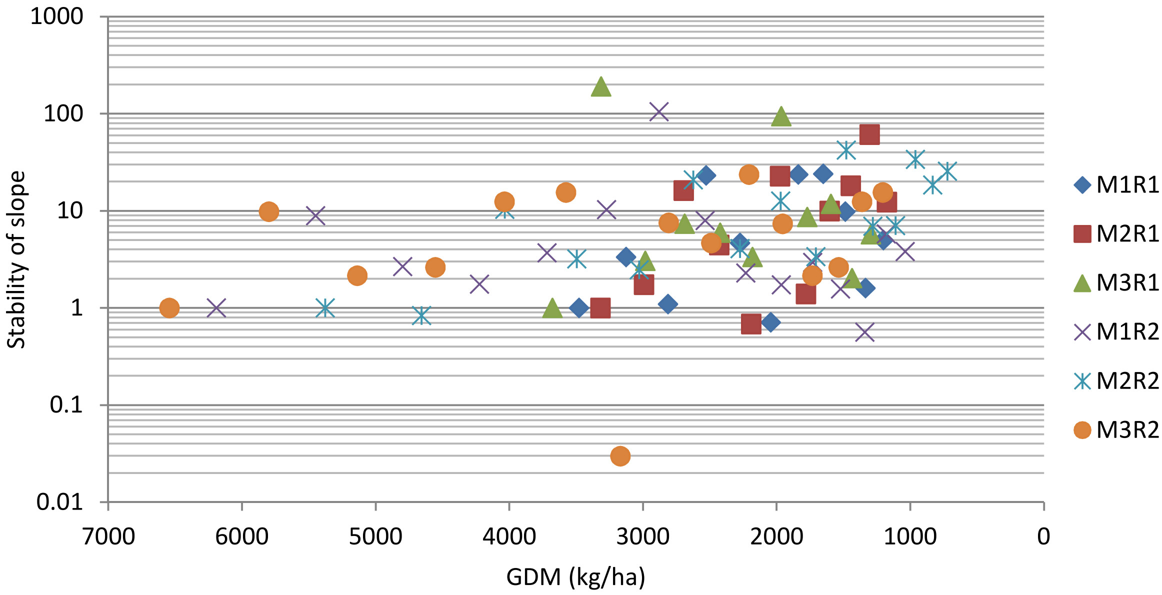


Figure 5.6 Daily stability of slope for distance moved as green dry matter (GDM) (kg/ha) declined for all mobs and rotations. M = mob number and R = rotation number

Speed-based Behaviour

Speed-based behaviour includes time spent moving (grazing and travelling behaviours combined). The daily moving time for all mobs in both rotations, Figure 5.7, was similar to daily proportions previously noted for grazing time (Arnold and Dudzinski 1978 20-58%; Vallentine 2001, 20-50%; Fraser *et al.* 2009, 34-40%) and a gradual increase occurred as GDM decreased. No clear pattern of behaviour emerged from rotation 1. Conversely, in rotation 2, before GDM reached 3,000 kg/ha moving time was low with little variation compared to after this point when a steeper increase of moving time was observed as GDM declined. Moreover, in M2R2 (which reached the lowest biomass) a decline in moving time is observed after approximately 1,477 kg/ha GDM. Although not as clearly, M1R2 also follows this trend.

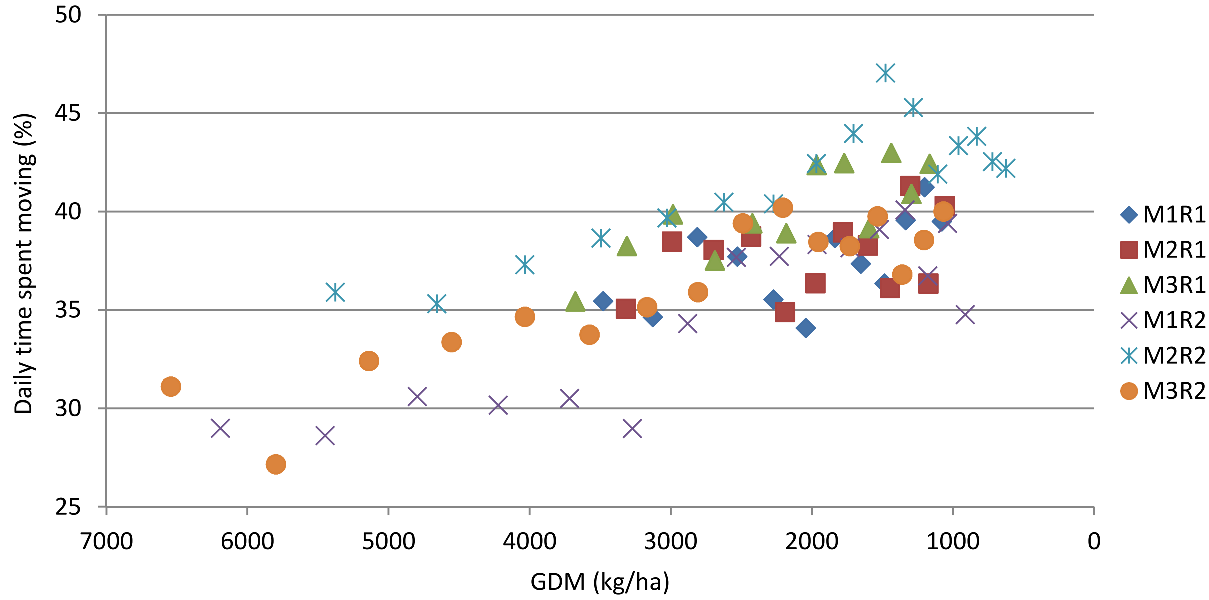


Figure 5.7 Average time spent moving (% of day) as estimated green dry matter (GDM) (kg/ha) declines for all mobs in both rotations. Each data point is the average of all animals within a mob. M = mob number and R = rotation number

The rate of change for the average time spent moving increases as biomass declines (Figure 5.8). Aside from this, the mobs have several dissimilarities. In rotation 1 there are no periods of low and unchanging rate of change. Conversely, M1R2 and M2R2 show very little change from maximum biomass to approximately 3,300 kg/ha GDM for M1R2 and 2,200 kg/ha GDM for M2R2. Mob 3 in rotation 2 begins with a higher rate of change than other mobs. Rate of change then decreases before increasing again after 3,000 kg/ha GDM.

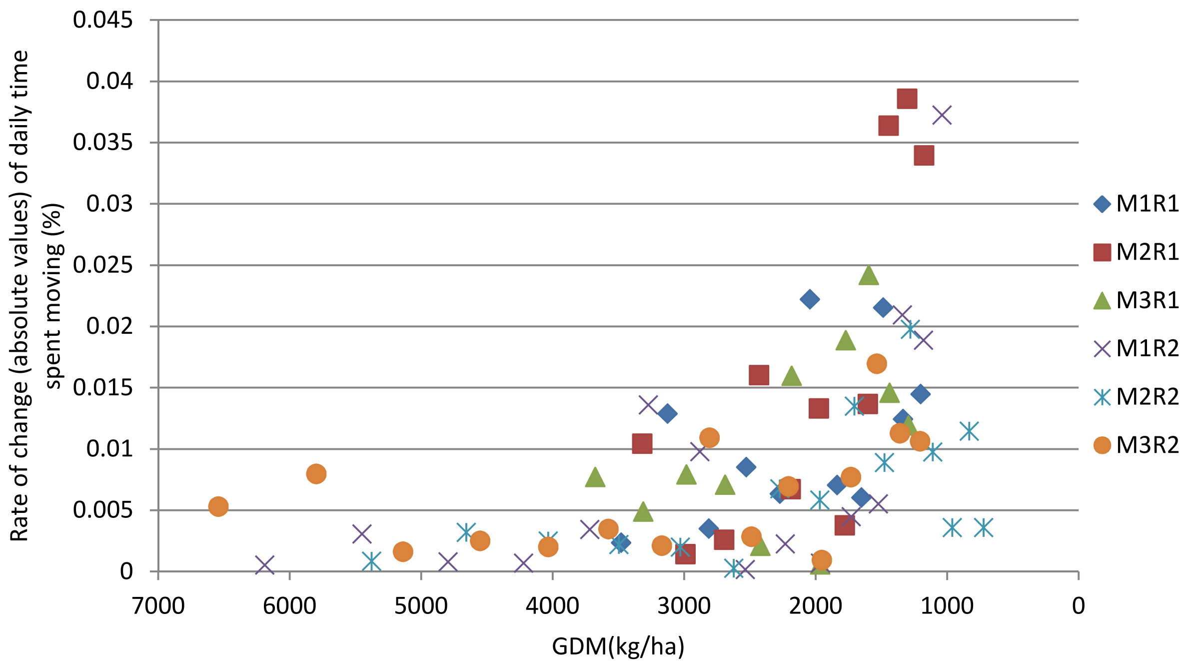


Figure 5.8 Absolute rate of change for time spent moving as green dry matter (GDM) (kg/ha) declined for all mobs and rotations. M = mob number and R = rotation number

The stability of the slope for rate of change of daily time spent moving is presented in Figure 5.9. While slope appeared less stable as GDM declined, no clear association with specific biomass was observed. The stability of daily moving time did not exceeded 20 until biomass declined to below 2,600 kg/ha GDM (M1R1). All mobs breached stability of 20 by 1,279 kg/ha GDM.

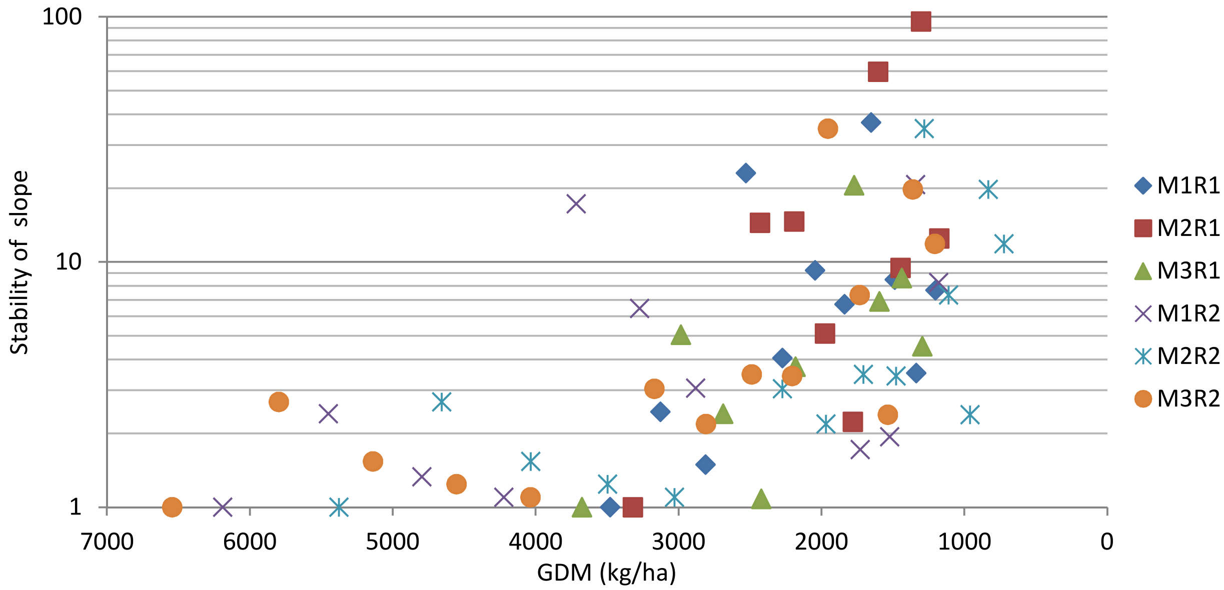
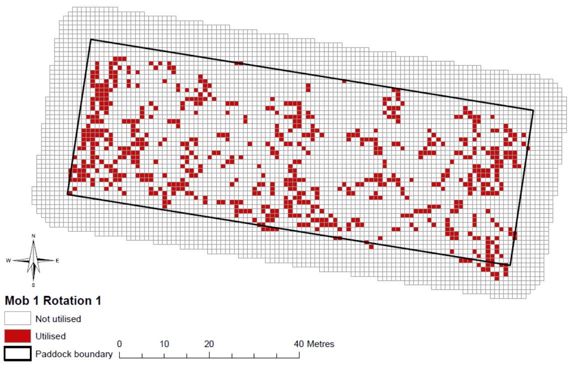


Figure 5.9 Stability of slope for daily moving time as green dry matter (GDM) (kg/ha) declined for all mobs and rotations. M = mob number and R = rotation number

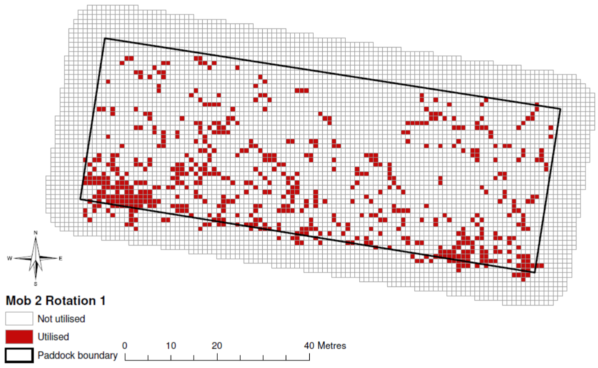
Spatial Distribution

The LRIs presented in Figures 5.10, 5.11 and 5.12, are the first, middle and last day of all mobs in both rotations. These LRIs depict where the cattle were when moving and cells are considered utilised when there is one or more positions recorded within them. In rotation 1 there was a shift in areas of high utilisation from west to east as the experiment continued. In rotation 2 this was not observed. In all cases, on the final day the cattle utilised the eastern ends of the paddocks more. This is close to the water troughs, gates and away from the tree belt. It is notable that most of the utilised cells outside the paddock boundary occur on the southern side. Additionally, cattle in the northern paddocks (Paddock 1, M2R1, and Paddock 2, M1R2) showed higher utilisation on the southern boundary. For Paddocks 5 (M3R1) and 6 (M2R2), the southern-most paddocks, cattle displayed higher utilisation close to the northern boundaries and the cattle in the middle two paddocks, 3 and 4 (M1R1 and M3R2 respectively), appear more evenly distributed across the paddocks. While this is more obvious for rotation 1 in these selected LRIs, it was evident in rotation 2 and further investigation of LRI maps and raw point data from all days of the experiments (not presented) supported this.

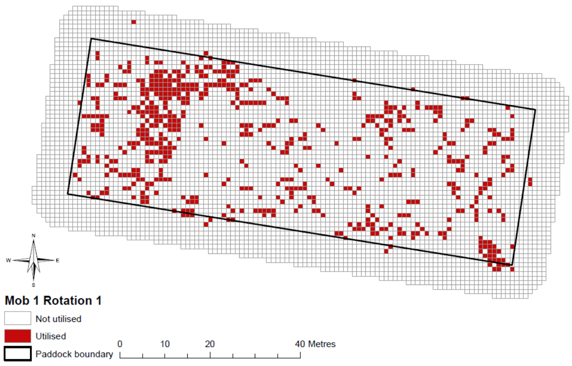
A)



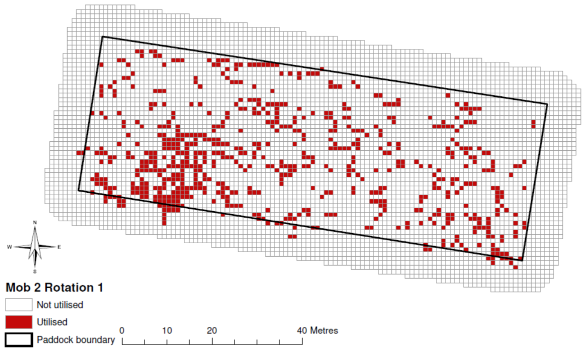
D)



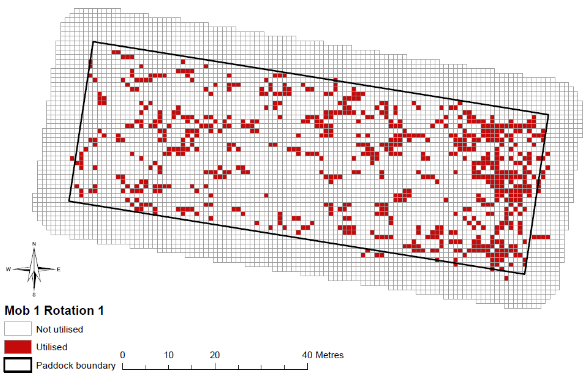
B)



E)



C)



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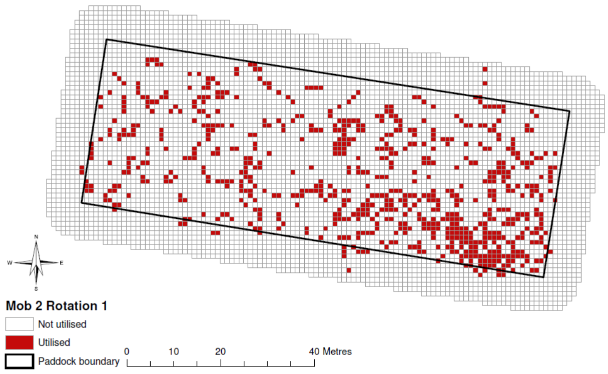

Figure 5.10 Moving time livestock residence index maps for mob 1 rotation 1 on A) day 1; B) day 6; and C) day 12 and for mob 2 rotation 1 on D) day 1; E) day 6; and F) day 12. Red cells are utilised and white cells are unutilised. Utilised is defined as having one or more moving positions logged within a cell.

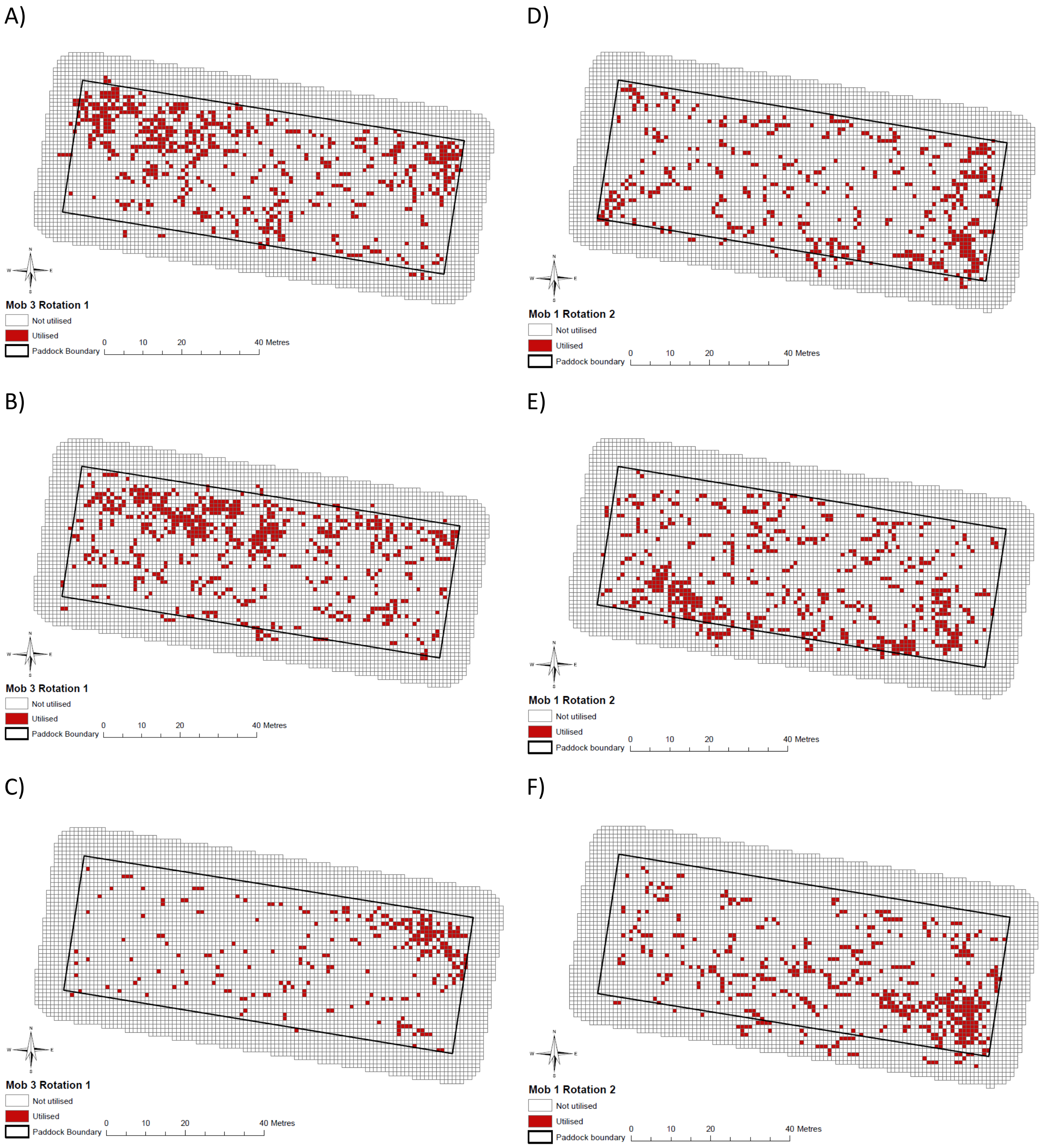

Figure 5.11 Moving time livestock residence index maps for mob 3 rotation 1 on A) day 1; B) day 6; and C) day 12 and for mob 1 rotation 2 on D) day 1; E) day 8; and F) day 16. Red cells are utilised and white cells are unutilised. Utilised is defined as having one or more moving positions logged within a cell.

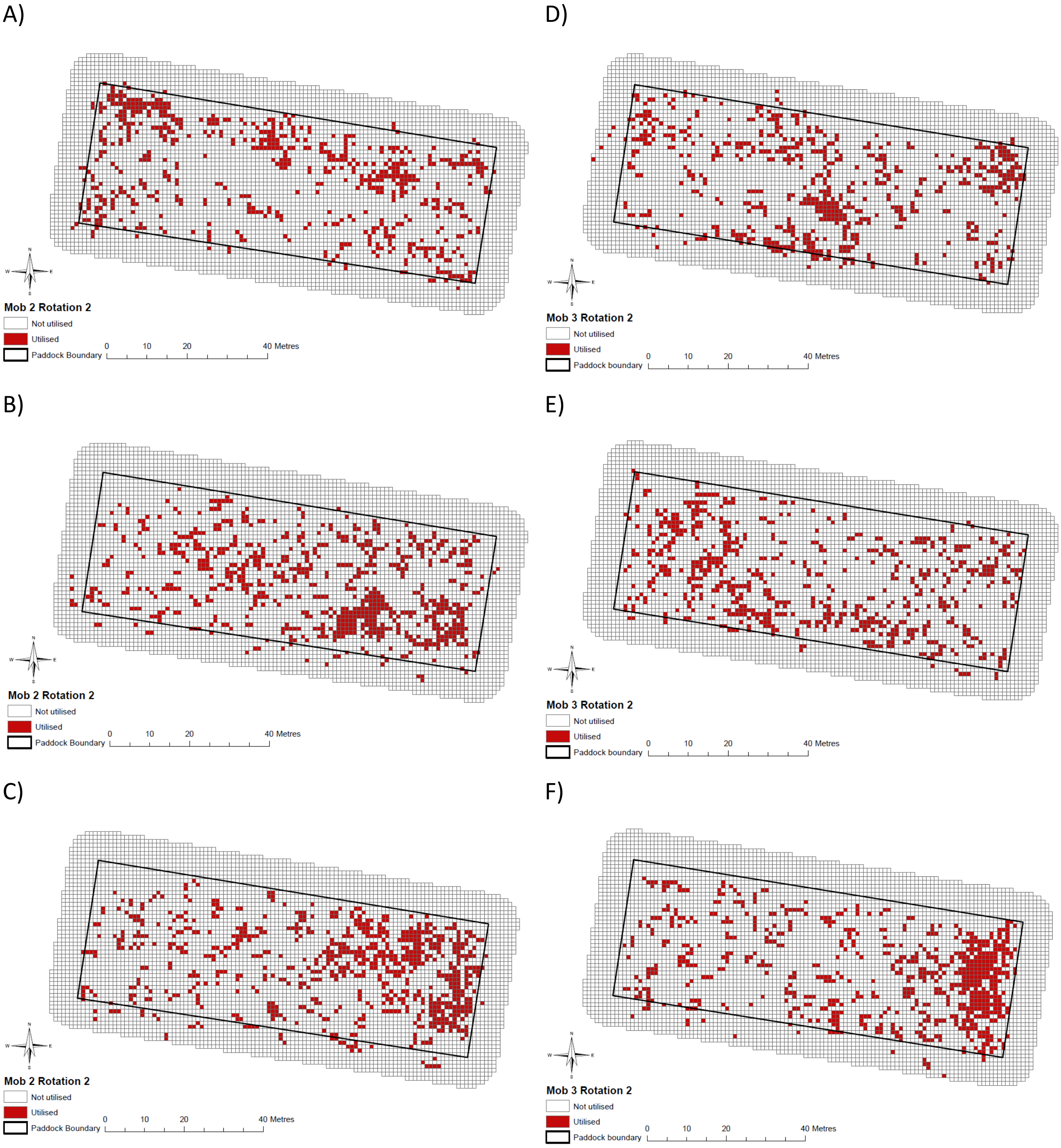

Figure 5.12 Moving time livestock residence index maps for mob 2 rotation 2 on A) day 1; B) day 8; and C) day 16 and for mob 3 rotation 2 on D) day 1; E) day 8; and F) day 16. Red cells are utilised and white cells are unutilised. Utilised is defined as having one or more moving positions logged within a cell.

The LRIs were converted into proportion of paddock utilised when moving for each day. These values were compared with declining biomass, presented in Figure 5.13. There are several noticeable mob/rotation related points of interest. In rotation 1 there was a lot of day-to-day variation for all mobs and a clear pattern of behaviour was not evident. In rotation 2, behavioural patterns were more noticeable with mobs 1 and 2 following a similar pattern, although mob 1 utilised a smaller area compared with all other mobs and rotations because of the loss of collar 15. The proportion of paddock utilised for M1R2 and M2R2 followed a similar pattern to moving time. Mob 3 appears to be an outlier, with much higher utilisation initially, before following a similar pattern towards the end of the experiment. After 3,000 kg/ha GDM is reached there is a clear increase in proportion of paddock used before a decline. A further increase is present for M2R2 on the last 2 days of the experiment.

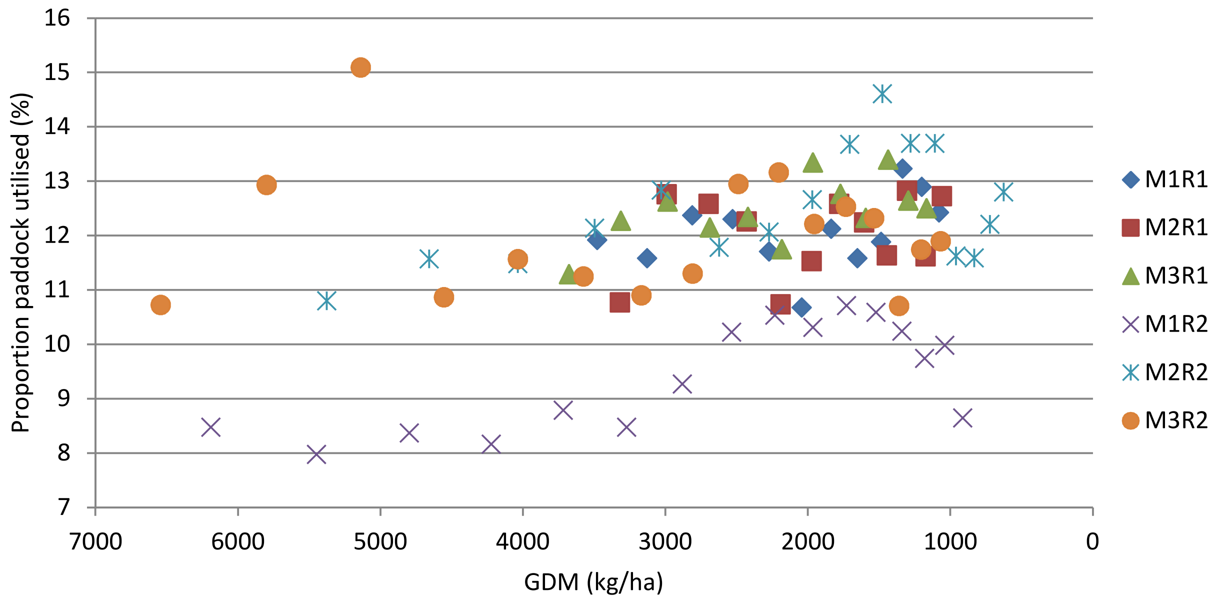

Figure 5.13 Proportion of paddock utilised by the cattle while moving as calculated by livestock residence indexes as green dry matter (GDM) (kg/ha) declines. M = mob number and R = rotation number

The rate of change for the proportion of paddock utilised results (Figure 5.14), are similar to those for distance moved and moving time. The rate increases faster as biomass declines after approximately 3,000 kg/ha GDM. Mob 3 in rotation 2, presents a high rate of change compared to M1R2 and M2R2 at large biomass amounts down to approximately 4,000 kg/ha of GDM. Mob 3 in rotation 2, presents a high rate of change compared to M1R2 and M2R2 at large biomass amounts down to approximately 4,600 kg/ha of GDM. Mob 1 in rotation 2 has little variation in rate of change compared to other mobs over the whole experiment.

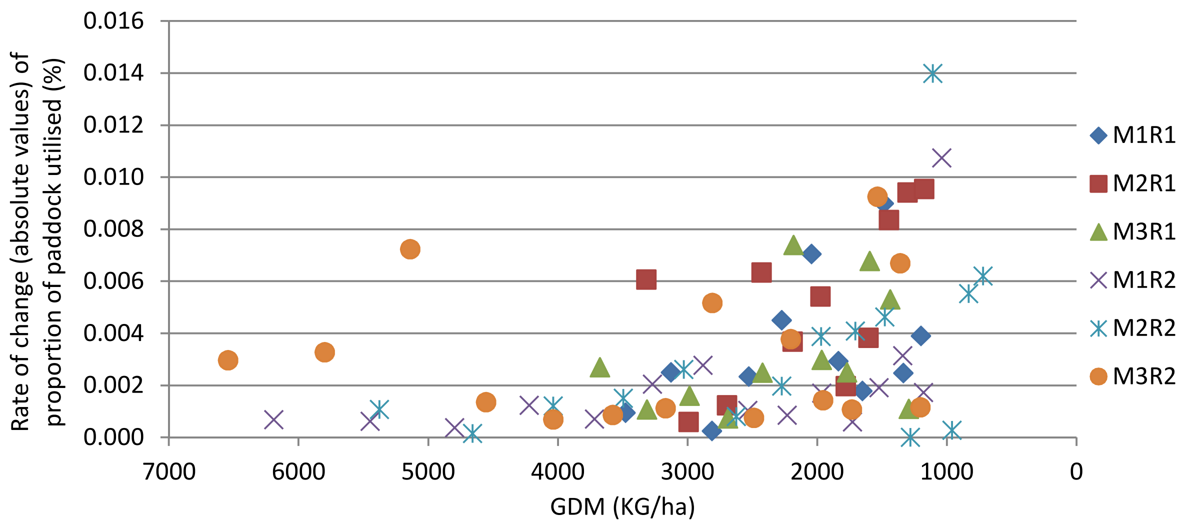

Figure 5.14 Absolute cumulative rate of change for proportion of paddock utilised while moving as green dry matter (GDM) (kg/ha) declined for all mobs and rotations. M = mob number and R = rotation number

The slope stability of the proportion of paddock utilised when moving as biomass declined is displayed in Figure 5.15. Stability exceeds 20 at high biomass, above 5,000 kg/ha GDM for M3R2 and above 3,700 kg/ha GDM for M1R2. For all other mobs it occurs below 2,500 GDM (kg/ha). Very high values occurred for M2R1 and M3R2, at above 600.

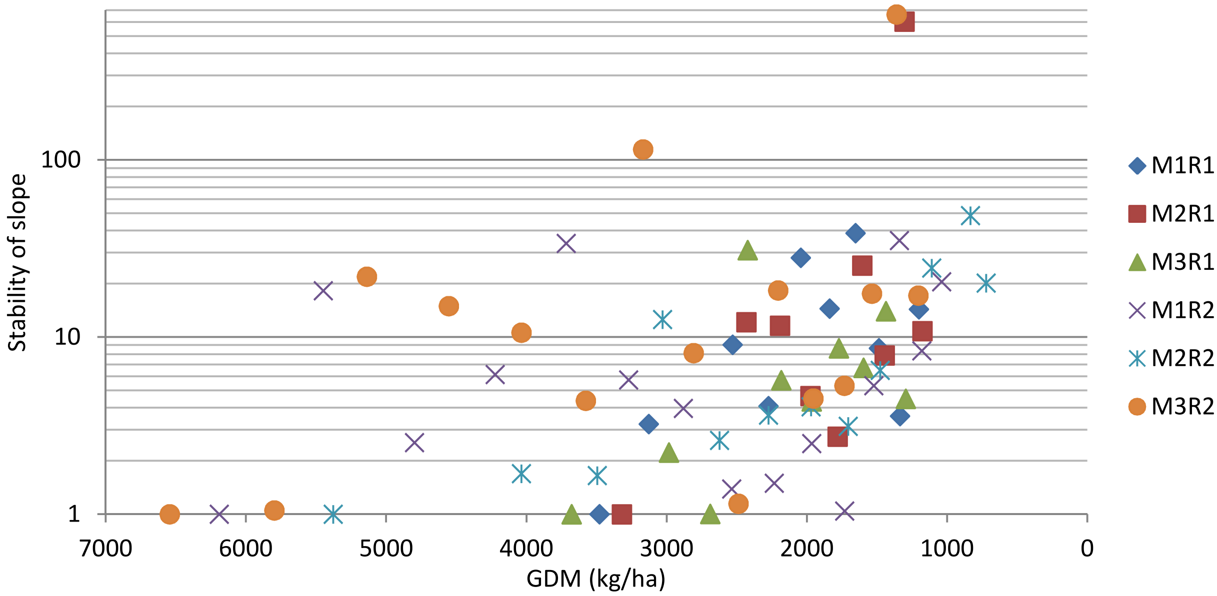

Figure 5.15 Daily stability of slope for paddock proportion utilisation as green dry matter (GDM) (kg/ha) declined for all mobs and rotations. M = mob number and R = rotation number

Daily paddock utilisation and corresponding moving time is presented in Figure 5.16. It was clear that there is a positive linear relationship between grazing time and paddock utilisation. There were some outlying points however. The resulting R^2 values for the linear relationships between paddock utilisation and moving time for each of the mobs and rotations are displayed in Table 5.6. The overall relationship between paddock utilisation and grazing time had an equation of $y = 0.241 + 2.555$ and an R^2 of 0.44. This is low, however an investigation of the individual mobs (by rotation) showed that for all mobs in rotation 1 and M1R2 a strong relationship exists (R^2 ≥0.75). The relationship is weaker, but still present, for M2R2 (R^2 = 0.52), and non-existent for M3R2 (R^2 = 0.001).

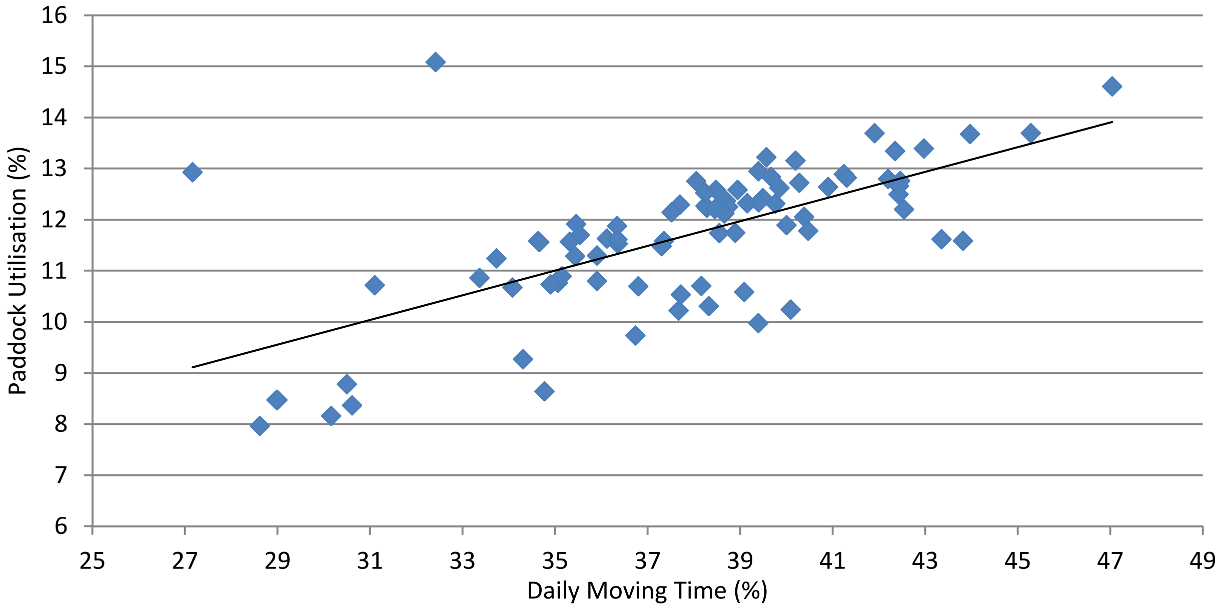

Figure 5.16 Relationship between paddock utilisation when moving (%) and daily moving time (%) for all mobs and rotations.

Table 5.6 Relationship between paddock utilisation (%) and daily moving time (%). M = mob number and R = rotation number

Mob Rotation	R^2
M1R1	0.75
M2R1	0.84
M3R1	0.77
M1R2	0.87
M2R2	0.52
M3R2	0.001
All	0.44

SOCIAL DISPERSION

The hour of each day which had the maximum dispersal of cattle was identified, as shown in Figure 5.17. Based on this result, these maximum dispersion hours of 7-8 (in the morning) and 14-15 (in the afternoon) were selected as time windows to investigate the mean cattle dispersion over time and against biomass as these hours had the highest count. Interestingly, the day hour maximum count follows the diurnal activity trend of cattle with peaks soon after dawn and in the early afternoon.

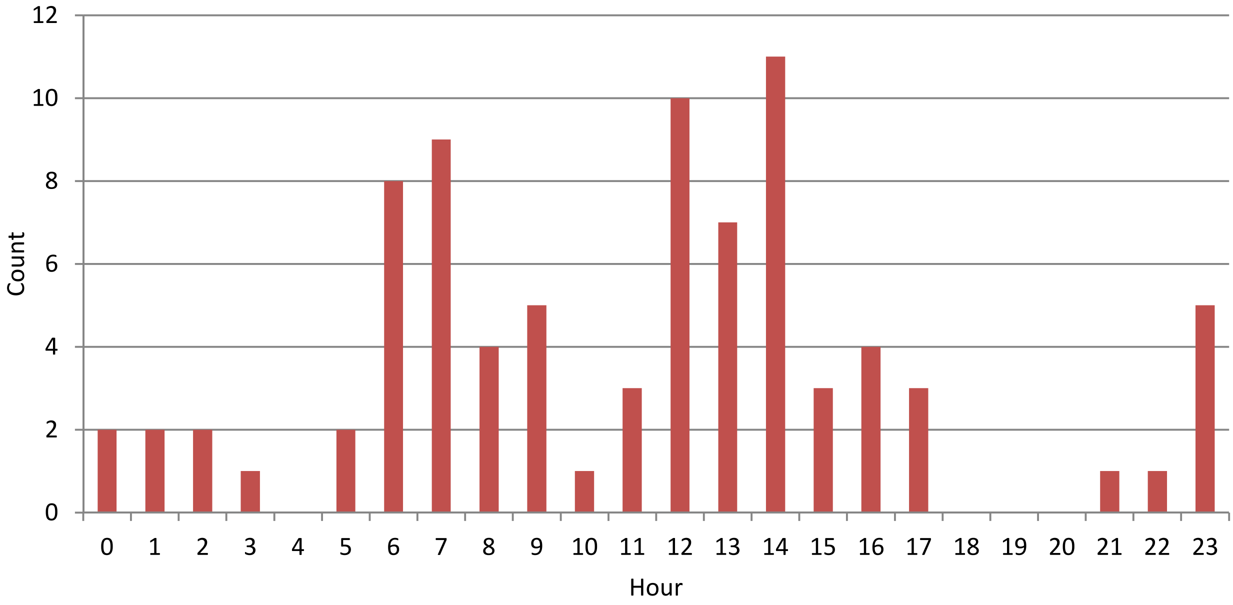

Figure 5.17 Count of the hour of the day containing the maximum average distance apart value for all mobs in both rotations.

The daily IHD for all mobs in both rotations in the hour of 7-8 is presented in Figure 5.18, and at the hour of 14-15 in Figure 5.19. Intra herd dispersion was also compared biomass in Figures 5.20 and 5.21 for the morning and afternoon window respectively. Inter herd dispersion appears erratic when both investigated in relation to day and biomass. Consequently, no clear observable trends are apparent.

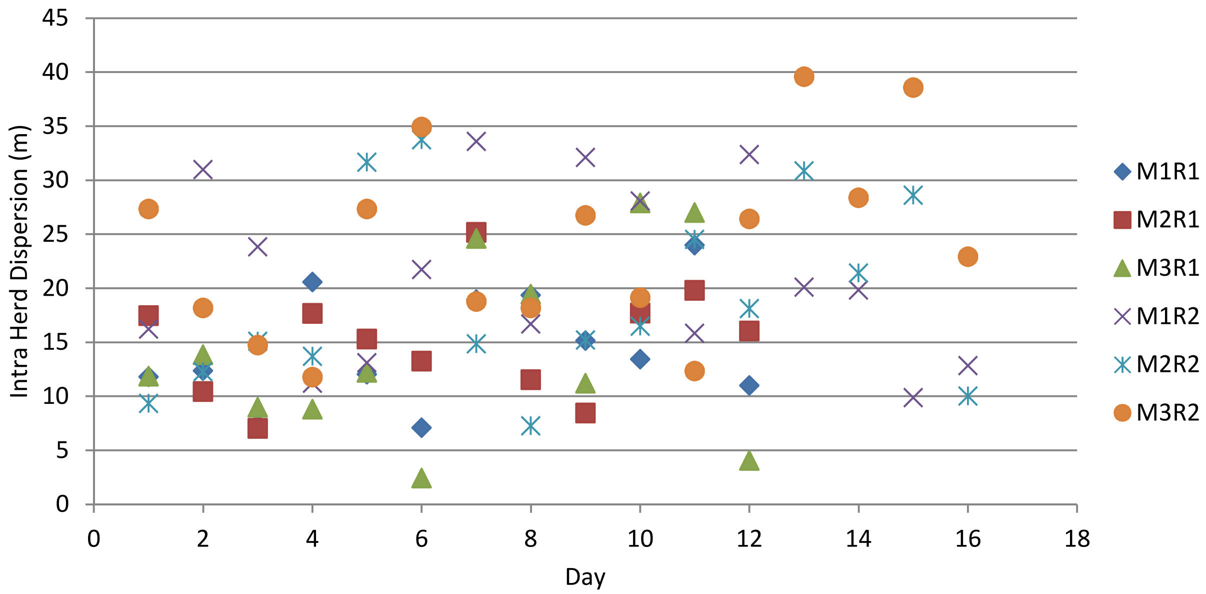

Figure 5.18 Daily mean intra herd dispersion for all mobs and rotation between hours 7 and 8. M = mob number and R = rotation number

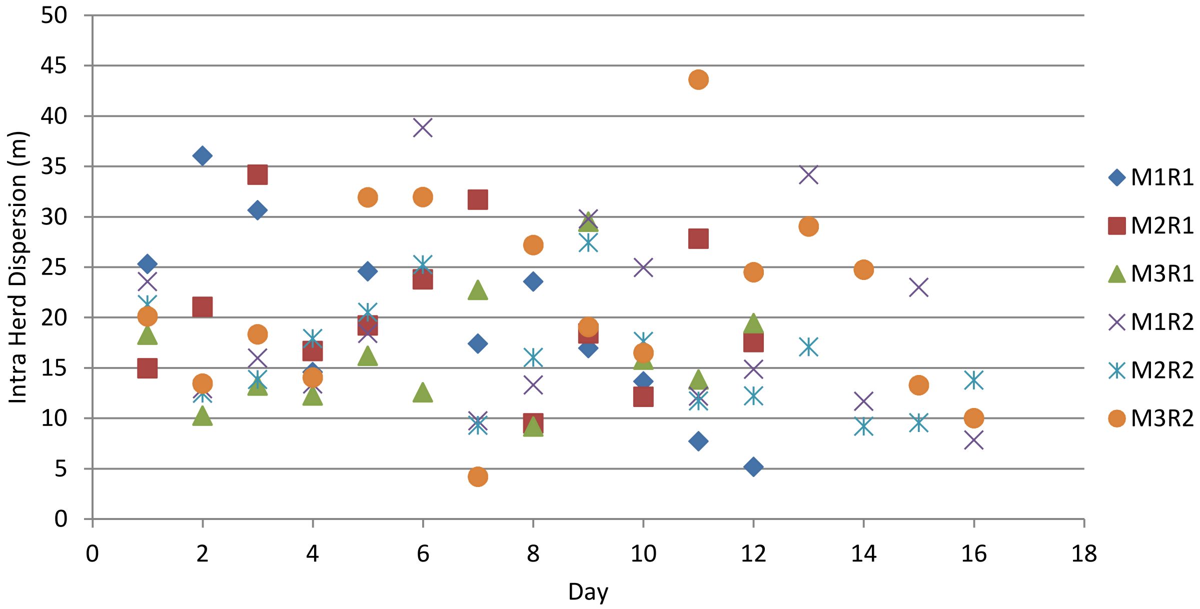

Figure 5.19 Daily mean intra herd dispersion for all mobs and rotation from between hours 14 and 15. M = mob number and R = rotation number

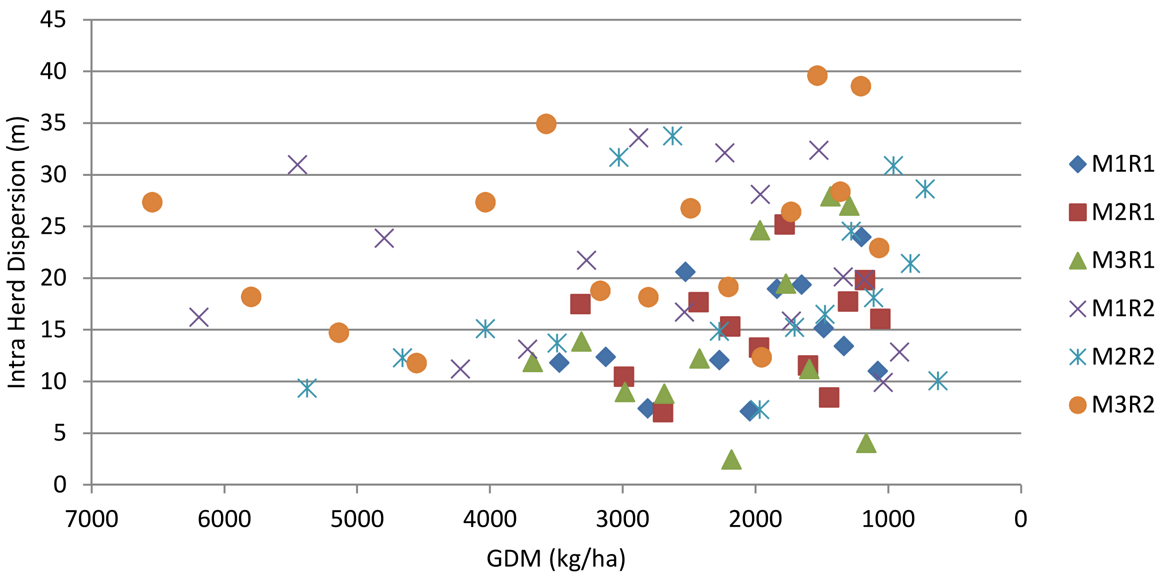

Figure 5.20 Daily mean intra herd dispersion as green dry matter (GDM) (kg/ha) declined for each mob in both rotations from between hours 7 and 8. M = mob number and R = rotation number

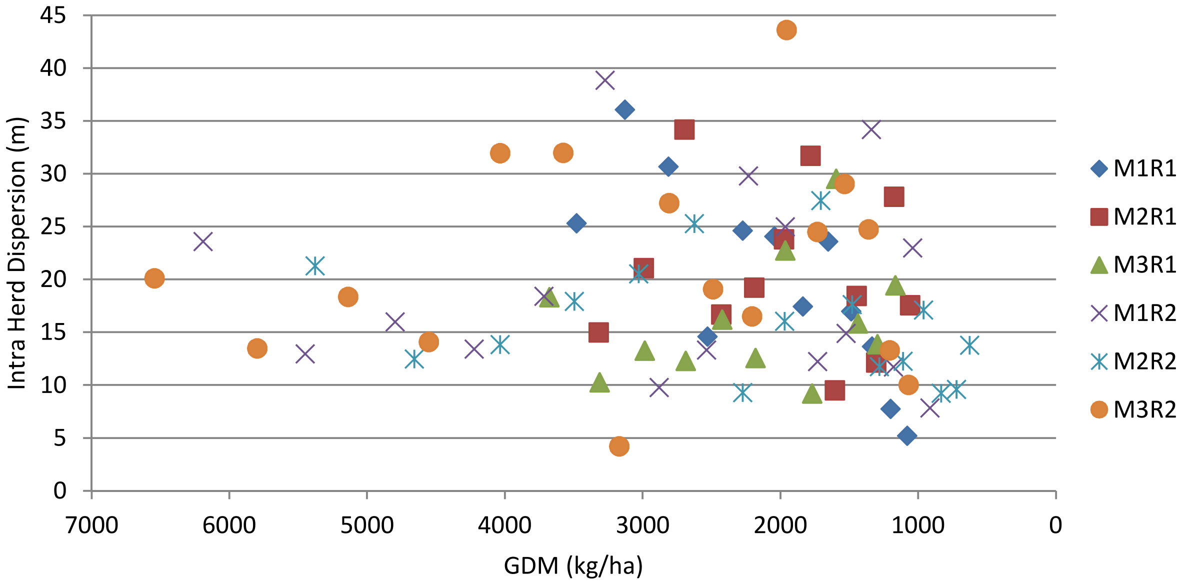

Figure 5.21 Daily mean intra herd dispersion as green dry matter (GDM) (kg/ha) declined for each mob in both rotations from between hours 14 and 15. M = mob number and R = rotation number

Mob average mean and max IHD for each rotation is displayed by time window in Table 5.7. In rotation 1, the cattle are further apart in the afternoon. The opposite is observed in rotation 2, with larger distances observed in the morning.

Table 5.7 Average intra herd dispersion (IHD) (m) of monitoring windows, between hours 7 and 8 (AM) and 14 and 15 (PM), for each mob and rotation. Note: in rotation 1 AM mean and max IHD is lower than for PM and for rotation 2 PM mean and max IHD is lower than for AM. M = mob number and R = rotation number

Mob Rotation	Mean		Max	
	AM	PM	AM	PM
M1R1	14	20	27	39
M2R1	15	21	29	42
M3R1	14	16	29	32
M1R2	21	19	39	35
M2R2	19	16	37	31
M3R2	24	21	47	41

The absolute rate of change of IHD at day hours 7-8 and 14-15 are displayed in Figure 5.22 and Figure 5.23, respectively. Intra herd dispersion had higher rate of change at larger biomass in the afternoon (hour 14-15); although overall the highest values were recorded in the morning (hour 7-8) for M3R1 and M2R2. The morning and afternoon IHD saw different relative rates of change for the mobs. Mob 2 in rotation 2 had the highest rate of change in the 7 to 8 hour, alternatively, in hour 14 to 15, in relation to other mobs had low results. The opposite occurred for M1R2 and M2R1.

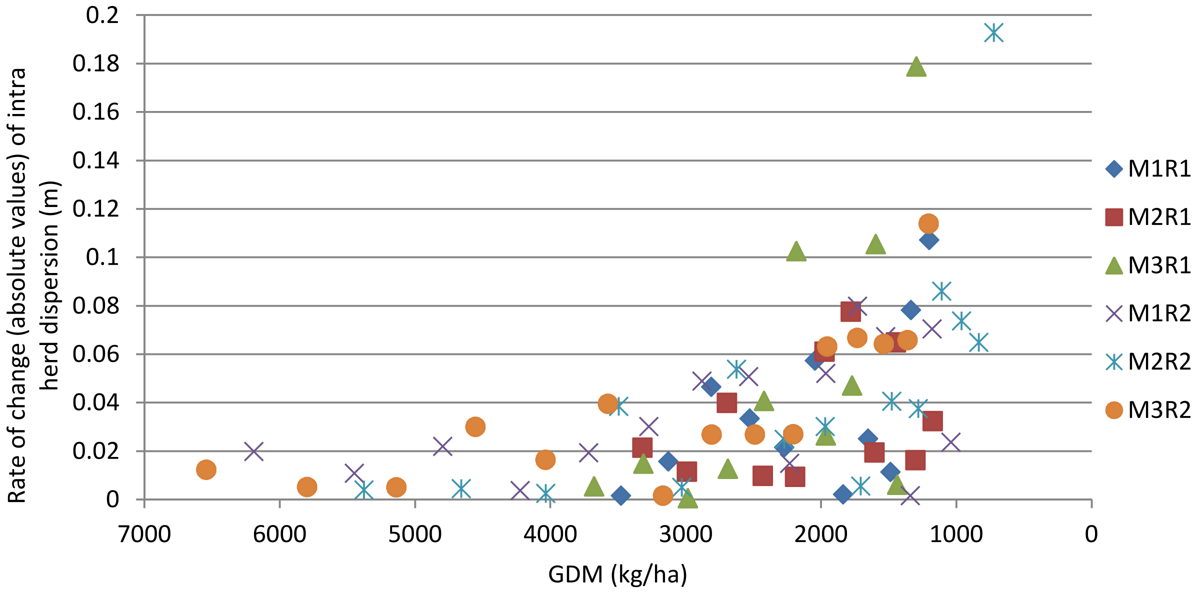

Figure 5.22 Daily absolute rate of change of intra herd dispersion as green dry matter (GDM) (kg/ha) declined for all mobs and rotations from between hours 7 and 8. M = mob number and R = rotation number

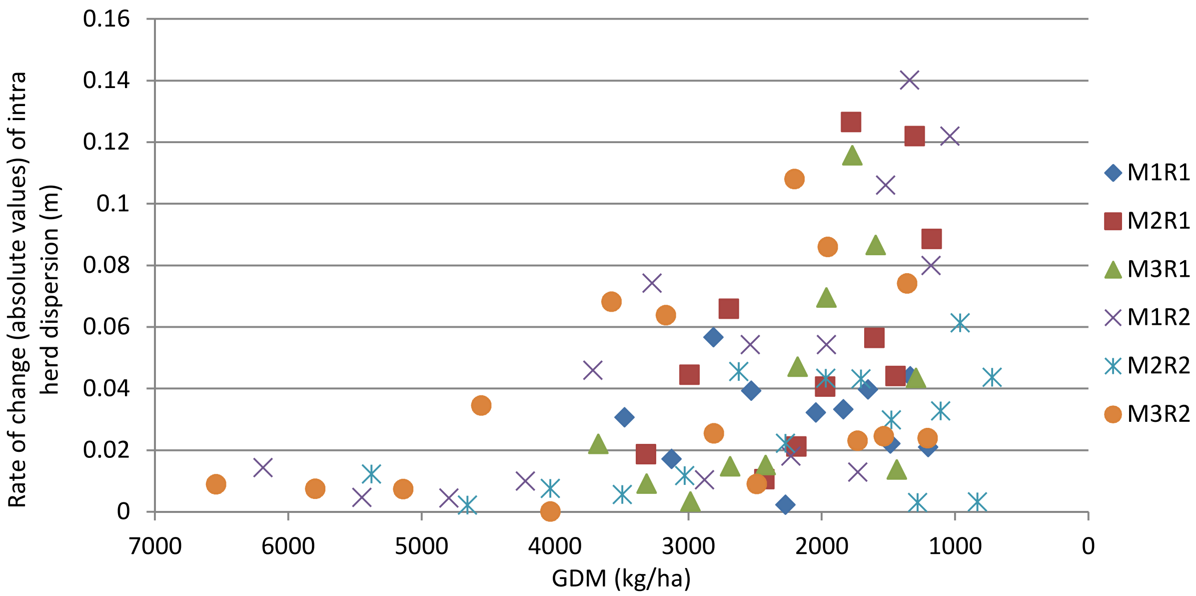

Figure 5.23 Daily absolute rate of change of intra herd dispersion as green dry matter (GDM) (kg/ha) declined for all mobs and rotations from between hours 14 and 15. M = mob number and R = rotation number

The stability of the slope of rate of change for both rotations and time periods are presented in Figure 5.24 (hour 7-8) and Figure 5.25 (hour 14-15). The stability of slope for IHD shows several instances over 100, and in one case in excess of 900 (M2R1). These large stability values only happened after GDM is less than 3,000 (kg/ha). Between hour 7 and 8 stability does not exceed 20 until biomass is less than 3,000 GDM (kg/ha). For IHD between hours 14 and 15 stability exceeds 20 at GDM of 3,168 kg/ha. While, the stability cannot be aligned to a specific biomass amount, it is obvious that variation is much larger at lower biomass amounts.

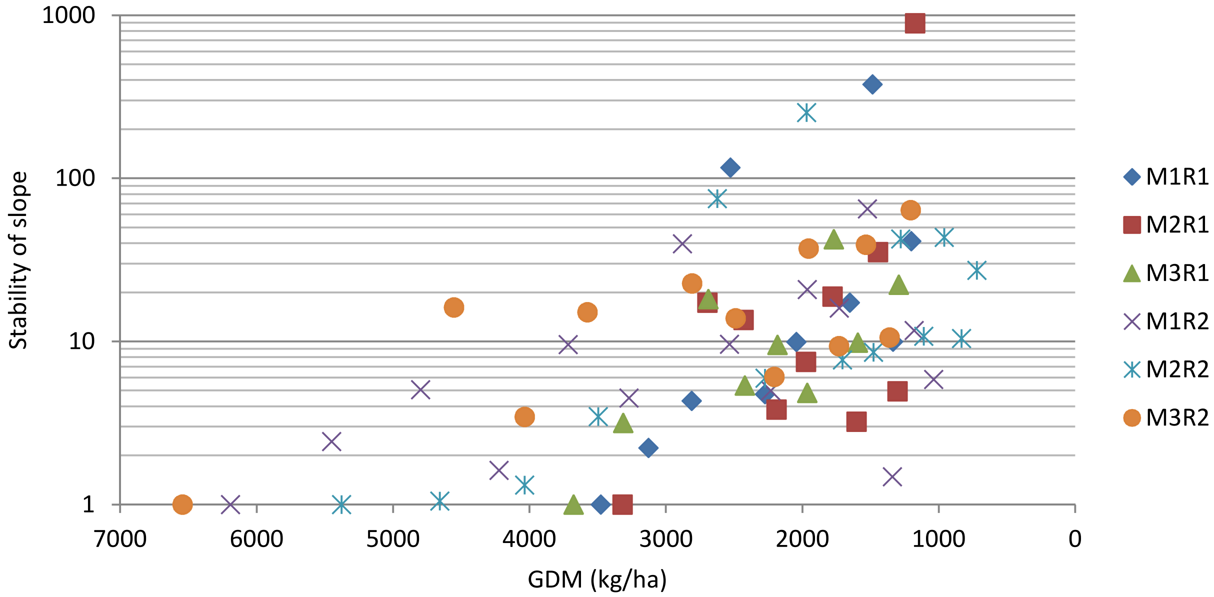

Figure 5.24 Daily stability of slope mean intra herd dispersion as green dry matter (GDM) (kg/ha) declined for all mobs and rotations from between hours 7 and 8. M = mob number and R = rotation number

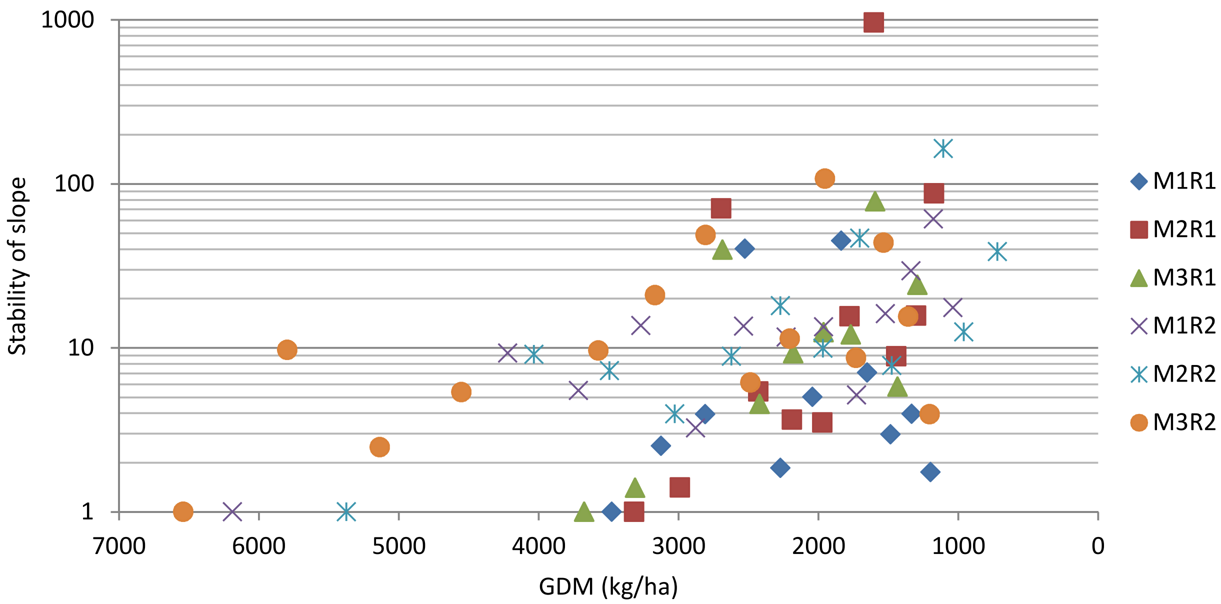

Figure 5.25 Daily stability of slope mean intra herd dispersion as green dry matter (GDM) (kg/ha) declined for all mobs and rotations from between hours 14 and 15. M = mob number and R = rotation number

5.4 Discussion

5.4.1 The Plant System

An RMSE of 632 GDM kg/ha was calculated for the biomass estimate calibration. This equated to 34% of the mean GDM. This result is very high compared with the results of Chapter 3 (12%) and also several literature sources. Root mean squared error of pasture reported in the literature ranges from 8 to 24% (Künnemeyer *et al.* 2001; Schut *et al.* 2006). The method of subsampling biomass for the vegetation calibration could have contributed to the RMSE; introduced error of up to 13% was shown (Table 5.3).

Despite the high biomass prediction error, (RMSE), the pattern of biomass decline and the levels that relate to cattle behaviour (where trends are apparent) show comparable estimates of biomass amount across plots. Thus, behaviour was relatable to biomass amount. Nevertheless, when considering the actual biomass values, and, in particular, when comparing with other studies, the high RMSE must be considered.

5.4.2 The Animal System

System Performance

All GPS devices received at least 89% of expected fixes, from an average of 8.3 satellites with an average HDOP of 1.3 (Table 5.5). These GPS devices are considered successful in relation to other studies (Ganskopp 2001; Ganskopp and Bohnert 2006; Ganskopp and Johnson 2007; Johnson and Ganskopp 2008; Swain *et al.* 2008; Trotter and Lamb 2008; Ganskopp and Bohnert 2009; Anderson 2012; Henken *et al.* 2012) (see Table 1.2). Despite the success compared to other studies; the GPS devices did not achieve as many of the expected fixes (96%) or average satellites (8.8) presented in Chapter 3. The lower number of fixes may be due to the higher number of positions required (five) in the same awake time (120 seconds) as was used in Chapter 3 (four). If the GPS devices were delayed in receiving the first positions of the burst log they may not have had time to determine the final positions before reaching the maximum awake time.

Despite the positive results achieved for GPS fix rate, when the data was visually displayed in ArcGIS® (not presented) there was an observable trend in positioning error. Many positions were recorded outside the southern boundaries. It is unlikely that the shift was caused by incorrect paddock boundary mapping as the recording of boundaries was undertaken with a Trimble dGPS, which accounts for atmosphere and has a high level of accuracy (<1 m) (Trimble Navigation Limited 2000). The descriptive statistics indicate success of the GPS devices, with high fix percent, high satellite and low HDOP. Despite the descriptive statistics indicating that the GPS had adequate satellite numbers and HDOP, there still appeared to be systematic error. This may be because of environmental factors such as canopy cover and terrain (Lewis *et al.* 2007). The experimental site is located alongside a row of tall trees on a hillside. Other reasons known to affect GPS include GPS position on animal (D'Eon and Delparte 2005) and time interval (Jurdak *et al.* 2010); however it is unlikely that this was the cause of error. The UNE Tracker II collars are designed so the GPS antennas face skywards and were set for multiple-interval tracking. While it is accepted that there is GPS locational error, the data are considered valid. Firstly, the shift was less than 7 m, which is within the expected range of position accuracy (5 to 10 m) (Swain *et al.* 2011). Secondly, speed-based behaviours were unlikely to be affected by this shift because of the multiple-interval tracking. This provides a more accurate estimate of the relative speed between two points, and therefore geo-locations are not as crucial.

For paddock utilisation derived behaviours, the paddock grid was extended outside of the paddock boundary to ensure that all data was included in the analysis.

Abiotic Influences

As in Chapters 2 and 3, the weather data was collected offsite and included maximum temperature and rainfall. Days of rainfall are highlighted in Table 5.1. The author investigated the behaviours of the cattle on notable weather days (e.g. rainfall event); although, again, a relationship was not apparent. As in previous experiments, the weather data recorded did not appear to influence cattle behaviour. While weather is known to affect the behaviour of the cattle (Hafez 1968; Malechek and Smith 1976; Roath and Krueger 1982; Finch *et al.* 1984; Blackshaw and Blackshaw 1994; Prescott *et al.* 1994; Vallentine 2001), it was not evident in these results as peaks or troughs of behaviours did not occur on the same day as prominent weather events. There are several possibilities as to why a weather affect was not observed. Firstly, as the weather station was offsite it may not have accurately represented the experimental site. Secondly, the effect on behaviour was small and therefore not detected in the analysis; and lastly the combination of other variables affecting the steers was convoluted and masked the relationship with weather.

Human Influence

The cattle in this experiment were very familiar with people. There was a 3 day cycle of biomass monitoring, cattle monitoring and no human presence (Table 5.1). The behaviour results were compared by the researcher to the human interaction days. Conversely to Chapter 2, there was no notable effect, likely, because the cattle were exceedingly familiar with people.

Distance Moved

Daily distance moved by the mobs was compared by day and daily estimated biomass. The distance moved (1121 to 2229 m) is within the range reported in the literature; in a range of paddocks from 0.01 to 2000 ha cattle walked between 900 and 12600 m/day (Albright and Arave 1997). Short distances were expected as the paddocks were quite small (0.35 ha). The low levels of average daily distance moved were most likely a result of the fact that new feeding patches and water were never far away.

The results reveal some relationships may exist between average daily distance moved and both day and biomass. However, these are not clear and inconsistent between rotations or mobs. In rotation 1, mobs 1 and 3 showed stability or a slight decline in average daily distance moved per day before an increase in the final 3 days (Figure 5.3). A similar pattern is observed with rotation 2, although the spike in distance moved does not include a lead-up, before a decrease and final increase is monitored in the final 3 days. When compared with biomass (Figure 5.4), there is a similar (increasing) trend observed in mobs 1 and 3 in rotation 1 and 2; however mob 2 showed a distinctly different pattern of behaviour. This mob, generally exhibited higher distances moved and a more erratic nature.

Rate of change of distance moved over the experiment (Figure 5.5) is unchanging for rotation 2 up to 4,000kg/ha GDM. There were no periods of little variation in rotation 1. This may be related to biomass as rotation 1 never exceeded biomass values of 3,600 kg/ha GDM. Mob 3 in rotation 1 and M1R2 had, overall, the least varying rate of change with most values below 0.5. Aside from the increase at lower biomass, a consistent relationship with biomass across rotations or mobs was not exhibited. The stability for distance moved (Figure 5.6) was variable throughout. It is worth noting that all mobs breached a stability value of 20 between 3,311 and 1,973, kg/ha GDM. Interestingly there is no pattern of stability in relation to biomass, between mobs or within rotations. Apart from the increase at lower biomass, neither the absolute rate of change nor stability of the slope for average daily distance moved provided a consistent relationship with biomass across rotations or mobs.

Speed-based Behaviour

Putfarken *et al.* (2008), Anderson *et al.* (2012) and Guo *et al.* (2009) all reported travelling behaviour in their research. Travelling behaviour was rarely observed in this experiment, and therefore speed could not be attributed to it, as such, a 'moving' speed threshold was determined which included travelling and grazing behaviour. The effect of pooling both grazing and travelling time will be small. The lack of travelling behaviour could be related to the small paddock area, with little distance required to reach camp areas, water or feed patches. Compared with paddock sizes in other speed model development research, (Putfarken *et al.* (2008) = 180 ha; Anderson *et al.* (2012) = 433 ha; Guo *et al.* (2009) = 7 ha), at 0.35 ha, these paddocks are very small.

In rotation 1, there was no clear relationship between time spent moving and GDM (Figure 5.7). However, the hypothesis was supported in rotation 2. The expected results of an increase in time spent grazing as biomass declines were observed, based on grazing time in Chapter 3 and the literature (Chachon and Stobbs, 1976; Gibb *et al.* 1999). Additionally, it was expected that a maxima would be reached after which eating behaviour will decline. This was most clearly apparent in M2R2, and less so in M1R2. Chachon and Stobbs (1976) relate this pattern to fatigue from limited energy gained from feed. It is possible that very early fatigue occurred in rotation 2, especially in mob 2, located in paddock 6, which reached the lowest available GDM in this experiment (Figure 5.2), explaining why this maxima is not apparent for other mobs.

Initially, the rate of change for daily moving time (Figure 5.8) was similar to that of daily distance moved. There was an initial period of low rate of change until approximately 4,000 kg/ha DM for rotation 2, with the exception of the first 2 records of M3R2. In rotation 1, and at biomass below

4,000 kg/ha GDM for rotation 2, the rate of change remained variable throughout. Stability of slope for daily moving time (Figure 5.9) was somewhat unchanging initially for rotation 2, until a biomass of approximately 4,000 kg/ha GMD was reached. This aligns with the result of rate of change. Stability remained below 20 until after approximately 2,600 kg/ha GDM, lower than for distance moved. All mobs had exceeded 20 by 1,279 kg/ha GDM; again lower than daily distance moved. If this is a reflection of biomass (although the lack of a clear pattern masks it); it suggests that daily distance moved may react to biomass decline sooner than moving time. There was not a consistent relationship with biomass across rotations or mobs for rate of change or stability of slope.

Spatial Distribution

Despite designing the paddock rotations so that inter-mob interactions were limited, it appears that this still occurred. In the LRI maps (Figures 5.10 to 5.12) it was evident that the cattle in paddocks to the north spent more time on the southern boundary (M2R1 and M1R2) and the cattle most south spent more time on the northern boundary (M3R1 and M2R2), closer to the mob in the middle paddocks (M1R1 and M3R2). The cattle in the middle paddocks appeared to be more evenly distributed. Obviously, cattle socialisation is not limited by the minimum distances of 35 m seen in this experiment, and in future research cattle mobs should be further apart. Cattle prefer to be in close proximity to other herds (Trotter and Lamb 2008). Additionally, sheep and goats are thought to be able to recognize the presence of humans and predators up to 1 km away in some situations (Arnold and Dudzinski 1978). To exclude a social affect entirely, further research on communicative distance needs to be undertaken. In a commercial setting, true separation of herds is unlikely to be achieved for some management styles, for example on small farms. Therefore, herd interactions should be taken into account as a potential factor when monitoring biomass affected behaviours.

The range of proportion of paddock utilised is similar for all mobs across rotations except M1R2 (Figure 5.13). A collar was lost from one steer; consequently, only five datasets were available. Because of this, up to 1/6th less paddock utilisation was expected.

In rotation 1, similarly to time spent moving, a strong behavioural pattern was not apparent for the proportion of paddock utilisation (Figure 5.13). While not all mobs and rotations followed a similar pattern, rotation 2 appeared to have a relationship with biomass. There is a clear pattern of M1R2 which matches the behaviour of paddock utilisation expected based on the results of Chapter 3. As hypothesised, paddock proportion increased (at approximately 3,000 kg/ha of GDM) and began to decrease after approximately 1,500 kg/ha GDM. In M2R2 and M3R2 this is also evident although not as clear.

There was a positive relationship between paddock utilisation and daily time spent moving (Figure 5.16 and Table 5.6). As anticipated, paddock utilisation increases with daily moving time. This was expected as cattle move between grazing patches during a feeding event, the more they move while grazing the more feeding patches are visited. A good relationship was apparent for rotation 1, with all the R^2 values over 0.75. In rotation 2, there was a large range of results between the 3 mobs and no linear relationship for M3R2, with a very low R^2 of 0.001. Nevertheless, there might be additional factors influencing the relationship for this mob. It is possible that intra- and inter- mob social interactions (or lack thereof) lead to increased proportion of paddock used in relation to moving time.

The rate of change (Figure 5.14) and stability (Figure 5.15) results for the proportion of paddock utilised were similar to those of distance moved and moving time. Initially, (until approximately 3,500 kg/ha GDM) the rate of change for M1R2 and M2R2 was very small, and increased as biomass declined. All other mobs showed little consistency. The results of the proportion of paddock utilised and biomass amount (Figure 5.13), highlight large variation of the 2nd and 3rd daily records and an increase in the proportion of paddock utilised, which aligns with the high rate of change. This was observed for moving time, to a lesser extent, although not for the moving distance so is unlikely to be related to an exploratory period. The stability of the proportion of paddock utilised metric (Figure 5.15) was unstable at higher biomass values than for distance moved and moving time. The proportion of the paddock utilised had some very high stability values (above 600) indicating this behaviour was one of the least stable.

Social Dispersion

The maximum dispersion occurred most commonly between hours 7 and 8 and 14 and 15 (Figure 5.17) for each of the herds and rotations. This pattern is reflective of typical cattle diurnal activity with a peak in the early morning, post first light, and again in the early afternoon, with some activity in the middle of the night (Arnold and Dudzinski 1978).

The summary of the average IHD, Table 5.7, highlights in rotation 1, as expected, cattle were on average more dispersed in the afternoon than in the morning (Trotter *et al.* 2010b). Conversely, in the rotation 2 IHD was higher in the morning. This suggests unusual behaviour exhibition in the second rotation.

The IHD was the most erratic metric monitored both when considering day (Figures 5.18 and 5.19) and GDM (Figures 5.20 and 5.21). Because of this, the hypothesis was not supported as no trends were observed for any mobs. Days when there were similar responses between mobs were investigated in relation to other influences, such as, weather. However, there did not appear to be a link with any monitored potential effectors.

The lack of expected results was possibly explained by the size of the paddocks. The small paddocks restricted the dispersion of cattle. The variation of IHD was never more than 40 m, and it is likely that paddock size restricted cattle dispersion. Additionally the methods of IHD, which are novel in this research, may not have been appropriate for monitoring spatial behaviour in small paddocks or possibly at all.

As M3R2 appears to be an outlier for several days at the beginning of the rotations, comparisons of behaviours were considered. This mob showed low daily distance moved, low daily time spent moving, a high LRI and low IHD at peak moving time. The high proportion of paddock utilised when moving contradicts the low IHD during peak moving. During peak grazing on these days, it is possible cattle were close together but spread out during other grazing events, or this may indicate that the methods for IHD do not accurately reflect cattle behaviour. Inappropriate methods as a causation is supported by the lack of behavioural pattern of IHD and supports the need for an in-depth study on this metric. Such an investigation should consider the best method for determining accurate IHD and how paddock size may influence social behaviour.

Similarly to distance moved and moving time, the rate of change for IHD (Figures 5.22 and 5.23) is least variable for rotation 2 at high biomass values. An abundance of rate of change fluctuation appeared after approximately 3,000 kg/ha GDM in the morning and 3,700 kg/ha GDM in the afternoon. Intra herd dispersion is the least stable of all the metrics (Figures 5.24 and 5.25). The highest value of slope stability was 895 for M2R1 in the morning and 963 in the afternoon. This mob also presented a high value in the stability of proportion of paddock utilised (Figure 5.15), with 604. Mob 3 in rotation 2 also resulted in a high value (above 600) for proportion of paddock utilised, however, in this metric, appears more consistent with no values over 64 in the morning and 108 in the afternoon. While stability is larger after approximately 3,200 kg/ha GDM, as for all slope stability investigated in this experiment, the stability at low biomass is more variable.

5.4.3 Towards Indicator Metrics

This overall lack of relationship between distance moved and biomass was similar to the results observed in Chapter 3. This supports previous assertions that distance moved alone is unlikely to provide a suitable metric for producers to apply in any real-time remote autonomous animal monitoring system aimed at giving an indication of biomass status.

The time spent moving responded as expected to declining biomass for several mobs. While the pattern of behaviour was only evident for two mobs in rotation 2, the result is still positive. Despite the overall lack of repeated response, it highlights that at least some cattle appeared to be effected by the declining biomass in the same manner as previously observed (Chapter 3). Therefore, this metric, whether derived from speed as grazing or as moving speed (when travelling behaviour is restricted by paddock size) can identify response to biomass in varying situations. While other results may have been hampered by the paddock size, there is evidence to support the success of speed-derived eating behaviour over other metrics when cattle are monitored in small areas. This has positive connotations for the use of such a metric in a range of production systems.

The metric displaying the clearest response to declining biomass in this experiment was the proportion of the paddock utilised. Despite such small areas, all mobs in rotation 2 presented the same response as biomass declined. This response matched that of Chapter 3, with an initially linear trend at high biomass, before a quadratic shaped trend with a sharp increase followed by a decrease as biomass declined. Although this was less obvious for mob 3, and the initial linear phase did not match mobs 1 and 2, the quadratic-like phase was still apparent. It is interesting that despite space being somewhat limiting for other metrics, such as travelling related activities, it did not appear to completely overshadow this spatial behaviour. Regarding time spent moving, this positive result supports the application of this spatial distribution metric in varying environmental and management style situations to monitor biomass decline.

The lack of observable IHD patterns suggests this method is not appropriate as a cattle monitoring metric in this context. Alternatively, this could simply be a function of paddock size. If social dispersion, which showed promise in Chapter 3 (with a slightly different method of calculation), is to be pursued, it definitely requires further research and development of methodology and for paddock area.

The stability for the behavioural metrics was similar in some respects. For all of the behaviours stability is low at very high biomass, but in all cases very high stability values occur and more commonly as biomass declines. Unfortunately, the results of stability did not appear to relate to biomass in a way which could obviously be incorporated into movement-based behaviours to determine key biomass thresholds.

5.5 Conclusions

The hypothesis was supported for two of the investigated behavioural metrics. Expected and repeated moving time and proportion of paddock utilisation trends in response to declining biomass occurred for some mobs. Despite a lack of repetition across all mobs and rotations, this result is positive for the further development of an ASLM system for determining when biomass is becoming limited in a grazing situation.

The lack of repeated behaviours could be attributed to paddock size, time in paddocks and overall biomass amount. The small size of the paddocks limited the expression of certain activities such as distance moved in a day, grazing patch searching behaviour and social dispersion. The cattle could not travel far to reach points of interest as everything was relatively close together. The low distances overall throughout the experiment highlight this. Additionally, social dispersion was probably limited by the cattle not physically being able to spread out as far as they desired during grazing events.

The short rotation time periods may have restricted expression of behaviours associated with declining biomass that were previously observed. The expected results observed in this experiment occurred in the longer rotation (rotation 2), and across a larger range and decline of biomass amount. Additionally, the level of biomass remaining at the end of the rotation may not have been sufficiently limiting, or reached a limiting level too quickly for the cattle to express expected behavioural trends.

All behavioural metrics examined in this experiment demonstrated large variation. Further investigation of this, through absolute rate of change and stability, highlights that variation increases as biomass becomes depleted for all metrics monitored, although the biomass at which variation clearly increases is not consistent across mobs, rotations or metrics. It is concluded that variation observed in the results reflects true behaviour as metric results produced values in the expected ranges and some behaviour trends did occur. However, it is not clear what is driving this variation; weather and human activity was not reflected in rate of change or stability analyses. It is possible that variation could be an indicator of limiting biomass in conjunction with other metrics; however any further research should aim to identify main drivers of this variation, as it appears (from the lack of a clear relationship) that biomass is likely to be a minor contributor.

The lack of consistent behavioural patterns, suggests the behaviours monitored are either not clearly expressed in this grazing situation or did not occur as they were not induced. This has implications for commercial application of spatial behavioural monitoring. To determine whether this lack of repetition was a result of experimental design or environment, further research in varying commercial systems, focusing on diverse paddock sizes, stocking density, pasture type and growth is required. It is likely that a variable (or combination of variables) other than biomass had the largest effect on behaviour metrics monitored in this experiment as the majority of the results did not follow the expected patterns when biomass declines.

Inter mob social interaction was highlighted in the results of the spatial distribution metric. It was evident that cattle were spending time on the fence lines closest to their nearest neighbours. Consequently, any online ASLM system developed for detecting declining biomass must take into account the effect of neighbouring animals on each other.

The most successful metrics related to biomass amount were daily time spent moving and proportion of paddock utilised. For these two metrics alone, repetition of expected behaviour occurred for several (albeit not all) mobs. The effective detection of expected behaviours suggests these metrics would be successful in a range of grazing situations. Daily time spent moving and proportion of paddock utilised should be investigated further in any future research in the development of a commercial on-animal sensor for indicating limited feed availability of grazing livestock.

CHAPTER 6 – GENERAL DISCUSSION AND CONCLUSION

6.1 INTRODUCTION

The aim of this thesis was to identify if spatial and temporal livestock information can contribute to understanding livestock-biomass interactions. The specific intention was to determine if such information could assist producers making management decisions in extensive rotational grazing systems, by relating spatio-temporal animal behaviour to biomass. A link between true animal behaviour and the data collected by GPS tracking devices could be used to help graziers make key management decisions around grazing rotations. Recent developments of commercial livestock tracking systems (Trotter 2012) highlights on-farm execution of such systems are nearing reality. Therefore, the development of models based on key behaviours could enable producers to make real-time management decisions. This could have a profound impact on the production efficiency of grazing operations by improving the ability of producers to match animal needs with available feed and optimise the impact of grazing on the plant system. This would lead to increased pasture utilisation and positive environmental outcomes.

6.2 CATTLE BEHAVIOUR

Cattle distances, time spent undertaking speed-related behaviours, spatial and social dispersion were all monitored with GPS devices. The daily distance cattle moved was always in the expected range, however, did not exhibit a strong relationship with declining biomass. In most cases, speed-based activity appeared to be related to biomass, although when the range of biomass and rotation time was short, this relationship became less apparent. When spatial dispersion was adapted to allow paddock evaluations (proportion of paddock utilised), a relationship with biomass decline was observed. Social dispersion, a lesser understood behaviour of cattle, showed promise, however, a strong, repeatable pattern in response to biomass was not evident.

There was large daily variation for many of the behaviour metrics investigated. As inconsistencies were present throughout this research, it is likely that some day-to-day variation reflects true animal behaviour. Behaviours with naturally large day-to-day variation are more complex for use as a pasture biomass indicator, as inherent variation may be confused with causal change, resulting in incorrect assumptions of pasture decline. Thus, behaviours which normally exhibit low daily variation would be superior for relating to biomass, for example grazing (or moving) time.

Some behaviour metrics exhibited different variation patterns throughout this investigation. In order to successfully monitor behaviour, an investigation into 'normal' day-to-day behavioural variation is required. Further experiments should be undertaken to determine the extent of experimental conditions on cattle behaviour, for example, small paddocks limiting the expression of social dispersion. This would inform if this research should be pursued on specific behaviours in the context of developing a real-time ASLM system.

It is likely that key management aspects including stocking density, paddock size, rotation duration, and plant species influenced the exhibition of grazing related behaviours. These factors were chosen because of the requisite to achieving limiting biomass. In this research, paddock size, stocking density, grazing duration and feed varied. In some cases, unexpected and unexplained results occurred. It is likely that paddock size limited the expression of spatial behaviours as cattle in small paddocks are able to roam the entire area many times within a day and, if desired, conversely reduce exploration as features would be easily remembered. There is little travelling required to access water or preferred areas. Different spatial use patterns occur in small paddocks, for example, more even grazing (Teague *et al.* 2008). This highlights the need to explore cattle behaviour in a large-scale commercial environment, which should be the next step for this research.

6.3 Towards Indicator Metrics

This research was undertaken in the context that, in the future, behaviour related to biomass availability could be useful in commercial ASLM systems. For this purpose, rapid analysis of real-time data is required. This must be considered when determining the best metrics and how they change in relation to biomass. Grazing behaviours (and the normal range of variation) must relate to actual pasture biomass or to proportional changes. Additionally, changes need to be consistently measurable, for example, certain degrees of behavioural change indicating a biomass amount. It was highlighted that an unstable metric may provide a false estimate of biomass availability. So, considering only how cattle behaviours relate to biomass, the most appropriate metrics investigated in this research are time spent grazing (or moving) and the proportion of the paddock utilised, monitored through LRIs. These metrics often exhibited a simple quadratic relationship with biomass, for both forage oats and fescue pasture. If a quadratic relationship was found to be a consistent indicator metric (in a commercial situation) then key thresholds could be developed that triggered an alert to the producer. In the case of a quadratic relationship, the steepness of an incline or decline, or occurrence of a maxima or minima might provide these trigger points.

While the social metrics (MCP and IHD) are very interesting, they are more complex. Intra herd dispersion showed more potential than MCP, as not all animal's locations are required for accurate analysis, as IHD is an average. The presence of behavioural phases has potential to be compared to biomass with change point analysis (Gurarie *et al.* 2009) if pursued as an online tool. To further investigate the potential of the social metrics, future analysis should be undertaken with synchronised devices to improve accuracy of these results. However, high daily variation of dispersion metrics need to be better understood before they could be considered for ASLM.

Due to the complexities of cattle grazing behaviour and the various influences, the use of ASLM systems to assist with commercial cattle management will likely require calibration to cattle type, paddock size, pasture type, and biomass threshold levels to be successful. Despite this, a potential benefit of investigating behaviour trends (as in this research), rather than exact values, is that this method focuses on the change of behaviour. Therefore, the trend of behaviour response to declining pasture availability may not change significantly based on situation variation (i.e. paddock area). The scale of the metric may be larger or smaller; however, the relative shift in behaviour response is the important aspect. Further investigation of cattle behaviour in a commercial context is necessary. A behavioural metric with a repeatable response pattern as biomass decreases in any rotational grazing environment is required. This research has already highlighted that spatial behaviour monitoring in this context may not be appropriate for very small paddocks or rotation time. If this is determined to be true, parameters for minimum paddock size and/or stocking density must be investigated.

Calibration of speed-based behaviours in a commercial setting will be more challenging than distance moved, MCP or IHD. Speed thresholds vary for individual herds (Putfarken *et al.* 2008; Guo *et al.* 2009; Anderson *et al.* 2012; Section 4.3.3) and animals (Section 4.3.3) and the process of validating speed models is complex. This has negative implications for the use of speed-based behaviours in a commercial context due to the extra establishment required and the possibility that this metric may be different depending on log interval, paddock size, pasture species and cattle type. Small variation of these parameters is not likely to largely affect a singular model and so they may be predetermined using knowledge of the aforementioned influences, without the need for specific calibration. Deepening the understanding of these influences on speed would be valuable and needs further investigation before speed-based metrics are pursued.

6.4 Additional Outcomes

As raised in the introduction, this research has potential implications for environmental management. For example, several researchers have highlighted that overgrazing is a common issue which may never be eliminated (Taylor *et al.* 1985; Norton 1998), and should be the focus of pasture management (Hart *et al.* 1993). Overall declining paddock biomass was easily compared with animal behaviour. However, whole paddock biomass does not provide insight into the health across the entire pasture. Thus, a second potential benefit of cattle tracking in relation to pasture biomass would be to monitor animal utilisation of sensitive areas, such as preferred locations which are often overgrazed. Consideration of pasture biomass and LRI maps can inform of repeated cattle visitation to specific areas of a paddock. Comparing cattle behaviour, such as LRIs against known sensitive locations could determine if and when cattle exclusion zones should be implemented. For example, during a grazing rotation cattle could initially have access to an entire paddock until a threshold based on time spent in, or a change in visitation to, sensitive locations is reached. This information could trigger a farm manager to evaluate pasture and determine if cattle exclusion should occur to promote regrowth, reduce overgrazing and prevent erosion. There is an excellent opportunity for exploring this further.

Small paddock size has been identified as a potential limitation in experimental design of this research. Additionally, paddock area is thought to influence cattle adaptation to an environment when areas are large due to time and energy constraints (Bailey *et al.* 1996). Thomas *et al.* (2011) began investigating paddock size as a covariate of distance travelled by cattle. Unfortunately, the results presented don't explicitly investigate whether paddock size influenced distance travelled. Distances travelled were adjusted for the plot size, and the results suggested that relative to paddock size, distance travelled (km/day) was insignificant. Nonetheless, paddock size is likely to have an effect on some grazing behaviours. It would be useful to further investigate this to determine if behavioural patterns vary significantly depending on available grazing area.

It is possible that an accurate picture of the herd may be gleaned without tracking all animals. Mattachini *et al.* (2013) researched how many cattle represent the whole herd. Unfortunately, this research studied the behaviour of dairy cows in a housed management system. To the authors knowledge no studies of this nature have been conducted and in a recent review of studies utilising GNSS behaviour monitoring of grazing cattle. Anderson *et al.* (2013) also identified a lack of research in this area. The behaviour of grazing beef cattle is not directly comparable to housed dairy cows. This is particularly important for this research as the focus is feed availability; a key difference between grazing and housed farming systems. The conclusions that can be drawn from the research of Mattachini *et al.* (2013) are, firstly, it may not be necessary to monitor all cattle in a herd (~40 % in the example), and secondly there is a tried method to determine the proportion of herd monitoring required. This kind of investigation is outside the scope of this research, but has positive implications for the potential of ASLM as a commercial tool for pasture monitoring. Including the influence on research, the number of animals tracked is also important when considering the reason for this research – improving management of commercial cattle production systems. Benefits of monitoring representative animals include lower expenditure to implement and maintain a system, and reduced data storage and processing requirements.

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APPENDICES

APPENDIX A: ANIMAL ETHICS AUTHORITIES

A.1 ANIMAL ETHICS AUTHORITY

Form C **AUTHORITY Nº:AEC08/017**
(Animal Research Act 1985 Section 25)

THE UNIVERSITY OF NEW ENGLAND
ANIMAL ETHICS COMMITTEE

ANIMAL RESEARCH AUTHORITY
And Approval for Animal Experimentation

RESEARCH TEAM: A/Prof D Lamb, Mr M Trotter, Mr M Curkpatrick & A/Prof G Hinch

EMERGENCY CONTACT: 6773 3565
0428 886 088

Are authorised to conduct the following research:

TITLE: Developing a low-cost GPS tracking collar for monitoring cattle & sheep movements.

ANIMALS (number): Cattle & Sheep (50 & 50)

LOCATION(S): Sundown Pastoral Co.-Inverell, Douglas McMaster-Warialda, Kirby, Clarkes Farm & Newholme

PROCEDURES: 1

This authority remains in force from 27/05/2008 - 27/05/2009 unless suspended, cancelled or surrendered.

CONDITIONS: Nil.

This statement must be read in conjunction with the Conditions for Animal Experimentation at UNE as stated on the reverse.

27/05/2008

Jo-Ann Sozou
Secretary, UNE AEC

A.2 ANIMAL ETHICS AUTHORITY

AUTHORITY Nº:AEC10/055

THE UNIVERSITY OF NEW ENGLAND
ANIMAL ETHICS COMMITTEE

ANIMAL RESEARCH AUTHORITY
And Approval for Animal Experimentation

RESEARCH TEAM:	Dr M Trotter, Prof D Lamb, Prof G Hinch, Dr D Savage & Ms J Roberts
EMERGENCY CONTACT:	6773 3565 0447 441 841 or 0429 392 116

Are authorised to conduct the following research:

TITLE:	Spatially Enabled Livestock Management: Increasing Biomass Utilisation in Rotational Systems.
ANIMALS (number):	Cattle (270)
LOCATION(S):	"Laureldale", Cluny Road, Armidale NSW 2350
PROCEDURES:	1

This authority remains in force from 23/07/2010 to 23/07/2011 unless suspended, cancelled or surrendered.

CONDITIONS: Nil.

This statement must be read in conjunction with the Conditions for Animal Experimentation at UNE as stated on the reverse.

23/07/2010

Jo-Ann Sozou
Secretary, UNE AEC

A09/2583

A.3 Animal Ethics Authority

AUTHORITY Nº: AEC11/087

THE UNIVERSITY OF NEW ENGLAND
ANIMAL ETHICS COMMITTEE

ANIMAL RESEARCH AUTHORITY
And Approval for Animal Experimentation

RESEARCH TEAM:	Dr M Trotter, Prof D Lamb, Prof G Hinch, Dr D Savage & Ms J Roberts
EMERGENCY CONTACT:	6773 3565 0447 441 841

Are authorised to conduct the following research:

TITLE:	Spatially Enabled Livestock Management: Increasing Biomass Utilisation in Rotational Systems.
ANIMALS (number):	Beef Cattle (269)
LOCATION(S):	"Laureldale" Cluny Road, Armidale NSW 2350, "Newstead" Inverell NSW & "Sundown Valley", Kingstown NSW
PROCEDURES:	1

This authority remains in force from **08/09/2011** to **08/09/2012** unless suspended, cancelled or surrendered.

CONDITIONS: Nil.

This statement must be read in conjunction with the Conditions for Animal Experimentation at UNE as stated on the reverse.

08/09/2011

Jo-Ann Sozou
Secretary, UNE AEC

A11/94